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Innovative Approaches to 3D GIS Modeling for Volumetric and Geoprocessing Applications in Subsurface Infrastructures in a Virtual Immersive Environment

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Innovative Approaches to 3D GIS Modeling for Volumetric and Geoprocessing Applications in Subsurface Infrastructures in a Virtual Immersive Environment

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ABSTRACT

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Pragya Srivastava

As subsurface features remain largely 'out of sight, out of mind', this has led to challenges when dealing with underground space and infrastructures and especially so for those working in GIS. Since subsurface infrastructure plays a major role in supporting the needs of modern society, groups such as city planners and utility companies and decision makers are looking for an 'holistic' approach where the sustainable use of underground space is as important as above ground space. For such planning and management, it is crucial to examine subsurface data in a form that is amenable to 3D mapping and that can be used for increasingly sophisticated 3D modeling. The subsurface referred to in this study focuses particularly on examples of both shallow and deep underground infrastructures. In the case of shallow underground infrastructures mostly two-dimensional maps are used in the management and planning of these features. Depth is a very critical component of underground infrastructures that is difficult to represent in a 2D map and for this reason these are best studied in three-dimensional space. In this research, the capability of 3D GIS technology and immersive geography are explored for the storage, management, analysis, and visualization of shallow and deep subsurface features.

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Dedicated to

my beloved grandparents

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CHAPTER – I
Introduction

Geographic Information Science (GISc) has played a significant role in the storage, analysis, visualization, and management of location-based information. Extensive research has been undertaken in the study of numerous surface features in GIS, yet there has been only limited study of 3D GIS and the study of the subsurface environment. The subsurface environment includes both natural and man-made features. The subsurface has been central to embedding infrastructure on a massive scale since the 19th century and to a more limited extent much earlier. A significant difference can be seen between the historical use of subsurface space and contemporary use in that early subsurface usage was rarely planned, and management and sustainably issues especially in the case of subsurface utility infrastructures, have become highly problematic. The 'hidden' nature of subsurface features has contributed markedly to many challenges experienced in contemporary society and to the unsustainable nature of buried features and subsurface space for decades. Currently, subsurface space is used worldwide for facilities and infrastructure such as utilities that in some instances must be located below ground or are unacceptable, undesirable, or expensive to place above the ground (Goel, Singh, and Zhao; 2012). Subsurface space has been widely used for utilities, tunnels, subways, underground storage facilities, commodity carrying infrastructure, and oil and gas extraction wells to name just a few. Subsurface infrastructure plays a major role in supporting the needs of modern society and not least because of the emphasis on infrastructure management, oil and gas exploration, and environmental sustainability (Kaliampakos and Benardos, 2008). The analysis and visualization of subsurface infrastructure relates to both shallow and deep subsurface phenomena. Urban space extends beyond the surface to include the immediate subsurface; a theme especially important in the context of commodity carrying utilities (He et al., 2012; Canto-Perello and Curiel-Esparza, 2013; Hunt et al., 2016; Bobylev, 2016). This urban subsurface environment is generally considered to be the shallow subsurface located within 50 meters or so of the ground surface (Rosenbaum, 2003) as shown in Figure 1.1.

Figure 1.1: Shallow subsurface infrastructure. Reprinted from ASCE Utility Standards, In *SlideShare*, by J. Anspach, Retrieved December 17, 2019, from https://www.slideshare.net/asceoc/asce-utility-standards.

Deep subsurface features are related more to petroleum reservoirs, groundwater resources, and infrastructure such as bore-wells, and deep subsurface storage facilities (Turner, 1989; Rosenbaum, 2003) and as represented in Figure 1.2.

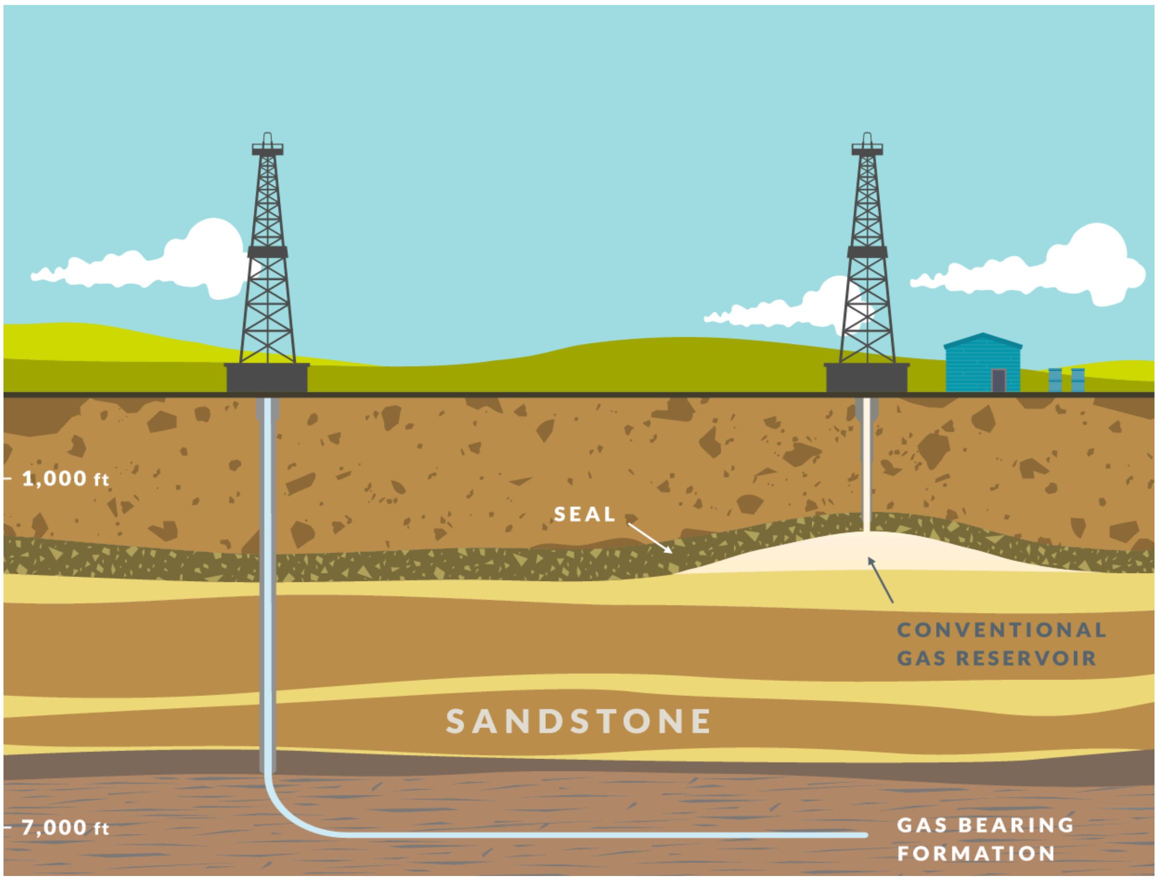


Figure 1.2: Deep subsurface infrastructure: horizontal and vertical oil and gas wells. Reprinted from Difference between horizontal & directional drilling, In *SlideShare*, by We-Bore-It, Retrieved December 17, 2019, from https://www.slideshare.net/weboreit/difference-between-horizontal-directional-drilling

Subsurface space is an important part of daily life as it contains infrastructure that transport extensive commodities that are basic to everyday life. Subsurface infrastructures such as water-pipelines, electrical cables, traffic signal wires, street lighting circuits, fiber optics, telecommunication wires, sewage, and heating systems are essential for the everyday functionality. Subsurface infrastructures are the life support system for mega-cities, cities, and townships that are required to utilize their subsurface space sustainably to fulfill the needs of modern society without compromising the requirements of resources for future generations. A functioning urban area in particular requires a well-maintained aboveground and subsurface infrastructure and the sustainable use of such subsurface space has long been recognized as one of the important factors contributing to liveable cities (Bobylev, 2016; Goel, Singh, and Zhao; 2012). The historical unplanned utilization of shallow subsurface space has led to a spider's web of differing utility networks (Jeong and Abraham, 2004). The mapping, management, and visualization of these subsurface infrastructures are problematic and challenging especially as the world's population is becoming more urbanized at an unprecedented rate (Jeong and Abraham, 2004; Li et al., 2015). This heavy population migration to urban areas places considerable pressure on the use of subsurface space. The modern urban life-style demands advanced mechanical and technical facilities along with achieving a clean, healthy and sustainable urban environment and the efficient use of the subsurface is central to these needs.

The daily maintenance demands of public utilities are considerable. For the decade 2001-2010 it is estimated that subsurface excavation related accidents lead to utility service disruptions and amount to approximately $200 million of property damage (Talmaki and Kamat, 2014). Utility strikes remain a major problem with a staggering estimated 500,000 utility strikes in the United States every year (Talmaki and Kamat, 2014). The management of subsurface space requires a comprehensive system for planning, maintaining, and sustaining these subsurface utility infrastructures. Many questions related to above ground surface features and phenomena can be addressed through GIS and 2D mapping, but the third dimension is critical to the study and management of subsurface features. The lack of real-time spatial information and the unavailability of an effective means to communicate 3D information are two causes that contribute to severe injuries, costly service disruptions and heavy repair costs (Li et al., 2015). Similarly, deep subsurface infrastructure, such as oil and gas extraction wells and subsurface storage tanks, are equally problematic when examined in a predominantly 2D analytical and mapping system.

It is suggested in this study that the use of 3D GIS, 3D geoprocessing, and virtual immersive technologies for the visualization and analysis of complex multidimensional data of subsurface infrastructures is valuable in producing analytical outputs and revealing patterns that have challenged traditional 2D GIS and mapping applications. Numerous examples of the need for 3D geoprocessing exist including the relationship of fracking wells, bore wells, and deep subsurface storage tanks with surrounding water aquifers. These analyses depend on factors such as hydraulic conductivity, porosity, stratigraphy, fracture faults, and the availability of real-time monitoring conditions.

After the installation of subsurface facilities, it is valuable to have available an integrated geospatial technology capable of examining the interaction between deep infrastructure and geological features. Goel (2012) suggested that, “underground planning should adapt a holistic approach that considers all four resources (space, water, energy and material) and their interactions for multiple-use planning, which includes geological and environmental effects as well as economic efficiency and social acceptability" (Goel, Singh, and Zhao; 2012, p.7).

The development of a reliable digital mapping and visualization system is thus crucial for the planning and maintenance of the subsurface infrastructures. However, before being able to manage and plan subsurface use, even with 3D capability, it is necessary to know what is already in the subsurface. This requires features located below ground to be digitally mapped. To date, subsurface utilities have been very poorly documented or mapped (if at all) and this applies worldwide (Jeong and Abraham, 2004). Abandoned and unmapped pipelines and other infrastructure abound and yet this complex network of shallow subsurface infrastructure is either undocumented, incomplete, or outdated (Jeong and Abraham, 2004). Most subsurface maps that do exist remain on analog media and in 2D.

GIS is a powerful technology in the mapping and analysis of surface features. To address subsurface features and processes this research explores the nature and use of 3D GIS to develop and display multi-scale, three-dimensional shallow and deep subsurface infrastructure models in addition to geo-processing and volumetric computations. Furthermore, it is proposed to use immersive visualization to display these 'hidden' systems in virtual immersive environment to support spatial decision-making. This study contends that 3D GIS modeling coupled with immersive visualization will be increasingly critical to the management of installed infrastructure and in the coordinated installation of new infrastructure especially for a sustainable subsurface space. Rosenbaum (2003) states that *"Users want solutions, not data and users want information they can use immediately in a form they can understand".* A 3D enabled immersive visualization environment has the potential to enhance a user's cognition and to help communicate information in a way that users and decision makers can use effectively (Behzadan, 2015).

1.1 Challenges in Subsurface Modeling

In conducting research related to integrated subsurface environments, the challenges primarily occur in the form of data collection, data storage, data integration, the topological encoding of complex 3D geometries, scale issues, and uncertainty estimation to name but a few. In the case of shallow subsurface infrastructures, the datasets tend to be available in two-dimensions. However, in 2002 the American Society of Civil Engineering (ASCE) developed the National Consensus Standard titled *ASCE C-I 38-02, Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data.* The ASCE guidelines include capturing depth information of subsurface utilities and were developed to guide the collection of below-ground infrastructure data in order to reduce the risks and costs that emerge from many utility strikes every year. This National Consensus Standard (NCS) follows the ASCE standard and the related American National Standard Institute (ANSI) standard.

The reconstruction of complex subsurface geometries and their integration into one model is a major challenge. Using different platforms and architectures that support simple and complex geometries and integrating architectures in one robust model have proven to be a useful approach to tackle such issues. However, the limited interoperability between various platforms including the facilities to import and render 3D models from desktop environments to immersive environments lack geometrical support that can result in broken geometries, the loss of geometric information, and the failure of spatial and topological analysis. Furthermore, scale is also a challenge in the representation of the complete profiles of deep subsurface infrastructures included in one model especially for visualization in an immersive environment. The vertical scale for deep subsurface infrastructures, especially for oil and gas wells, ranges from a few hundred feet to several thousand feet. In such cases, the user will struggle to visualize and analyze the detailed structure of the model. However, visualizing the model in 3D cross sections can help to tackle this issue.

Apart from these complexities, subsurface representations are invariably uncertain due to geological complexity, interpolation effects, and the quality, accuracy, and the reliability of the data (Tacher et al., 2006; Russell et al., 2013). Stochastic modeling approaches have been favored to help characterize the most probable subsurface conditions based on limited data (Turner, 1989; Stafleu et al., 2011; Russell et al., 2013).

1.2 The Significance and Purpose of this Research

Many initiatives have been taken for the planning and management of underground utilities though most of them are restricted to two-dimensional databases. The utility companies that continue to use analog location data face significant risk during utility construction or repair projects and through necessity are migrating toward maintaining digital utility data. In the late 1960s the emergence of automated mapping/facility management (AM/FM) was a result of a groundbreaking experiment between IBM and the Public Service Company of Colorado that used the geospatial technology for utility mapping and management. In the 1980s and 1990s due to the extended capabilities of desktop computing and software, almost every utility board in North America and most local government agencies began implementing geospatial information technologies. GIS, remote sensing, and global positioning systems (GPS) have increasingly been integrated and brought to bear on complex network and infrastructure utility issues. GIS is now among one of the top ten technologies used in electric, gas, pipeline, telecommunications, water and wastewater utility industries for database management, spatial analysis and mapping.

Though the utility industries started using spatial information technologies in the 1980s for database management and analysis, subsurface utility planning, monitoring and maintenance have since been predominantly carried out in a 2D environment. The data management and visualization of such subsurface environments requires data in three dimensions at a minimum. In addition to mapping, system maintenance and monitoring, the damage resulting from utility strikes has raised the profile of subsurface mapping and resulted in the 'one-call law' that requires anybody carrying out an excavation to obtain the location of utility lines within the excavation zone (Figure 1.3).

Figure 1.3: A site with the typical mark-out of buried infrastructure. Reprinted from *How Accurate Is Underground Utility Locating?*, by Shan Wei, Published on January 23, 2015, Retrieved December 17, 2019, from https://www.enviroprobe.com/single-post/2015/01/23/How-Accurate-Is-Underground-Utility-Locating

However, accidental disruption to utilities through utility strikes continues to occur because it is difficult to delineate the depth of buried utilities on the basis of these markings. Excavation related accidents could lead to severe injury, costly service disruptions, and heavy repair costs. Creating and analyzing a 3D model of the existing underground infrastructures before starting any construction projects decreases the risk of utility strikes, promotes timely completion of the construction work, and reduces projects costs. Based on such information opens up the opportunity to use augmented-reality devices during excavation to reduce the risk of excavation related accidents.

Utility strikes are not the only concern related to subsurface infrastructures, for aging of the subsurface infrastructures is a pressing problem that has often been neglected because of the unmapped and difficult to access nature of the subsurface utilities. In many cases, these utility systems are 60 to 70 years old, well past their original service lives, and often require many repairs throughout the year. One obvious solution to maintaining the 'health' of subsurface infrastructures lies with utility workers and public officials and of course the availability of useable data. Public outreach and awareness about these critical infrastructure issues can also reduce the number and the cost of repairs significantly. 3D modeling and immersive geovisualization can help enhance user's cognition and represent the information in a way that users and decision makers can use effectively. While the cognitive contribution of 3D GIS visualization is valuable, the ability to perform 3D spatial analyses and geoprocessing, such as the computation of volume and pressure in the networks, can also assist in analyzing, monitoring, and maintaining complex scenarios related to these subsurface infrastructures. 3D geoprocessing, real-time 3D data editing, and immersive visualization then, have considerable potential to assist decision makers to test and validate existing networks and proposed implementation plans.

A deep subsurface environment consists of geological layers, faults, folds, and other displacements and disconformities in these geological layers as well as the infrastructure itself. A combined study and analysis of subsurface geology and infrastructure is thus crucial. Geological structures can be better understood in three-dimensions due to the complex multidimensional nature of the phenomena that they represent. 3D models play an important role in volumetric computations and 3D geoprocessing that are not computationally possible with two-dimensional mapping. To represent a real-world entity as a digital model it is necessary to represent the topology and spatial relationships of an object in three dimensions as 'solid' 3D objects.

To cover all the issues related to subsurface infrastructure is beyond the scope of this research but the base idea of displaying and analyzing subsurface information in a 3D environment has the potential to solve many real-world problems related to the planning and management of subsurface infrastructures. The primary scope of this research is to explore the capabilities of 3D GIS, immersively display 3D subsurface features, and perform 3D geoprocessing and volumetric computational analyses. Although, some preliminary work related to the 3D modeling of subsurface infrastructures can be found on the internet, the documentation of real-world applications is almost non-existent. This research proposes and implements a methodology that can be applied in solving real-world problems related to the data display and sharing and planning and management of subsurface infrastructures at different scales.

1.3 Research Objective

To summarize then, subsurface utilities have been poorly documented worldwide if they are documented at all. Many abandoned and indeed operational pipelines are not recorded on any map. The networks of shallow subsurface features are now so complex, poorly mapped, and the records outdated or incomplete that this represents a major challenge to utility companies (Goel, Singh, and Zhao; 2012). Most subsurface utility and geological maps are still in 2D formats and yet the study of these networks and regions require a 3D perspective. Even in cases where the utility infrastructure is documented, these maps are often recorded on old, fragile, decaying media that was manually updated prior to the digital age. The use of these maps in the field is thus problematic and requires construction workers to remotely identify utility pipes via metal detectors. Mapping the subsurface utility infrastructure in three-dimensions with high accuracy and complete information is thus valuable to support system maintenance and could reduce the risk of utility strikes during excavation. In the case of deep subsurface infrastructure systems such as oil and gas wells which cannot be reasonably excavated or detected, the value of 3D GIS and virtual immersive technology is even more apparent.

Recent advances in 3D GIS technologies have made 3D data storage, analysis and visualization feasible. The goal of this research is to explore, develop, and apply 3D GIS modeling and immersive visualization techniques in the recording, planning, maintenance and monitoring of deep and shallow subsurface infrastructure networks. This research uses two case studies focused on the 3D modeling and immersive visualization of both shallow and deep subsurface infrastructures related to shallow utility networks and oil and gas exploration and system maintenance respectively.

To achieve this goal several specific research questions were pursued:

- **Research Question 1:** What are the challenges and steps involved in acquiring and ingesting 3D capable spatial data and 3D models of subsurface features into a 3D GIS?
- **Research Question 2:** What are the challenges to be overcome in generating the topological encoding required to perform 3D GIS analysis on 3D subsurface models?
- **Research Question 3:** What systems could be used to develop 3D geoprocessing functionality and 3D data import capabilities and how might this 3D processing be accomplished in the most widely adopted GIS platform, ArcGIS Pro?
- **Research Question 4**: Using the two cases studies involving deep horizontal boreholes and subsurface utilities, how might the 3D GIS be implemented in order to assess the systems geoprocessing capability to perform the following tasks and analytical functions:
    - Display 3D visualizations
    - Undertake buffering in 3D
    - Undertake object intersection in 3D
    - Intersect a 3D line with multipatch models
    - Perform ‘near’ 3D proximity analysis
    - Perform a 3D ‘union’
    - Perform 3D volume and flow rate computations
    - Perform cut and fill volumetric analyses
- **Research Question 5:** What steps must be performed in order to view these 3D models in an immersive virtual environment? To what extent does the

representation of 3D GIS in an immersive environment improve the visual and analytical acuity for the researcher and decision-maker?

- **Research question 6:** Evaluate the 3D system of subsurface features developed here guided by the specifications laid out in research question 4. Based on the case study findings, what are the visual and analytical benefits and/or limitations involved in analyzing subsurface objects in a 3D GIS and immersive environment?

CHAPTER II
Background and Literature Review

2.1 From 2D GIS to 3D GIS

GIS has traditionally focused on a 2D paradigm and has been remarkably successful in a wide variety of applications for storing, mapping and analyzing spatial data. However, as a result of technological advancements, the spatial primitives and topological principles of 2D GIS are progressively available for modeling 3D spatial data and enable more complex 3D analysis and visualization (Dore and Murphy, 2012). Adding the third dimension to 2D GIS requires an investigation of the critical topological relationships between 3D spatial objects in an appropriate analytical GIS environment (Alias and Pilouk, 2008; Gia et al., 2013). In an overview of 3D GIS development, Alias and Pilouk (2008) concluded that ideally 3D GIS should possess the same robust functionality as 2D GIS. It should be noted that many so-called 3D spatial applications, especially for visualization purposes, are really pseudo 3D and in reality, are 2.5D 'wireframe' representations of 3D objects. True 3D should not be confused with 2.5D where the third dimension is represented as a surface attribute value dependent on x and y coordinates in 2D space rather than as an independent value. 2.5D systems can only accept a single elevation (z) value for any surface at any given location. In contrast, 3D systems comprise three independent coordinate axes and can accept repeated occurrences of an elevation or depth value at any given location thus enabling 3D capability. As the demand for true three-dimensional functionality has grown, 3D GIS data structures with robust spatial and topological relationships between objects have emerged (Wu, 2004). To analyze change in any phenomena (in 3D) over time requires 4D information where time represents the fourth dimension.

2.2 3D Spatial Data Models

The key to 3D applications is the availability of 3D spatial data models. A spatial data model is a mathematical construct that enables the representation of geographical features as graphical elements. Different spatial data models can be used for varying purposes based on the particular criteria of the application. Gia (2013) provided a detailed comparison between different 3D GIS models based on data-size, topology, spatial query, level of detail (LOD), applications, and the primitive and geometric elements of the model. To this end 3D GIS spatial data models can be categorized based on 3D spatial object representations that are boundary-based representations, voxel-based representations, a combination of 3D primitives, or combined models (Gia, 2013).

2.2.1 Boundary Based Representation of 3D Spatial Object

Boundary based representations, also known as B-rep, are defined by point, line, surface and body. B-rep can be considered as an extension of the wireframe model where the volume is an extension of the surface and represents 3D blocks. The B-rep is built on the premise that a physical object is enclosed by a set of faces, which themselves belong to closed and orientable surfaces. B-rep is suitable for representing regular or artificial shapes (Gia, 2013). Most GIS platforms support B-rep data structures. B-rep includes the 3D-FDS (Formal Data Structure) proposed by

Molenaar in 1990; the TEN (Tetrahedral Network) proposed by Pilouk in 1996; the Multipatch data format developed by Esri in 1997; the OO Model (Object Oriented Model) proposed by De la Losa and Cervelle in 1999; the SSM (Simplified Spatial Model) proposed by Zlatanova in 2000; the UDM (Urban Data Model) proposed by Coors in 2003; the OO 3D (Object Oriented 3D) proposed by Shi and colleagues in 2003; and CityGML proposed by Gerhard Groger and colleagues in 2007 (Gia, 2013).

A multipatch object uses triangle fans and strips and rings to construct the boundary of a 3D feature (Esri, 2008). The multipatch data format was initially developed for the extrusion of 2D object footprints into 3D objects for 3D visualization. Multipatch overcomes the limitations of the 2D and 2.5D data formats by facilitating the creation of a closed solid geometry that can enclose a volume and thus can be used for volume computation. Moreover, multipatch also facilitates the texture storage and color transparency that makes them useful for realistic representation of the 3D features. The geometrical construction of the multipatch allows them to create complex objects such as 3D textural buildings and trees.

The OO Model uses an object-oriented approach to represent and manage complex spatial objects such as a 3D tunnel. The SSM uses only two geometric elements, nodes and face, and four basic objects: point, line, surface, and body with an explicitly represented topology. The SSM supports 3D GIS applications with web-based technologies. The OO 3D has proven effective for display and provides better processing speed than previous spatial data models due to the characteristics of the object-oriented approach even when the data size is large. CityGML was proposed as a common definition related to the entities, attributes and relationships in 3D models such that different applications can share a common data source and format.

In addition to the above-mentioned models, freeform curves and surface representations such as NURBS (Non-Uniform Rational B-Splines) and Bezier curves can also be integrated within 3D GIS for modeling complex 3D objects such as detailed buildings, towers, and tunnels (Zlatanova, 2006). The curves and surfaces of NURBS are defined by low order polynomial mathematical functions joined together by splines (Scianna, 2013). NURBS and Bezier are two different mathematical representations for curves. NURBS are a generalization of Bezier and Non-Rational B-Splines. NURBS are well suited for representing highly detailed real-world objects with a smooth finishing (Figure 2.1).

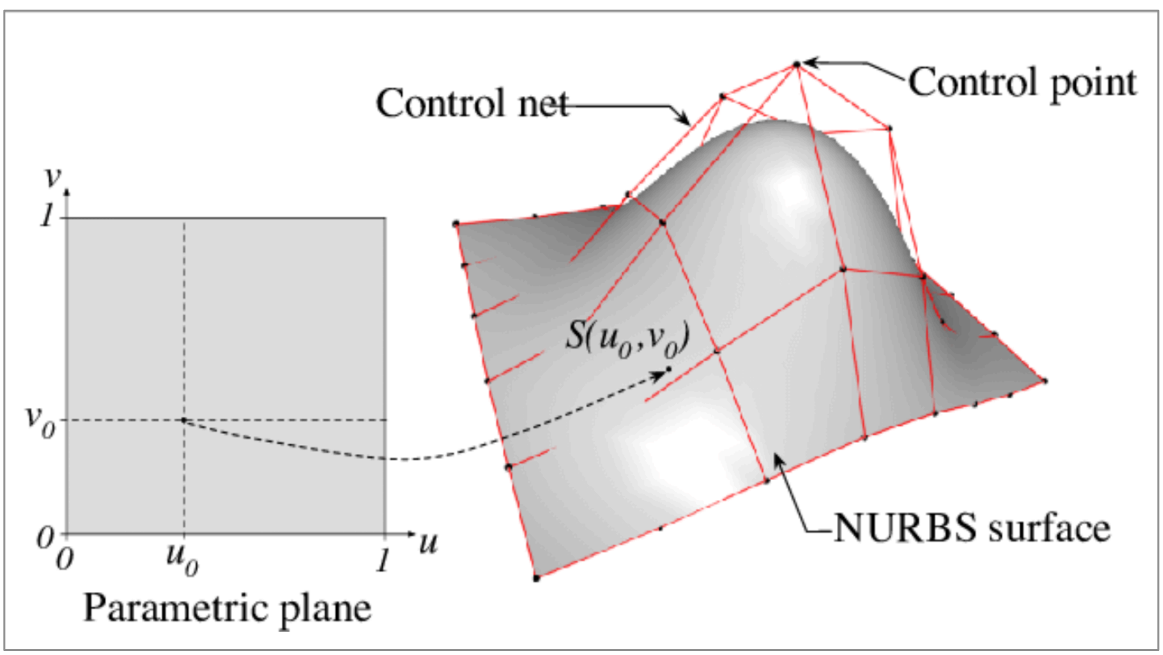


Figure 2.1: NURBS representation. (Estratat, M., and La Greca, R., 2006)

2.2.2 Voxel Based Representation of 3D Spatial Object

In contrast to boundary-based models, voxel-based models represent an object volume as a solid geometry based on 3D cubes rather than 2D rasters (Figure 2.2). Voxels were introduced specifically to represent geo-bodies (Fritsch, 1996; Gia, 2013). The term voxel originated from two words 'volume' and 'pixel'. Three-dimensional Arrays and Octrees use voxels to represent an object.

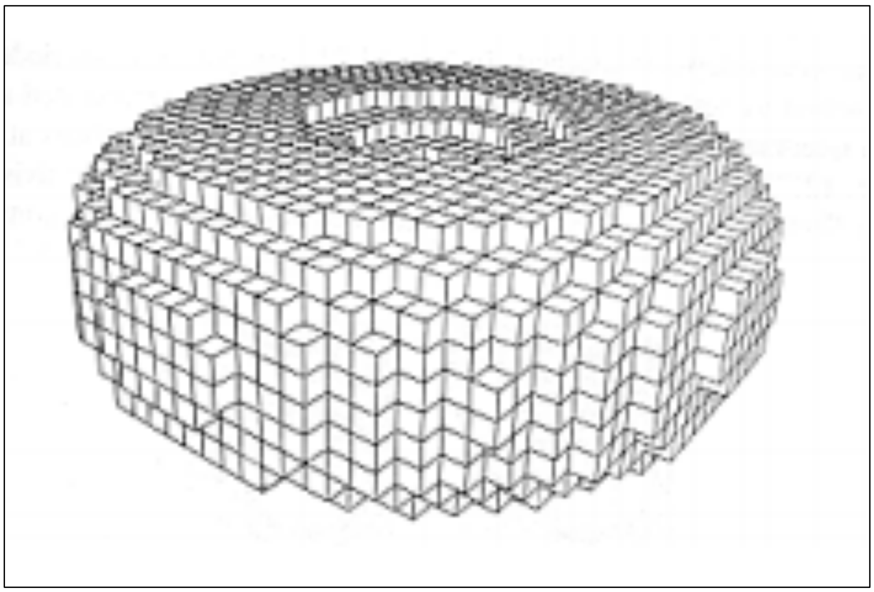


Figure 2.2: Voxel representation. Adapted from *Voxel-based Solid Models: Representation, Display and Geometric Analysis* (Doctoral dissertation, Indian Institute of Technology, Bombay Mumbai) by S.S. Patil, 2005, p. 7.

The 3D Array has a simple data structure with two possible binary values (0 and 1). The value 0 represents the background and 1 represents the object. Meagher proposed the Octree model in 1984 (Gia, 2013). Octrees are the three-dimensional extension of a 2D Quadtree data model. Similar to a Quadtree, an Octree uses a recursive decomposition algorithm that divides each voxel further into smaller voxels (Figure 2.3). However, the data size can be very large and required processing resources are greater.

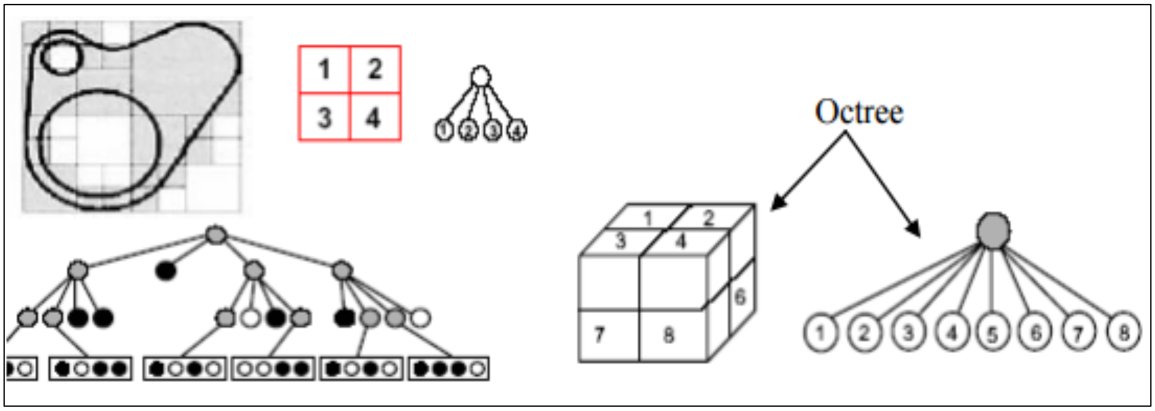


Figure 2.3: Quadtree and Octree architecture. Adapted from *Voxel-based Solid Models: Representation, Display and Geometric Analysis* (Doctoral dissertation, Indian Institute of Technology, Bombay Mumbai) by S.S. Patil, 2005, p. 11.

2.2.3 Constructive Solid Geometry

CSG (Constructive Solid geometry) uses a combination of 3D primitives such as the cube, cylinder, cone, prism or sphere to represent 3D objects (Figure 2.4). Samet and Tamminen proposed the concept of CSG in 1985 where transformations and logical operators control the relationship between 3D primitives. The CSG model is commonly used in CAD (Computer Aided Design). CSG is particularly useful in volumetric computations but is not suitable for representing objects with unusual or irregular geometry though it can represent curved surfaces quite well.

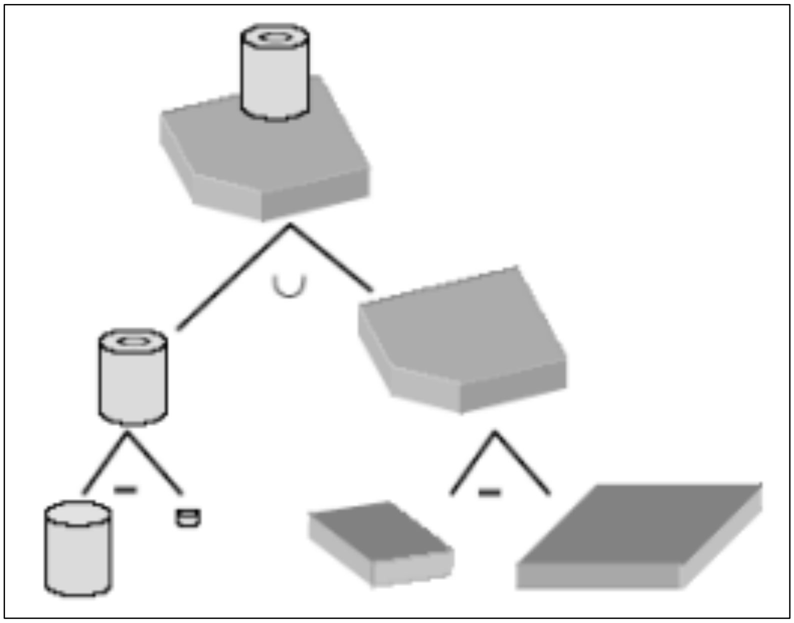


Figure 2.4: CSG representation. Adapted from *Voxel-based Solid Models: Representation, Display and Geometric Analysis* (Doctoral dissertation, Indian Institute of Technology, Bombay Mumbai) by S.S. Patil, 2005, p. 7.

2.2.4 Combined 3D Spatial Data Models

Combinatorial models are based on the integration of existing 3D data models. Wang (2000) and colleagues proposed a hybrid model named, V3D. V3D is an integration of vector data and raster image in a 3D GIS model (Gia, 2013). Chokri et al. proposed the combinatorial model of B-rep and CSG in 2009 (Gia, 2013).

2.3 Current Approaches in 3D Modeling

In GIS, 3D modeling is a process of building digital 3D models of a spatial object or a geographical phenomenon explicitly incorporating three-dimensional space. In 3D GIS modeling, spatial objects can be represented by using a set of points that are connected by various geometric primitives such as lines, cubes, triangles, cylinders, polyhedrons, surfaces, and curved surfaces. The 3D models that are defined as purely graphical or geometrical representations support visualizations but struggle with spatial geoprocessing. 3D models containing semantic, topological and geometrical aspects are better suited for spatial and thematic queries, analytical tasks, and spatial data mining.

An increasing number of city governments and companies are building virtual 3D city models for different application areas such as urban planning, mobile telecommunication, disaster management, cadastral mapping, tourism, vehicle and pedestrian navigation, and facility management and environmental simulations to name a few. The European Cooperation in Science and Technology (COST) initiative, for example, initiated an international level intergovernmental project that focused solely on providing improved subsurface management capability. The COST Action Sub-Urban project sought to enhance the technological knowledge of the subsurface in terms of data acquisition, data storage, data-sharing formats, data modeling, and other criteria that contributed to the better communication of the subsurface knowledge to the decision makers from different stakeholders (Venvik et al., 2018). The COST Action Sub-Urban project was initiated to bring a holistic approach to urban planning where subsurface space is as important as the aboveground space in planning and management of urban areas.

2.3.1 International Standards for the exchange of 3D Models

To counteract the lack of 3D model standards, CityGML has become the international standard for the Open Geospatial Consortium (OGC) for the representation and exchange of 3D models. CityGML defines the three-dimensional geometry, topology, semantics and appearance of the most relevant topographic objects in urban and regional contexts with different well-defined Levels-of-Detail (Gröger and Plümer, 2012). The focus of CityGML is on the semantic aspects of 3D models, their structures, taxonomies and aggregations, and allows users to employ virtual 3D models in advanced visualizations in a variety of application domains. CityGML is based on the Geography Markup Language (GML), which provides a standardized geometry model. CityGML has been used on a worldwide scale since its inception in 2008. CityGML includes Application Domain Extensions (ADE) that specify additions to the CityGML data model to support application specific extensions (Gröger and Plümer, 2012). The first ADE was developed for noise pollution simulations as employed in environmental noise dispersion according to the Environmental Noise Directive of the European Commission. Hijazi and Hemphen (2013) note that CityGML models can be extended to include utilities infrastructure such as water or gas pipelines using a Utility Network ADE (Becker et al., 2011).

The Industry Foundation Class (IFC) is an open and standard data format for Building Information Modeling (BIM). IFC is an object-based file format with a data model developed by buildingSMART (formerly the International Alliance for

Interoperability) to facilitate interoperability in the architecture, engineering and construction (AEC) industry, and IFC is a commonly used collaborative format in BIM based projects. The IFC model specification is open and available and registered by the International Organization for Standardization (ISO). BIM is a digital representation of the physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decision-making during the life-cycle of a facility from its earliest conception to demolition. Current BIM software are used by individuals, businesses and government agencies who plan, design, construct, operate and maintain diverse physical infrastructures, such as water, electricity, gas, communication utilities, roads, bridges, ports, and tunnels. Since the limited interoperability of models inhibits the broader use of 3D models, the use of a standard data format is an important element of these models for the exchange and integration of 3D city models with subsurface information garnered from various sources (Coors and Ewald, 2005, p. 89).

2.3.2 3D Modeling Software

There are several 3D modeling software platforms available in the market today. Some are available gratis, and others come at a significant cost. Many non-geospatial 3D modeling software systems are designed for 3D gaming and animation purposes and to some extent support data exchange with geospatial software such as 3ds Max, Unity 3D, Blender, and Maya from Autodesk. In addition, ArcGIS Pro while primarily designed for handling 2D geospatial data has more recently been equipped to handle 3D data. A single software package may not have the full capability to handle 3D spatial data modeling as well as spatial analysis and visualization and many applications that require 3D visualization and 3D analysis have been achieved by the loose coupling of 3D modeling software and GIS software: for example, ArcGIS and SketchUp (Wei et al., 2013), GIS with BIM and 3D CAD (Liu and Issa, 2012; El et al., 2013).

Scianna (2013) presents a review of open source 3D modeling software to represent geographical objects and concluded that Blender has advantages for modeling geographical objects. Blender is a free and open source 3D creation suite and supports the entirety of the 3D pipeline modeling, animation, simulation, rendering, compositing and motion tracking along with video editing and game creation. Blender can handle several geometries and has import/export support for many different programs such as 3ds Max, COLLADA (DAE), Autodesk (DXF), VRML and X3D. Blender uses Bezier curves and NURBS to represent 3D objects. K-3D is a free 3D modeling and animation software with tools to build and edit NURBS, patches, and curves but it has limited import-export formats (Scianna, 2013). K-3D supports animations with 4D data where time represents the fourth dimension. K-3D can be integrated with PostGIS platforms to represent 3D GIS data. PostGIS supports geographic objects in the PostgreSQL object-relational database. In effect, PostGIS spatially enables the PostgreSQL server allowing it to be used as a back-end spatial database for GIS, such as ESRI's SDE or Oracle's Spatial extension. PostGIS has many features and is well suited to allocate and manage large quantities of geographical data (Scianna, 2013).

Trimble SketchUp is a 3D modeling software with a relatively accessible user interface. Trimble SketchUp GIS plugin alleviates some of the complexity of 3D editing and updating textures by providing an exchange interface between ArcGIS and SketchUp (Xu et al., 2009; Mu and Gao, 2013). AutoCAD Map 3D is a geospatial, 3D modeling software that is compatible with ArcGIS. The ArcGIS for AutoCAD plugin facilitates data exchange and the editing of ArcGIS data created locally within the AutoCAD drawing or exported from ArcGIS Desktop. Esri CityEngine is a 3D modeling software that specializes in the generation of detailed large-scale 3D urban environments. CityEngine supports procedural modeling that uses rules to batch create 3D models and textures. MicroStation from Bentley allows data-driven BIM-ready models for infrastructure professionals of any discipline. BIM based architecture supports universal modeling with full data integrity.

2.4 Immersive Visualization Technologies

Virtual reality, mixed reality, augmented reality, virtual environments, immersive virtual environments, cyberspace, immersion, and presence: these are some terminologies that are often used to describe technologies associated with immersive visualization. These terms have different interpretations though often some of these terms are used interchangeably.

The term ‘cyberspace’ came into use in the 1990s and epitomized many of the new immersive visualization ideas and technology. Cyberspace represents many of the interconnected digital technologies that create an interactive virtual or digital space for people to collaborate. Henthorne (2010) described cyberspace as “a special kind of place that represents virtual domains as a single, continuous space that is independent of any particular user, a place that is there whether it is being used or not, a place where people can meet, where things can be built or destroyed”. ‘Virtual reality’ became popular with the dawning of the digital age (Massumi; 2014, p.55). The term ‘virtual’ connotes the artificial or illusionary and virtual environment builds on this sense of the illusionary (Lv et al., 2017). Virtual environments represent advanced computational platforms and technologies that are particularly well suited for the display of 3D models (Dunston et al., 2011; Paes et al., 2017).

Virtual immersive environments are computer-generated three-dimensional environments where users can be partially or fully immersed in a scene and can interact with the scene in real-time. Immersion within a virtual environment creates a perceptual sense of being physically present in a non-physical artificial space. This perception is created by capturing the user’s peripheral vision and through stereo enabled images, spatial sound, smell and other stimuli that provide an engrossing total environment. This sense of immersion or presence is a state of consciousness whereby a user’s awareness of physical self is transformed within an artificial environment. The extent to which belief can be suspended, equates to a greater degree of presence being achieved. The terms ‘immersion’ and ‘presence’ are sometimes used interchangeably (Riva et al., 2003; Calleja, 2014; Slater and Wilber, 1997). In recent years, a variety of innovative immersive technologies have been developed that offer different ways of representing 3D models and geospatial information in an immersive environment with real-time interaction (Chen et al., 2011).

2.4.1 Categories of Virtual Reality Environments based on the degree of immersion

The emergence of affordable virtual reality environments provides an interactive simulation and experimental environment that is suited to the display of 3D models and landscapes (Chen et al., 2011). Virtual environments can be categorized into non-immersive, semi-immersive and fully immersive virtual environments depending on the degree of immersion, and the sense of presence that is generated (Nan et al., 2014). Immersive presence is the product of several parameters including the level of interactivity, image complexity, stereoscopic view, field of view and the update rate of the display.

In a non-immersive environment, a portal or window is utilized to view standard high-resolution monitor and desktop systems and interaction is typically by means such as keyboards, and mice. A semi-immersive system comprises a relatively high-end performance graphics computing system, which can be coupled with either a large screen monitor or projector system, or multiple television projection systems. Semi-immersive systems increase the sense of immersion or presence by using a wide field of view. The most extreme experiential sense of immersive is achieved through fully immersive virtual environment systems. These systems are widely known virtual environment implementations where the user either uses a Computer

Assisted Virtual Environment (CAVE) or wears a Head Mounted Display (HMD) or other head-coupled display that provides a 360° field of view. All fully immersive systems provide a sense of presence that cannot be equaled by non-virtual environments. Fully immersive virtual environments tend to be the most computational demanding in terms of cost, computing power, graphics capabilities, and level of technology required to achieve a satisfactory level of virtual realism.

The CAVE is a fully immersive Virtual Environment with three or more stereoscopic projectors. First designed by Cruz-Neira in 1992 the user is physically situated within a digitally simulated world and experiences a cognitive involvement in the projected scene while suspending belief in the actual physical environment in which the user is situated (Cruz-Neira et al., 1992). This immersive environment provides a unique position in visualization technologies and among other user interfaces.

2.4.2 Virtual Environments coupled with GIS

According to Faust (1995), in order to provide GIS functionality in a virtual environment a system or user interface should be capable of representing the three-dimensional nature of geographic areas; should provide users with the capability of free movement within and outside of the terrain; should be able to perform basic GIS functions such as search, query, select, and overlay within the three-dimensional database; and should be capable of viewing the results from any vantage point. The system, he suggests, should also include viewpoint functions such as line-of-sight, and viewshed analysis. Few virtual and immersive environments support basic GIS functions such as spatial data capture, projection and transformations, attribute data retrieval and classification, and overlay.

2.4.3 Augmented reality and Mixed Reality

Augmented reality (AR) is an immersive technology that creates an environment where virtual objects are combined and integrated with the actual physical environment in real-time (Mota et al., 2017; Raja and Calvo, 2017; Zhao et al., 2017). The term AR is often used interchangeably with the term mixed reality (MR) but in both instances the projected image contains elements of both the real and artificially generated worlds. Google Glasses™ or PokemonGo are probably the best examples of AR/MR technologies (Espíndola, 2010; Quint et al., 2015).

2.4.4 Components of Immersive Visualization Technologies

Much of the recent upward trend in immersive visualization technologies has been enabled through advancements in computer hardware and software technology and especially computer graphics, image processing, image rendering, high-resolution stereoscopic projectors, and human computer interfaces. Immersive visualization technologies comprise two main components: hardware and software. The hardware can be further divided into computer or virtual reality engine and I/O devices, while the software can be divided into application software and database management systems (Bamodu and ye, 2013) as illustrated in Figure 2.5.

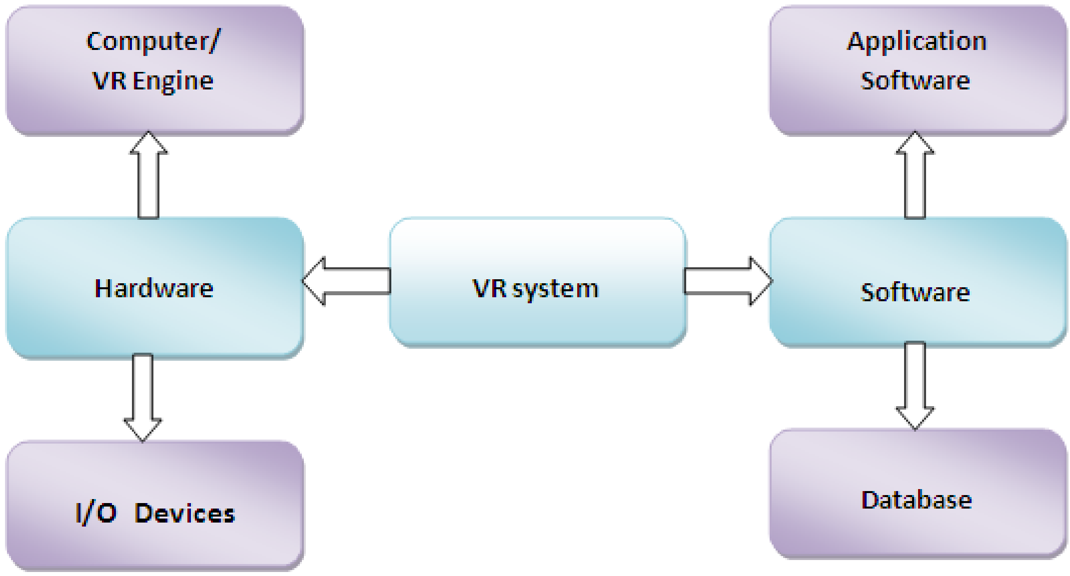


Figure 2.5: Components of immersive visualization technology. (Bamodu and Ye, 2013)

The input devices send signals to the computer system/VR engine to provide corresponding reactions back to the user through the output devices in real-time (Figure 2.6).

Figure 2.6: Hardware components of immersive visualization technology (Bamodu and Ye, 2013)

Input devices comprise tracking devices or position sensors, neural or muscular controllers, voice recognition devices, and navigation controllers (Bamodu and Ye, 2013; Guttentag, 2010; Craig et al., 2009). The computer system/VR engine plays the primary role in calculating and generating the graphical models, object rendering, lighting, mapping, texturing, simulation and display in real-time (Bamodu and ye, 2013). Selection of the computer system/VR engine depends on the application field, user needs, I/O devices, and the level of immersion and graphical output required (Bamodu and ye, 2013). The output devices receive feedback from the computer system/VR engine and deliver it to the user to stimulate the senses through graphics (visual), audio (aural), haptic (touch, contact, force), smell and taste (Bamodu and ye, 2013).

Driving the immersive visualization system is a collection of tools and software that design, implement, and operationalize the virtual environment and the database where the data is stored (Bamodu and ye, 2013). These software tools can be divided into 3D modeling tools and system development tools. Some common examples of 3D modeling software are SketchUp, 3ds Max, Unity, Maya, ArcGIS, and Solidworks. The development tools can be virtual world authoring tools, VR toolkits/software development kits (SDK) and application program interfaces (APIs).

2.4.5 Application of Immersive Visualization Technologies

Paes et al. (2017) investigated if an immersive environment provides an improved perception of a three-dimensional virtual representation compared to the spatial perception obtained using traditional display systems. These research findings signified that the immersive environment provided improved spatial perception of the virtual space and that the immersive environment enabled users to perceive spatial features more accurately than conventional systems. Virtual environments are also valuable in providing a collaborative decision-making space by allowing multiple parties to simultaneously simulate displays and planning scenarios and to gather instant feedback in the process (Bishop and Stock, 2010). Apart from professional GIS analysts and users, the use of virtual and immersive environments can be enormously helpful for expert workers and for public participation in decision-making processes. Urban planning, environmental monitoring, safety management decision support systems play a significant role in the daily lives of society and public participation can be increased for such purposes by representing complex geographical phenomena in an easily understandable visual form with the help of virtual and immersive environments. This research contributes to providing such applications. The Oculus Rift, HTC Vive, Kinect, Hololens, Leap Motion, Google Daydream, Samsung Gear VR, Playstation VR, Zeiss VR One, CAVE, Google Cardboard, IrisVR, Project Morpheus VR, Meta Glasses, and Open Source Virtual Reality (OSVR) are fast developing and leading virtual immersive environment platforms available in the market.

CHAPTER III
Methodology

The methodology for this research is based on widely used GIS software that was used to build an integrative approach to analyze and visualize three-dimensional underground features in a virtual immersive environment. Two case studies were undertaken to develop a 3D GIS to store, manage, analyze, and visualize the data for shallow underground infrastructures and for deep underground infrastructures. Figure 3.1 shows the complete process of the research process and methodology in the form of a flow chart. The flow chart includes the following components of this research:

Equipment: The software and hardware platforms used for 3D data storage, 3D modeling, 3D geoprocessing, and immersive visualization of the subsurface infrastructure and features are mentioned under this section.

Operational Framework: The operational framework of the research is presented in four phases. The first phase includes the problem formulation that comprises the literature review, research goal, and research questions. The second phase represents the system development including database design and management, and 3D modeling. The third phase constitutes the integration of the 3D models and the implementation of geoprocessing and volumetric computation analysis. The fourth phase includes the import/export and visualization of the geospatial 3D models in the virtual immersive environment.

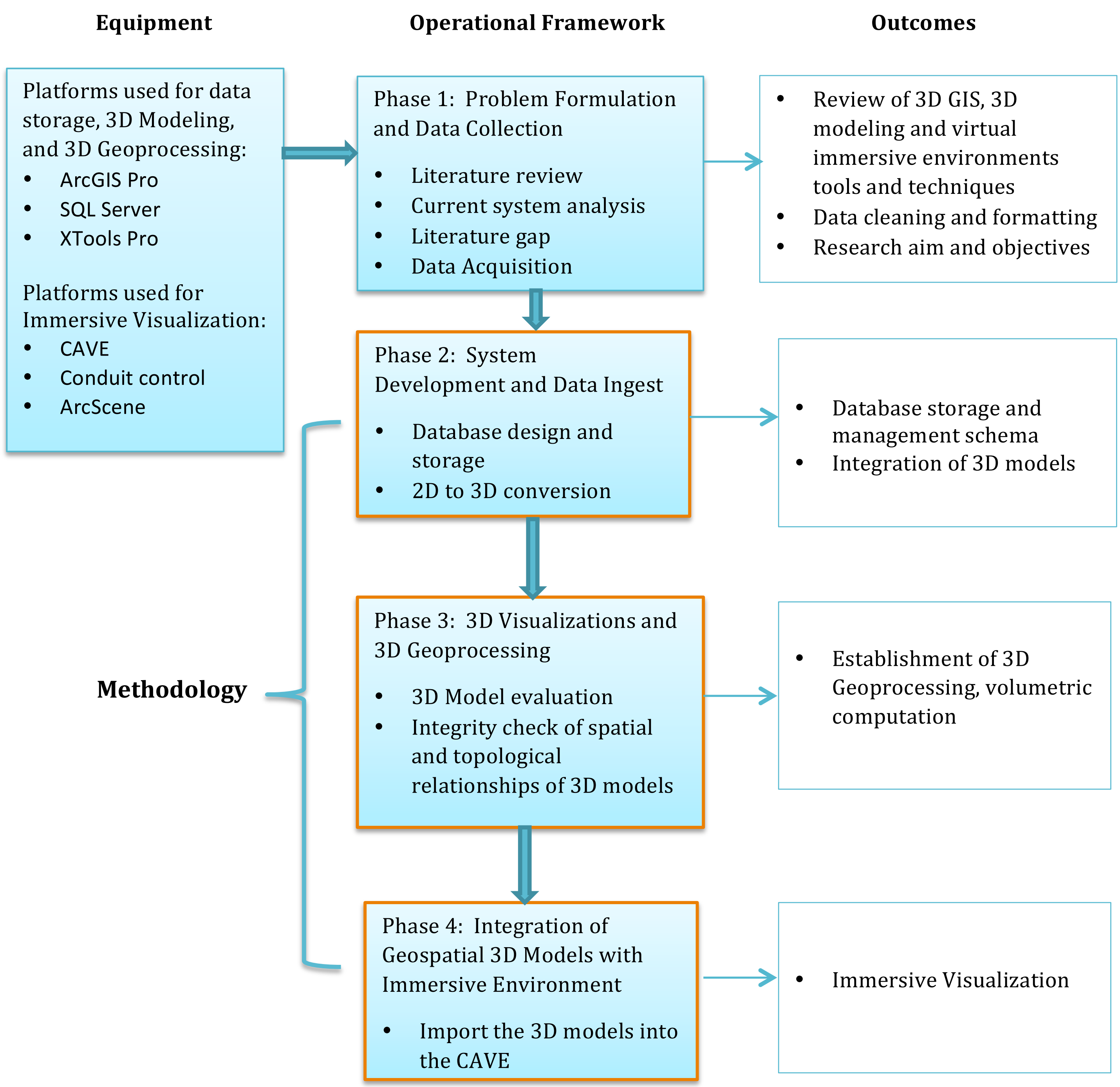


Figure 3.1: Research framework

Outcomes: This section includes the outcomes from the four phases of the operational framework.

3.1 Operational Framework of the Research:

Methodologically the intent of this research was to devise an integrated platform of software, tools and techniques to achieve a 3D GIS implementation. The operational framework of the research includes database storage management, 3D GIS modeling, geoprocessing, and visualizing the 3D models in a virtual immersive environment. Figure 3.2 summarizes these four phases of the research for the two case studies.

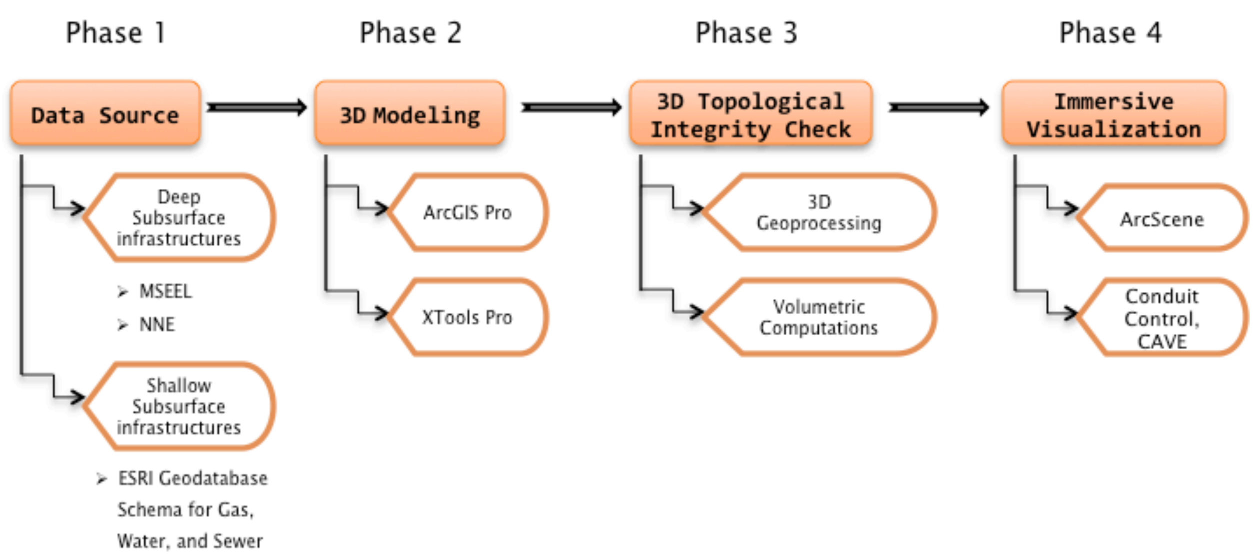


Figure 3.2: Four phases of the research method development for the case studies

3.1.1 Phase 1: Data collection for the shallow and deep underground infrastructures case studies

For the first case study, gas, water, and sewer utility networks were selected as being most typical occurrences of shallow underground utility features. A residential area in Morgantown in West Virginia was selected as the study site for this case study. As data for these shallow underground infrastructures was sought it became evident that the availability (or more accurately non-availability) of the data was subject to proprietary and homeland security issues. In this respect the data acquisition for shallow underground infrastructures from the respective utility agencies was not feasible. As a result of the unavailability of utility data it was necessary to generate typical utility networks for these three example networks according to the best industry practices. This was a time consuming and arduous process. Esri provides the industry-standard and industry-specific geodatabase template and schema for utility networks such as, water, sewer, storm-water, electric, and gas and these geodatabase schemas were used to guide and create the utility network for the gas, water, and sewer system for the study site. Since residential areas mainly contain only the distribution networks of utilities only the distribution components of the particular utility network were created for the study site. Table 3.1 shows the data template for gas, water, and sewer utility networks used for this case study. The table represents the feature classes for each utility network and the asset group for each feature class. In the utility network geodatabase schema designed by ESRI, the asset groups are used to categorize and classify the attributes that help in maintaining the data integrity. More details about the geodatabase schema of the utility networks are included in the case studies chapter.

Shallow Subsurface Utility Data Template		
Utility Network	**Feature Class**	**Asset Group**
Gas	• Gas_Line • Gas_Device • Gas_Junction	Distribution Pipe, Customer Pipe Controllable Tee, Flow Valve Connection Point
Water	• Water_Line • Water_Device • Water_Junction	Water Main, Service Controllable Valve and Service Connection Fitting
Sewer	• Sewer_Line • Sewer_Device • Sewer_Junction	Collector Main, Lateral Pipelines Service Connection, Cleanout Fitting

Table 3.1: Data template for the three shallow underground infrastructure networks

The data for the second case study includes four directional oil and gas wells at the Morgantown Industrial Park in Morgantown in West Virginia along with the geological rock horizon surrounding the horizontal wells. The data for these deep underground directional wells were acquired from the MSEEL (Marcellus Shale Energy and Environment Laboratory) and NNE (Northeast Natural Energy) projects which jointly operate and regulate the site. The MSEEL project was started to advance understanding of unconventional shale resources and to study the issues related to the environmental and societal impacts of shale gas development. MSEEL provided the data for multiple related research areas. The four directional wells at the Morgantown Industrial Park (MIP) are known as MIP3H, MIP5H, MIP4H, and MIP6H. The data for the directional wells was acquired in Microsoft Excel file format that included attribute information for the wells such as, northing and easting values, true vertical depth, measured depth, and inclination angle. The data acquired for the geological rock horizon contained attribute information for five geological layers: Hamilton, Upper Marcellus, Cherry Valley, Lower Marcellus, and Onondaga. Table 3.2 contains the summary data for this case study. More details about the data and data sources are included in the case study chapter.

Data Summary for Deep Subsurface Features		
Feature	**Feature Class**	**Attribute Information**
Directional Wells	• MIP3H • MIP5H • MIP4H • MIP6H	Northing and Easting, True Vertical Depth, Inclination Angle
Geological Rock Horizon	• Hamilton • Upper Marcellus • Cherry Valley • Lower Marcellus • Onondaga	Northing and Easting, Depth

Table 3.2: Data summary for the deep subsurface case study

3.1.2 Phase 2: Data ingestion and 3D spatial database management

Central to the case studies is the availability of 3D data at various scales and resolutions for underground features and infrastructures. Data formats for subsurface 3D data can vary because of the variety of groups, companies, and agencies involved. According to the Open Geospatial Consortium's (OGC) 'Underground Infrastructure Concept Study Engineering Report' published in 2017, a standard global data exchange format for underground infrastructures, especially shallow underground infrastructure, is still a work in progress. The organization and management of these datasets, especially large-scale underground datasets that include both natural features and infrastructure, is challenging. An additional challenge is that the storage and management of 3D datasets acquired from various sources are in such varied and different formats. In a spatial database management system, a well-designed and well-managed spatial data schema is key to optimal performance and effective analysis and visualization. Spatial database design can best be described as the storage of real-world information as spatial indices that are structured optimally in order to speed up access to the data for spatial query and analysis.

A 3D spatial database management system should be capable of storing the spatial, topological and geometrical information of 3D spatial objects in a digital space. A core implementation for storing 3D geo-information must be capable of handling differing spatial data types, creating spatial indices, providing a corresponding query language, preserving the topological relationships between the objects, and facilitate spatial data processing (Rahman, 2006). 3D geometry and 3D topology are most critical to preserve the 3D characteristics of objects in a geodatabase and to support spatial functionality and operations. 3D geometry necessarily contains three independent coordinate values of x, y, and z but 3D topology that enables the combinatorial structure and relationships between objects in 3D space is critical for spatial operations.

In this research, the ArcGIS Pro database management system or geodatabase was used to store and manage the large-scale 3D data for both shallow and deep underground infrastructure and their physical environments. The 3D models of these features were created by using ArcGIS Pro and the XTools Pro extension for ArcGIS. The 3D objects in the two case studies were represented by the 3D geometries including 3D lines and multipatch polygons. ArcGIS Pro allows the storage of information for each object in the feature's geometry and provides a set of geoprocessing tools for building, managing, analyzing, and validating spatial and topological relationships of the 3D features.

3.1.3 Phase 3: Software for 3D modeling of Shallow and Deep Subsurface Infrastructures

Esri launched ArcGIS Pro in 2015 with the purpose of providing a tighter integration of the entire ArcGIS suite in one desktop application. ArcGIS Pro was selected to build the 3D models and perform 3D geospatial analysis and volumetric computations for both case studies. ArcGIS Pro provides an integrated 2D-3D environment that combines data, maps, and now 3D scenes. ArcGIS Pro has 3D editing capabilities and allows above and below ground navigation. The 'Edit Topology Functions' in ArcGIS Pro assists in checking and maintaining the topological integrity of the 3D data that is essential for subsequent geoprocessing and volumetric computations. The 3D spatial analysis tools such as Buffer 3D, Difference 3D, Intersect 3D, Union 3D, Near 3D are available in ArcGIS Pro though as an embryonic 3D GIS platform there are many bugs and challenges involved in processing in the system. The customization of these analytical tools has to be performed through Python Scripting. The automated and manual QA/QC tools assist in detecting anomalies concerning the features, attributes, and relationships in the database. ArcGIS Pro makes it possible to label the data in 3D with the help of Maplex Label Engine and Standard Label Engine. XTools Pro is an extension for ArcGIS Pro and was partly used in the 3D modeling of the deep underground infrastructures.

3.1.3.a Topological integrity of 3D models

Topology plays a crucial role in GIS data management and integrity. Topology can be defined as a set of rules in a geodatabase that defines how feature geometries share a geographic space. In GIS, the topological integrity of the data is important in order to establish and analyze the spatial relationships between the features. A topological data model in 3D GIS uses nodes, faces, and edges as topological primitives to represent the spatial relationships of point, line, and area features. In conventional GIS or 2D GIS system, the topological models are well established but these 2D approaches cannot be simply extended for 3D or higher dimensions. The topology of 3D models is more complex than 2D or 2.5D since features can be adjacent to multiple features in both the horizontal and vertical directions (Thomsen et. al., 2008). Although there is no direct extension of 2D topological models into 3D space, there are 3D spatial data models available to represent 3D features. In 3D GIS the geometrical components of a 3D object can be described through sets of points, curves, surface, and volumes and the topological components comprise a mesh of nodes, edges, faces, and solids. These topological components describe both the interior structure of the object and mutual neighborhood relationships in 3D space.

However, the use of a particular spatial data model depends on the requirements of a specific application.

ArcGIS Pro provides geodatabases based on the advanced topological models for 3D data storage. ArcGIS Pro has an inbuilt tool to check the topological integrity of the 3D models in the geodatabase. The tool validates and fixes geodatabase-topology and validates the network-topology which is a critical component of the utility network geodatabase schema.

3.1.3.b 3D Geoprocessing and Volumetric Computations

The ability to perform 3D geoprocessing and volumetric computations are a critical part of this research. A volumetric object satisfies the following characteristics: closeness, interior connection, face-construction and proper orientation. 3D spatial analyses can be performed only if the 3D objects satisfy all these geometrical and topological conditions. ArcGIS Pro includes a set of tools to check and validate the geometrical and topological integrity of the 3D features. After the geometrical and topological validation of the 3D models, the following geoprocessing and volumetric computations can be performed in ArcGIS Pro:

- 3D Buffering
- Intersection in 3D
- Intersection of a 3D line with multipatch features
- ‘Near’ 3D proximity analysis
- 3D ‘Union’
- 3D volume and rate of flow computations

- Cut and Fill volumetric analyses

3.1.4 Phase 4: Components of immersive visualization

The Mechdyne CAVE (Computer Assisted Virtual Environment) is the immersive visualization technology used for this research. The CAVE is a room-sized setup with four stereoscopic projectors (Figure 3.3). There are three wall or vertical projectors and one floor or horizontal projector in the CAVE. The fourth, floor projector uses a mirror to reflect and project the data onto the floor. The CAVE can be used in immersive mode and in flex (non-immersive) mode.

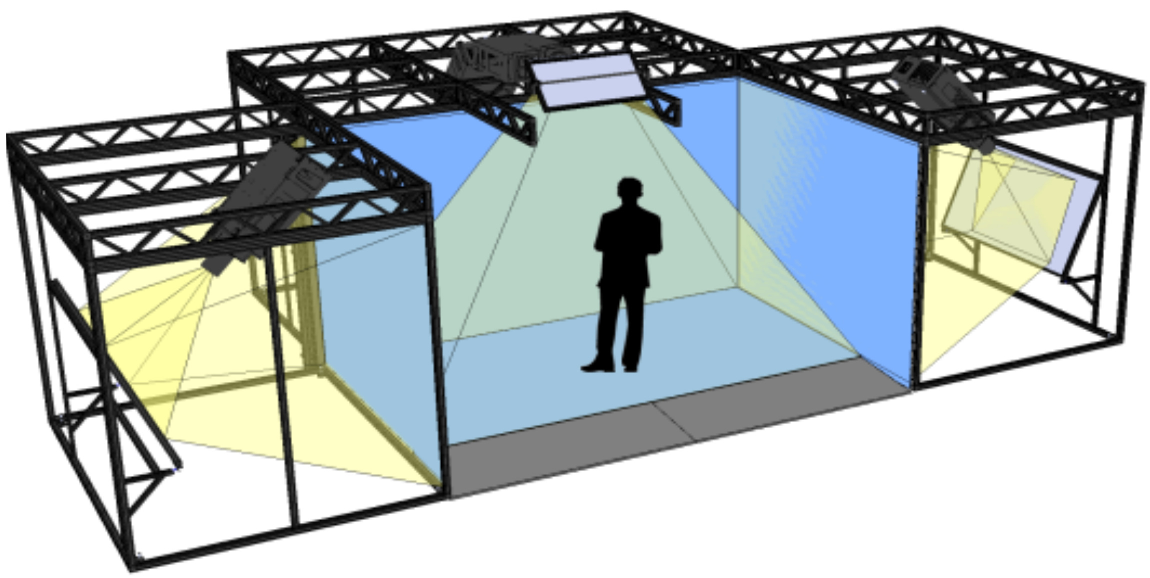


Figure 3.3 Schematic representation of the CAVE. Reprinted from Virtual Reality CAVE, by Windsor-Essex Autonomous Vehicle Innovation Network, Retrieved December 17, 2019, from https://www.wavin.ca/vr-cave.html

The CAVE uses two computer systems serving as the Master node and Render node. The master node is used as a front-end computer system where the user interface software is installed. The Render node is used as the back-end computer system that is responsible for processing and rendering the data and parsing it to the stereoscopic projectors. The external high-resolution, multi-display graphic cards are critical to the CAVE and the CAVE uses two Quadro-Plex 7000 each holding two Nvidia 6000 graphics cards. Communication boxes separately process signals from the external graphics cards to the left and right eye and scalar boxes convert the video signals to the appropriate ratio for the display walls. A wireless Xbox controller is used to navigate through the scenes in both immersive and flex mode. Users are required to use CrystalEyes 3D stereoscopic glasses to visualize the data projected through the stereoscopic projectors in the CAVE. The projectors project stereoscopic images for both left and right eyes in rapid, alternating succession and the undetectable fast shuttering produces stereovision. A tracking device attached to the stereoscopic glasses relays the users' position to the Render node. The system reproduces the image to reflect the user's perspective at a rate of 10 frames per second. One or several users can simultaneously visualize and analyze a simulation from within the CAVE. Thus, in contrast to individual head-mounted devices, the CAVE is ideal for shared and collaborative work. A user interface, called LaunchXPanel, is used to turn on and off the wall and floor projectors and the stereo mode for projectors. Another user interface, named Conduit Control, facilitates the access to the in-built 3D visualization software such as ArcScene and Google Earth which render the 3D models to the stereoscopic projectors.

CHAPTER IV
The Case Studies: Output and Analysis

4.1 Case Study I: Shallow Subsurface Infrastructures

A residential area in the South Park District of Morgantown in West Virginia was selected as the study site for the shallow subsurface infrastructure case study (Figure-4.1). A particular challenge for this study was that the data for shallow subsurface utilities are subject to proprietary and homeland security issues.

Figure-4.1 Case study-I study area in South Park, Morgantown, WV

To pursue research into the capability of 3D GIS in shallow subsurface infrastructure applications, the author fabricated a database for water, sewer, and gas utility networks. The prototypical data created for this case study follows the standard database schemas for water, sewer, and gas utilities designed by Esri and which are based on its close collaborations with utility companies, engineers, and academic professionals in the design of industry-standard databases for each utility network. Esri's geodatabase was used to create and store the utility network data for this casestudy. This geodatabase can only be used through the 'Utility Network Package Tools' extension for ArcGIS Pro. A utility network is a dense network of interconnected features that collect, transport, and distribute a commodity. Esri provides a GIS platform on which the utility network features can be stored, analyzed, and visualized using industry-specific pre-defined geodatabase schemas. Although Esri provides the predesigned geodatabase schema for the utility networks, it is a complex and challenging process to stage the utility network in the enterprise geodatabase. The 'Utility Network Package Tools' require particular system and software specifications such as the version of the RDBMS (Relational Database Management System) to create an enterprise geodatabase or the version of the ArcGIS Pro to support the installation of the 'Utility Network Package Tools'. There are many specific steps to be followed in order to create the enterprise geodatabase and to then add Esri's predefined geodatabase schema for the particular utility network under study to that enterprise geodatabase. If the enterprise geodatabase were not created using the specific versions of the SQL server and ArcPro software, users would not be able to add Esri's predefined geodatabase schema for the utility networks.

4.1.1 Specifications of Utility Network Package Tools

The Utility Network Package Tools is a beta release for ArcGIS Pro that facilitates the modeling of industry-standard geodatabase schemas for subsurface utilities. The Utility Network Package Tools consists of a broad assemblage of functions to create, edit, import, and export utility network data. The Utility Network Package Tools is installed through a Python Package Manager in ArcGIS Pro. In the process of using this method of utility modeling several major software errors were identified and reported to Esri. Although Esri tries to fix reported bugs and errors in the updated software release, many errors that have been identified to date have not been resolved and this has entailed several complex and time demanding workaround solutions having to be developed. For example, during the installation of the Utility Network Package Tools a software bug [Bug:000112192] was encountered that caused the install button to be grayed out. To bypass this particular software bug entailed uninstalling and reinstalling ArcGIS Pro, as well as creating and activating a new project environment in the Python Project Manager, and then a reinstallation of Utility Network Package Tools. Several other errors were encountered during the development of this work that lead to time consuming and complex workarounds.

The Utility Network Package Tools requires an enterprise geodatabase to ingest the geodatabase schema for the specific utility network and an active ArcGIS Enterprise portal to publish the content. Esri's predefined geodatabase schemas for utility networks are available as Asset Packages for download. An Asset Package is an interchangeable geodatabase file format that facilitates the import and export of the geodatabase schema configurations and, if available the data, in a utility network. An Asset Package can contain geodatabase configurations such as network attributes, connectivity rules, attribute rules, asset groups, asset types, and many other utility network related settings.

4.1.2 The Process of Adding a Predefined Geodatabase Schema to an Enterprise Geodatabase

To use the geodatabase schema for the utility network, an enterprise geodatabase was created in ArcGIS Pro. Microsoft SQL server 2017 was used as the Relational Database Management System (RDBMS) to store the enterprise geodatabase. A Feature Dataset was created under the enterprise geodatabase to store and organize all the spatially related feature classes into a common dataset. A polygon feature class, called service territory, was then created under the feature dataset. A service territory is a polygon feature class that represents the network boundary as well as the editable area for the utility network. In the service territory feature class, a polygon was created to represent the boundary of the utility network in Morgantown. After creating a boundary for the utility network in Morgantown, the Stage Utility Network tool was used to create a set of point, line, and polygon feature classes on which the Asset Package or Esri's predefined geodatabase schema was later applied in order to configure the utility network. While running the Stage

Utility Network tool, a software bug [Bug: 000115745] was found that caused the tool to fail. An alternative workaround for this software bug was researched and the service territory feature class was placed in a file geodatabase rather than in the enterprise geodatabase and was used as an input parameter in the tool. The feature classes created by the Stage Utility Network Tool are divided into two groups: structure network feature classes and domain network feature classes. To explain the complex hierarchy of the utility network geodatabase an image of the geodatabase structure and feature classes is included here (Figure 4.2).

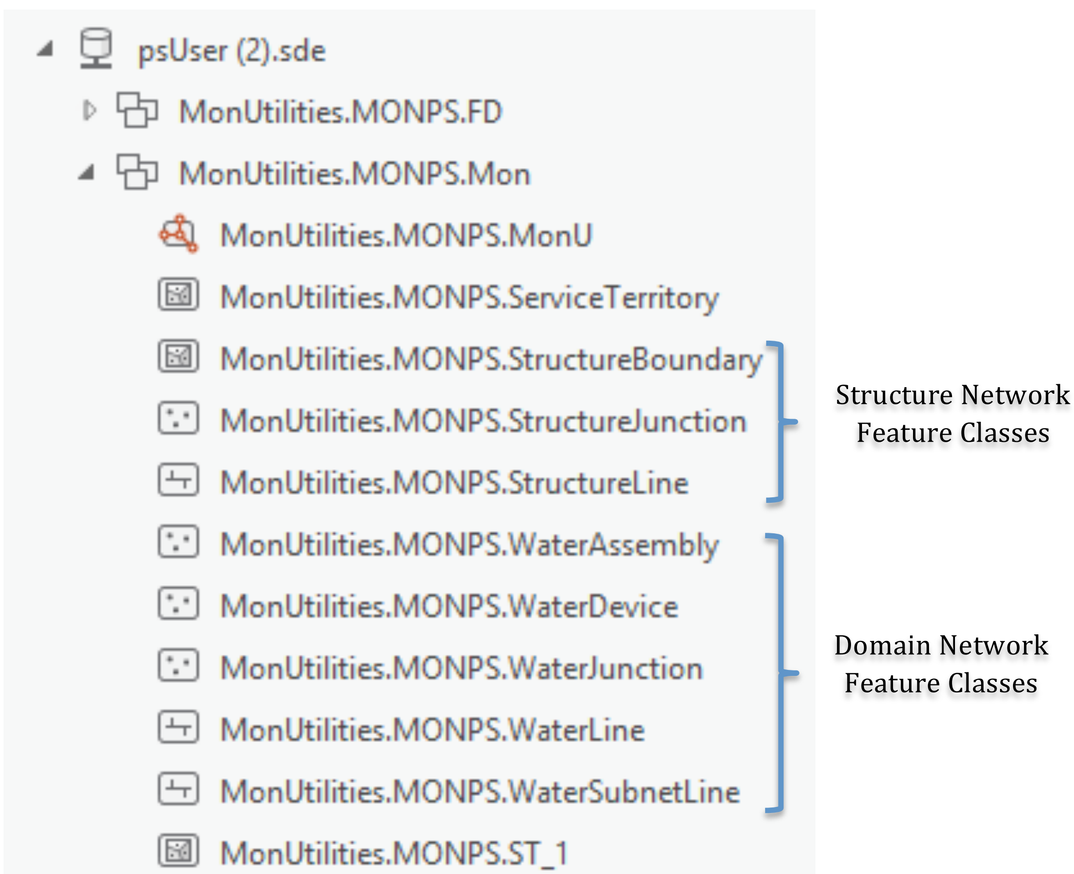


Figure-4.2 Geodatabase schema for a utility network

4.1.2.a Structure Network Feature Classes

A structure network contains three feature classes: StructureJunction, StructureLine, and StructureBoundary (Figure 4.2). StructureJunction is a point feature class that represents the features to which other features are attached or contained within, for example poles. StructureLine represents linear features that can carry a resource such as a duct carrying electricity or can be a container of the resource-carrying-features such as a duct bank containing several ducts. StructureBoundary are polygon features that represent the boundary of structure lines, structure junctions, substations, and other features and assemblies.

4.1.2.b Domain Network Feature Classes

A utility network can contain one or more sets of domain network feature classes. Different sets of domain networks can be created for differing parts of the same utility resource, such as with the distribution and transmission systems for water. Domain network feature classes contain the features that gather, transmit, and distribute the resource. The resource/commodity then flows through the domain network features. There are five feature classes in a domain network (Figure 4.2) named as line, device, junction, assembly, and subnetwork_line.

- Resource flows through domain *lines*
- *Devices* control the flow of the resource
- *Junctions* represent the connectivity of the features
- *Assemblies* represent the collection of lines, devices, and junctions
- *Subnetwork_line* defines the extent of resource flow

If there are two or more domain networks present, then they share the features represented under structure network feature classes. Theoretically, the Utility Network Package Tools also facilitates the integrated storage of two or more utility networks (for different commodities) that share some common features such as poles, pads, duct-banks, and cabinets. However, since the Utility Network Package Tools is still in its development phase, one enterprise geodatabase can only currently store the utility network for one commodity at a time. If an additional utility network needs to be added to the same geodatabase, the tool currently throws a software error (Bug:000118645) that causes the Asset Package tool to fail in the presence of an existing gas Asset Package. A workaround was to create different utility networks for different utilities rather than to create more than one utility network within a single enterprise geodatabase. As such three separate geodatabases were created for water, sewer, and gas utility networks for this case study. After establishing the geodatabase schema for all three utilities, the Asset Packages for gas, water, and sewer utility networks were imported from ArcGIS Solutions and applied to the respective enterprise geodatabases.

4.1.3 The Gas Utility System and Gas Utility Network Data Creation

The natural gas pipeline system is generally composed of three segments: gas gathering pipelines, gas transmission pipelines, and gas distribution pipelines. The gas gathering system is a network of pipelines that transport gas from the gas wells to the compressor station, processing point, and main trunk pipeline. 'Gathering' pipelines are usually small diameter pipes that move gas or hazardous liquid from the field to a central point. Gas transmission pipelines are mostly interstate pipelines and transmit gas from a source or sources of supply to one or more distribution centers. Transmission pipelines are generally made up of large diameter steel pipes, traverse longer distances of about 1,000 miles, and operate under high pressure. The gas distribution pipelines supply gas to the public consumers. Gas distribution pipelines are also known as gas mains. This distribution network is the final step in the delivery of gas to end users such as residents, businesses, and industries. Thus, most of the gas distribution pipelines are located in highly populated areas. Natural gas has been distributed by pipeline for over a hundred years in some areas though new pipelines are being added all the time as populated areas expand. The distribution pipelines themselves can reflect a mix of older technologies and materials such as cast iron, copper, and bare steel, or newer polyethylene plastic.

The study area selected for this case study is a residential area and reflects the presence of gas distribution pipelines in that area rather than other parts of a gas utility network. An enterprise geodatabase with structure network feature classes and domain network feature classes was created for the gas utility network. A gas domain network has five feature classes: GasLine, GasDevice, GasJunction, GasAssembly, and GasSubnetLine. The GasLine feature class contains three prominent linear features of the gas utility network: the Transmission Main, the Distribution Main, and Residential Service. The Asset Package was applied to the structure and domain feature classes as per Esri's predefined geodatabase configurations for gas utility networks. After adding the Asset Package, the gas distribution system was digitized using Esri basemap as a reference guide. The depth of the features from the surface is a critical component for a utility network. In this instance a constant depth value or z value was set before the digitization of the features and that z value was stored with the feature geometry.

Figure 4.3 The gas utility network overlaid on a satellite image

In the utility network database schema the feature attributes are classified into Asset Groups. In the GasLine feature class, two asset groups, distribution pipe and customer pipe were digitized. The distribution pipes deliver gas to the customer pipes. In the GasJunction feature class, one asset group, connection point was digitized. Features under this asset group represent the junction between the structures and pipes. In GasDevice feature class two asset groups, controllable tee and flow valve were digitized. The controllable tee asset group contains features that mechanically control the flow of gas through the pipe system. The flow valve asset group includes the features that control the direction of the flow of the gas. These features were selected for the data template according to the connectivity rules predefined in the gas Asset Package (Figure 4.3).

4.1.4 The Water Utility System and Water Utility Network Data Creation

The water distribution system's structure and its operation play a significant part in the water quality and the quantity of water supply. A drinking water distribution system typically includes storage facilities, interconnecting underground mains or pipes, valves, fire hydrants, service connections, and pumping stations. As with the gas utility network data generation, an enterprise geodatabase with structure network feature classes and domain network feature classes was created for the water utility network. The Asset Package was applied to the structure and domain feature classes according to Esri's predefined geodatabase configurations for the water utility network. After adding the Asset Package, the water distribution system was digitized using Esri basemap as a reference guide. A constant depth value or z value was set in the map before the digitization of the features.

A water domain network has five feature classes: WaterLine, WaterDevice, WaterJunction, WaterAssembly, and WaterSubnetLine. In the WaterLine feature class two features of water transportation system that are categorized as the water main and service were digitized. The water mains deliver water to the service pipes and the service pipes deliver water to the customers. In the WaterJunction feature class, a feature called 'fitting', was digitized which connects the water mains with the service pipes. In the WaterDevice feature class two devices that control the flow of water, the controllable valve and service connection, were digitized. The controllable valve includes features that permit or prevent flow of water through the pipes (Figure 4.4).

Figure 4.4 The water utility network overlaid on a satellite image

4.1.5 The Sewer Utility System and Sewer Utility Network Data Creation

The sewer utility system collects wastewater from customers and transports it to the wastewater treatment facility. Most of the sewer utility systems are gravity fed and the sewer mains often follow a downhill path to the wastewater facility that is usually located in a low-lying area. To create the data for the sewer utility an enterprise geodatabase was created. The utility network was created using the Stage Utility Network tool, and the Asset Package for the sewer utility network was applied. A sewer domain network has five feature classes: SewerLine, SewerDevice, SewerJunction, SewerAssembly, and SewerSubnetLine.

Figure 4.5 The sewer utility network overlaid on a satellite image

In the SewerLine feature class collector, the main and lateral pipelines were digitized using Esri's basemap as a reference. The lateral pipelines collect the wastewater from each building or house and the waste flows to the collector mains. In SewerJunction feature class, the sewer fittings were digitized. According to the predefined connectivity rules in Esri's Asset Package, the fittings connect the lateral pipelines to the collector mains. In the SewerDevice feature class, the service connection and cleanout features were created (Figure 4.5).

4.2 The Results of Case Study I

4.2.1 Conversion of Utility Network Data from 2D to 3D:

Once the entire three utility networks were created for the study area, the networks were converted from a 2D form into a 3D form. To convert the point and line geometries from 2D to 3D, the feature classes containing the geometries are required to be 3D enabled. In ArcGIS Pro the 2D map containing all the feature classes for gas, water, and sewer utility networks were converted into a 3D scene. In the scene the point features were symbolized as 3D spheres and 3D cylinders, and the line features were symbolized as 3D tubes for the three-dimensional representation of the model. The 3D symbols represent the extended properties of the 2D symbols in the z-axis direction. Those 3D symbols bring visual realism to the 3D model. Figure 4.6 represents a planar view of the Morgantown utility scene containing the gas, water, and sewer utility networks in the study area. The scene facilitates the editing and modifications in the geometry and the attributes of the 3D

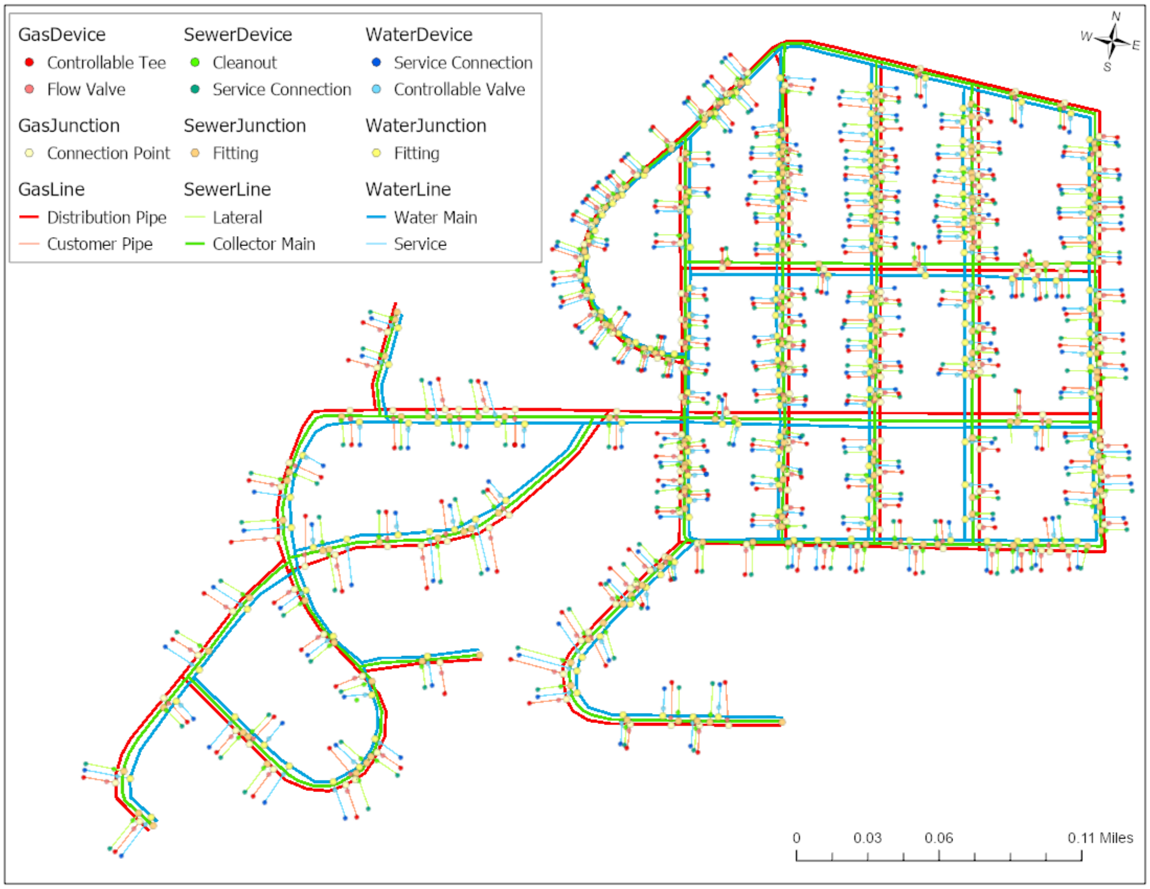


Figure 4.6 Planar view of the scene containing gas, water, and sewer utility networks in the study area

features. In the scene, 3D features can be labeled, attribute tables can be used to configure pop-ups, and pictures can also be attached to the 3D features and used as pop-ups to enrich the data with additional information. Besides these features, a scene can be shared and published as a web layer through ArcGIS Online. Figure 4.7 shows a close-up representation of the 3D scene of the gas, water, and sewer utility networks. One benefit of using a 3D representation of the utilities is that in Figure 4.7 the relative vertical position of the features can be seen clearly. The 2D maps of the utility features cannot display the utility features in a vertical manner even though depth is a very critical component of the subsurface features.

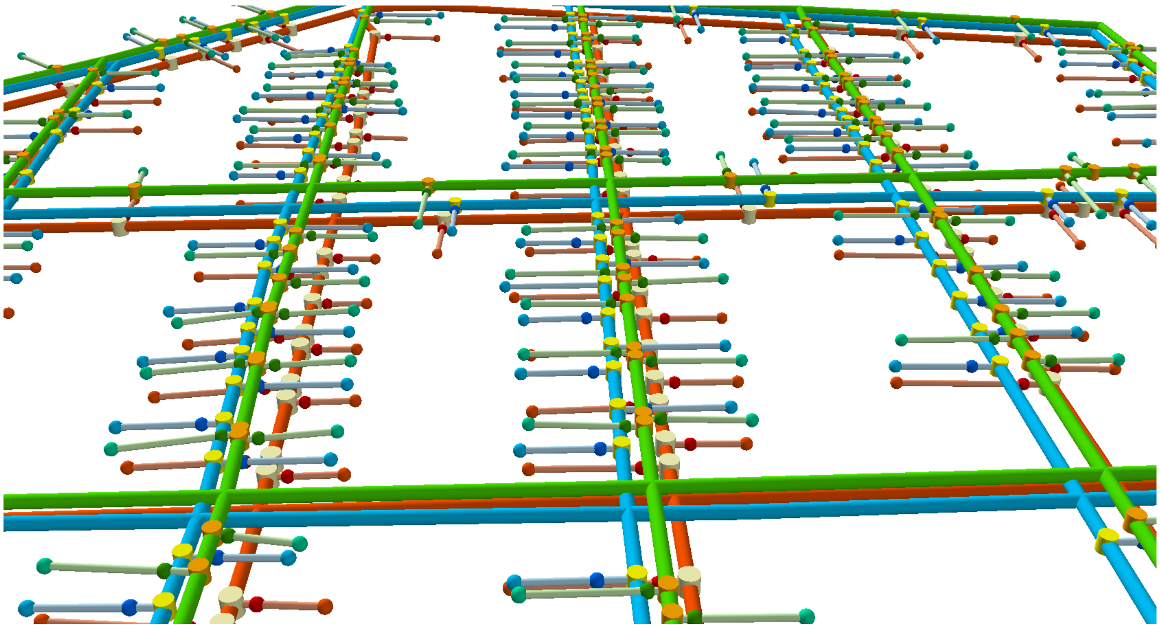


Figure 4.7 Close-up display of 3D model of gas, water, and sewer utility networks

4.2.2 Topological integrity of the utility features in 3D models:

The Utility Network Tool Package in ArcGIS Pro facilitates the establishment of topological relationships between different point, line, and polygon feature classes. This topological encoding is referred to as network rules in the utility network. The network rules maintain the data integrity during data creation and data editing. The network rules also include the connectivity rules, structural attachment associations, and containment rules. Connectivity rules are a set of attribute-related conditions that can be applied to the geodatabase when joining two features. For instance, in the water utility distribution network, according to the predefined connectivity rules, the water mains can only be connected to the service mains through a connecting feature called a fitting (Figure-4.8). Such a connectivity rule is

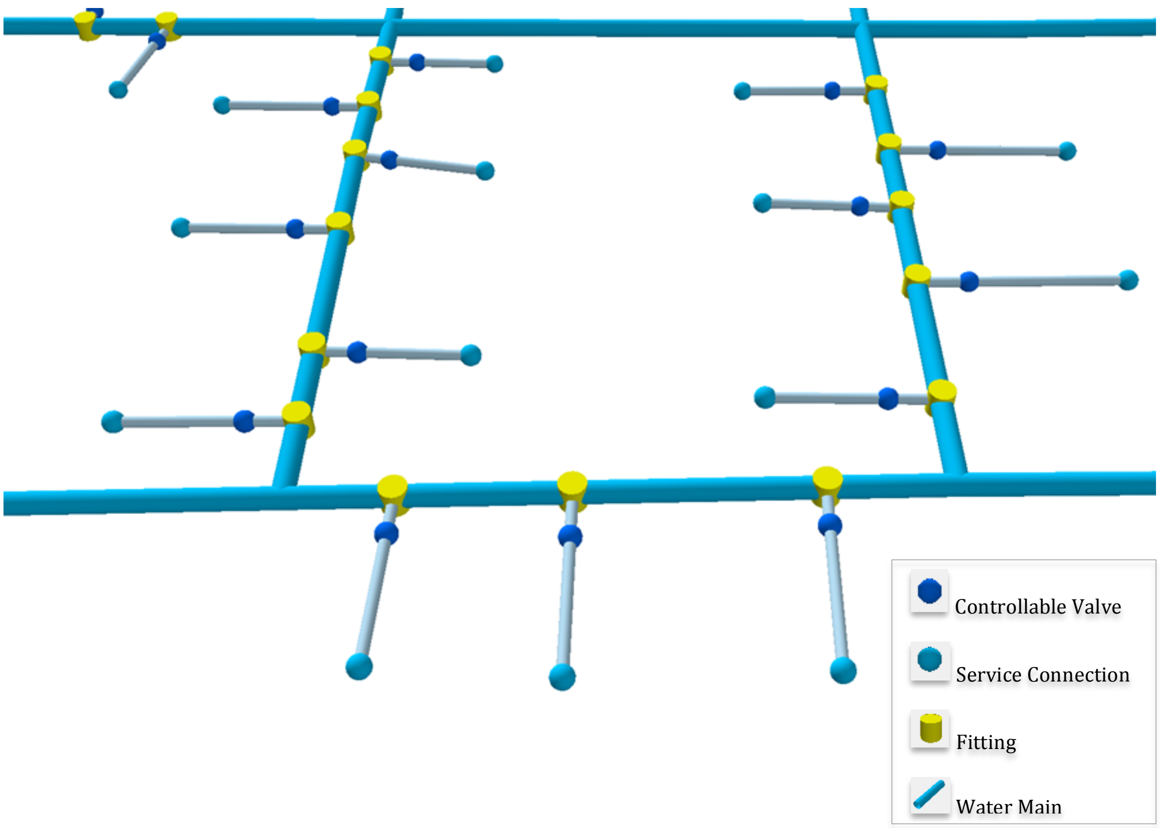


Figure-4.8 Connectivity of point and line features in water utility network

called an edge-junction-edge connectivity rule and controls the connectivity of the line features that can be connected using a junction point feature. Another type of connectivity rule used in the process of generating the utility data was the junction-edge connectivity rule which controls the line-end and mid-line connectivity to a point feature. For instance, in Figure 4.8 the controllable valve can be joined to the service pipes anywhere, but the beginning and end of the line and the service connections can only be connected at the end junctions of the service pipes. Establishing these connectivity rules helps to maintain the topological integrity of the data which is crucial to the subsequent spatial analysis of the utility network. Such a dataset can be used to plan the optimization of the paths for resources to flow, track the condition of the utility network, and identify problematic areas in the network. The trace feature in the utility network tool facilitates the tracking of malfunctioning features or deteriorating parts of the network. In the utility network, the integrity of the data can also be checked using the validate network topology tool. This validation tool applies validation rules to the network to identify feature errors.

4.2.3 3D Geoprocessing:

Three-dimensional modeling is certainly valuable for the visualization of subsurface features, though incorporating geoprocessing functionally into a 3D model further enhances the analytical capability of the model. The geoprocessing-enabled 3D modeling of utility networks is pivotal to determine the spatial relationships between different utility devices and structures. The outputs of the 3D geoprocessing are essential to solve complex location-based problems and to better understand exactly where and what is occurring in the utility network. Such spatial analysis helps to discover patterns that assist decision makers to see new perspectives in the planning and management of the utility infrastructure.

The 3D models generated in this study were tested with 3D geoprocessing analytics to explore the capability of the 3D modeling of the utility networks. 3D buffers were created for the gas, water, and sewer networks. However, the computer processing to create a 3D buffer of the entire utility network took several hours to complete on an advanced PC. However, it took only a few minutes to create 3D buffers for a single feature. Figure 4.9 represents a water distribution and service pipeline with a 3D buffer created by using an attribute field comprising numerical diameter values of the pipes in inches. The diameter of the water distribution pipes, used for creating the buffer was 6-inches and the diameter of the water service pipeline buffer was 1-inch. However, when a numerical attribute field is used in buffer creation, the buffer is created in the linear unit of the map. In this case, the linear unit of the map was in meters.

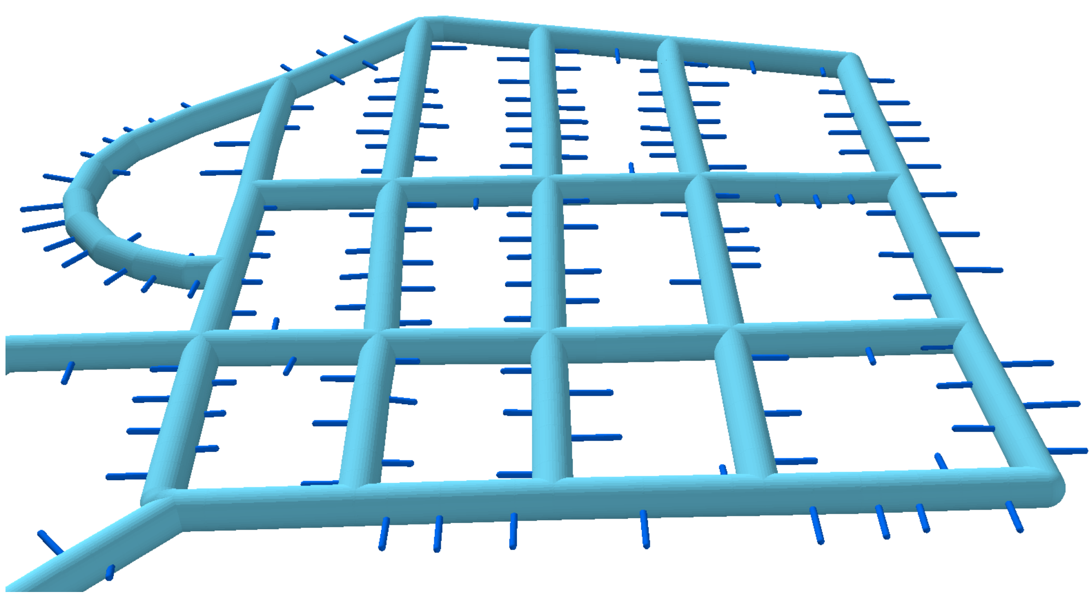


Figure-4.9 3D buffer of water distribution and service pipelines

The resultant 3D buffers are multipatch features that can be used in volumetric computations in GIS. The ‘Is Closed’ tool was used to check whether the resultant multipatch output was a closed geometry polygon or an open geometry polygon. It was observed that the 3D Buffer tool creates open multipatch outputs if the ‘joint-type’ is selected as ‘round’ (Figure 4.10). If the ‘joint-type’ were selected as ‘straight’ (Figure 4.10), the 3D Buffer tool creates a closed multipatch polygon that is required in order to compute volume. The ‘Joint-type’ in the 3D Buffer tool determines how two vertices connect.

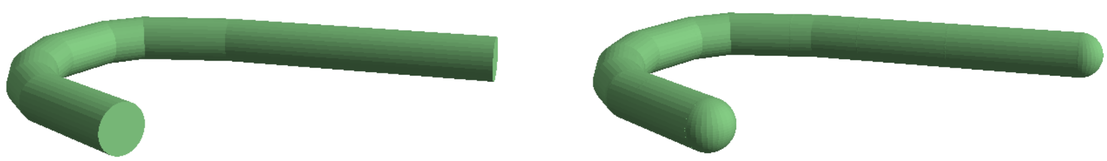
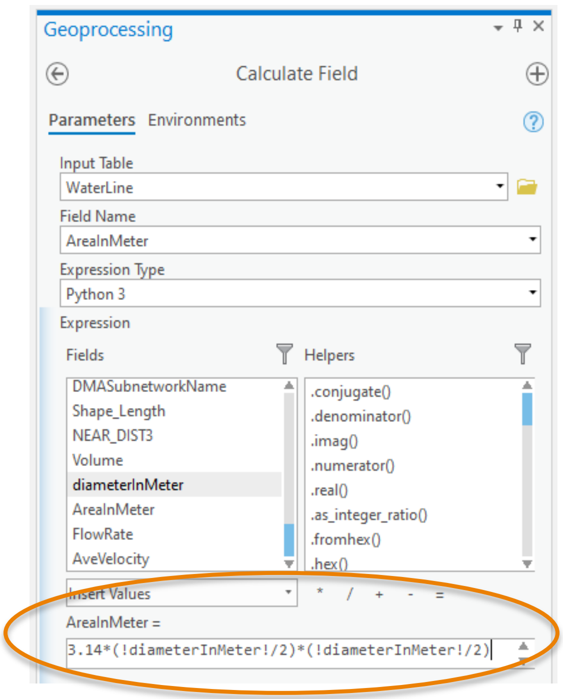


Figure-4.10 3D buffer outputs: straight joint-type (left) and round joint-type (right)

3D buffers can be used as a base for advanced spatial analyses as in assessing the spatial proximity of nearby features to a pipeline feature or to analyze and visualize how installing a new utility pipe might affect existing pipes. The 3D Buffer tool in ArcGIS also facilitates ‘cut and fill’ type volumetric computations such as estimating how much soil needs to be extracted to accommodate a new pipeline or to repair an existing pipe. Figure 4.11 represents a 6-inch buffer for a water pipe along with the attributes associated with the feature that includes the surface area and volume.

Figure-4.11 3D Buffer of 6-inch water pipe

ArcGIS Pro also provides the capability to calculate the volume of the closed multipatch polygons using the 'Add Z Information' tool. The volume of the 3D lines and flow-rates can be calculated by using attribute values within the GIS. These attributes can thus be displayed and published with the 3D models of the utility network for further analyses. Figure 4.12 shows the calculation configuration for an area and the attribute information of the water pipes using the diameter and measured-length attribute fields.



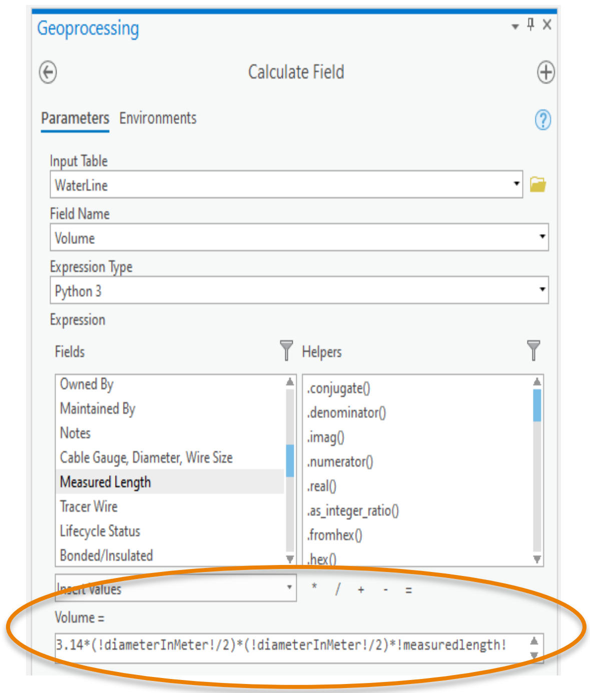


Figure-4.12 Calculation of area and volume of the water pipes using the attribute table

The flow rate of water through a pipe was calculated within the GIS by using the area of the pipe and the average velocity of the water in the water distribution system (Figure 4.13). The velocity of the water in the water distribution system must not exceed certain limits in order to avoid noise and long-term damage to the pipes and fittings. The ideal range of the fluid flow velocity in a water system is between 0.9 meter/second to 2.4 meter/second (Engineering ToolBox, 2003). The average value from this range was used as the velocity of the water to calculate the flow rate of the water in the water utility system.

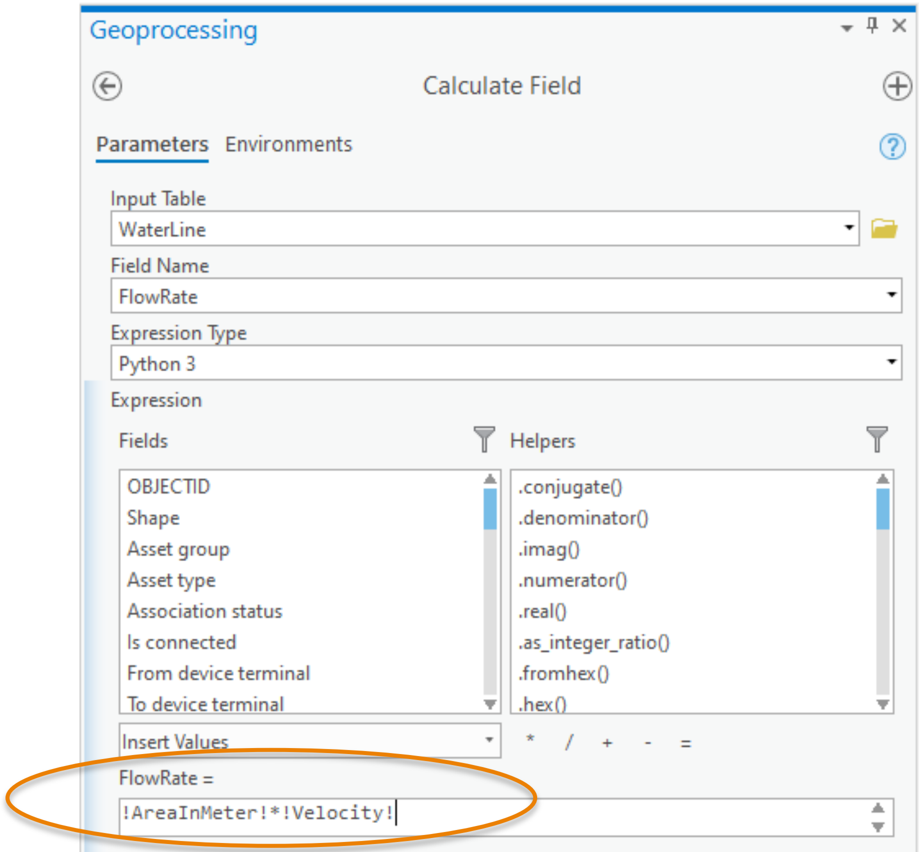


Figure-4.13 Water flow rate calculation within the GIS

Figure 4.14 and Figure 4.15 show the attribute information of selected water pipes. Integrating such attributes within the 3D models helps to enrich them with relevant information required by decision makers from different specialty fields.

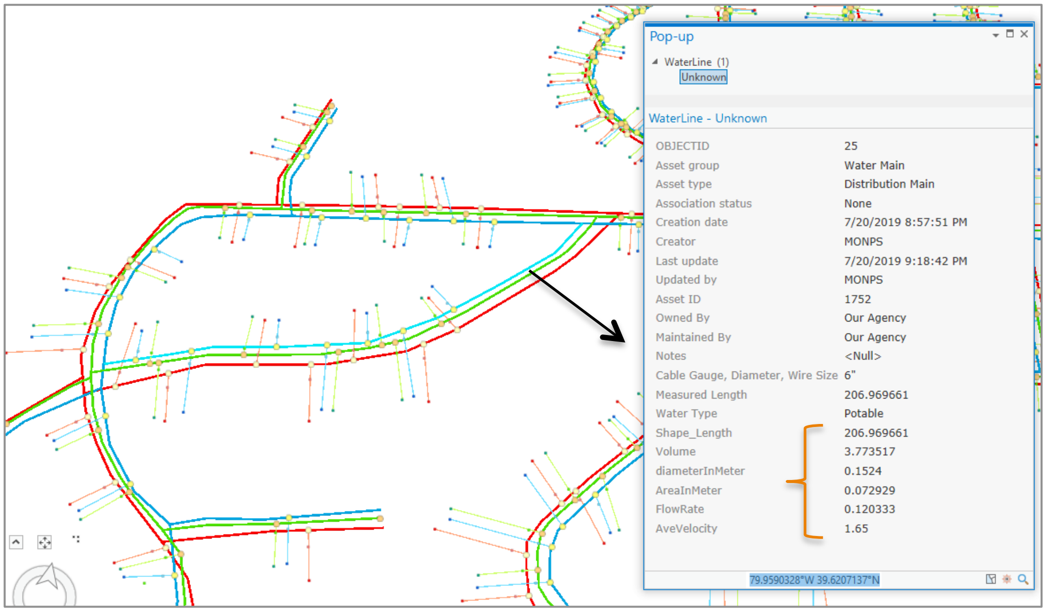


Figure-4.14 Attribute popup for the selected water-main

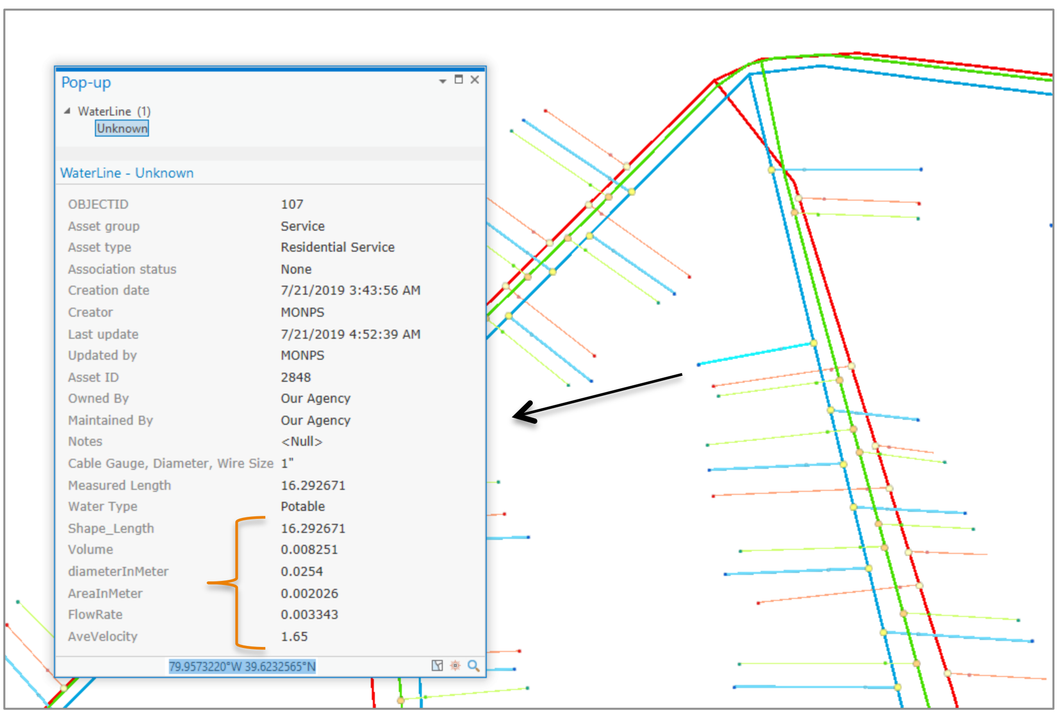


Figure-4.15 Attribute popup for the selected service water pipe

The 3D models of the utility network can be published via ArcGIS Online in a web scene (Figure 4.16) and web app. The web scene provides an interactive display of the 3D spatial data and attribute information that can be accessed and edited using a web browser on a desktop or mobile device. The web scene in Figure 4.16 displays the water, gas, and sewer utility network under a semi-transparent satellite image. The web scene supports interactive visualization by providing functions such as the on-off layers, legends, base-maps transparency control, slides or bookmarks, measurement scale, and attribute popups. The published web scene of the 3D models of the utility network can be accessed using the following link:

http://wvu.maps.arcgis.com/home/item.html?id=c666586d906c42899e5c830a68af23af

Figure-4.16 Web scene (3D utility network) published via ArcGIS Online

Other 3D geoprocessing functions that can be performed on such 3D models of the utility networks are Intersect 3D, Union 3D, Inside 3D, Near 3D, and Difference 3D. Intersect 3D computes the overlapping volumes of two multipatch features, and Union 3D is used to merge two or more overlapping polygons, Inside 3D can be used to determine if the 3D features are located partially or fully inside another multipatch feature in the same feature class, Near 3D can be used to calculate three-dimensional distance from the input feature to the nearest feature, and Difference 3D eliminates the overlapping volume of the input features (Esri, n.d.).

4.2.4 Immersive Visualization:

Once generated, the 3D models of the gas, water, and sewer utility networks were imported into the CAVE. The CAVE system uses Conduit Control software to display the GIS 3D models through Esri ArcScene. Before the stereoscopic projection of the 3D models, the 3D features had to be symbolized using the 3D symbols palette in ArcScene. After implementing the 3D symbology, the 3D models were rendered for stereoscopic projection. The 3D geometries remained intact and were displayed without any broken geometries during the 3D model rendering (Figure 4.17). The 3D buffer of the utility network was also visualized in the CAVE (Figure 4.18). There was no loss of geometrical information in the immersive visualization of the 3D buffers. The interactive CAVE facilitates horizontal as well as vertical navigation of the 3D model. Vertical navigation provides a planar view of the 3D model that displays a complete view of the network of pipes.

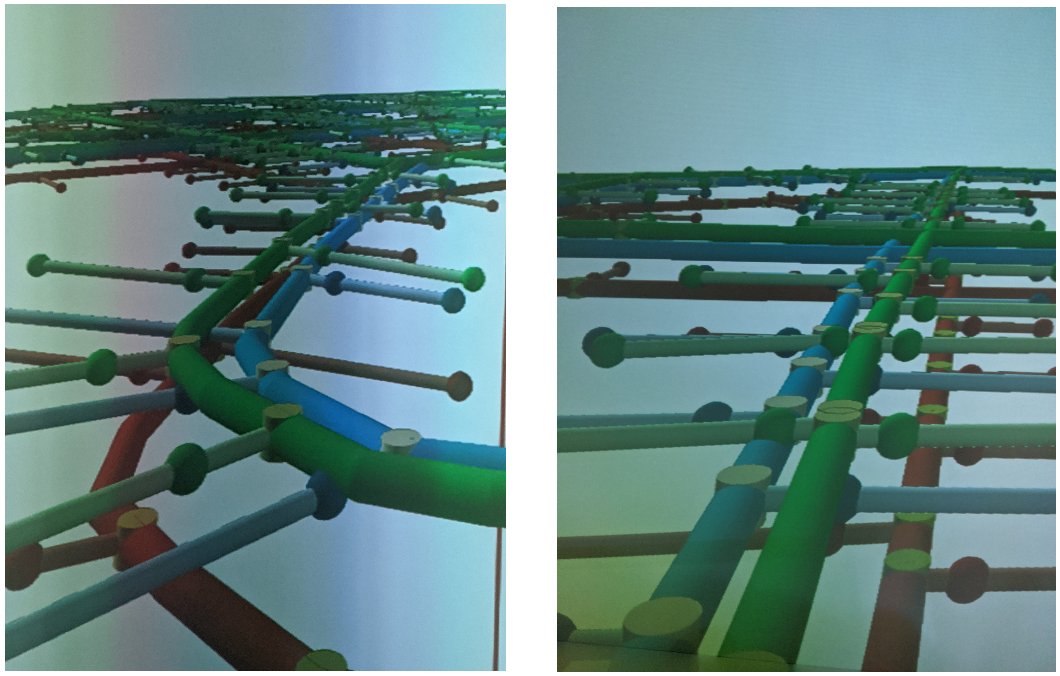


Figure-4.17 3D model rendering of utility networks in the CAVE

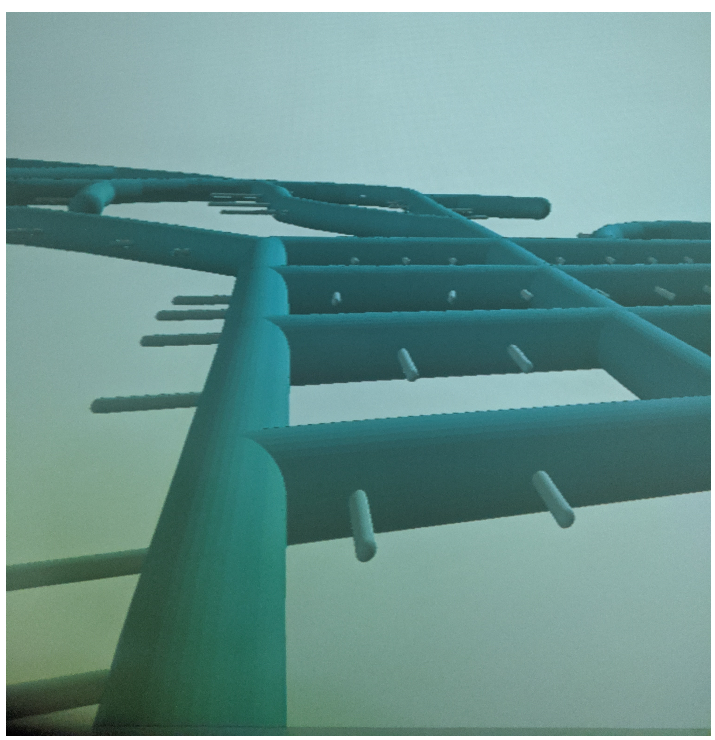


Figure-4.18 3D buffer of the water utility pipelines in the CAVE

4.3 Case Study II: Deep Subsurface Infrastructure

The data for the second case study includes the directional wells data and geological stratigraphy that were acquired from the Marcellus Shale Energy and Environment Laboratory (Figure 4.19).

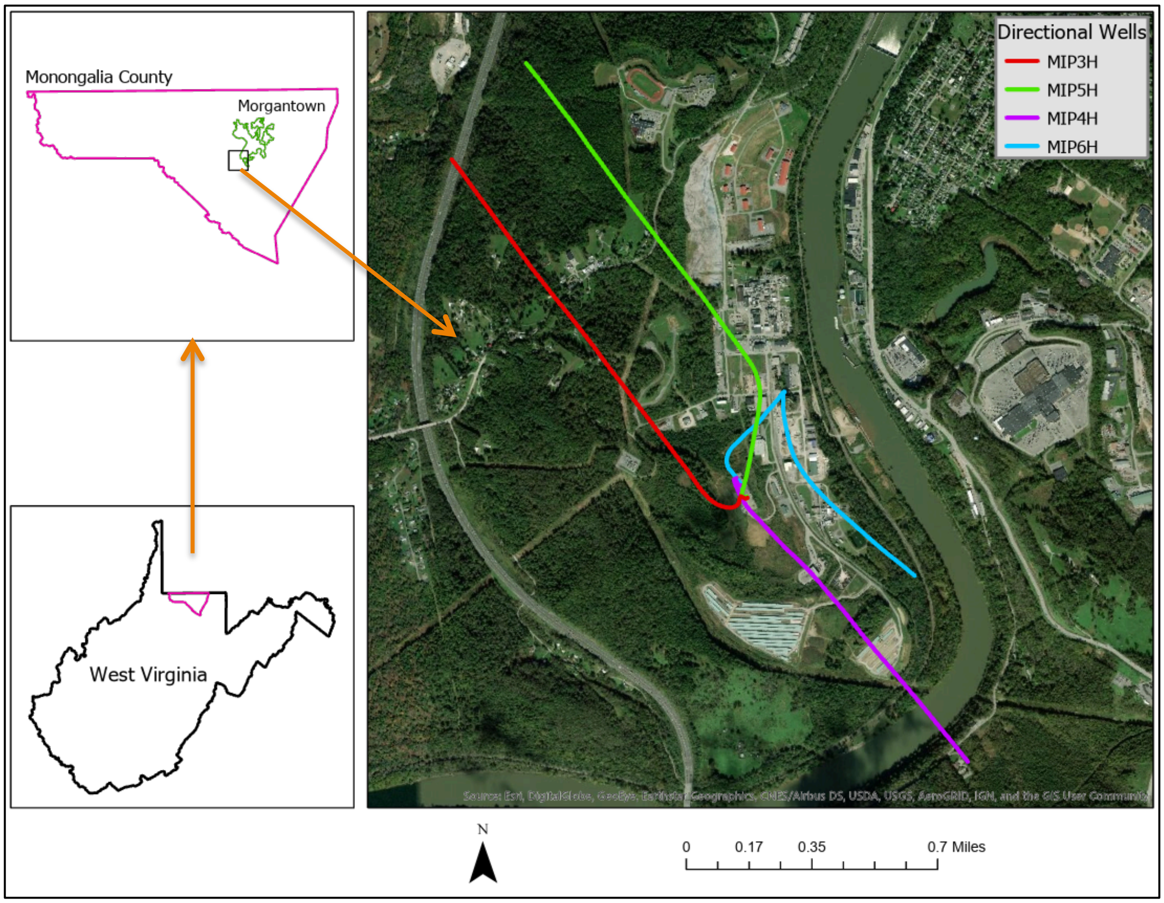


Figure-4.19 Case study-II study area

4.3.1 Conversion of the 3D directional wells from points to line vectors

The data for the horizontal wells was acquired in a .csv file format. The dataset included Northing and Easting values, true vertical depth (TVD), and the inclination angle for the wells. The data format was rectified according to the requirements for importing into ArcGIS Pro. Northing (Y) and Easting (X) values were used to import the data as a table for all four horizontal wells and the tables for the four wells were then converted into 3D enabled point feature classes. In the attribute table of all four wells, the TVD values were converted into negative values to represent the depth of the wells and to display the wells below the ground in the map (Figure 4.20). For further visualization and analysis, the 3D point layers were converted into 3D lines. It was challenging to convert the point feature classes for the directional wells to the line feature classes in ArcGIS Pro. While ArcGIS Pro provides full functionality and a set of tools to generate line features that have either vertical depth or features with horizontal depth, a directional well has both vertical and horizontal components to it. The XToolsPro extension for ArcGIS was used to convert the vertical and horizontal profile of the 3D point feature classes into 3D polyline feature classes. During the point to line conversion a software bug was encountered that would cause the conversion tool in XToolsPro v17 to fail. After the release of software update the bug was fixed in the XToolsPro v18. Besides the XToolsPro, such point feature class can be converted into line feature classes using a Python Script in ArcGIS Pro. The 3D polylines created in the XToolsPro were imported and stored in ArcGIS Pro and the 3D line feature classes were symbolized as 3D tubes in the scene (Figure 4.21).

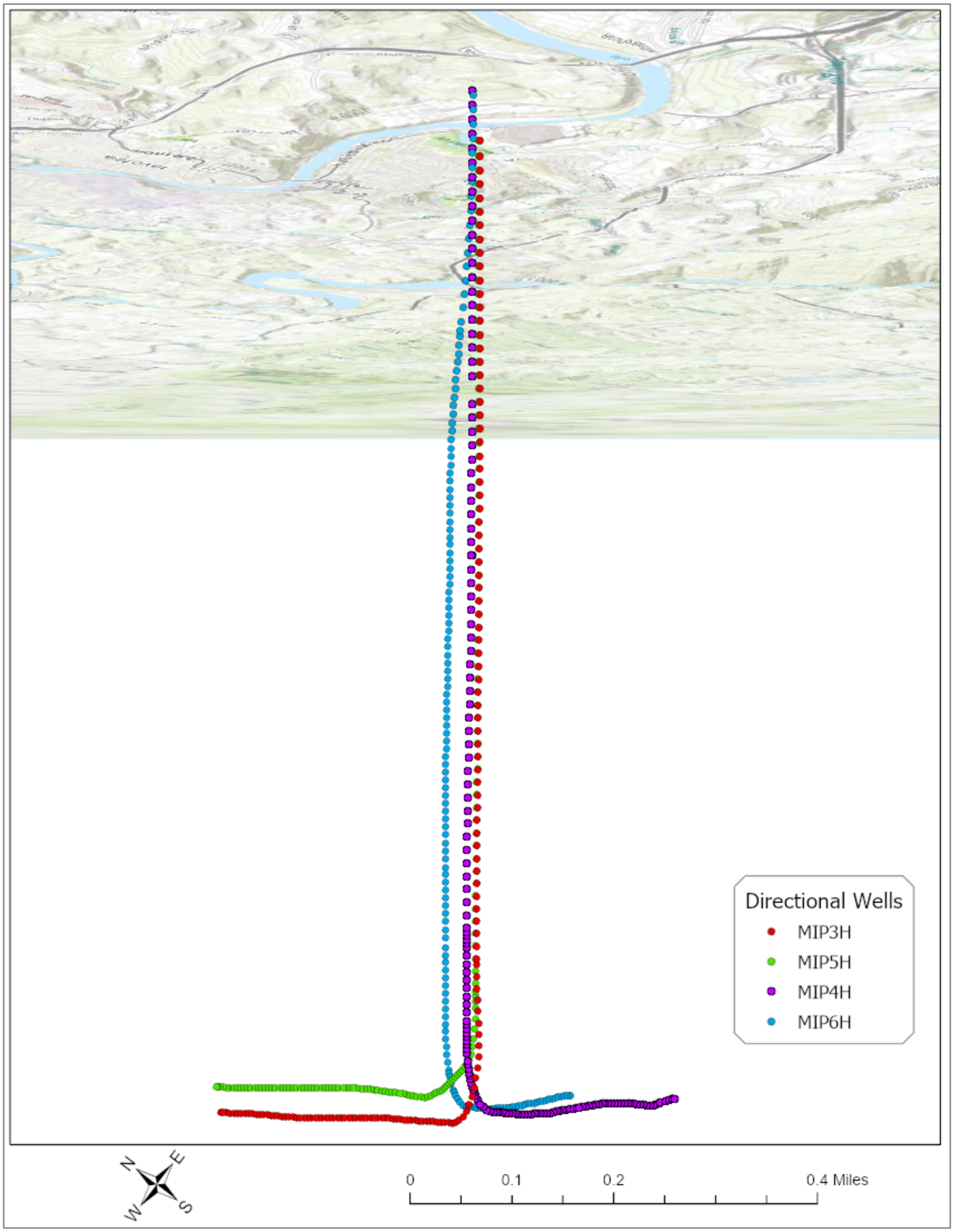


Figure-4.20 Directional wells point feature classes under the basemap

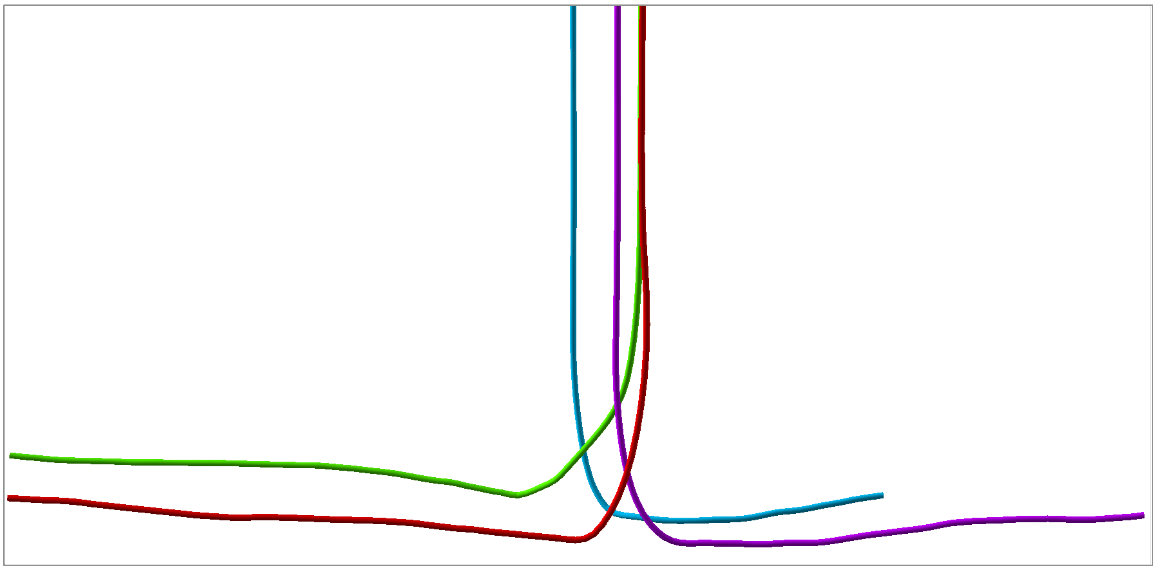


Figure-4.21 Close-up of the 3d polyline profiles of the directional wells

4.3.2 Creation of 3D geological strata polygon from points

The 3D point data for five geological strata surrounding the horizontal part of the directional wells were also acquired from MSEEL. The five geological layers from the surface down were: Hamilton Top, Upper Marcellus Top, Cherry Valley Top, Lower Marcellus Top, and Onondaga (Figure-4.22). The point data for all the geological layers were regularly and densely spaced except for some data anomaly on the edges of the point layer datasets. These irregularly spaced data along with the outliers were removed to produce a clean dataset. After cleaning, the data was transformed and reprojected (Figure 4.22).

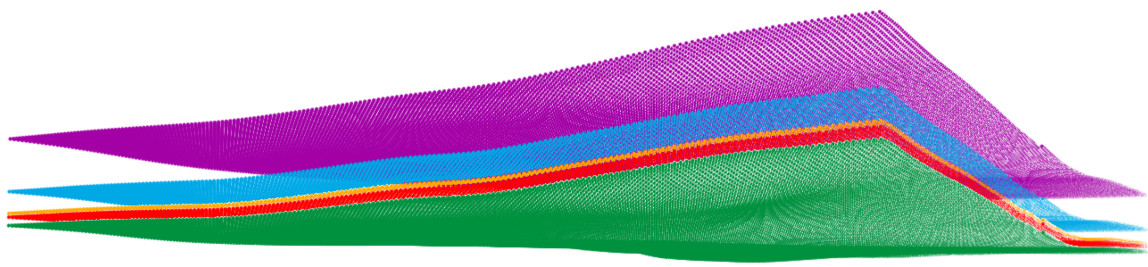


Figure-4.22 Point layers for the geological rock horizon

A vertical projection system was also added to the data for further processing. The point layers were interpolated using Empirical Bayesian Kriging to generate a raster surface. The interpolated raster outputs were then converted into TIN (Triangulated Irregular Networks) surfaces (Figure 4.23).

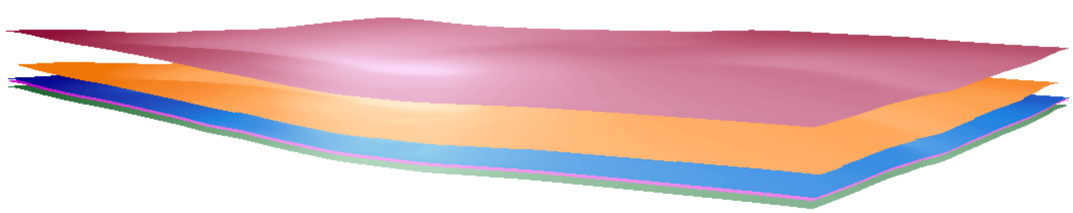


Figure-4.23 TIN surfaces of the geological rock horizon

A TIN surface can be generated directly from the point layer, however, interpolating the points into a raster surface and then converting the raster to a TIN surface produces a somewhat smoother TIN surface. ArcGIS provides the functionality to generate a three-dimensional polygon using the TIN surfaces. Five TIN surfaces representing the five geological surfaces were used to generate multipatch polygons. A multipatch polygon as a closed polygon can then be used for volumetric computations in GIS. The TIN surfaces were extruded using the 'Extrude Between' function in ArcGIS Pro to generate 3D multipatch polygons representing the geological strata (Figure 4.24).

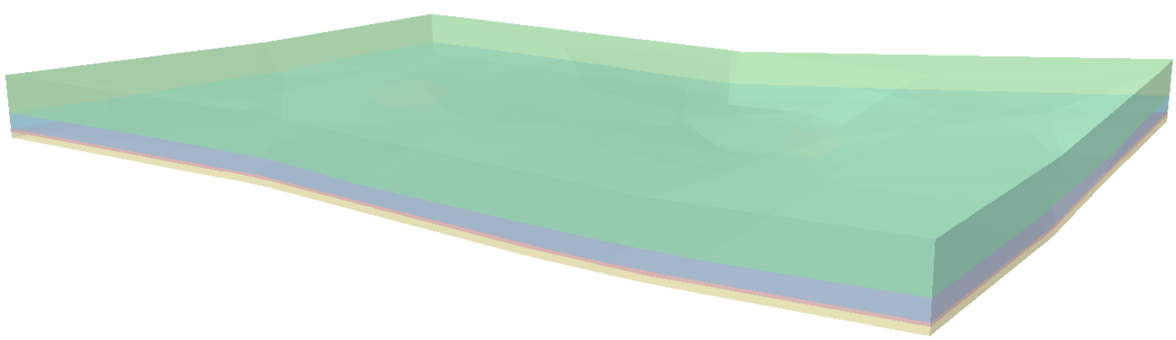


Figure-4.24 3D multipatch polygons representing the geological strata

ArcGIS provides a set of tools to evaluate whether a multipatch polygon completely encloses a volume of space. If any open multipatch is found, it necessarily must be converted to a closed multipatch feature, especially for 3D geoprocessing and volumetric computation. The multipatch polygons were symbolized as semi-transparent 3D polygons in order to display the directional wells within the strata (Figure 4.25).

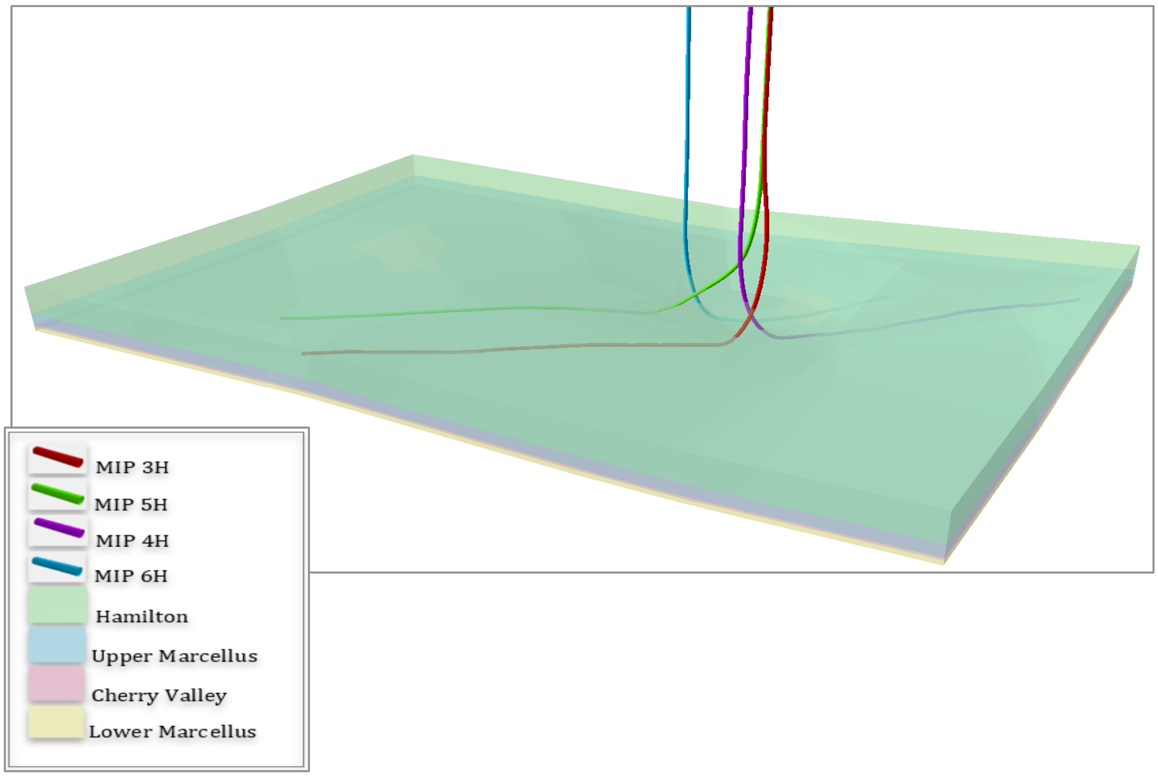


Figure-4.25 3D directional wells with 3D geological strata

4.4 The Results of Case Study II

The analysis of case study II includes the detailed examination of the outputs from the 3D modeling, 3D geoprocessing, and immersive visualization of deep subsurface features that include four directional wells and the geological strata at the horizontal part of the wells. 3D visualization of the directional wells and geological formations is valuable for interactively visualizing which rock formation was penetrated by which borewell and where. The directional wells can be visualized with all the surrounding geological strata or the position of the well can be visualized within the context of a single geological stratum. Such visualization and analysis are helpful for geologists and geophysicists to further analyze whether the route of a well is optimized for well production. Figures 4.26 to 4.29 display the route of the directional wells in different geological rock horizon. However, in seeking to display this material it becomes immediately obvious how difficult it is to visualize and understand such a comprehensive display using a 2D medium. A three-dimensional display system provides an interactive visualization of the phenomena where the features can be visualized comprehensively from different perspectives. Moreover, the immersive visualization in which users are 'in' the data display provides the user with a whole new range of perspectives to examine their data.

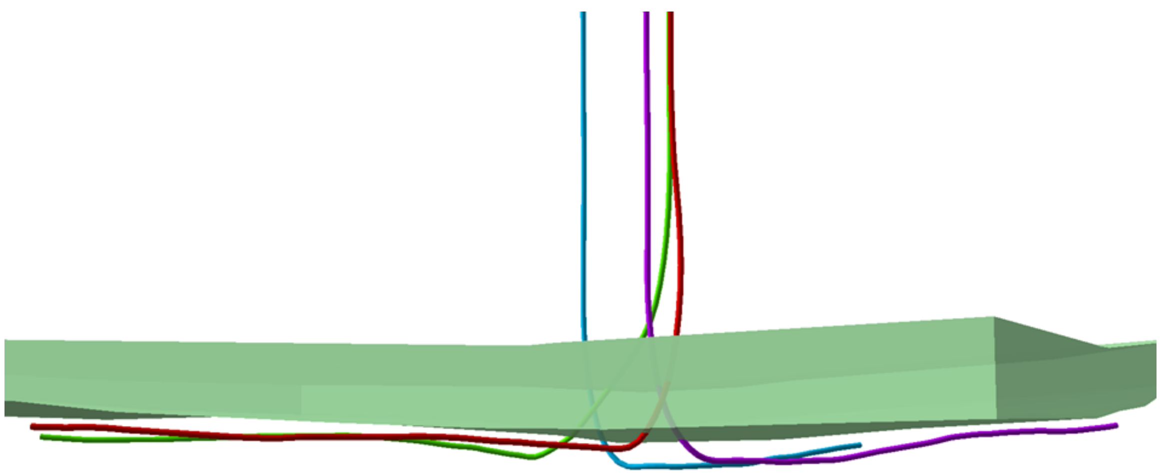


Figure-4.26 Directional wells below the Hamilton geological stratum

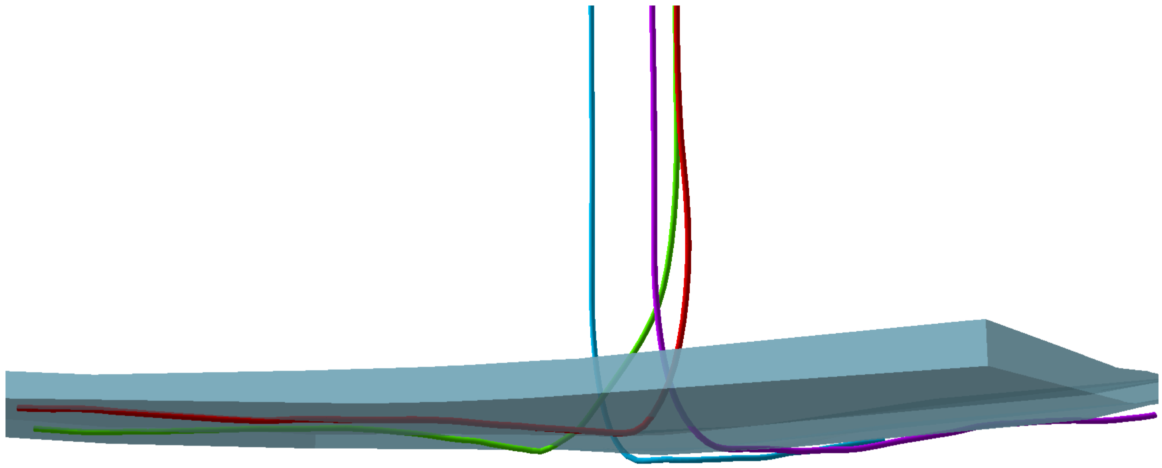


Figure-4.27 Directional wells intersect with the Upper Marcellus geological stratum

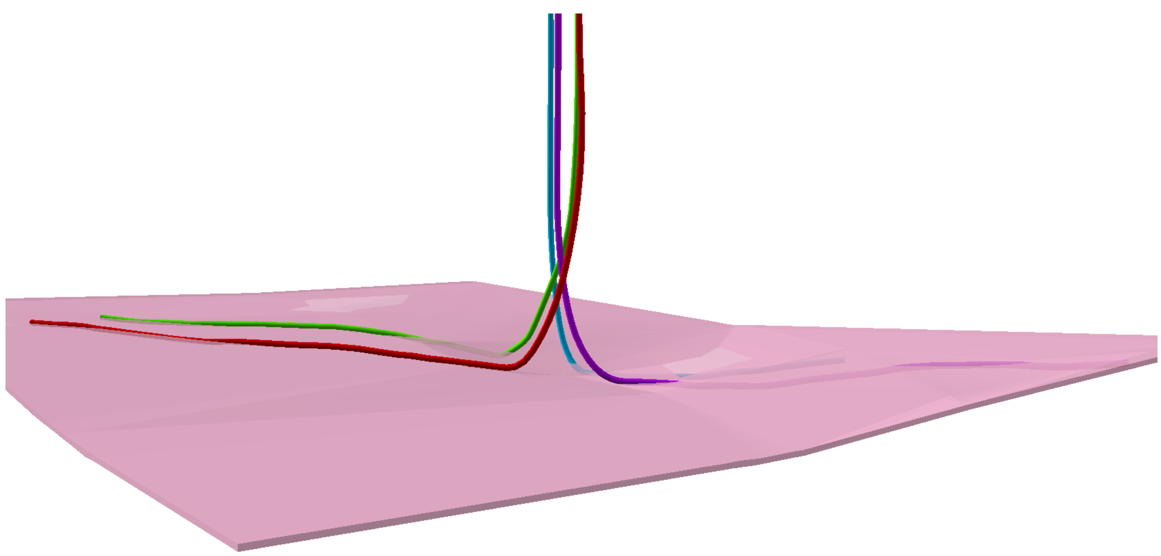


Figure-4.28 Directional wells intersect with the Cherry Valley geological stratum

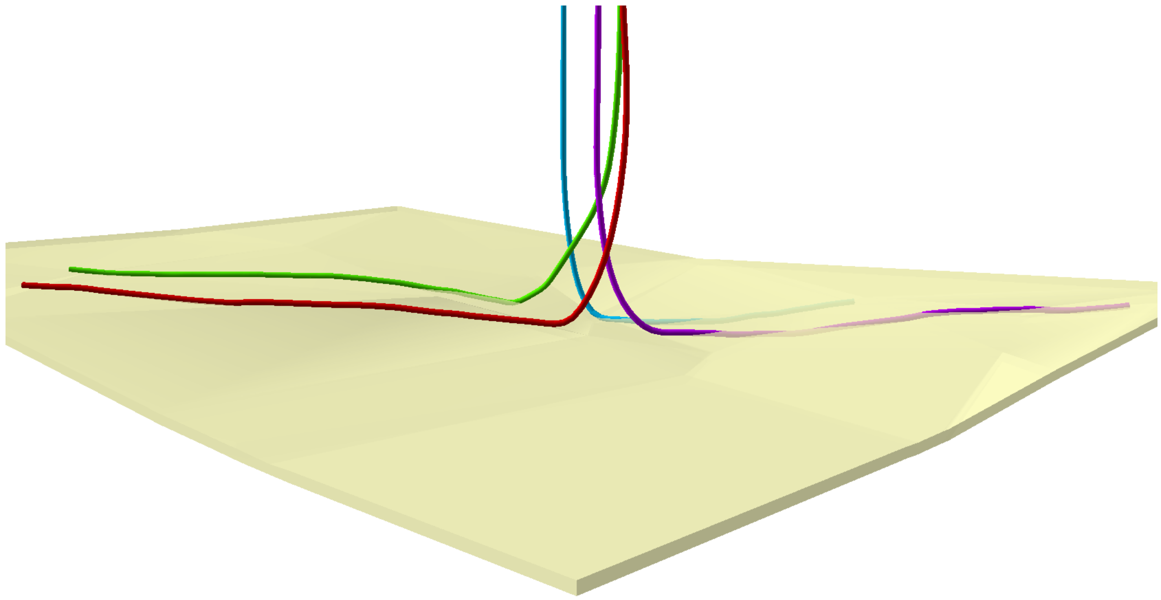


Figure-4.29 Directional wells intersect with the Lower Marcellus geological stratum

4.4.2 3D Geoprocessing outputs for the deep underground features:

After the deep subsurface features were successfully rendered in a 3D model, 3D geoprocessing and volumetric computations were performed in order to test the analytical capabilities the model. First, 3D buffers were created for two horizontal wells. Figure 4.30 shows a close-up view of the 3D buffers that were created for MIP4H and MIP5H wells. The 3D intersection was the next geoprocessing function used on the 3D model of deep subsurface features, which demarcated the intersection points of the 3D directional wells and the 3D geological blocks. In ArcGIS the intersection of a 3D line and a multipatch polygon produces a line feature class and a point feature class. The output point feature class includes the number of geometric intersections and the 3D distance of the intersection points from the surface. The output line feature class is divided at the intersection points.

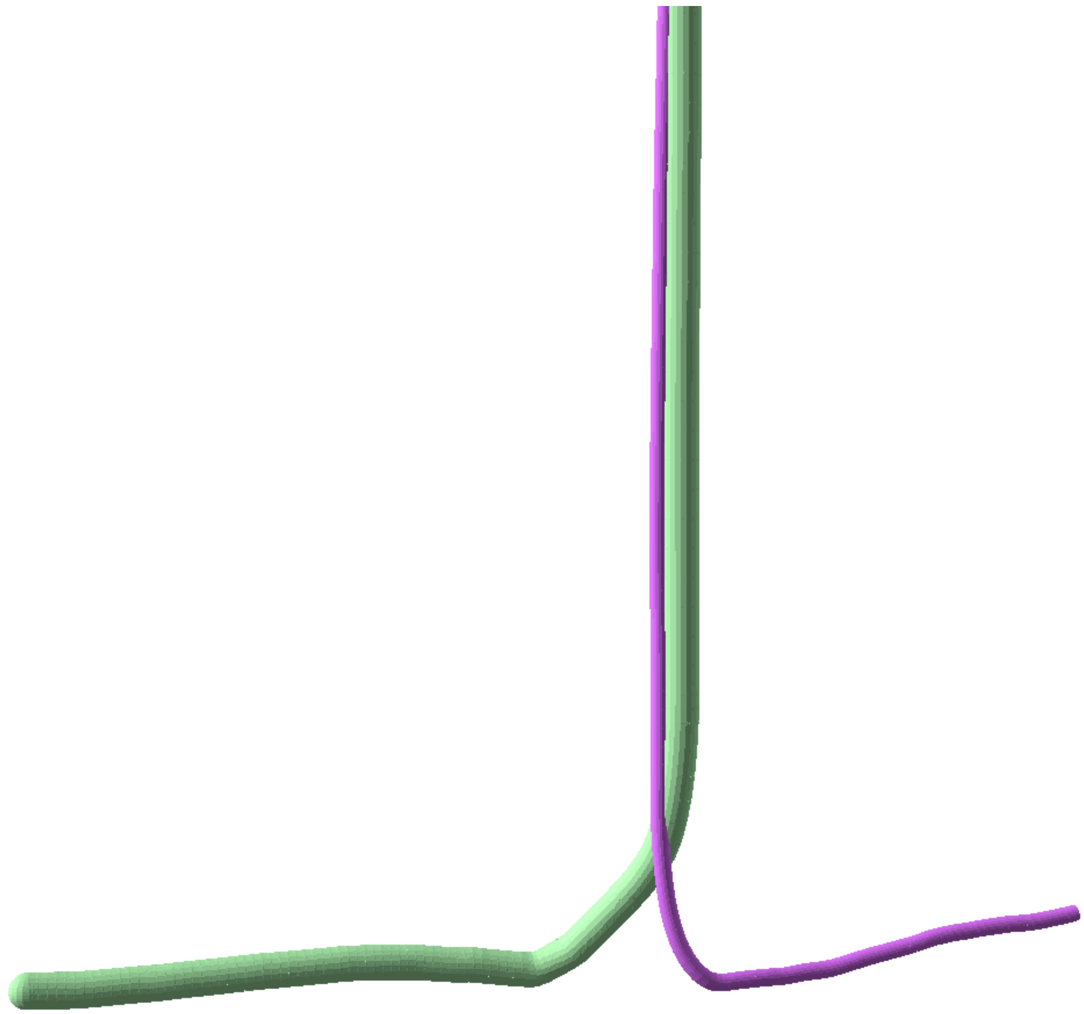


Figure-4.30 3D Buffer of directional wells

The attribute table of the output line feature class contains the length of the line segments and other additional information about slope and distance. 3D line features can also intersect with TIN surfaces in ArcGIS Pro. The intersection of 3D lines with a surface generates an output point feature class and a line feature class as well. Figure 4.31 displays the output of a 3D intersection between each borewell and geological rock horizon. ArcGIS Pro facilitates the display of the labels for 3D features. Output 3D line features were symbolized using the unique values of the shape-length of the line segments. Different colors for the line indicate where the line was divided at the intersection points. The intersection points show the name of the rock horizon that intersected with the wells and the distance of the intersection points from the surface in meters. Such geoprocessing outputs provide additional visual and quantitative information to visualize and analyze the relationship between the gas production rate of the wells and the borewell paths. Such information can be useful for future drilling decision-making. 3D intersection and 3D buffer function combined with other factors can be beneficial to study the long-term effects of the drilling on nearby water resources using GIS as well.

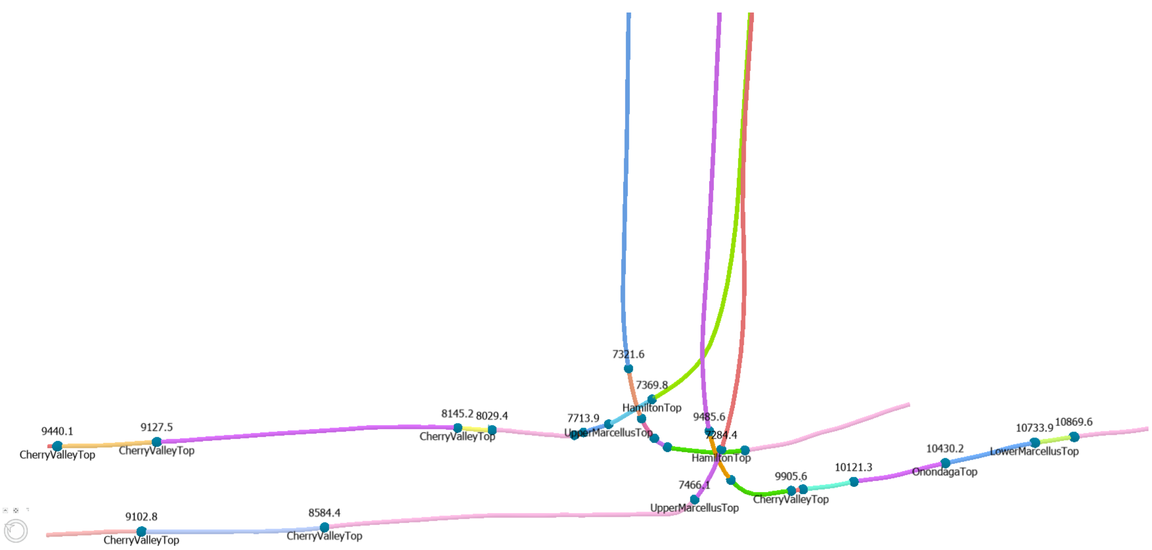


Figure-4.31 3D Intersection of directional wells with the geological strata

Since the output features from 3D geoprocessing of the 3D models of the deep surface features possess same geometrical properties as the 3D geoprocessing outputs of shallow subsurface infrastructures, they too can be used in the same volumetric and computational analyses as displayed for the shallow subsurface infrastructure case study. The 3D geoprocessing analyses selected to be performed for shallow and deep case studies were based on the type of data required and data availability for an analysis. The 3D models of the deep subsurface infrastructure were then added to the same web scene used to publish shallow subsurface infrastructure (Figure 4.32). Such integrative display of the shallow and deep subsurface infrastructure 3D models supports the idea of the holistic approach of the geospatial data representation and planning for a geographical space. The modern urban planning approach emphasizes on the holistic urban planning where both surface and subsurface (shallow and deep) urban space is planned sustainably. In the web scene the slides or the bookmarks can be used to conveniently navigate from the shallow to deep subsurface features and all the features. The web scene provides the same functionality for the deep subsurface features as mentioned earlier for the shallow subsurface features. The published web scene of the 3D models of the deep subsurface features can be accessed by using the following link:

http://wvu.maps.arcgis.com/home/item.html?id=c666586d906c42899e5c830a68af23af

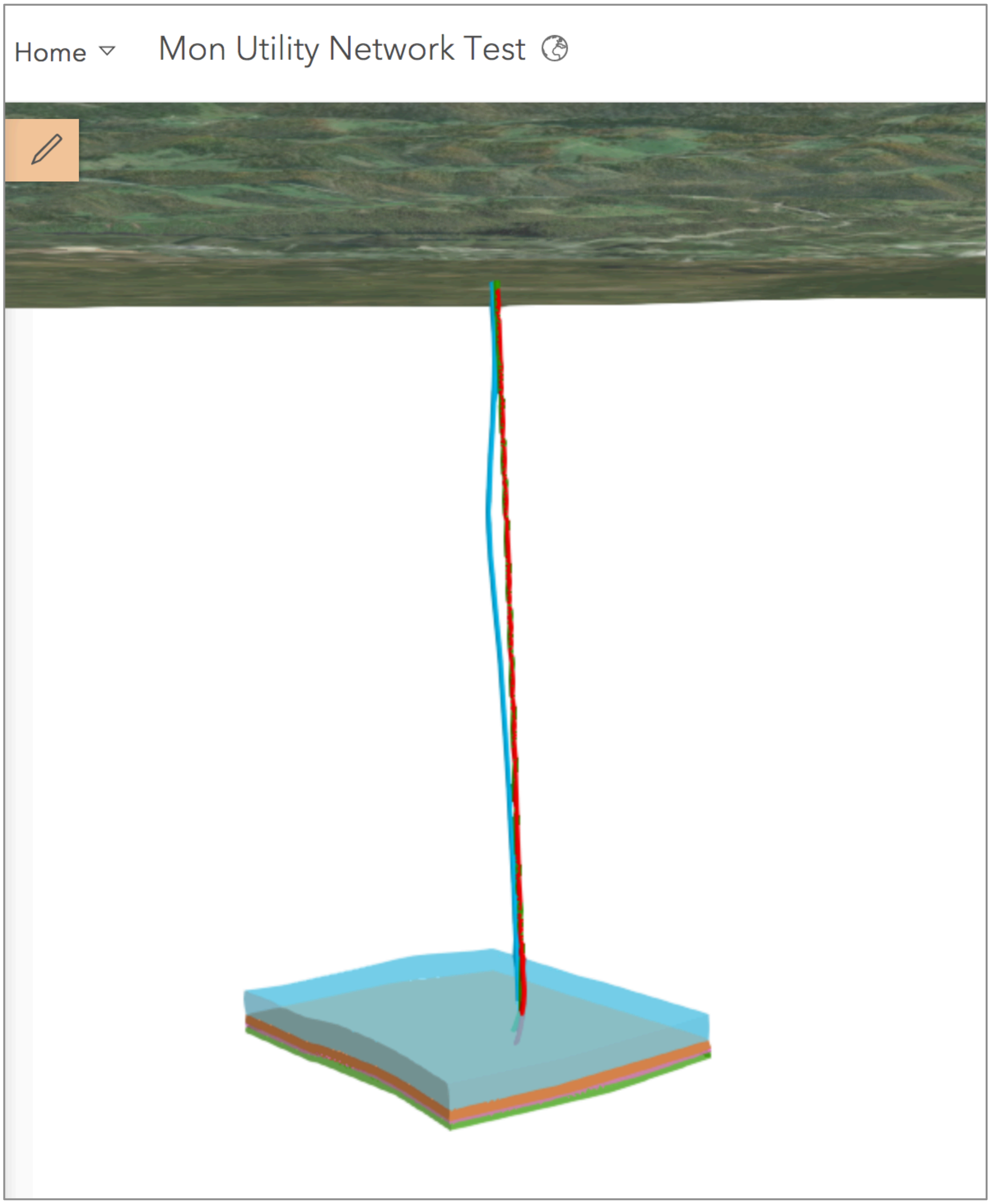


Figure-4.32 Web scene (deep subsurface features) published via ArcGIS Online

4.4.3 Immersive visualization of the deep underground features:

The 3D model of the deep subsurface features was imported into the CAVE. The 3D models of borewell and geological blocks were symbolized in 3D using ArcScene and rendered for stereoscopic display using Conduit Control software. The stereoscopic projection of the deep subsurface 3D models was free from any broken geometries. The horizontal and vertical navigation of the 3D model provided different perspectives of the phenomenon. Figure 4.33, Figure 4.34, and Figure 4.35 represent the visualization of the deep subsurface features in the CAVE. The figures show the navigation to the horizontal part of the wells between different geological strata. Such visualization provides the user a unique perspective to study and analyze their data. However, accessing the attribute information of the 3D features in the CAVE was not possible.

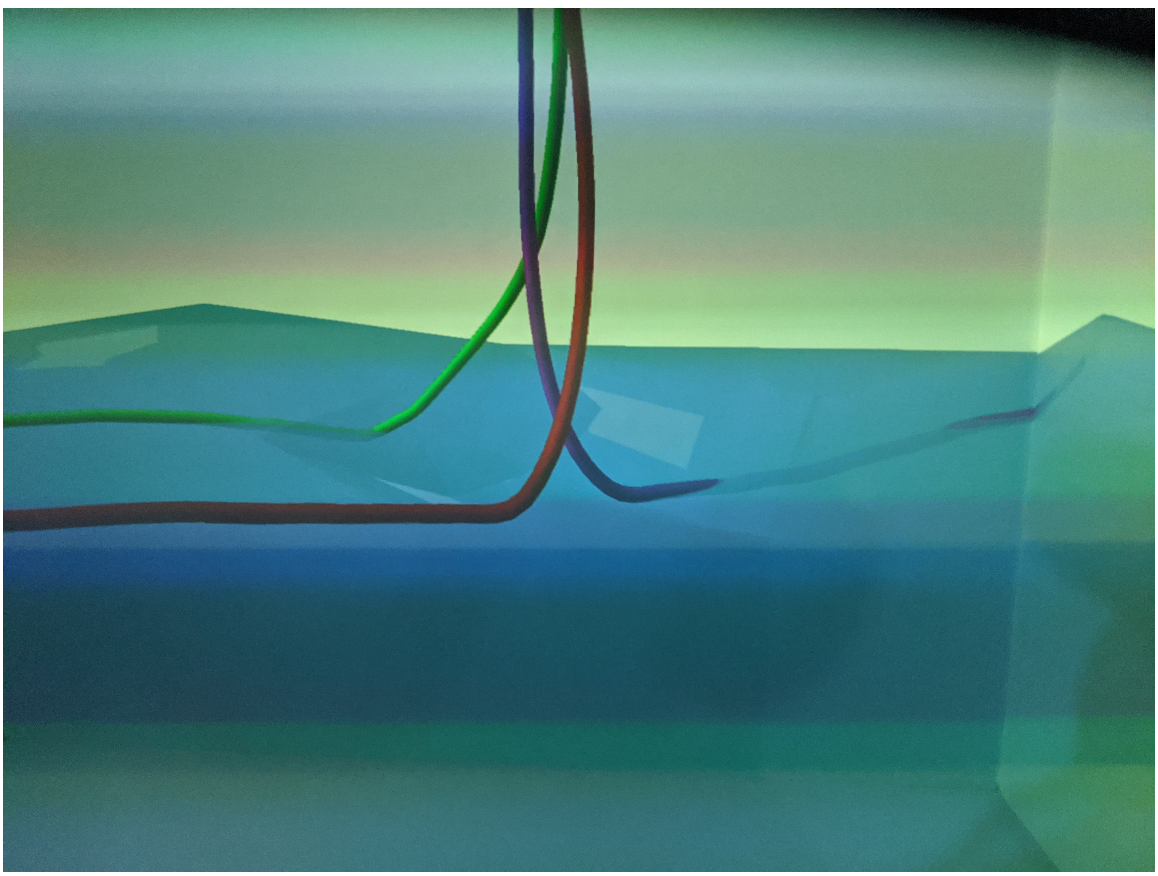


Figure-4.33 Navigation to directional wells within geological strata in the CAVE (view1)

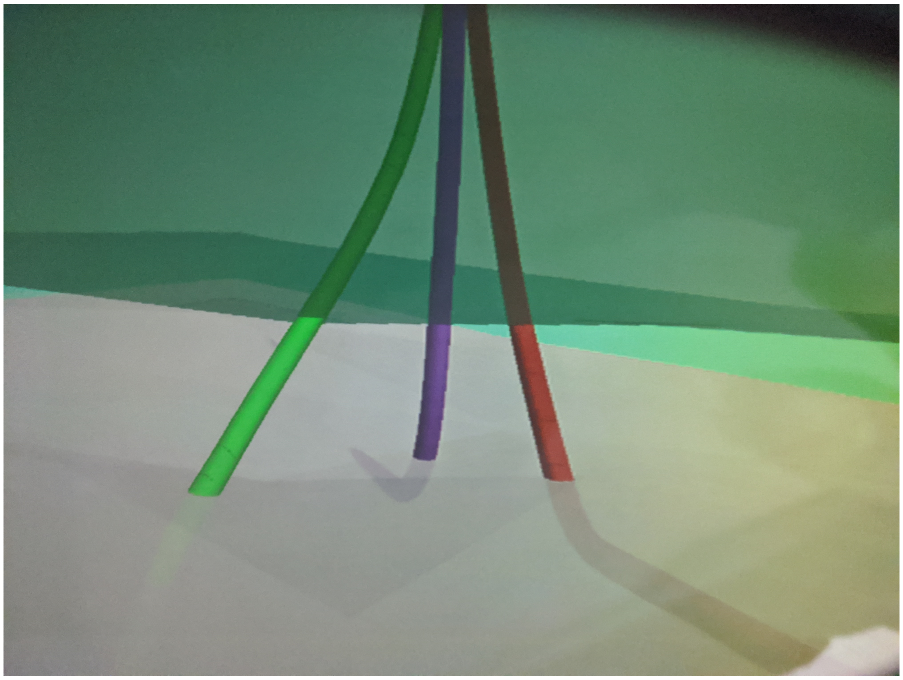


Figure-4.34 Navigation to directional wells within geological strata in the CAVE (view2)

Figure-4.35 Navigation to directional wells within geological strata in the CAVE (view3)

A three-dimensional study of shallow and deep underground features is possible using advanced GIS technology. ArcGIS provides a platform for the processing of 3D data for both shallow and deep subsurface infrastructures and is compatible with augmented reality technology and immersive technology such as CAVE. It is evident through the case studies of this research that 3D visualization of the subsurface feature provides the capability to explore different perspectives of the subsurface phenomenon. Alongside facilitating 3D display, the geospatial 3D models provide the ability to transform the basic attribute statistics into meaningful information that can be used in the analytical and decision-making process. 3D geospatial modeling and 3D visualization of a phenomenon thousands of feet below the surface is challenging in the context of the scale of the 3D model. The integration of 3D GIS with the 3D modeling of oil and gas wells not only provides the 3D visualization of the deep wells within its rock horizon, it also facilitates examination of the spatial connections of the wells to the rock horizon and nearby aquifers and ground water resources. The study of such spatial relationships can be crucial to analyze the relationships and effects of these deep subsurface infrastructures to its surroundings and environment. Such phenomena are difficult to see on a two-dimensional map. The same applies to the 3D visualization and analysis of the shallow underground features.

CHAPTER V

Research Findings, Evaluation, Future Research Directions, and Conclusion

This dissertation set out with the premise that 3D GIS and associated 3D geoprocessing, coupled with virtual immersive technologies for visualization and analysis, could be generated and applied to the analysis of complex multidimensional data and especially subsurface infrastructure. Evolving from traditional 2D GIS and visualization into a 3D GIS environment introduces many challenges which had to be overcome in order to achieve a working and satisfactory outcome. In contrast to surface features that are largely visible and amenable to 2D GIS processing and map production, the 3D environment requires 3D GIS topological encoding and a suite of necessary 3D tools in order to generate satisfactory models. In addition, the challenge of acquiring 3D data introduces significant problems even in the case of small case study test projects as pursued here. Nonetheless, advances in 3D GIS processing provides opportunities for pursuing the true modeling of the third dimension and which was not previously possible and this research has sought to take full advantage of these developments.

This decade has witnessed exploration of the 3D capabilities of geospatial technology to visualize, analyze, and manage subsurface features, and especially pipelines. Much research work has been conducted to conceptualize different approaches and methods to 3D GIS using differing geospatial and non-geospatial technology, web applications, and immersive technologies or a combination of these to achieve a robust 3D geospatial system. However, a review of the literature from the past two decades shows a significant gap between the desire for such systems and the actual development execution of such a system. Pubellier (2003), for example, suggested that 3D GIS is a critical component for developing cost effective strategies for inspecting subsurface pipelines but no such system has been developed. Similarly, Du and Zlatanova (2006) proposed a 3D system for visualizing pipelines using an integrated platform of GIS and CAD, whereby the GIS was used for database management and the CAD for its 3D editing and visualization functionality. Du and Zlatanova (2006) emphasized the potential utility of the three-dimensional visualization of subsurface utilities using a combination of 3D symbols for point and line features. However, despite the desire for such systems, the technology used at the time lacked database management functionality and 3D geoprocessing capabilities to study subsurface infrastructure in the third-dimension.

Perhaps closest to the goal of this study was the work of Balogun et al (2011) who devised a method to create a 3D model of water pipes using ArcGIS 3D Analyst, VRML plug-ins, and 3D Studio Max for 3D visualization. The 3D models that resulted from this approach, however, lacked the database schema required for performing spatial analyses and the 3D editing and geoprocessing. Other studies have impinged on 3D GIS but not to the extent pursued in this study. Tabarro et al (2017) devised the integrated use of ground penetrating radar (GPR) and WebGIS system to facilitate interactive visualization of structural spatial data and GPR profiles to increase efficiency during GPR surveys. Van Son et al (2018) provided an overview of a Singapore government project, Digital Underground, for sustainable use of underground space by mapping underground utilities in 3D. The digital Underground project proposes the plan of integrated use of GPR, GIS, and augmented reality devices for different stages of utility 3D mapping. Dodagoudar (2018) used 3D spatial database management and interpolation to develop a geodatabase for the efficient management of diverse geotechnical data related to borewells, soils, and weathered rock. Vishnu and Saran (2018) pursued surface and subsurface modeling of a water utility system using OGC CityGML and Utility Network ADE. More recently, Ortega et al (2019) emphasized the utility of interactive 3D immersive environments in the management of the underground infrastructures and devised an application named MultiVis that was based on linking 2D GIS and immersive environments. However, all these approaches described above, lacked the advanced 3D editing and 3D geoprocessing capabilities demonstrated in this research.

5.1 Research findings

The primary scope of this research was to explore the capabilities of 3D GIS and immersive 3D visualization for processing both shallow and deep subsurface infrastructure and to enable 3D geoprocessing and volumetric computational analyses. To that end six research questions were posed that would guide this research work. In the first instance acquiring suitable 3D data turned out to be a major obstacle. Because of proprietary and security related issues a test case of shallow subsurface utility data was all but impossible to acquire and recourse was made to creating a database of three utility types. A relatively small area of Morgantown was populated with water, gas, and sewer utility networks constructed based on industrial utility network standards and as guided by the Esri Utility Network Package Tool. Although this was a time consuming and resource intensive exercise the resultant network database provided an excellent base for testing the goals and expectations of this study. Fortunately, an impressive deep well database was made available and this provided a case study for the deep subsurface part of the research exercise. Esri's 3D spatial geodatabase management system provided a viable and successful storage capability for the complex data schema of subsurface utility networks along with the successful storage of the 3D data for horizontal wells and geologic strata. While this robust RDBMS was capable of storing complex data schema it nonetheless introduced a complex architecture itself that had to be mastered. To accommodate the complex data schema, especially for Esri utility networks, an integrated architecture of specific versions of SQL Server, enterprise geodatabase, and ArcGIS portal were a basic requirement. Major challenges were faced in terms of data storage during the staging of the utility networks and in the initial three-dimensional display of the of the horizontal wells point layers, however, the problems were resolved through work-arounds or finding solutions to these errors.

A second guiding question was related to establishing the all-important 3D topological encoding required to execute 3D geoprocessing and volumetric analyses. The RDBMS uses topological data models that are basically mathematical functions to establish these topological relationships between features. In this research topological relationships were established between points, lines, polygons, and multipatch geometry features.

The third research question was to review possible 3D GIS platforms available to support this research. It became apparent early on that Esri's ArcGIS Pro provided a promising platform with which to establish the 3D topological relationships between differing 3D spatial primitives. The topological rules were defined in ArcGIS Pro by specifying connectivity rules, structural attachment and associations rules, and containment rules for the subsurface features. The topology validation tool was valuable in that it indicated the successful implementation of the topological relationships that were established between the subsurface features and which were necessary to perform 3D geoprocessing and volumetric computations. The 3D enabled data were then symbolized using 3D symbols for point, line, and polygon features for 3D visualization. The 3D visualization of subsurface features poses greater challenges than the 3D visualization of aboveground features especially in terms of underground navigation. Furthermore, the scale of the deep subsurface features adds additional complexity. Virtual immersive and augmented reality technologies provided considerable advantages in the display and interpretation of 3D subsurface features.

Guided by research question four, ArcGIS Pro was selected as the platform to provide the 3D geoprocessing and other 3D analytical capabilities. Importantly, ArcGIS Pro provides a range of 3D feature toolsets required for 3D geoprocessing and volumetric computations. Both shallow and deep underground feature datasets were successfully tested with these 3D geoprocessing tools including 3D buffer and 3D intersection. The output generated from these 3D geoprocessing methods provided for advanced 3D computation and analyses such as volume and flow-rate computations. It was recognized that other 3D geoprocessing methods such as 3D union, near 3D, and cut and fill volumetric analyses equally provided successful results. Although not originally proposed as part of this research the ability to publish the 3D models and the results on the web via ArcGIS Online as a web scene are valuable. The web scenes can be accessed from mobile devices that can be conveniently used in the field to access the 3D data for 3D visualization and attribute information.

A fifth research question was to not only take GIS into the third dimension but to then create a 3D visualization environment for viewing the 3D features. The 2D visualization of 3D features was less than satisfactory and, in many ways, negated the visual advantages of producing 3D products. A significant part of this research then was to integrate the GIS generated 3D spatial models within a virtual immersive environment. 3D immersive visualization was achieved through the integration of ArcGIS Pro 3D processing, ArcScene, and a virtual immersive environment platform in the form of the CAVE. This research demonstrates the results from the integration of the two technologies for both case studies. The import and export of the 3D models from ArcGIS Pro to the CAVE can be a complex process especially because the import or export functions can result in the loss of geometric information. In the case of both case studies, no geometric loss was experienced in the move toward immersive visualization. A remarkable feature of virtual immersion is that the user is provided with a unique sense of presence in the viewing of their data. The immersive visualization provided a distinct and unique viewing perspective to users and enabled them to navigate through their data scenes and greatly facilitated interpretive abilities.

5.2 Research reflections

Many studies have emphasized the perceived utility of 3D GIS and even the use of immersive environments in the management of underground infrastructures, yet few operational systems exist. The mapping, management, planning, and sustainable use of subsurface space and the need for technological solutions to a series of problems and challenges that have evolved over many years are increasingly demanded. A growing urban population continues to place immense pressure on the urban environment and those responsible for the provision of utility services and urban infrastructure. Though often hidden from everyday sight, subsurface space is arguably as important as that of the ground surface. The data for subsurface facilities are extremely difficult to come by and whereas the ground surface is increasingly well mapped, the subsurface is less well documented or mapped. Proprietary concerns about subsurface data, homeland security issues, an inadequate map base, and aging media all contribute to significant data challenges. Traditional methods for mapping surface features with their related attribution are not easily transferable to the subsurface realm. Indicative of this fact is that to pursue this 3D research a utility grid had to be created in the absence of other data to test.

Despite the many challenges encountered during this research, this study has sought to develop and explore a robust approach to 3D GIS that facilitated the whole process from the 3D data storage to 3D modeling, 3D visualization, 3D geoprocessing and volumetric computation, data publishing and sharing via web to immersive visualization of the complex networks of the shallow subsurface infrastructure as well as challenging (scale wise) deep subsurface features.

Transitioning from a 2D GIS to 3D for the modeling and geoprocessing of subsurface features is a significant leap forward that promises significant gains. The outcome of this study into 3D modeling and the analysis of subsurface infrastructures and feature demonstrate both the need and the value of 3D GIS. Despite being released in beta mode and exhibiting several severe bugs ArcGIS Pro facilitated the 3D visualization and 3D geoprocessing of shallow subsurface features and utilities. The raw analog data was ingested and efficiently stored in the ArcGIS geodatabase. The Utility Network extension in ArcGIS was demonstrated to support enterprise geodatabase architecture and provided a powerful multiuser-editing environment. This database-versioning enables a database administrator to assign differing roles and database-editing capabilities to different users that facilitate convenient model updates to reflect newly added or modified data. Several challenges were faced during the creation of the utility database because of software bugs which will likely be resolved in later versions of the Utility Network Tool following notification from this author. In the second case study, 3D GIS was used to represent two types of deep subsurface features; directional wells and geological strata. Both of these features were successfully represented in three-dimensional space for 3D visualization and 3D geoprocessing. The extension of ArcGIS Pro and enterprise geodatabase to accommodate 3D topology has been only a recent achievement, based on this study however, 3D GIS appears to present an advantageous platform for the 3D geospatial modeling of heterogeneous data types and scales and a useful range of tools for 3D symbology and labeling of the 3D models.

ArcGIS Pro now provides an integrated platform capable of supporting 2D and 3D mapping and modeling. Such integrated capabilities greatly facilitate powerful spatial-analytic and visualization tools especially for urban environments. The 3D models created using ArcGIS Pro were published and shared using ArcGIS Online, which is a cloud-based platform for publishing and sharing GIS data through customizable and interactive web maps and web apps. ArcGIS Online also enables and facilitates editing of the data through these web maps. In this research the CAVE was used to explore the role of immersive visualization in the representation of 3D subsurface infrastructures. The CAVE is a powerful multiuser immersive environment in which to view and present three-dimensional objects. Furthermore, as a collaborative space, many stakeholders from expert to community representatives can intuitively experience and communicate about the complex spatial relationships of 3D features and representations. However, the data published through ArcGIS Online are compatible with augmented reality apps such as AuGeo, AR Toolkit, and Argis Lens. In this way, these apps can be used on mobile devices that can in turn help to visualize the shallow subsurface infrastructures on site.

5.3 Evaluation of the research outcomes

To obtain feedback about the applicability and usefulness of 3D geoprocessing, volumetric analyses, and immersive visualization of the subsurface infrastructure this research was demonstrated to six professionals working within the oil and gas industry, academia, urban GIS, city management, and utility companies. The evaluation process included demonstration of the 3D models and the analytical capability of the system on the desktop, in the CAVE, and accessibility to online published 3D models and features via mobile device. To maintain confidentiality the identity of the evaluators is not given here, but instead their job titles are used to reference the feedback. The feedback was recorded separately for each evaluator based on a series of question and answer sessions and open discussion which was focused on the perceived utility of the 3D modeling approach and immersive visualization in the evaluator's field of work.

In all instances, and without exception, all evaluators expressed great interest and support for the system. Indeed, almost immediately, the evaluators began to identify ways in which the system could be enhanced to address points of specific interest to themselves. Thus a professor of geology was intrigued not only by the system but the potential for extending its capabilities to record and evaluate the different stages of fracking, represented as separate clusters of the holes in the horizontal sections of the wells: *"Such 3D modeling approach can be helpful to visualize and analyze the gas pipeline system above the surface too."* The gas well senior drilling engineer similarly stated: "*This 3D model would be extremely helpful in Finite Element Analysis (FEA) for flows, structures, and designing infrastructures from valves to everything. This is awesome."* The engineer noted that the built-in attributes in the 3D models would be very efficient in their work in enabling them to access pipeline attributes such as elevation, volume, flow-rate, velocity, and pressure to name a few. These attributes inform how the aboveground pipeline infrastructure from the well to the sell point affects the flow of the gas. The data they currently use is in a 2D GIS system and they are required to manually visualize, analyze, and record the elevation changes in the pipelines on site, and then calculate hydrostatics. They continued "*having something like this can help to pull that information quickly and helps to see that phenomena in 3D.*" During the demonstration of the 3D models in the CAVE, the EHS Manager from the same oil and gas company mentioned that this environment would be helpful to visualize the different pipe sizes and the elevation pattern of the pipes in a utility network.

The GIS Analyst from local government stated, "*I think it is very powerful and also very informative because* you *are seeing more or less closer to reality than any two-dimensional map will show you.*" They suggested that the 3D models would be very useful especially for decision makers: *"Just by looking at it, it shows immense potential. It can be powerful for decision makers. Just be able to adapt it and be able to have a city official or governor put on a headset or look at their phone and be able to visualize what's going on underneath their feet and being able to immediately start* *thinking in their head what's going on here, what can we improve on, what can we change about what we are doing now by using this technology."* They added that such a system would be convenient and save time in their work in collating the information from several different utility organizations so that decision makers from many specialty areas would be able to conveniently access and understand the data.

The GIS Specialist from a gas utility company mentioned that they would want to use such technology in their work and especially the visualization of the utility networks with associated attributes and particularly so if their entire department had access to such information on the fly: *"I just wish that I could get everybody to understand that seeing things spatially would be so much of help."* The gas company they work for partly uses GIS, but the full potential of the GIS is not being used, let alone the potential of 3D GIS. To this end they considered that, *"It's beneficial to see it the way it is actually represented in the CAVE because so many people can't grasp the design of the infrastructures and how it's put together without some sort of 3D visualization."* They mentioned that many companies want to jump into using immersive technologies but due to the cost they tend to not invest into it. During the demonstration of the 3D models and 3D geoprocessing for the deep underground infrastructures they pointed out that the 3D models and 3D geoprocessing outputs would be very helpful for seeing the relationship between the deep subsurface features and immersive technology was beneficial to seeing these relationships as well.

During the demonstration to a City Engineer the data challenges became apparent and especially as the lack of sub-surface data contributed to accidents occurring during projects. The City Engineer mentioned that they use CAD drawings and utility reports to locate the below-ground utility pipes but it was still common to hit a pipe that was shown on the drawing. Once again, this discussion led to the advantages of having full access to the 3D data with associated attributes in the field using mobile devices which he that thought has enormous potential to help them better locate the utilities.

Another series of discussions focused on the use of quantitative analysis in project development and execution: *"Adding the data processing like flow-rates calculation to any utility network data would be a big help in many types of utility network analyses."* Use of the system for the monitoring and maintenance of utility networks was emphasized and especially how very useful it would be to have the information about the age of the utility pipes available in the geodatabase. Furthermore, he stated, *"Seeing the entire model can be overwhelming to get a clear picture of what's going on but it would be helpful to zoom in on certain area that the user is working on and see what's going on in that area. The integrated picture of the features that link the subsurface utilities to the ground would also be beneficial."*

The feedback from the evaluators in each instance was very positive and each was able to appreciate the value of such a system in their own specific context. Indeed, it was notable how each evaluator quickly extended the discussion to explore additional 3D functionality and uses. As such this system should be viewed as a basis form 3D modeling and visualization which would be extensible to numerous additional capabilities. Furthermore, such 3D modeling is not limited to any particular field of study but could be extended to archaeology, maritime purposes, tunnels, aquifers, deep underground storage facilities, and soil layers to name but a few.

5.4 Future research directions and conclusion

Future research in the area of 3D GIS studies opens many areas for investigation beyond that of subsurface features even though the subsurface will likely remain a major avenue for continued investigation. As this study has emphasized, and the system evaluators have reinforced, one could imagine many functional enhancements to this system and many additional application areas. 3D data availability is clearly an issue. Much as the availability of GIS spurred the greater emphasis on the acquisition of 2D digital mapping, analog to digital map conversion, airborne sensors, Lidar, Drone mapping and the like, so the availability of 3D GIS would likely stimulate and encourage greater focus on the need for subsurface data. The application of 'new' technologies such as extending Ground Penetrating Radar to subsurface utility features and GPS enhanced internal pipe routing devices can be envisaged as future contributors to the 3D data vacuum. Similarly, extension of the visualization component of the study to mobile devices and particularly Augmented Reality enabled mobile devices would be a natural next step.

One possible significant area of investigation could be to extend the complexity of the 3D models by adding temporal data as the attribute values and then use the 3D models to visualize patterns or changes over the time. The integration of time data with the shallow underground features could help reveal patterns of subsurface use over time. A temporal component could also be used to approximate the age of the infrastructures in a particular area. In the case of deep underground infrastructure temporal data, along with temperature data patterns over time could help reveal patterns in gas production.

In the future, it is to be expected that the greater availability of 3D spatial and attribute data will considerably add to the value of the 3D models of the shallow and deep subsurface features and support complex and advanced 3D geoprocessing analyses such as computing rates of flow, the pressure of a commodity through the pipe network and other volumetric features. Uncertainty remains an issue in the subsurface 3D GIS analyses and the use of interpolation methods to handle discontinuous data invariably introduces some uncertainty. As with 2D GIS contending with accuracy and uncertainty is equally applicable to the subsurface space. Uncertainty, however, could be used as an attribute value and be incorporated within analyses and not least in the visualization and display process.

Despite these continued challenges it is contended here that 3D GIS and immersive visualization are now a reality and shows enormous potential in a range of exciting and innovative areas in which it represents a true frontier in geospatial analysis.

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