Subsurface Modeling and BIM

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ABSTRACT

This paper evaluates how subsurface database management fits into and complements the traditional procedures and practices in geoenvironmental engineering and enables easier interoperability with other engineering disciplines. The presentation reveals how subsurface data, when properly managed in geoenvironmental database can be easily turned into information and supplied to engineers in various disciplines in a desirable form that can be quickly and easily interpreted. Managing and modeling subsurface data consists of many aspects and this presentation places an emphasis is placed on modeling of subsurface strata, Building Information Modeling (BIM) and an interdisciplinary approach.

RÉSUMÉ

Ce document évalue comment la gestion de bases de données souterraines s'inscrit dans les procédures et pratiques traditionnelles en ingénierie géo-environnementale et les complète et permet une interopérabilité plus facile avec les autres disciplines d'ingénierie. La présentation révèle comment les données souterraines, lorsque proprement gérées dans des bases de données géo-environnementales, peuvent facilement être transformées en information et être fournies aux ingénieurs de disciplines variées dans une forme désirable qui peut être facilement interprétée. Bien que la gestion et la modélisation des données souterraines consiste en différents aspects, cette présentation met l'emphase sur la modélisation des strates souterraines, la modélisation des données du bâtiment (MIB) et une approche interdisciplinaire.

1 INTRODUCTION

Large infrastructure projects, ever increasing stringent geotechnical and geoenvironmental regulations, and sustainable design initiatives require an interdisciplinary approach for design, construction, maintenance and operation of infrastructure objects that involve geotechnical and geoenvironmental data.

Large infrastructure projects require a massive amount of data that needs to be collected, analyzed, processed, reported, and exchanged among stakeholders involved. An increasing number of Architecture/Engineering/Construction (AEC) companies treat subsurface exploration data as an asset, and incorporate it in Building Information Modeling (BIM).

Management, reporting and modeling of subsurface data as a part of asset management and BIM is discussed and evaluated as a complementary approach to traditional geotechnical and geoenvironmental engineering practices.

2 MANAGING SUBSURFACE EXPLORATION DATA

Geotechnical organizations and companies often struggle with the quantity and quality of data collected on site or produced in laboratories. Until a couple of decades ago most data collected and processed was on paper. Much has changed, including an increased quantity of data to process, the need for quality control and quality assurance, and the size and complexity of projects. A few things contracted: budgets and deadlines. All of these factors have strained traditional paper-based workflows.

The step many organizations took to update their data management and reporting was adopting generic, readily-available pieces of software such as Microsoft Office Word or Excel, or Computer Aided Design (CAD) software. While turning data from analog into digital form helped in some respects, it fell short in providing engineering decision-making tools. Soon inadequate technology and tools made tasks even more time consuming obscuring the primary focus of the engineering discipline. Data saved in these formats was difficult or impossible to reuse. It behaved, for the most part, as electronic paper, and every time this data needed to be passed down the project workflow, it meant data re-entry, essentially defeating the purpose of going digital.

The next step in the transition and evolution of data management and reporting was a development of specialized software based on a database, to include calculations, local design codes, quality assurance (QA) and quality control (QC) tools. The significance of this approach is that it addresses three important points; (1) data was structured in a database, (2) data was more transparent or easier to use by discipline experts, and (3) data was much easier to exchange among stakeholders using different software within different engineering disciplines on the same project. Further this kind of approach forced establishment of subsurface data interchange formats. One such data exchange format being instituted is Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS, diggsml.org). The major breakthrough at this level of data management evolution and reporting is a centralized database and data reusability. Having field and lab data properly structured in a database laid a foundation for further advances in intelligent handling and management of subsurface data such as data acquisition on mobile devices, direct publishing of subsurface data in geographic information systems (GIS), treating data as an asset, consuming it in BIM, and utilizing data interchange formats to name a few of the benefits. In this paper two aspects of subsurface data management are discussed – asset management and BIM.

3 MANAGING SUBSURFACE DATA AS ASSETS

Once subsurface data is collected, reported on, and used for infrastructure design, its worth in many respects persists. Many soil properties or stratigraphy have no expiration date. Significant resources are required to explore a subsurface, and acquired data has value for a long time after a project is completed. Even in localities where new subsurface exploration is mandated for every new project, legacy subsurface data may be used for preliminary analysis or to optimize required resources for the new exploration.

Asset management is specified by the International Organization for Standardization, ISO 55000:2014 standard in particular. Asset is defined an '*item, thing or entity that has potential or actual value to an organization*'. Most subsurface exploration findings have permanent potential or actual value. For example soil-samples, well-contamination data, lab data or stratigraphy fit the asset definition of an asset. Further, asset management is defined as '*coordinated activity of an organization to realize value from assets. Realization of value will normally involve a balancing of costs, risks, opportunities and performance benefits*'. Based on best industry's practices subsurface exploration data's value may be fully realized only when data is aptly structured, stored, is reusable and interchangeable, in other words, managed by a database.

Properly and proactively managed assets help articulate engineering and business goals into optimized, cost-effective, and collaborative processes and workflows. In the framework of asset management, subsurface exploration data is valuable not only for immediate stakeholders involved in data acquisition, analysis and reporting, but also for all stakeholders in an infrastructure project lifecycle, all the way through the operation and maintenance (O&M). Treating and managing subsurface data through asset management processes, techniques and tools has become mission critical for large organizations with intensive operations that deal with sizable amounts of data.

As demand for better understanding and visualization of subsurface data has increased, and a collaborative approach increasingly has been preferred if not mandated by the industry, a synergy with BIM has emerged.

4 BUILDING INFORMATION MODELING (BIM)

The notion of Building Information Modeling (BIM) originated in the 1970s. The term BIM first appeared in a 1992, but BIM really took off in early 2000s. According to The US National Building Information Model Standard Project Committee '*Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.*'

Conventional building design, and infrastructure design in general, has been reliant upon two-dimensional (2D) technical drawings. That continued long into adoption of Computer Aided Design (CAD) practices.

BIM extends object and infrastructure handling not only to three-dimensional (3D) design, but also adds a time component to it as the fourth dimension (4D), and cost as the fifth dimension (5D). Simply put, BIM positions an infrastructure object in the context of space, time and cost–benefit analysis (CBA) from its earliest conception to demolition. There are many interesting aspects of BIM to observe. Some of them are briefly discussed here.

BIM manages data in databases. The databases are shared and interactive among all stakeholders. Data can be turned into discipline-relevant information by other industry-specific software applications. This is a powerful concept allowing for a ripple effect and what-if scenarios leading to optimal design or operation solutions in the shortest time.

BIM allows the automatic generation of drawings and reports, design analysis, schedule simulation, asset and facilities management, and collaboration among multiple disciplines, multiple companies, and multiple project phases.

While BIM does not exist outside of Information Technology (IT) and software in general, BIM is not a single software application. BIM is the implementation of software tools used for generating and exchanging intelligent models based on structured federated data in a collaborative environment.

It is important to state that the scope of BIM expanded over the years beyond just buildings, and today can be applied to all types of infrastructure assets, including subsurface data.

5 PUTTING IT IN A CONTEXT

It is not uncommon that subsurface exploration findings, both field and laboratory, are routinely submitted in the form of paper or electronic paper reports. For example, borehole logs, well construction reports, environmental logs, and lab reports are frequently submitted either as a hard copies or as electronic equivalent of hard copies in the form of pdf, Excel, or Word files. These kinds of reports are of great value to professionals who produce them. For example, borehole logs are designed and shaped in such a format that the information conveyed is relevant to and easily understood by geotechnical community. From the visualisation stand point, however, the borehole log is a one-dimensional (1D) report showing information down the borehole depth. With current information technology advancements, especially in asset management and BIM technologies, data visualisation can be significantly enhanced, and subsurface data shared with other disciplines in a collaborative, interactive environment.

Soil samples collected by a geotechnical engineer is often and in many respects an asset to environmental professionals, geologists and perhaps mining specialists. This benefit is mutual. Subsurface exploration data collected by environmental professionals, geologists or mining professionals could be an asset to geotechnical engineers. Consequently managing and consuming subsurface data calls for a collaborative ecosystem. One example is the USGS (U.S. Geological Survey) website, a frequent stop for many professionals, not only geologists. Also it is important to emphasize that geotechnical, environmental, geology and mining professionals are stakeholders who collect, interpret and own subsurface data. But they are not the only stakeholders who consume such data.

Subsurface data is commonly published by GIS professionals on interactive maps for everybody to view, search, query, filter or extract. Civil engineers routinely use subsets of geotechnical data for infrastructure projects such as road, railroad and land development projects. Subsurface exploration data in the form of soil properties is essential to geotechnical and structural engineers who design retaining walls, dams, slope stability, and foundations for building and bridges. Professionals in water resources, hydraulic and hydrologic design need subsurface data in the form of hydrologic soil designation on topography maps, hydraulic conductivity or soil stratification.

Subsurface exploration data collected by geotechnical, environmental, geology and mining professionals is an asset not only to their rightful owners but for many other stakeholders in infrastructure design, construction maintenance and operations. It is not unusual that processes and workflows are still compartmentalized. This phenomenon is known as the silo effect. As data is moved from one stakeholder to another in paper or electronic paper form, it frequently requires re-entering, as opposed to sharing it from a central source in a collaborative environment. Data re-entry is error-prone and time-consuming in iterative processes such as infrastructure projects. On the other hand when data is managed in databases it allows for a collaborative environment in which data is entered once, remains up to date, and any subset of it is easily extracted by any stakeholders in a project lifecycle and turned into discipline-specific information.

Figure 1 shows a borehole log on the far right and a subset of the borehole log information placed in an infrastructure context. While a borehole log is a native way of visualising data among geotechnical professionals, other stakeholders may experience problems interpreting it or may not need all data presented. This is a situation where asset management and BIM become valuable, allowing for retrieving relevant data subsets and implanting the data into the appropriate context.

Normally, investors and project managers try to ration project budgets. This routinely translates into a minimal subsurface exploration effort required by legislation. In particular for geotechnical subsurface exploration, this may commonly lead to specifying a minimal number of boreholes as required by legislation. With such limited data a construction site in its entirety needs to be classified. Accordingly, most subsurface explorations undergo three distinct phases; (1) data acquisition, (2) data analysis, and (3) data interpretation. Hence one needs to distinguish between factual data and interpreted data. A typical example of factual data is data produced from a soil sample collected on the site, while typical example of interpreted data is stratigraphy. Stratigraphy is interpreted formations that is, distinct subsurface strata

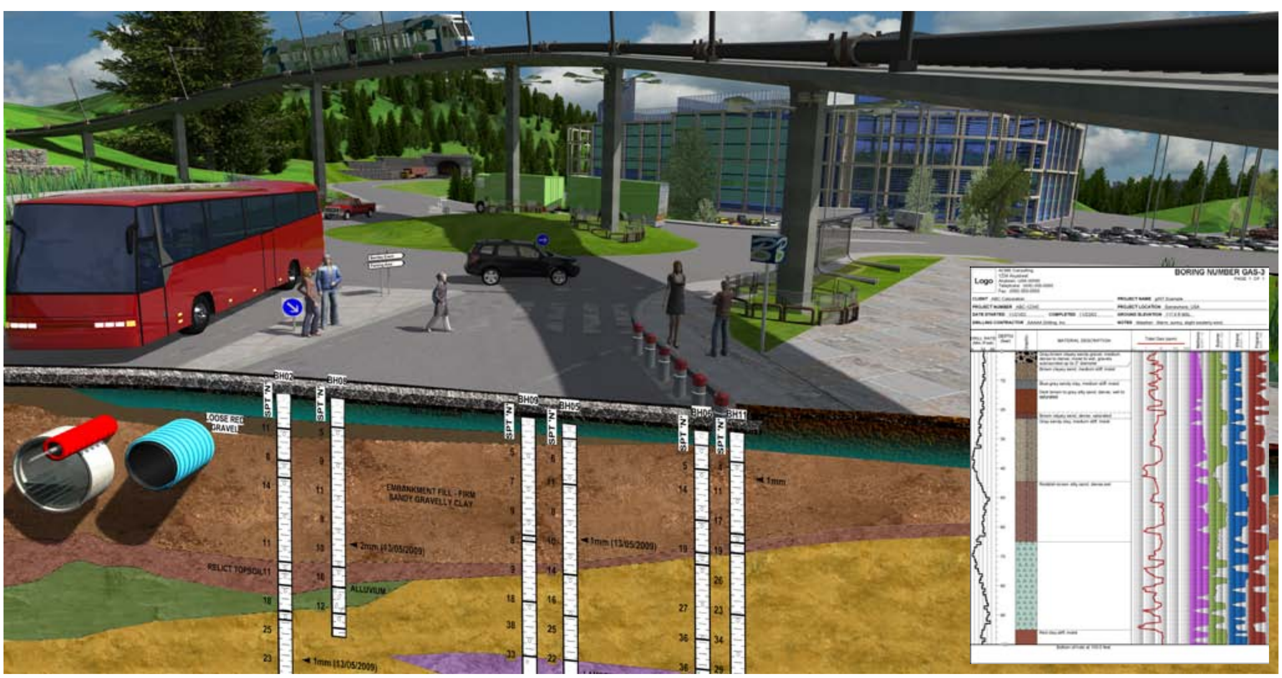

Figure 1. Placing borehole log information in an infrastructure context. Notice limited number of boreholes and interpreted stratigraphy.

which are consistent between boreholes. Notice in Figure 1 continuous stratigraphy developed based on discrete borehole locations.

Data acquired in the field during subsurface exploration is factual data. Such data is then analysed and interpreted. For the purpose of delineating stratigraphy data is interpreted in the form of interpolation and extrapolation. Identifying a borehole stratigraphy is one of the primary tasks for a geotechnical engineer. It is a good practice that such interpretation is supervised by a seasoned professional because resulting stratigraphy is crucial information for most stakeholders. For example identifying fill or clay strata may be critical to geotechnical engineers in analysis and design of retaining walls and foundations. A rock stratum is typically critical to civil engineers for cut/fill analysis in a road and railroad design, because cutting rock is frequently prohibitively expensive. Strata affected by a contaminant plume are critical to environmental professionals for soil replacement and clean-up jobs.

Typically, defining stratigraphy starts with borehole log based soil sample frequency down the hole and based on data analysis by the seasoned professional. This kind of stratigraphy interpretation on a borehole log is linear (1D). From a BIM perspective there is a compelling reason to visualize subsurface findings as 3D objects with business properties or attributes. For example a soil sample may be presented as a 3D object with its attributes such as soil type, N-blow values, or water content. A borehole may be presented as a 3D object with attributes such as soil samples, stratigraphy delineation, location and elevation, etc. Such 3D objects could be natively incorporated into BIM for all stakeholders to consume. Multiple borehole objects with delineated stratigraphy attributes present a foundation for generating 3D stratigraphy in the form of surfaces. BIM has a number of tools to interpolate or extrapolate continuous 3D surfaces based on a number of discrete boreholes. In BIM such 3D surface objects are often referred as to Digital Terrain Model (DTM). Creating DTMs based on discrete boreholes is not necessarily easy and straightforward, but if properly handled it can produce tremendous benefits for all stakeholders in the project. Next, modeling of subsurface strata as DTMs is discussed.

6 INTERPOLATION METHODS

After essential subsurface reports such as borehole logs, well logs, and laboratory reports have been produced, it is not uncommon for subsurface exploration professionals to start to interpolate data among boreholes, or occasionally to extrapolate it beyond exploratory borehole cluster but within site boundaries. Many stakeholders seek straightforward insight of subsurface conditions, and a delineation of stratigraphy is a universal lingo. Stratigraphy is frequently presented in the form of 2D subsurface profiles outlining strata in CAD software, drafting it manually or semi-manually. See Figure 2 – Subsurface Diagram. This kind of subsurface profile provides clear understanding for all stakeholders. In

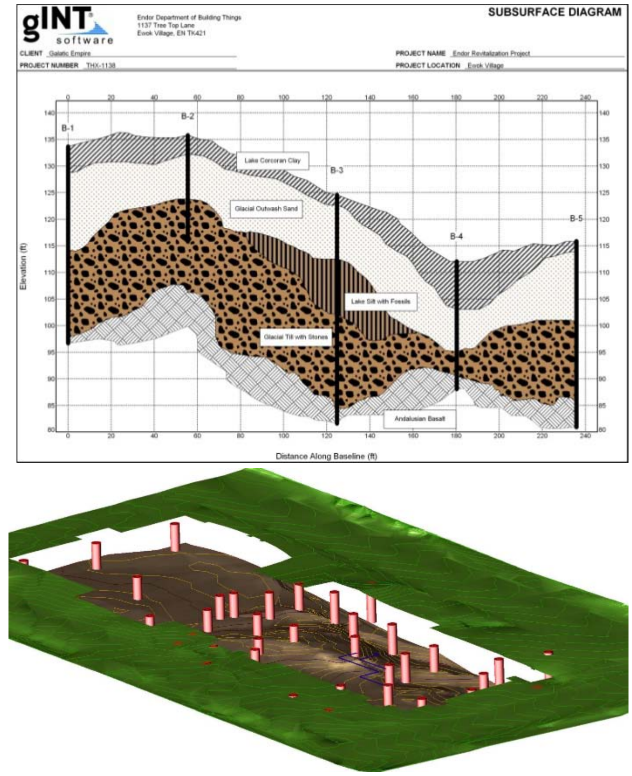

Figure 2. 2D CAD profiles vs 3D models

addition to required experience, developing such a subsurface profile in CAD takes a fair amount of time. The resulting profile is static, which means it cannot be easily or automatically updated. Because the profiles are static, if additional data is supplied later (such as additional boreholes drilled in the vicinity), it again requires fairly significant effort to incorporate newly added data and modify the subsurface profile accordingly. In order to understand the subsurface condition of an entire construction site, multiple profiles need to be created criss-crossing the site. Creating, editing, and updating multiple subsurface profiles in such a manner compounds time and effort invested. There is a tremendous opportunity in shortening and advancing the process and workflow by generating 3D dynamic subsurface models, especially in BIM context, in lieu of static 2D CAD profiles. See Figure 2, bottom part showing a 3D foundation excavation model illustrating boreholes, ground surface, and rock surface in the form of DTMs. Much like 2D subsurface profiles, 3D models require time and supervision of experienced professional while being developed. The huge benefits of 3D models are that they can be automated to a much greater extent than 2D profiles, they provide arbitrary model views by orbiting the model in real time, they can be dynamic, and they allow for cutting any number of subsurface dynamic profiles with minimal effort and time required for updates or editing the model. In BIM context these models comprise intelligent, interactive objects with attributes. In other words, approaching subsurface analysis as modeling rather than drafting provides notable benefits in terms of time saving, understanding and analysis in a discipline-interactive BIM context.

Needless to say, generating 3D surface models represents interpreted information based on a factual data from discrete boreholes. While this is a large topic to cover, a few essential interpolation methods will be briefly discussed to provide a basic understanding of surface modeling. In broad mathematical terms this is essentially a problem of limited number point data extracted from boreholes, being interpolated and fitted by a surface. These points are characterized by a location (X, Y coordinates) and elevation (Z coordinate). Based on these spatial points a surface may be modeled, and in BIM this surface may be augmented by intelligent business properties.

Once a 3D subsurface model is developed it may quickly and automatically produce its derivatives, such as contours, isopach contours, dynamic profiles, thematic maps, vector maps, and volume calculations to name a few. When such a model is developed in a BIM context it is seamlessly shared in a collaborative environment among all stakeholders.

There is a great number of interpolation methods that deal with developing a surface based on discrete points, which are used for 3D surface modeling. Some of these methods are Triangulation with Linear Interpolation, Kriging, Minimum Curvature, Inverse Distance, Local Polynomial, Moving Average, Natural Neighbour, Nearest Neighbour, Polynomial Regression, and Radial Basis Function. A few of the most frequently surface interpolation methods are briefly discussed here.

6.1 Triangulation with Linear Interpolation

The Triangulation with Linear Interpolation method is based on Delaunay triangulation. The algorithm creates triangles by drawing lines between data points. The fundamental property for an algorithm is the Delaunay criterion. In mathematics and computational geometry for a set of points in a plane (2D), a Delaunay triangulation criterion ensures that no point is inside the circumcircle of any triangle. Another way to describe it is that that the points are connected in such a way that no triangle edges are intersected by other triangles. For a set of points in space (3D) Delaunay triangulation constructs tetrahedra that satisfy the empty circumsphere criterion. The resulting model is a mesh of triangular faces. It is often referred to as a triangulated irregular network (TIN). To recap in engineering terms, a TIN is a digital vector-based representation of the physical surface like existing ground surface in survey, finished grade surface in a road or land development design, or a bedrock or sand stratum surface in subsurface exploration. For the subsurface exploration modeling, a TIN is generated based on irregularly distributed points with location and elevation data (x,y,z) extracted from boreholes. These points are connected with lines that are arranged in a mesh of nonoverlapping triangles or faces. A TIN is often used by a major infrastructure design software to generate a DTM.

Triangulation with Linear Interpolation is most effective when the points or boreholes are relatively densely distributed over the construction site. The triangulation is not effective for small data sets because it generates angular contours and it does not extrapolate elevation values beyond those found in the source data.

6.2 Kriging

Kriging is a geo-statistical method unlike straightforward methods such as Nearest Point, Trend Surface, or Moving Average. It was originally developed for use in geology by D. G. Krige. It is frequently used in GIS for interpolation of spatial data. The data is a set of spatially correlated observations of some variable of interest. An example could be bedrock elevations encountered in boreholes, or contaminants at certain depths in context of subsurface exploration. Kriging is a flexible gridding method that produces smooth surfaces from irregularly spaced data. The resulting surface is probably smoother than the authentic surface and consequently it generates appealing contours as opposed to a triangulation method that generates angular contours. The smooth contours and smooth isopach contours are preferred by many subsurface exploration professionals.

Kriging is probably the most often used method for solving interpolation problems.

6.3 Minimum Curvature

Minimum Curvature is used extensively in the earth sciences. This method was developed by W.H.F. Smith and P. Wessel in 1990. The interpolated surface generated by the Minimum Curvature method is described as analogous to a thin, linearly elastic plate passing through each of the data values with a minimum amount of bending. Minimum Curvature is not an exact interpolation method, which means that source data is not always honored exactly. It does, however, generate the smoothest possible surface while attempting to honor data as closely as possible. Minimum Curvature is an iterative method and the grid node values are recalculated until the value assigned threshold or the maximum number of iterations is reached. The method may extrapolate grid node values beyond the source data boundaries. Because Minimum Curvature surfaces may have large oscillations and extraneous inflection points they may not be suitable for gridding in all applications.

7 SUMMARY AND CONCLUSION

For large infrastructure projects, a vast quantity of subsurface data is collected and processed in various forms. An increasing number of AEC companies and organizations now recognize subsurface data as an asset. At the same time AEC companies realize the advantages that BIM offers such as collaborative, modeling-based analysis and design.

The essential step to enable subsurface data to be treated as an asset, and incorporating it into BIM, is structuring it into a database. This triggers a need for data to be easily exchanged among various BIM software and databases. Consequently subsurface data interchange formats such as DIGGS have been developed.

Properly managed assets incorporated into BIM help articulate engineering and business goals into streamlined, optimized and collaborative workflows. BIM provides a great opportunity to shorten and advance the process of understanding and visualizing subsurface conditions by generating 3D dynamic models. Subsurface data observed in a BIM context is more transparent and intuitive to use for all stakeholders.

Figure 3 shows an extract from British Standard PAS 1192-3:2014 describing various levels of BIM maturity extended to asset information management, from static linework to a dynamic 3D models and objects with attributes used in collaborative environments with interoperable data.

Further, factual vs. interpreted subsurface data was discussed. Creating subsurface profiles and 3D models is invaluable in understanding subsurface conditions. Creating 3D surface models, however, is a far more promising approach because it provides better insight and allows automated generation of dynamic profiles,

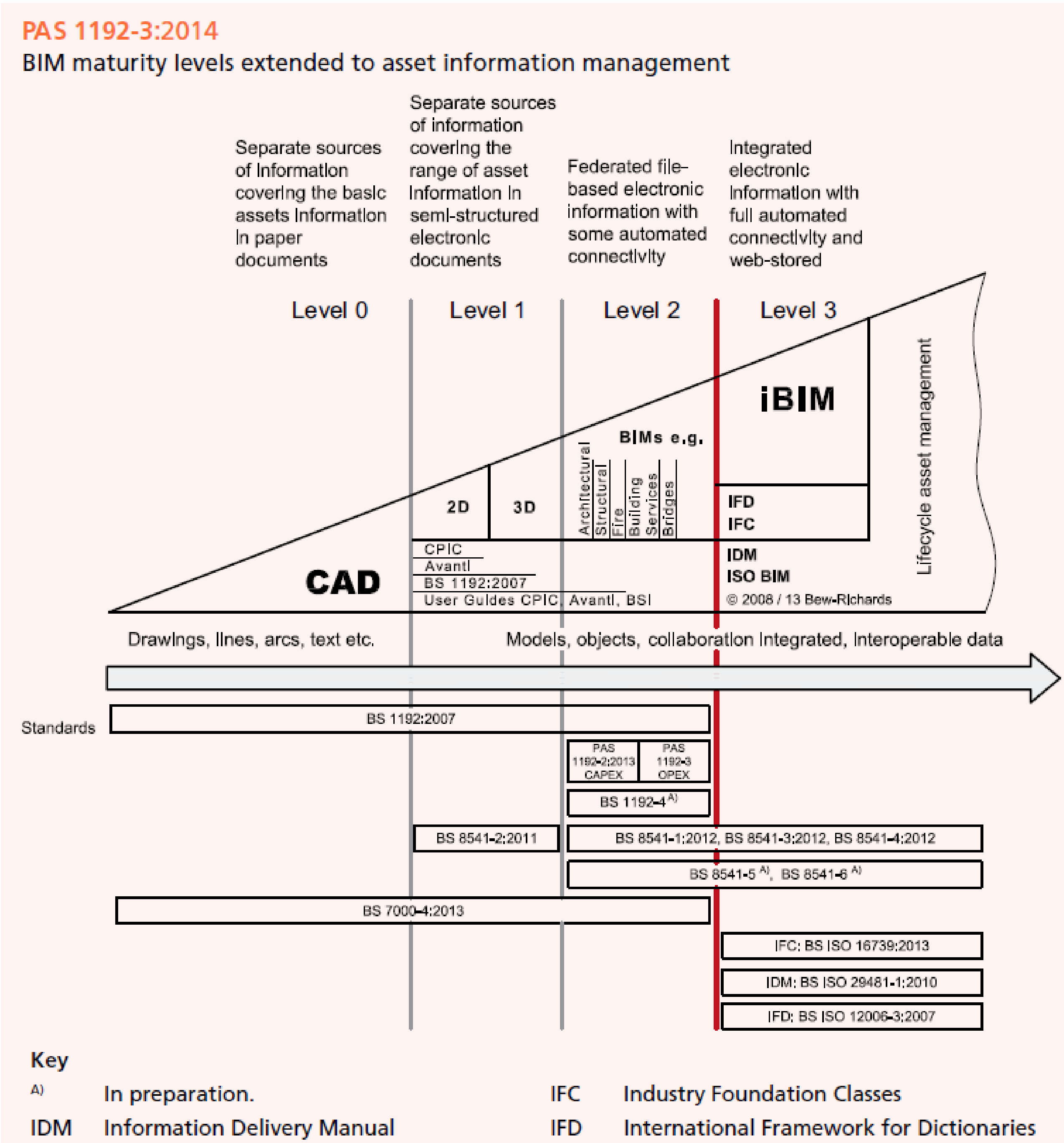

Figure 3. BIM maturity levels extended to asset information management.

contours, isopach contours, thematic maps, vector maps, and volume calculations.

Considering that 3D stratigraphy surface modeling is interpreted information, and that it is based on a limited number of discrete points extracted from boreholes, the surface interpolation has elements of art embedded in it. No two geotechnical professionals will produce exactly the same subsurface profile, based on the same set of discrete boreholes. The same applies to 3D surface modeling. The success of interpolation and the quality of the resulting surface depends on the configuration of input data, the selected method, parameters of interpolation, grid size, and of course the experience of the professional performing it. There is a great number of mathematical interpolation methods that deal with developing a surface based on discrete points. These interpolation methods help reduce uncertainties and automate modeling. Three of these methods, the most frequently used by BIM software, were briefly discussed earlier in this paper.

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