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USING SUBSURFACE 3D MODELLING FOR PLANNING WATERFRONT CONSTRUCTION IN ARCHAEOLOGICALLY SENSITIVE AREAS

ABSTRACT

Work-stopping archaeological discoveries during waterfront construction further increase awareness of the risks associated with construction undertakings in potentially sensitive areas of historic interest. The increasing awareness combined with the risks themselves introduces a challenge to the waterborne transportation industry. Specifically, a tool is needed that allows for more efficient representation of site data to accurately define an Area of Potential Effects (APE) and the effects to be caused by planned undertakings. As a progressive solution, subsurface 3D modelling shows existing conditions with utmost clarity, in a manner comprehensible to all associated parties. The application provides a focal point for stakeholders, regulatory agencies, and project teams, and in turn, leads to the ongoing and collaborative communication necessary for beneficial project planning and development. Subsurface three-dimensional modelling is unique in nature, and this article attempts to demonstrate its benefit to the waterborne transportation industry on a universal level. The article outlines a progressive approach intended to assist in evaluations of sites as potential points of waterfront access. It offers a

modern approach to the challenge, utilising computer software to compile a site's topographic and subsurface data and effectively present it as a visually lucid three-dimensional (3D) model.

This article is based on the author's paper, "Subsurface 3D Modeling: An Application to Waterfront Project Planning and Site Evaluation" which was the PIANC USA 2008 De Paepe-Willems Award winner and a presentation at the PIANC USA Annual Meeting in June 2008. This adapted version is reprinted with permission.

INTRODUCTION

Significance

Throughout past decades, the unearthing of ancient artifacts and ancestral remains of races indigenous to waterfront regions has brought with it an increasing likelihood of further archaeological findings. A notable

Above: A 3D model of the terrain at a waterfront site, as it would appear if it were excavated in order to construct a waterfront facility: Underlying red, green, and purple masses represent discernible layers of historic interest, which have been detected in the vicinity of the project.

example was the discovery of more than 10,000 artifacts along with more than 300 intact skeletons of the ancient Klallam village, Tse-whit-zen. The discovery was made in late 2003 along the Port Angeles waterfront during construction of a new graving dock as part of the Hood Canal Bridge Project, funded by Washington State Department of Transportation (WSDOT). The graving dock was intended to be used for casting concrete floating pontoons and anchors to be used as part of the proposed Hood Canal Bridge. Construction was halted indefinitely, while WSDOT faced high-stakes decisions revolving around the state's need for a casting facility in conjunction with the right of a resting place for the Klallam Tribe's ancestry. Abandonment of the site severely delayed the project and ultimately amounted to construction losses in excess of \$60 million.

Arguably the most significant archaeological discovery in western Washington State in the U.S. to date, the unearthing of the Tse-whit-zen village is one of numerous occurrences to halt construction of a public works project. In 1994, artifacts were recovered during excavations for expansion of the West Point Sewage Treatment Plant in Puget Sound, Washington. The project

was under a court mandated completion date and the discovery introduced concerns that the public would potentially be exposed to fines for each day of construction extended beyond the mandated completion. In Kahului, Hawaii, construction of the Lahaina Bypass was delayed as a result of recent discoveries of archaeological sites. Another similar occurrence was the series of archaeological findings that delayed revisions to U.S. Route 101 near Astoria, adjacent to the Oregon-Washington border. With the continual emergence of historic discoveries made throughout the state of Washington alone, the importance of a site's history becomes increasingly apparent to waterfront projects everywhere.

As a result of adverse impacts introduced by unanticipated discoveries during construction, agencies are adapting to a more stringent protocol for preliminary site investigation of waterfront construction projects. Requiring deep-site testing is becoming more frequent, along with a greater utilisation of consulting firms during pre-construction phases in order to define and evaluate the Area of Potential Effects (APE) of a given site.

The APE is defined by 36 CFR Part 800 – Protection of Historic Properties, Section 800.16 (Definitions), as “the geographic area or areas within which an undertaking may directly or indirectly cause alterations in the character or use of historic properties, if any such properties exist. The area of potential effects is influenced by the scale and nature of the undertaking and may be different for different kinds of effects caused by the undertaking”.

Conventional modes of site evaluation

Waterfront sites are currently evaluated for archaeological potential by collecting data from a variety of sources, then using the data to create documents that intend to convey to an assortment of parties, an understanding of potential effects to existing site conditions. The presentations and documents created depend on the project's nature, extent, and requirements set by governing agencies. The documents, combined with presentations and other communications, provide the definition of

a site, including the APE and known effects, and serve as basis for opinions and decisions during a site assessment.

Formal methods of site documentation that are often contained in reports and presentations include various archaeological predictive models, geographic information systems (GIS) maps, geologic profiles and stratigraphic sections, and composite representations such as fence diagrams or combinations of models. The majority of archaeological predictive models are essentially maps, indicative of archaeological remains likely to exist in a given area relative to a specific region. “This is a map which cartographically indicates predictions with regard to the situation of (as yet) unknown archaeological sites” (Marrewijk 1997:62).

Predictive modelling is further enhanced by GIS, which captures, stores and analyses data spatially referenced to the earth, and is becoming more popular as a setting for predictive modelling. GIS-based models are capable of revealing spatial relationships of prescribed variables, such as density or frequency, as they are distributed across a broad region. “Readily available digital data and ease of GIS software application facilitate the entire modelling process” (Kvamme: 2006:4).

Different types of predictive models are derived from different hypotheses, but they all share a common trait: They are all accounts of probability. Different types of predictive models are desirable for different purposes. For example, a waterfront developer would have interest in a predictive model useful for deriving statements about the probability of potential finds underlying a specific area within a region of available project sites. On the other hand, an archaeologist participating in a university study that aims to define a region for future archaeological survey might seek a predictive model capable of defining specific environmental parameters that can be used in a layer-identification process.

Archaeological predictive maps are useful to designers when superimposed onto conceptual design drawings by assisting in

site selection and horizontal design considerations. Vertical design considerations are similarly assisted by geologic profiles and stratigraphic sections, which are typically included in waterfront project documents and can be accurately sketched from borehole data or archaeological trenches. However, when section cut lines are established and sections are drawn prior to design development, the sections may be of little or no use to designers, depending on their locations and orientations relative to design features. This is often the case when sections are drawn for environmental purposes before a design is fully conceptualised.

For example, if a section cut is taken in the north-south direction and sketched during an environmental permitting (pre-design) phase, but is located 50 feet to the west of a future utility line that will be routed in the same direction, it will be useless in comparison with a profile drawing of the utility unless additional analyses are conducted to verify material consistencies within the 50-foot separation distance. Probabilistic models such as Markov Chains can be used to simulate stratigraphic sections (Krumbein 1969:1) and to quantify geologic units, although these types of analyses are generally not practical enough to be considered well suited for waterfront construction projects and their associated environmental processes. “Budget and time constraints often undermine the depth to which background investigations can occur” (Naunapper 2006:279).

Project documents created by numerous parties during successful projects of the past prove that available sections and various predictive models can be useful tools during different phases of waterfront construction, particularly when they are overlain by design drawings. An array of information is provided and the associated parties must then use the information as a foundation to apply judgment and form opinions that are ultimately weighed to make decisions. Those parties, some of whom are decision-makers, likely to utilise the materials typically include:

- Cultural resources specialists;
- Environmental specialists;
- Archaeologists;
- Geomorphologists and Geologists;



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graduated from Montana State University and since then has been employed by Moffatt and Nichol as a waterfront planning and design engineer (EIT) in Seattle, Washington. His work typically consists of waterfront planning, design, and topside/underwater inspection of ports, ferry terminals, marinas, and other marine facilities. His paper, "Subsurface 3D Modelling: An Application to Waterfront Project Planning and Site Evaluation" was named the PIANC USA 2008 De Paepe-Willems Award. This award is presented annually by PIANC USA for the most outstanding technical paper prepared on an aspect of waterborne transport. The aim of the award is to encourage Young Professionals to submit technical papers in the field of interest of PIANC.

- Regulatory agencies;
- Engineers and designers;
- Stakeholders including developers, investors, land-owners, indigenous peoples, and interested public.

The primary disadvantage associated with review by different parties of a widespread collection of information is a loss of collaborative communication. As a result, a consultant may need to develop several different drawings, tables, figures, and descriptions to convey a single understanding to multiple agencies.

Aside from difficulties that are inherent to a network of communication, there are other drawbacks to conventional methods of conveying information about a site's APE and the effects. Utilising drawings to fully understand a site adds an unnecessary degree of complexity to the already arduous task of defining an APE and the layers beneath it. The definition of an APE is typically included in a Request for Proposals (RFP) if it is known. If they are not provided an adequate description of the APE in an RFP, proposing consultants

attempting to provide a reasonable scope of work and budget are at a disadvantage.

Plan and section drawings provide a limited amount of definition to a complex formation of materials underlying a site. The possibility of overlooking information when interpreting between plan and section drawings as a means to understanding subsurface conditions introduces an amount of risk. The intricacy in the configuration and arrangement of the materials allows localised occurrences of significant materials to be overlooked. However, interpolation between section views is currently the most commonly accepted form of interpretation of existing subterranean conditions. In other words, attempting to define a 3D formation in two dimensions is insufficient. The exercise is lengthy and intensive, thus the method lends itself to error.

3D site modelling as a progressive solution

Computerised 3D modelling provides a single display of a site, its subterranean conditions, its APE, historic and proposed excavations and disturbances, and any other known features related to potential developments. A 3D model ties together virtually all the information that is typically required of a site, which would otherwise be documented by multiple forms, to convey a common understanding. The application is useful as a stand-alone tool, but also provides standard forms of site definition including plan, profile and section views as desired.

Rather than horizontally generalising across a broad region, such as predictive models often do, it allows specific existing and proposed features within a project site to be seen and exhibits thousands of precise, physical survey points. Another important characteristic of a computerised 3D model is its user's ability to rapidly magnify focus from a broad-based plan, isometric or perspective view to a small area relative to an entire project site. The physical arrangements of features visible at angles between plan and section views are effortlessly captured from as close in or as far away as desired.

A key feature that further sets this 3D modelling application apart from others is its unique user-interface. Namely, its users experience nearly unlimited virtual interaction. Because a 3D model is navigable, it provides users with a unique ability to intensely focus on individual areas of concern. This gives leeway for archaeologists, geomorphologists, geologists, and other specialists to collaborate in front of a projector screen and formalise their notions on "what exists where" while benefitting from each other's expertise. An APE can be defined with a high level of confidence. Moreover, the effects to an APE can be shown and project designers can be involved in these types of discussions to weigh in on design standards, possible deviations and limitations. These discussions are also extremely beneficial all parties faced with programme-level decisions.

The primary advantage of modelling a site in three dimensions is that it provides an accurate replication of subterranean conditions, which makes them visible and understandable to all parties interested in the site's potential development. The application is an ideal means of site representation because it displays known locations of existing data points and the interpolated conditions between them, and makes the intricacies of subsurface material formations clearly visible. The model is navigable and can be used interactively by allowing viewers to orbit and view anything from any angle.

Efforts of translating between plan and section views to understand what lies beneath a site are eliminated. Furthermore, project alternative layouts can be compared by superimposing excavation scenarios into the layers beneath a site and identifying interferences.

The overall influence of 3D modelling on a project is the encouragement of continuous and collaborative communication between interested parties. The application portrays data and information more conveniently and effectively so that communication is maintained amongst all parties and decisions can be made in a timely manner.

APPROACH

Data

The input data used for the inception of a model is important because it serves as the basis of a 3D model. Data is gathered from as many relevant resources as possible to ensure that a set of information is complete and not conflicting. Data obtained from the sources is used to show three pieces of a 3D model: the site as it appears above ground, or the terrain; past, present, and proposed construction excavations; and subsurface conditions, or the layers of soil and other matter below ground. A 3D model typically includes but is not limited to input from the following resources:

Survey

- Basemaps
 - o Topography and bathymetry
 - o Existing utility locations
 - o Existing structure locations

Agency and Project Team Files

- Historic drawings
 - o Former utility locations
 - o Former structure locations
- Alternative project layouts
 - o Proposed utility locations
 - o Proposed structure locations
- Geotechnical reports
 - o Soil boring location map
 - o Soil boring logs
 - Lithologic and stratigraphic data
- Environmental and cultural resources reports
 - o Plan view of APE
 - o Known effects
- Hazardous material reports
 - o Location of contaminated soils
 - o Location of underground tanks

From the data, a system of points is established. Interpolation between data points decreases as the number of data points increases, although some amount of interpolation and judgment will always be required.

In addition to gaining site background from documented data and information, agencies and stakeholders often turn to specialists including geologists, geomorphologists, archaeologists, and cultural resources

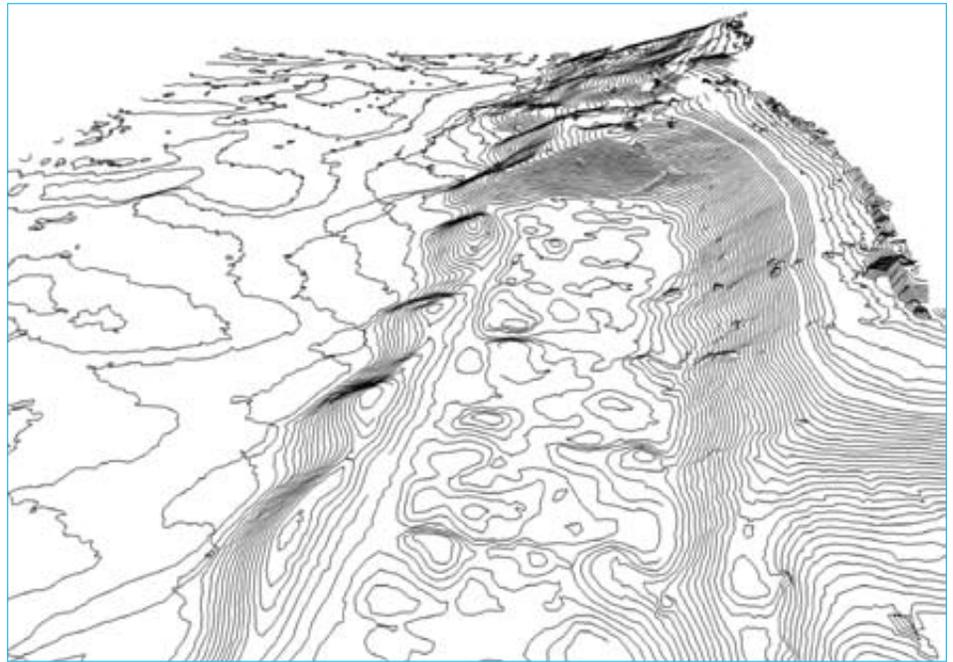


Figure 1. Stand-alone 3D contour lines in a set co-ordinate system.

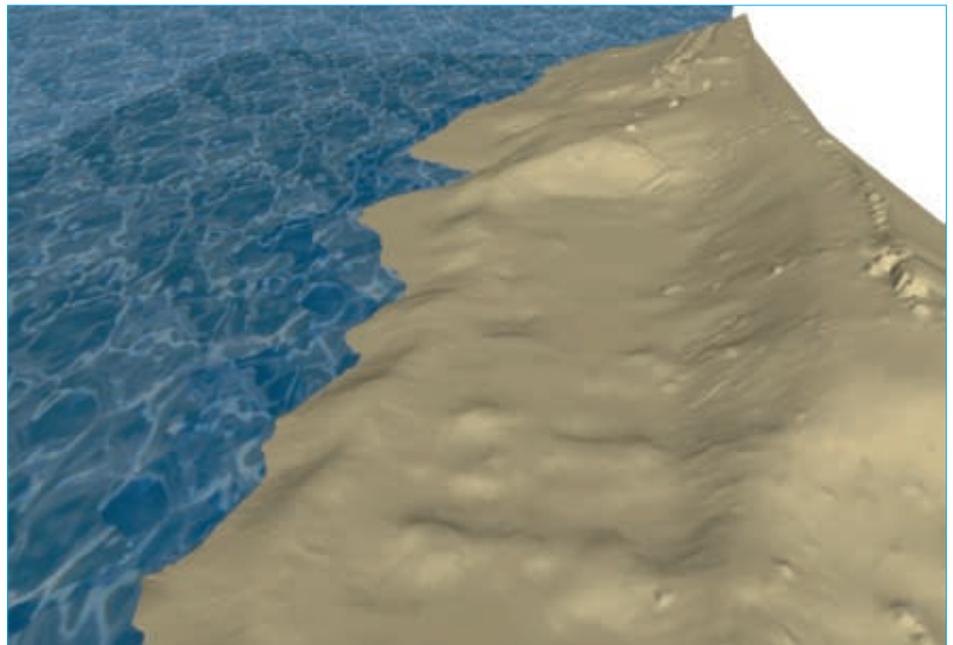


Figure 2. Resultant surface with a tide added in at mean lower low water (MLLW).

specialists for further rationale and input to a site's definition. For instance, a geomorphologist might theorise on the chronological formation of a site based on definition from the above data combined with knowledge of surrounding geology, past cultures and their associated uses of the area.

Terrain development: Application of survey data

Figures 1 and 2 show progression of a site's terrain. Figure 1 shows the first stage, stand-alone 3D contour lines in a set co-ordinate system. Figure 2 shows the resultant surface, with a tide added in at mean lower low water (MLLW).

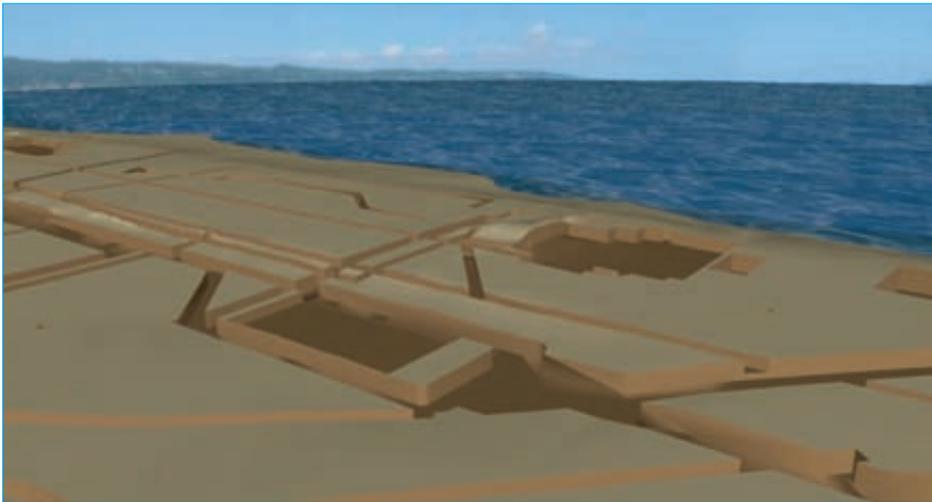


Figure 3. Site excavations as seen above ground.

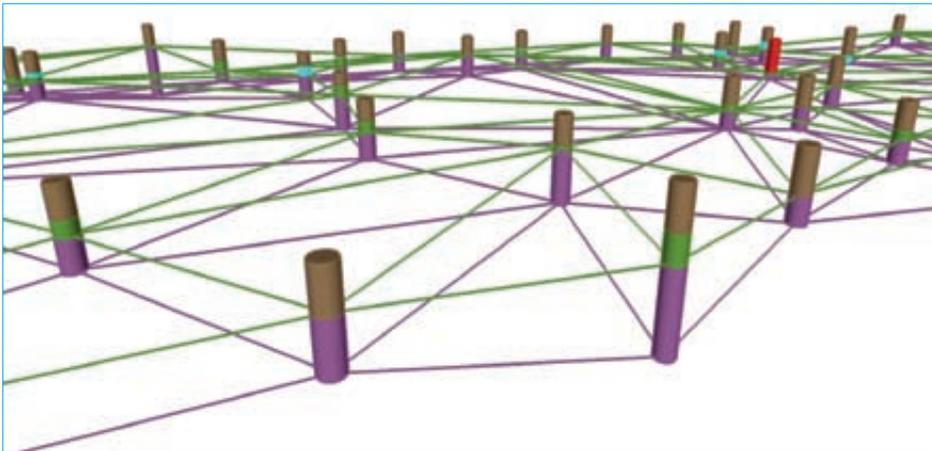


Figure 4. Upper and Lower TINs for a soil layer.

A co-ordinate system and other vertical and horizontal references are established. From the contour lines, a surface is generated. Figure 2 demonstrates the relationship between the survey contours and the modelled landscape.

Construction excavations: Application of drawings

Plan view locations of site features are known from drawings. From drawings, excavations are added into the landscape as shown in Figure 3. Trench and foundation excavation dimensions for features of proposed alternatives are estimated. The goal is to display the effects introduced to a site, and for some projects, excavations are not the only potential effects. Vibrations from pile

driving, soil displaced for drilled shafts, and soil contamination are undertakings that potentially alter the character of historic properties.

Subsurface conditions: Application of borehole data

Boring logs are first evaluated to identify layers in each sample. The layers, defined by numbers in spreadsheets, are then named and categorised. For lithology and stratigraphy, top and bottom depths of each defined unit as it occurs in each borehole are included in the spreadsheet.

A triangulated irregular network (TIN) is created for the upper and for the lower surface of each layer. Figure 4 shows a set

of soil borings in 3D, and the TIN lines used to form the upper and lower surfaces of a layer. The soil sample widths in Figure 4 are exaggerated so the colouration is visible. The colours represent instances of different units, or layers detected in each sample.

The layer bound by the TIN lines in Figure 4 is designated by purple. The green lines represent the upper TIN surface and the lower is represented by the purple lines. The TINs show how data points between actual boring locations are interpolated.

The presence of every unit will not necessarily be detected in each boring, which leaves gaps in some layers. More specifically, it is common for some borings to indicate presence of all known units, while others exhibit only two or three as seen in Figure 4; therefore, some of the layers have openings, or discontinuities within the network borings.

Insignificant layers are typically not shown in the model. For example, a consistent layer of fill existent from past site uses is commonly detected in a group of borings. Such layers are located above the more significant layers. Fill can be modelled and shown if desired, although doing so is unnecessary for all intensive purposes and its visualisation will likely be toggled off during the majority of the time spent viewing the model.

Input from specialists

Commonly one or more layers of special interest which require special consideration by experts are found to exist throughout most historical sites. These layers often establish the APE.

A common example of such layers is a "midden", a word used by archaeologists to describe a deposit containing shells, bones, or other evidence of human settlement. A midden is often a source that leads to further archaeological investigation after it is discovered. A latter section demonstrates how 3D modelling lends itself to assist specialists in the layer definition process.

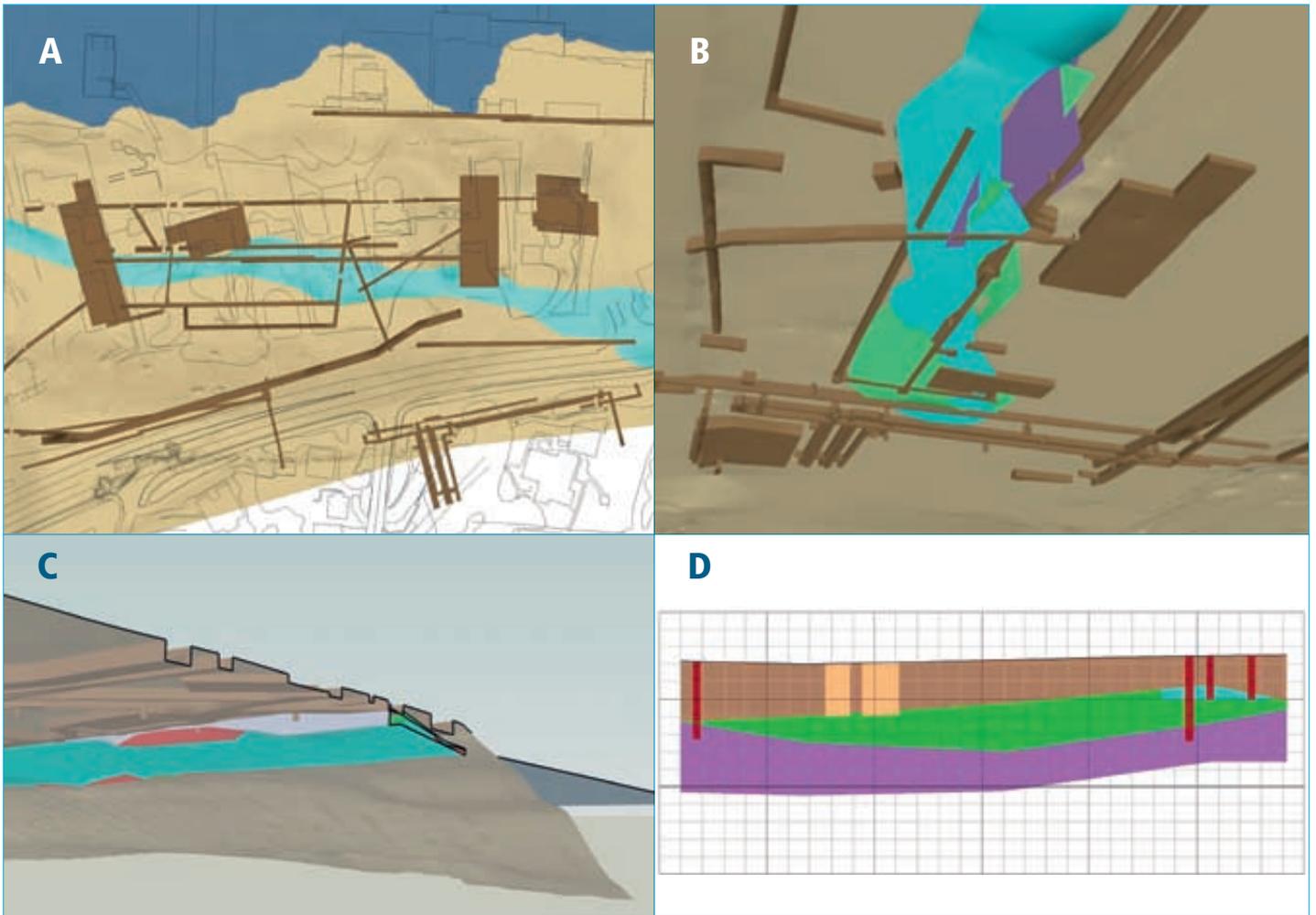


Figure 5. **A:** Plan view, **B:** subterranean view, **C:** section cut and **D:** cross section produced from model.

VISUALISATIONS, USES AND BENEFITS

Visualisations

A 3D model is interactive. Viewers can navigate or orbit around a 3D model and zoom in and out in any area as much or as little as desired. The application also saves a variety of views specific to individual needs. The model can be viewed through a perspective or a non-perspective standpoint. Perspective views are more realistic in comparison to isometric views. When section cuts or plan views are desired, a non-perspective view is favorable. Figure 5 shows a sampling of different views.

Existing features visible above ground can be shown if desired, but take away from the application's overall intent. A navigable model is extremely useful for viewing

subterranean arrangements of features and effects. Viewers are able to look up toward the underside of the surface, as demonstrated in Figure 5. A 3D model also allows for individual features to be toggled on or off during a viewing session and provides different view renderings that can be continuously changed throughout a viewing session. Renderings include but are not limited to frame-style views that clearly show TIN lines, X-ray views, or views that show surfaces but exclude lines and edges.

Use for comparing project alternatives

Modelling is a beneficial application for viewing alternative construction impacts to an APE. Stakeholders prefer to avoid impacts near a sensitive area whenever feasible; their needs can be facilitated with a 3D model that provides a project team

the ability to fully view and consider different options. Below-ground views are especially useful because they allow a project team to evaluate the overall risks of disturbing an area by choosing one alternative over the other. Provided a graphical representation of future excavations combined with existing subterranean conditions, the project team can discuss layer avoidance strategies.

For example, Figure 6 shows a midden overlain by soil displacements for two potential utility layouts. Trenching for an initial utility design layout is shown in brown, a midden in turquoise, and trench excavations for an alternative route are designated by red. The brown trench clearly intersects the midden in two locations, so the route shown in red is planned as an avoidance strategy.

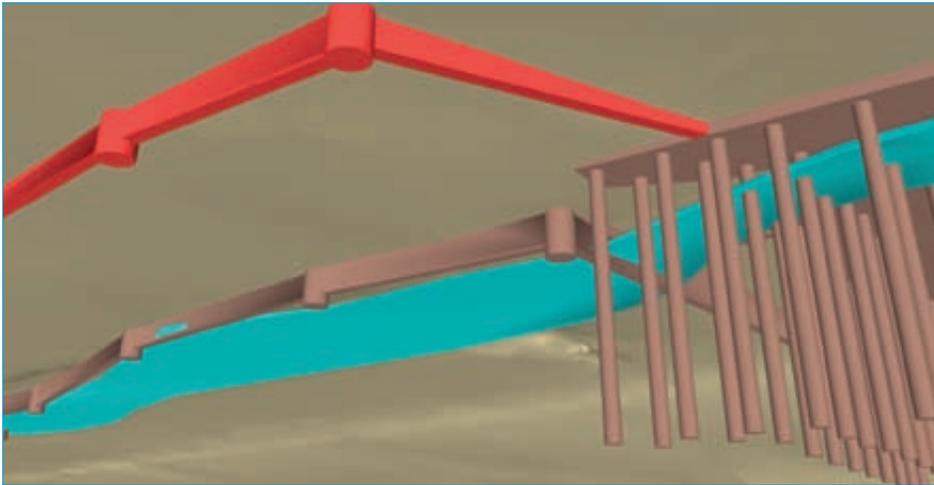


Figure 6. Subterranean view:
A midden overlain by soil displacements
for two potential utility layouts.

Uses by specialists

3D modelling is especially beneficial when a subsurface layer requires special definition. A 3D model uses borehole data and TIN lines as basis for specialists to apply judgment to precisely define a sensitive layer. The application promotes an iterative process of layer alteration, so layers reach final definition with a high level of confidence. Sensitive layers typically undergo several iterations before reaching a satisfactory definition. During the process, iterations are each documented and clearly viewed by agencies.

Figures 7 through 10 illustrate a process commonly used to modify a layer with input from specialists. Figure 7 depicts a network of 27 borings in an APE. Three layers are detected in the network. Layers 1, 2 and 3 are designated by brown, green, and purple, respectively. Say that layer 2 is determined to be a midden. Only 8 of the borings indicate presence of Layer 2. These 8 borings are connected by the red lines. Horizontal distances between the 8 borings are designated as d_1 through d_7 .

The midden is initially defined by the TIN lines shown in Figure 7. The resultant definition is shown in Figure 8.

Vertical and horizontal constraints must both be considered when strategizing avoidance measures. A site near the waterfront is typically limited by grade on at least two sides: The shore and the land access point. For example, a site planned for a new pier and roadway is vertically constrained. A new roadway would have to tie into an existing street at some point, which limits the amount of grade to work with. Transition between the new roadway and pier would limit the elevation for an access point to the pier. The second limiting factor is the use of the pier. For waterside access to the pier, vessel freeboard elevations must be considered and limit the design elevation of the pier.

To avoid conflicts to potentially sensitive areas while recognising limiting factors, there are essentially two options: Shift construction horizontally or adjust vertically (in lieu of shallower excavations). Utility

layout and small structure designs have the most flexibility. Changes in the design of pile supported structures, buildings, and bridges are more difficult because the structures often cannot be moved without rearranging an entire project.

Horizontal movement of utilities, or rerouting conflicting runs, requires analysis and co-ordination with governing agencies to determine the possibility and feasibility of doing so for individual lines and tie-in points. To adjust utilities vertically requires designing systems to a higher elevation, which usually means raising the proposed grade elevation to maintain minimum depths of cover above the utility lines. Optional grading and utility layouts vary between each alternative, so combining different utility and structure layouts gives leeway for many different scenarios aimed at avoiding a sensitive area; a 3D model facilitates the process.

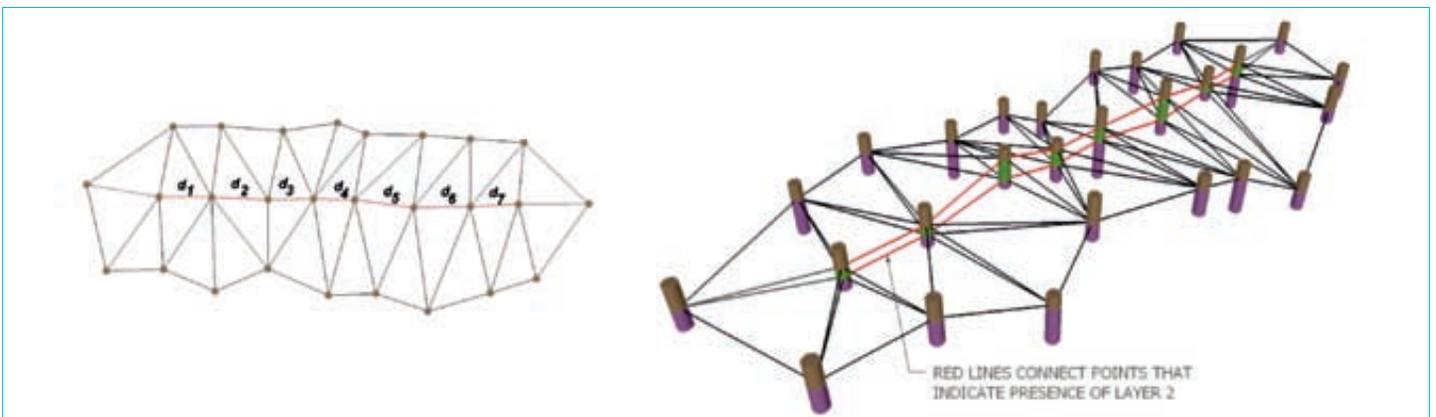


Figure 7. Plan and perspective views of a network of borings and TIN Lines.

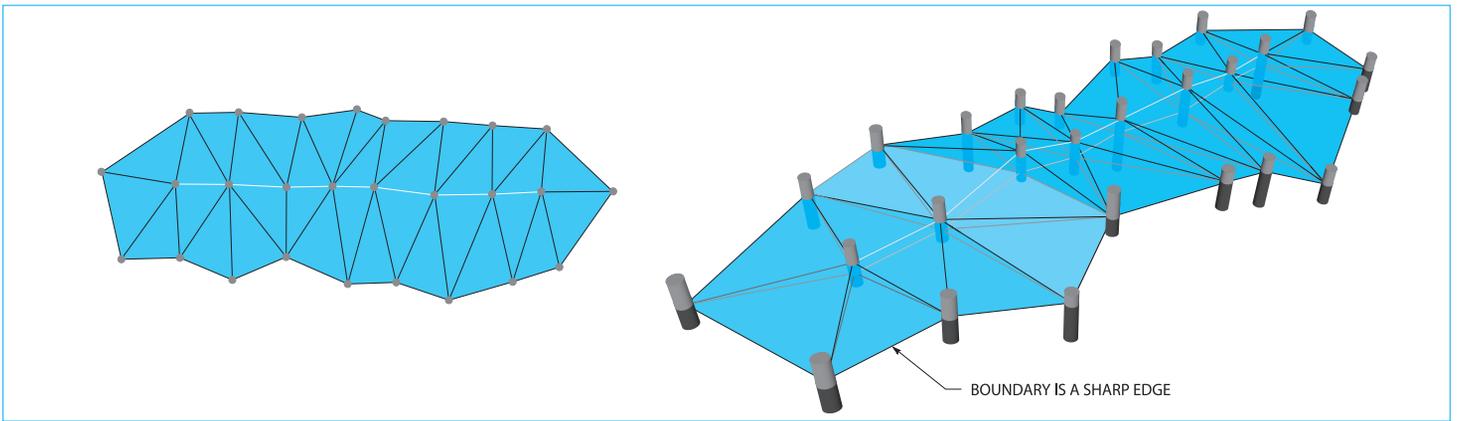


Figure 8. Plan and perspective views of Layer 2.

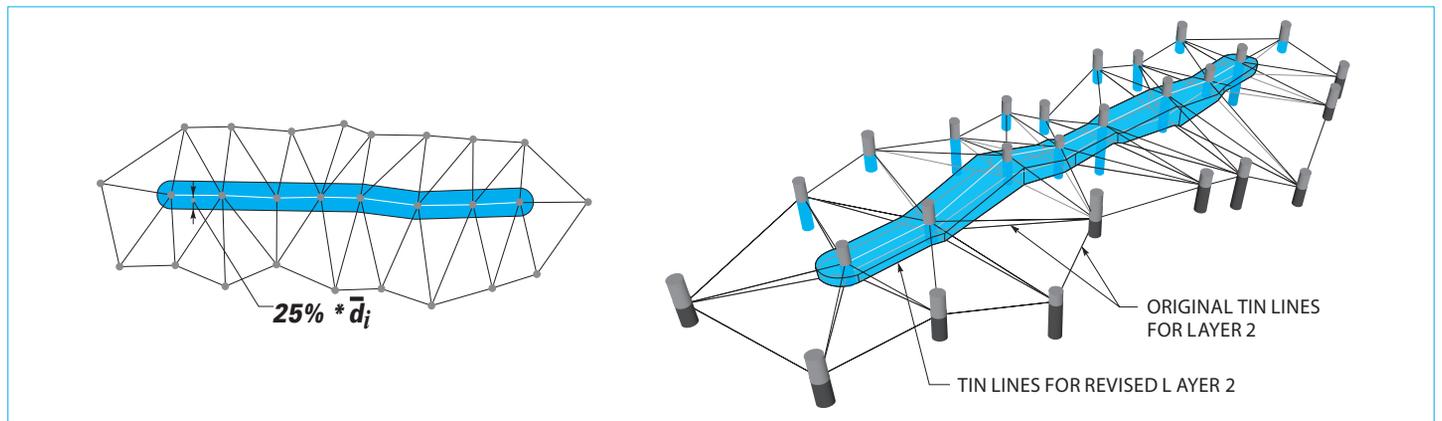
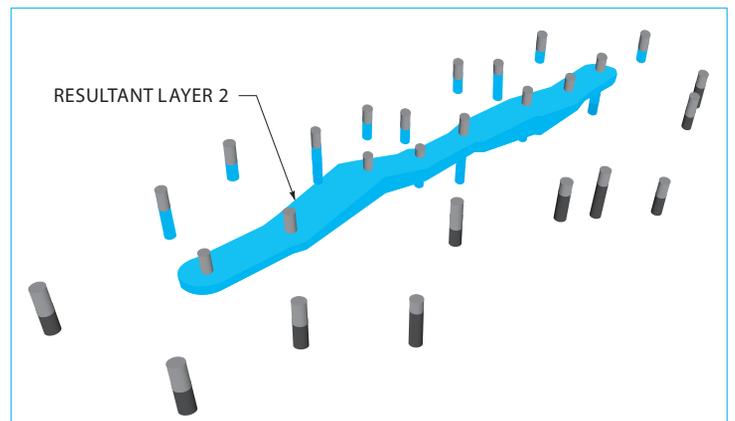


Figure 9. Post-modification plan and perspective views of Layer 2.

If the distance between borings is excessive, the likelihood of the midden existing as shown in Figure 8 is low, thus the definition is unrealistic. More precise definition is sought in lieu of requesting additional borings. One common strategy is to calculate 25% of the average distance between each of the eight consecutive points known to have a midden thickness greater than zero. The 25% factor is common to the industry because it has proven reasonably accurate and conservative in the past. The point group is horizontally offset by the calculated value, which adds TIN lines as shown in Figure 9. The final definition is shown in Figure 10.

Several factors should be taken into account during a layer's definition process. The number of borings and size of the sampling grid (sampling density) determine the accuracy of the analysis. Accuracy increases with higher density, so

Figure 10. Final definition of Layer 2.



conducting additional field sampling is a favourable course of action when project schedule and budget permit. If the 27 samples shown in Figures 7 through 10 were surrounded by hundreds of other borings, or if the borings were densely spaced, Figure 8 might be a more reasonable definition than Figure 10.

Other factors that should be considered include the size and nature of the project, the extent of the potential effects caused by undertakings, the location and arrangement of the layer relative to the water, the significance of the layer itself, and most importantly, the level of acceptable risk. For instance, if the definition given in Figure 10 is

deemed more realistic than that in Figure 8, the latter is still a more conservative shape that would better avoid risk when excavating around the material.

The risk of uncovering archaeological finds near a layer depends on how conservatively the layer's boundary is defined. The risk is generally greater along the shore-side boundary than it is on the side exposed to open land, so a combination of Figures 8 and 10 could be applied, with the full boundary assumed on the water-side, and the 25% factor applied to the land-based edge.

More complex definitions are also possible to achieve. Probabilistic methods of volume definition are available, but are not always desirable. As a method becomes more complex, the time and data required for analysis increases. Complex statistic and probabilistic approaches are often used in subsurface applications such as quantification of a soil contamination volume or estimation of a strata deposit. A special paper presented by John Dennison at the 82nd Annual Meeting of the Geological Society of America in 1969 demonstrates applications of statistics to geologic field work and how they relate to quantification processes. The paper is included in *Quantitative Geology*, by Peter Fenner (1972). Complex probabilistic approaches are generally better suited for applications involving highly irregular geometry and those in which the quantity of material is more significant than the boundary. "Many of the constructions and deposits for which volumetric data would be valuable are not of regular shape, so their volumes are not easily calculated by use of standard geometric formulae" (Sorant 1984:599).

There are also far less complicated methods of definition than the one outlined in Figures 7 through 10. For example, say a predictive map is used because sample data is insufficient. In this case a hand-sketched boundary around a high-sensitivity zone indicated on the map could suffice in combination with an assumed uniform depth. However, such methods can be highly inaccurate and overly conservative.

CONCLUSIONS

Decreasing site availability leads to increased consideration of subterranean conditions at potential waterfront project sites. Conditions beneath potentially sensitive sites are further regarded because of a timeline populated with instances of construction-stopping archaeological discoveries. Such instances strongly suggest the need for a more progressive tool that can be used by a project team to fully understand subsurface conditions prior to commencing with any high-risk undertakings.

The intent of three-dimensionally modelling a site is to provide an unhindered definition of its Area of Potential Effects (APE) and known effects so collaborative project-planning decisions can be made with a high level of confidence. Application of a 3D model makes efficient use of the information known about a site and allows it to be fully understood by stakeholders and regulatory agencies, specialists, designers and engineers. The overall concept is straightforward: A single 3D representation of the existing site and its subsurface layers, its historic excavations and proposed construction impacts. The approach also takes into account the significance of a site's planned uses, historic and geologic developments.

Conventional modes of conveying data and providing subsurface definition to evaluate project sites are useful to a limited extent, but lack the benefits appropriate for high-stakes waterfront construction projects. The 3D modelling application can produce the same forms of media common to the majority of past project documentation, including plan and profile views, so utilisation of past methods is enhanced, rather than precluded. Providing adequate assessment of an archaeologically sensitive area is an undertaking of utmost importance and should not be undervalued.

3D modelling promotes the ongoing, collaborative communication between agencies, stakeholders, specialists, designers and engineers necessary to adequately assess a site. Several goals are achieved by enabling all parties to interactively view a variety of information and concepts.

Overall, data is more efficiently used to allow for planning of alternative project layouts and options, which minimises the risk of disturbing potentially sensitive areas.

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