Methodology for Voxel-Based Earthwork Modeling

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Abstract: Building information modeling (BIM) can facilitate effective three-dimensional (3D) earthwork modeling by furnishing insightful information. An earthwork area is generally represented in a cell-based environment for planning purposes such as allocation plans or equipment plans. However, previous studies utilized conventional methods, which are tedious and time-consuming, to create cell-based representations. Therefore, a method that can be applied to automatically represent earthwork BIM models in a cell-based environment should be developed. To address that research gap, this paper proposes a novel method to develop voxel-based representations of earthwork models. The voxel-based method is parametric, and the size, number, and properties of the voxels can be easily varied. This method, validated for accuracy, rapidly creates a parametric voxel model linked with geotechnical information necessary for earthwork operations. A visual programming tool, Grasshopper, is used to develop an algorithm that can automatically divide the earthwork model into voxels. Finally, experiments are conducted to validate the proposed method using an actual earthwork BIM design. The paper contributes to the existing body of knowledge by proposing a voxel-based earthwork representation and algorithm that automatically create a cell-based 3D environment that is flexible enough to integrate geotechnical parameters. The results indicate that the proposed method will help project engineers, planners, and managers create an optimal-size voxel-based earthwork model with customized geotechnical information. **DOI: 10.1061/(ASCE)CO.1943-7862.0002137.** *© 2021 American Society of Civil Engineers.*

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Introduction

Earthwork is an essential process in most construction projects, such as those entailing roads, building sites, and dams. Delays in this process may result in delays in the overall project as well as cost overruns. Several factors, including earthwork properties, equipment properties, and site conditions, affect earthwork operations (Kim and Russell 2003a). Thus, earthwork construction should be planned at the design stage to account for these factors; further, earthwork areas should be depicted accurately before construction planning.

In general, cell-based area division is used to create an earthwork-related plan, such as an earthwork allocation plan, equipment plan, and others. In this representation, the earthwork site is divided into several small areas. Next, different tasks and resources are assigned to each cell, which enables a construction manager to handle many small cells easily, rather than one big model. Furthermore, these cells could be associated with each other based on their characteristics, such as soil properties and resources assigned. Thus, in this representation, a construction site comprises several work areas, each having different characteristics, while some may have similar characteristics. The most important characteristic of the cell-based representation is that spatial relationships and spatial distribution can be assigned to each cell, which is very significant for work-space planning (Akinci et al. 2002; Choi et al. 2014; Pradhananga and Teizer 2014). The cell-based representation can be used for efficient resource planning and construction site management (Park et al. 2012; Zhang et al. 2007). This is accomplished by dividing the space into identically sized 2D cells of size 3 × 3 m and assigning resources to each cell (Zhang et al. 2007). By applying this model to a case study, cell-based representation was determined to have advantages, such as ease of visualization and spatial relationship, over traditional methods (Pradhananga and Teizer 2015).

Other data structures are defined for cell-based representation. One such structure, the quadtree data structure, divides a two-dimensional (2D) construction site by recursive decomposition. Kim and Russell (2003a) proposed the quadtree data structure to execute tasks at an earthwork construction site effectively. Additionally, the quadtree data structure divides the space into four subdivisions recursively, where each division or leaf node exhibits unique properties and represents the work area within the construction site. However, these types of cell representations are based on 2D environments. The purpose of the earthwork design is to calculate the volume of the required cut and fill and to facilitate earthwork planning, which includes moving the earthwork materials. To achieve these objectives, a 2D representation is not adequate and exhibits limitations; for example, it does not include volumetric data. Furthermore, site information should be included for each cell to improve the construction process, which cannot be accomplished using a 2D representation. To cope with these limitations, a three-dimensional (3D) cell-based representation is required.

Creating cells in a 3D space will increase their functionality in terms of volumetric representation and calculation. They can be linked with other 3D patterns, such as resources, tasks, and

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geotechnical properties. Depicting cells in a 3D environment increases its potential for obstruction detection, which may hinder the motion of objects during construction (Wang et al. 2019). Other cell-based representations, which entail a 3D environment, are voxel-based and are commonly used to create an approximate cell-based environment by segmenting 3D objects into cubes, also called voxels. The upper face of each voxel forms a cell after the voxelization of the 3D objects.

Voxelization can be adopted under two types of strategies, self-adapting and identically sized voxelization. These two strategies differ from one another in size and recursion. The self-adapting voxelization strategy considers the size of the objects to be voxelized. The size of each 3D voxel is not identical. There are two forms of self-adapting voxelization strategy: the LEGO-based and the octree-based. The LEGO-based voxelization method segments 3D objects into LEGOs, which are building blocks developed by the LEGO company in Denmark that come in multiple forms (Min et al. 2018). The advantage of the LEGO-based method is that the height of the LEGOs varies and is self-adapting. This results in reducing the number of voxels a 3D object can contain. The smaller number of voxels has advantages in terms of the simulation time: it takes less time to convert 3D elements to LEGOs. The LEGO-based voxel method has been used in studies to support the creation of path planning environments (Wang et al. 2020) and 3D route planning in indoor spaces (Yuan and Schneider 2010). On the other hand, an octree is a hierarchical tree structure that divides each of its internal nodes into eight children. It is used to segment 3D models into recursive eight octants. The advantage of this method is that the octree is efficient in the voxelization of 3D space that is not fully occupied. In addition, the vacant space (which need not be voxelized) can be excluded from further voxelization. A recent study adopted a LEGO-based voxelization strategy for task planning wherein the octree voxelization strategy was rejected owing to difficulties in the relationships between neighboring cells, which is crucial for task planning (Wang et al. 2020). However, the size difference among cells renders the representation inefficient in the case of earthwork, given that earthwork design is complicated and different from other designs. Therefore, identically sized voxels are preferred in this study for the depiction of cell-based representation. The advantage of identically sized voxels is that all the voxels are spaced equally and are located one cell away orthogonally and diagonally from each other. These cells can have other engineering properties beneficial for earthwork construction since in engineering projects, additional information is required, which can be accomplished with voxel-based representation.

An accurate terrain model is required to create a voxel-based earthwork representation. The current trend of representing earthwork terrain models mostly focuses on surface-based models, such as triangular irregular network (TIN) surface models, which can be created from digital elevation models (DEMs). The surface model serves as an aggregated model and suffers from segmentation. Even if the surface model is segmented into several triangles by an explosion, including additional information, the work can be very tedious. To address the issue of segmentation, a voxel-based earthwork model is required. In contrast, BIM is beneficial for creating an nD digital model and provides an effective virtual environment to exhibit object geometry with semantic information. However, in most scenarios, a model created using the BIM process is not based on voxels. Therefore, techniques should be developed to automatically divide the earthwork BIM model into several small solid units in the form of voxels. The earthwork process is useful for soil filling, compaction, and moving, as conducted by different construction equipment and compounded by the interaction of the equipment with the soil. This process creates complex problems and calls for each solid unit to be characterized by the geotechnical properties of the site. Therefore, an integrated model, based on identically sized voxels with geotechnical properties, is required.

This study aims to develop an algorithm for the voxel-based earthwork model by adopting a strategy involving identically sized voxels. The major contribution of this study to the existing body of knowledge lies in its integration of the earthwork design model, a voxelization strategy capable of solving the problem of earthwork segmentation into 3D cells, and the attribute information for each segment, which is significant for earthwork operation. The algorithm is developed using a programming tool that uses the earthwork BIM model and converts it into a voxel-based model. The voxelization model is parametric, and the size of a voxel varies with its other parameters. The earthwork area is divided into parametric cubes, and geotechnical attributes are assigned to each voxel. Moreover, the integrated voxel-based earthwork model with parametric size and properties makes the workflow more flexible.

The remainder of this paper is organized as follows. First, the research background related to the proposed method is presented. The developed algorithmic procedure for earthwork voxelization is then explained. Next, the experiments conducted on actual field data to verify the correctness, speed, and real-time application of the proposed method are discussed. This is followed by a discussion of the algorithm and test results, which are presented in the results and discussion sections of each study. In the final section, the key findings of this study are summarized, along with their future scope.

Literature Review

Infrastructure passes through several stages during its life, beginning with planning, followed by design, construction, operation, and maintenance. Earthwork operations are encountered at the initial stages of construction. Additionally, the evaluation of the cut and fill quantities of earthwork, the comparison to balance these quantities, slope, grades of earthwork sites, and development of methods for moving these materials comprise a part of earthwork design (Shah et al. 2008). The volume of the cut and fill can be obtained via a comparison of the design surface with the ground surface. Accurate modeling of the ground surface and design surface is required for the precise measurement of cut and fill quantities because the duration and cost of a project depend on the estimation of these quantities.

Currently, earthwork area calculations are conducted using different techniques, such as the average end area and surface-to-surface methods. Digital terrain modeling (DTM) is mostly based on the surface-to-surface method, which is considered to be more accurate than the average end area method. Most research has focused on the modeling of earthwork volumes and improving techniques for calculating earthwork volumes (Cheng and Jiang 2013; Lee et al. 2020; Raza et al. 2017; Tanoli et al. 2018). Several commercial software programs (e.g., Civil 3D and Inroads) used for such modeling and calculations include these primary functions. However, these techniques are based on lines and surfaces and suffer from the fact that such types of designs serve as integrated designs. Although a model can be segmented using these tools, actions such as exploding the model into parts and integrating additional information into the model cannot be done efficiently. This is because such tools result in a very tedious and time-consuming workflow when information exchange and design changes are required. For example, Civil 3D has functions to segment the TIN surface by exploding it into several triangles; nevertheless, linking attribute data to each triangle is a tedious task. In contrast, extending these workflows to automated segmentation methods will ease the process of earthwork design.

Post modeling, earthwork planning also constitutes a significant part of earthwork design. The earthwork process should be planned at the design stage for the successful completion of the project. Delay in earthwork operations due to poor planning and design may result in increased project costs and duration. Generally, the earthwork area is divided into small work areas for path planning (Kim et al. 2012; Seo et al. 2011). Construction site planning is frequently based on cell-based representation for earthwork, and work orders for each cell are created during path planning analyses. However, earthwork modeling needs to be enhanced, and additional functionalities, such as soil properties and soil type, should be included before path planning analyses. The current frameworks lack these properties because they are based on 2D representation. For example, a 2D model cannot provide easy volumetric data and does not support the attachment of other relevant information (Cheng and Jiang 2013). A 3D earthwork model is created using BIM based on surface-based representations. The quantities of earthwork are calculated using a surface-to-surface comparison method. In this representation, the earthwork model is composed of many triangles based on the TIN technique. The TIN model acts as an integrated BIM model, such as a single surface made up of many triangles that represent the earthwork model, thereby limiting segmentation and also making it unsuitable for rendering volumetric objects (Lee et al. 2020). However, during the process of earthwork construction, site engineers come in possession of different kinds of information, such as geological and geotechnical parameters, whose values change for the different segments. The challenge in this model is that if the TIN model is segmented based on an explosion technique, it will be converted into many triangles that act as 2D objects, and attaching information to each triangle is not efficient because it is very tedious and time consuming. Furthermore, surface graphics representing the earthwork model are not suitable for holding volumetric information.

Voxelization can be used as an alternative to the earthwork model to create cells in 3D cell-based environments. The face result of each voxel can be approximately treated as a cell that can integrate with other properties necessary for earthwork modeling and planning. BIM considers physical and functional characteristics in 3D environments, and such models are built virtually with all the necessary characteristics before actual construction. However, no built-in function in the BIM process is present that can automatically create a voxel-based model for earthwork operations. Therefore, an algorithm-based method is required to convert the earthwork model into voxels. Using this algorithm will enable the voxel-based earthwork model to enhance the planning process for stakeholders and avoid the time-consuming and tedious cell-based processes.

Voxelization is a technique that is used to convert geometric meshes and surfaces into voxels, which are divisions of a volume into rows and columns in three dimensions. Voxelization is mainly used in computer graphics for converting implicit surfaces into voxels to increase their robustness and visualization (Dong et al. 2004; Stolte and Kaufman 2001; Zhang et al. 2018). Researchers have also worked on voxelization techniques in the architecture, engineering, and construction (AEC) industry. Nourian et al. (2016) and Shirowzhan et al. (2018) have used voxel-assisted techniques to convert point clouds into voxels. The composition of a 3D building structure can be recognized with the help of voxelization (Sun et al. 2018; Truong-Hong et al. 2012). The point cloud can be converted into voxels that facilitate finite-element analysis (Castellazzi et al. 2015; Hinks et al. 2013). The results of this approach were compared with those of a CAD-based finite-element model, demonstrating that voxelization in the field of structural analysis yields effective results in a short duration and increases the level of automation. A BIM model can also be voxelized for path planning purposes (Wang et al. 2020). The previously mentioned studies showed a significant increase in the voxelization of point clouds, curves, and surfaces in civil engineering for different purposes; however, its application in earthwork modeling remains unexplored.

In the earthwork construction process, planning is crucial for equipment and material movement. It involves cutting and filling volumes, which must then be moved using heavy equipment, such as excavators and dumpers. In some scenarios, cut and fill volumes are mostly balanced, and excavators are used to move the cut materials to the filling location. If the quantity of the cut material is more than that of the fill material, some cuts are moved to the fill places, and the rest are dumped at a planned site, and vice versa. A 3D voxel-based environment can help in this process because it provides a cell-based representation that enables the easy planning of construction equipment and materials (Kim and Russell 2003a; Seo et al. 2011). However, limited literature exists on the earthwork voxelization process, and developing necessary algorithms should be the focus of future studies. Further, existing studies did not integrate the properties of earthwork with a voxel-based methodology.

Two strategies exist for voxel representation—identically sized voxels and self-adapting voxelization. As discussed in the previous section, in the identically sized voxel strategy, all generated voxels are identical in size. Two approaches can be adopted for identically sized voxels—surface-based and slice-based voxelization. The object surface is used for voxelization, and other voxels are created based on the first voxel created in surface-based voxelization. The method proposed by Sun et al. (2018) in structural recognition relies on surface-based voxelization. In contrast, in the slice-based method, the model is sliced into several sections, and each section is voxelized, and then the sections are merged. In contrast, voxels in the self-adapting strategy can differ in size. The octree-based and LEGO-based methods are two such forms. Octree-based models face challenges associated with determining the relationship of voxels with their neighbors for path planning, such as in the study by Wang et al. (2020). That study assumed that identically sized voxels could not fit objects or models well if the voxels were not extremely small. However, the study focused on LEGO-based voxelization, which involve walls and floors that are mainly uniform or planar in shape. In contrast, earthwork design has slopes at the sides and top for stability and safety, and its design changes from site to site. Moreover, it involves earthwork volume being moved from one place to another during operation. Therefore, the use of identically sized voxels for earthwork could prove to be a better option as it adopts the design shape more accurately than in the case of LEGO-based voxelization, where voxels are small (Shapira 1993). To overcome this limitation, an approach based on parametric design should be developed to extend the functionality of earthwork design to voxelization. Parametric design with visual programming tools, such as Grasshopper, helps model objects based on parameters and constraints. Such parametric design is based on free parameters and constraints, and the shape of the model changes with visual codes that can lead to a small voxel size. Moreover, earthwork voxelization using this technique can represent a solution for researchers and practitioners, enabling the voxelization of earthwork design coupled with properties.

Knowing the properties of soil during the earthwork process is essential for the productivity of machines, such as excavators, dumpers, and graders. Parsakho et al. (2008) studied the effect of different physical properties of soil, including moisture content, bulk density, grubbing time, and soil porosity, on the productivity of hydraulic excavators. The authors determined that these properties had a significant effect on the productivity of excavators for earthwork operations. The soil type affects the penetration of excavator buckets during the earthwork digging process (Vaha et al. 2017). Moreover, equipment can encounter different types of soil layers during the digging process, thereby requiring a new equipment configuration (Lee et al. 2018). This implies that geotechnical properties should be integrated into earthwork models to improve the productivity of on-site machinery. During the process of earthwork construction, forceful interaction is involved between the equipment and soil. Soil properties have an impact on this interaction; for example, excavation in loose sand soil differs from excavation in compacted soil. Moreover, the level of difficulty changes while stripping and excavating soil, while changes in soil type affect equipment productivity and contractor financial investment (Kim and Russell 2003b). Shah et al. (2008) determined the critical factors that affect earthwork operation via a questionnaire and concluded that soil characteristics were among the most important factors. These soil properties are classified under nongeometrical properties and make earthwork operation of each project unique since soil properties change from site to site. Soil type, soil properties, elevation, travel distance, and job conditions are considered key factors among location-based properties known for improved equipment productivity (Jrade and Markiz 2012). Jakobsen et al. (2018) earthwork 3D model was integrated with a schedule and nongeometric information for visualization purposes. Earthwork design based on BIM can be integrated with machine guidance applications (Kim et al. 2019). Resource and time location information can be integrated with road earthwork that helps construction managers to use resource more efficiently (Dawood et al. 2010; Shah and Dawood 2011). However, such types of frameworks contain limited information and still need to be updated with more information concerning soil properties and the voxelization of earthwork.

Previous studies suggested that several researchers attempted to integrate earthwork modeling with other dimensions, such as the division of earthwork for planning and soil attributes. However, several of them worked on either the integration of properties with only schedule information or earthwork modeling with the division, wherein the division was based on a 2D cell-based representation. Design information was integrated with cost and schedule data by developing a 3D model partitioning system; however, the developed system does not include functionality related to voxelization and soil properties, which are also important (Lee et al. 2020). However, these frameworks still lack the integration of earthwork modeling with voxel-assisted algorithms or nongeometric information, significant for earthwork operation. To address these limitations, this study focused on integrating earthwork modeling, voxel-assisted algorithms, and geotechnical information.

Algorithm Design and Procedure

Voxelization aims to generate a cell-based environment in 3D space. The research contributes to the existing body of knowledge by providing a voxel-based representation of earthwork modeling that creates a cell-based environment. The research produces a novel algorithm that uses an earthwork model as input and creates the required size of voxel-based environment. The algorithm generates a parametric voxel model, and the size of the voxels conveniently varies with its other parameters. The developed novel algorithm performs intelligently with linear time complexity that quickly generates a 3D volumetric cell-based environment, which is a significant advantage over conventional modeling approaches. Furthermore, the most innovative aspect of this study is the integration of earthwork design, the voxelization strategy, and the earthwork attribute information. The voxel-based earthwork model created using the developed algorithm is flexible enough to assimilate geotechnical information linked to each voxel. The proposed method adopts the identically sized voxel method for earthwork representation that improves the traditional methods of surface-based representation. Additionally, in identically sized voxelization, all voxels have the same size and shape. To increase the functionality of the BIM process for modeling and addressing such problems, developers use programming tools such as Java, Python, C#, and visual programming (Khan et al. 2019). Wang et al. (2020) used the Revit Application Programming Interface (API) version 2017 in their methodology to augment the functionality of the BIM model.

Visual programming tools allow designers to solve problems using visual codes. Visual programming and BIM have been integrated in this study to solve the automatic conversion of the earthwork model into the voxel model. Considering the earthwork design model, the process of voxelization entails three steps: solid extraction of earthwork model, triangular mesh generation, and voxel generation on the mesh. All these steps are presented in Figs. 1 and 2. Fig. 1 presents the process of voxelization. First, the earthwork solid model must be established on the basis of the surface-based earthwork model [Fig. 1(a)]. After the solid model is generated, the model is converted into triangle meshes [Fig. 1(b)]. The mesh model is used as input in the voxelization algorithm. The algorithm first generates voxels along the diagonal of the model [Fig. 1(c)]. The voxels are translated along the U-direction, followed by the V- and W-directions, creating fully voxelized objects [Fig. 1(d)]. Fig. 1(e) illustrates the output voxels generated after the application of the developed algorithm. The pseudocode of the developed algorithm is presented in the appendix.

Solid Extraction

An earthwork area is generally depicted by a surface representation that shows the geometrical characteristics of the earthwork boundary. The ground surface and design surface constitute the earthwork design, and a comparison of these surfaces helps to obtain the earthwork volume. A solid can be extracted between these two surfaces using a computer-aided design (CAD) application and API functions that provide a visual representation of the earthwork model with topology information. In the first step, the solid is extracted and used in subsequent steps.

Triangular Mesh Generation

In the next step, after the solid model generation, the model is converted into triangular meshes and comprises several triangle facets. Studies on voxelization cited in the bibliography have also used a triangular meshing technique (Sun et al. 2018; Wang et al. 2020). Various BIM and CAD software programs have the built-in functionality necessary to create triangular meshes. In this study, a triangular mesh technique is used to create meshes for the generation of voxels from a solid.

Voxel Generation on a Mesh

This is the final step in the voxelization process, which converts a generated mesh from a solid into voxels. The Grasshopper tool was used for this step to process voxel creation in the triangular mesh. The algorithm takes a mesh as the input and processes the flow using Grasshopper components and connections between the input and output data.

The mesh geometry is faded into an axis-aligned bounding box that is a closed space surrounding all the objects and used for specific testing (Cai et al. 2018). The bounding box has attributes, and

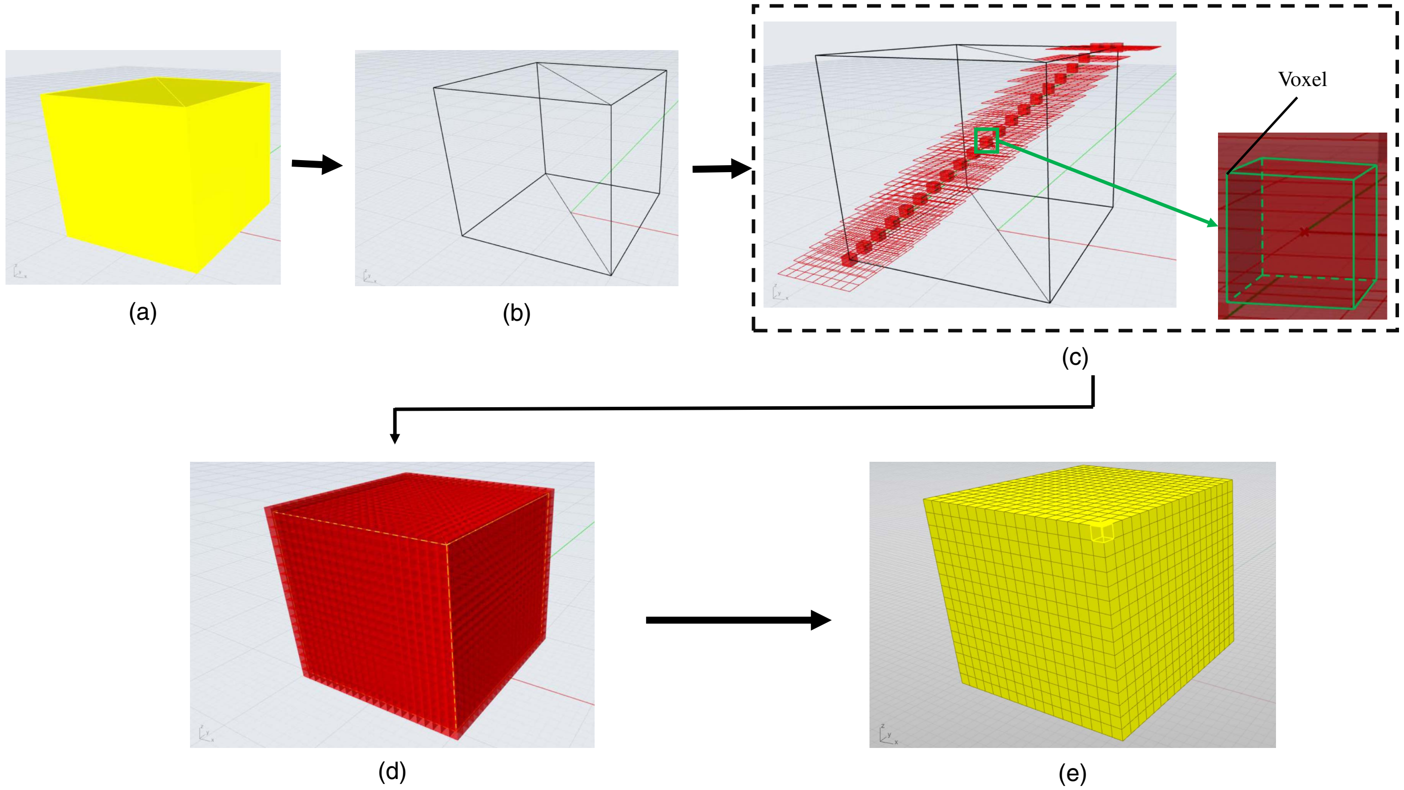

Fig. 1. Process of voxelization: (a) solid model showing design model; (b) mesh triangulation created from solid; (c) voxelization of generated mesh in progress; (d) voxelized geometry (preview); and (e) voxelized solid model after application of algorithm.

visual codes allow the retrieval of the bounding box properties. The properties of the boxes are useful for additional processes and provide information concerning the boxes, such as area, center, diagonal vector, and volume of the box. These properties are used to address the challenges associated with voxel creation.

A diagonal vector can be interpreted as the size of the bounding box in each direction. The algorithm begins voxelization from the center of the bounding box and iterates each created point until the object is fully voxelized. The diagonal vector has x, y, and z components, which are extracted. Points and vector planes are constructed using these components. Because Grasshopper can generate a parametric design, this diagonal vector can be divided into several components, constrained by users, via a number slider. The diagonal vector is deconstructed twice, and each one has its functionality with a parametric definition. The first voxel is created at the center of the bounding box and is then iterated upon with all the created points. Other voxels are created using predefined points at specified spacing and sizes with respect to each other, thereby preventing collision of voxels with one another.

The bounding box is evaluated with the input of the bounding box and U, V, and W parameters. These parameters are the steps of the components of the diagonal vector, and their results are planes and points in the box at these predefined local points. The center box is moved to these points, thereby creating voxels in different directions inside the bounding box. This leads to the creation of voxels only along the diagonal vector, which constitutes a problem. However, the purpose is to voxelize the whole bounding box in each direction. Finally, points created at the diagonal vector are cross-referenced, starting from voxels along the U-direction, followed by the V- and W-directions. The detailed process can be seen in Fig. 3.

In this process, the bounding box is voxelized with parametric cubes or voxels, and the size and number of voxels can be easily varied using a number slider. However, the actual shape of the design solid differs from the bounding box in the case of earthwork. An earthwork design surface and ground surface connect with a slope that varies along the length and sides of the surface. Furthermore, design criteria vary according to the objective, such as designing a road or a building. Voxels created in the bounding box are used for reference in this method and should be created inside the earthwork volume instead of a bounding box. To address this issue, a collision test is conducted between the triangular mesh and bounding box by using the *Collision One/Many* component. All voxels created in the bounding box are treated as a collider while the triangular mesh is treated as an obstacle. The obstacle ensures that all voxels outside of the earthwork mesh geometry are excluded, and voxels inside the mesh are left unaffected. The soil properties that affect earthwork construction are defined as parameters. The properties are then attributed to the earthwork voxel model.

The computational complexity of the algorithm is determined by varying the size of voxels and the simulation time taken by the algorithm each time in the conversion of meshes into voxels. These tests are run on a personal computer with an Intel i5-4460 CPU (two cores, 3.20 GHz) with 8 GB RAM. The runtime complexity of the algorithm is on the order of n, i.e., linear time complexity $O(n)$ as when the size of the input reduces, the number of voxels grows, and the time required by the algorithm to run increases accordingly. The concept is illustrated in Fig. 4. The accuracy and appropriateness of the new algorithm are verified by its implementation in a two-earthwork design with different shapes, sizes, and properties, and its comparison with surface-based representation results in high volume accuracy, achieving optimum sized voxels, and providing a ready-to-use cell-based environment that can be used by practitioners in earthwork construction for equipment plans, allocation plans, and so forth.

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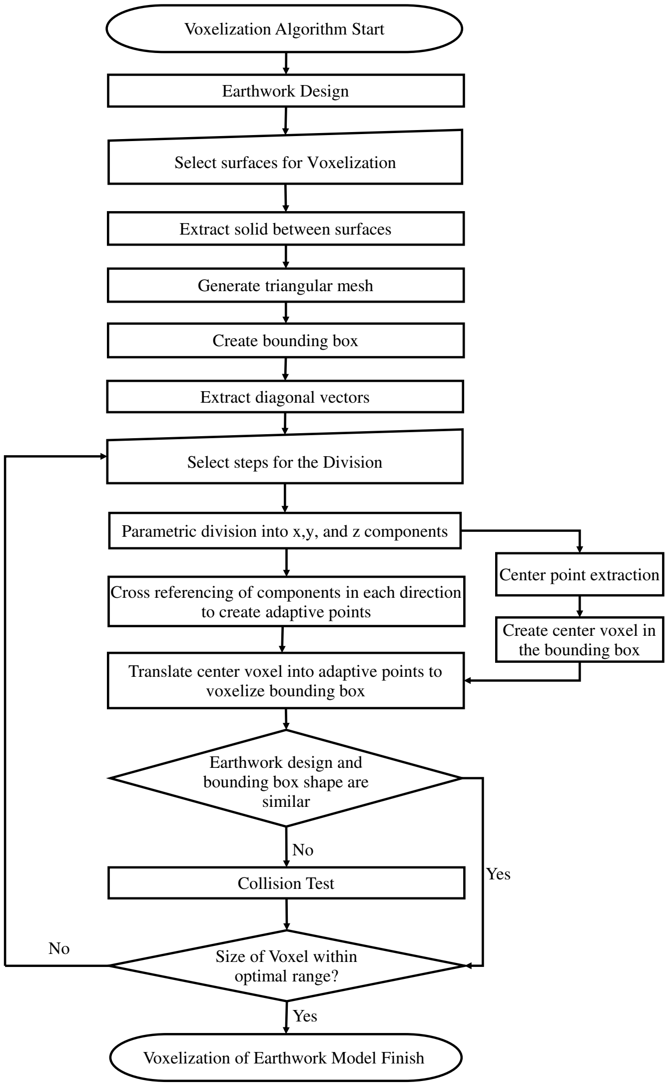


Fig. 2. Algorithm design showing process of voxelization.

Application of Proposed Method to Earthwork Projects

The proposed algorithm and the capability of the method are demonstrated by applying them to an actual earthwork design. The following two case studies are selected to check the procedure of voxelization in earthwork construction. The selected cases have different sizes and shapes because earthwork construction changes from site to site.

Case 1

A study at the Hanyang University Erica Campus, South Korea, was selected to verify the applicability of the proposed method on earthwork design data. Earthwork design passes through various stages to map the final design. First, for earthwork design, the construction site is surveyed using an unmanned aerial vehicle (UAV) to collect site images to create digital terrain models. These images are processed by software to create georeferenced point cloud data, where each point has its coordinates, as depicted in Fig. 6(a). The digital terrain model is constructed from point cloud data using Autodesk Civil 3D software. This commercial software can design the earthwork model, create visualizations, and analyze the cut and fill quantities. A detailed procedure for the Case 1 earthwork design is shown in Fig. 5. The TIN surface created with Civil 3D for Case 1 earthwork design is shown in Fig. 6(b).

After creating the ground surface, it was used as a reference for the design surface. The area of the design surface selected for the experiment was 6,392 m^2. A poly object was then drawn for the site design boundary. The poly object was used as a reference for a feature line that was stable and interactive, given that the properties of the feature lines make it suitable for the site design. To create grading for cut and fill slopes at the site, the grading group is required in Civil 3D. Site grading is created for cut and fill slopes at the site with a 50% slope. This implies that the design surface connects with a ground surface having a slope of 50%, or 1:2. Additionally, a 2% slope is provided at the top surface of the earthwork design for drainage purposes. The surface design of the selected experiment is shown in Fig. 6(c).

The original design of the earthwork site is complete with specified slopes at the top and the side. The next step in voxelization is the creation of a solid model. Civil 3D also includes functions to extract a solid from a surface with three different criteria. These criteria are used as a target for the solid: a specific depth, a specific elevation, or at a surface. Solid extraction from the surface by means of specifying another surface as a target will ensure that the solid is extracted between these two surfaces. The solid is extracted between the ground surface and the surface created from the feature lines for the site design shown in Fig. 6(d).

As mentioned in earlier, BIM software, such as Civil 3D software, has no built-in functionality for the voxelization of earthwork design. Fig. 6(d) depicts an extracted solid that has side slopes and was extracted using Civil 3D. The earthwork solid model is then imported into Rhinoceros and has a .dwg extension. Rhinoceros, also known as Rhino, is commercial CAD software whose geometries are based on the nonuniform rational basis spline (NURBS) mathematical model.

The next step in the voxelization of the earthwork model is the creation of triangular mesh geometry. Rhino has functions for creating triangular meshes from a solid model. The mesh geometry is then created using the imported design solid. This mesh was used as an input for the voxelization algorithm. Rhino geometries can be used with Grasshopper, and these geometries can be converted into permanent Rhino geometries using the baking command. The triangular mesh geometry in Rhino and the voxelization of meshes in Grasshopper are shown in Fig. 7. The voxel geometries of the earthwork from Grasshopper into Rhino are presented in Fig. 8. As geotechnical properties are essential for earthwork construction, this method supports the attribution of the properties to each voxel. However, the soil properties in this case study were not known from lab experiments, and properties were assumed based on experience and literature. Different geotechnical parameters are selected that affect earthwork design and equipment performance from the literature, such as soil type, swell factor, angle of internal friction, cohesion, density, plasticity index, N values, and water content, and are attributed to each voxel in the earthwork design model. All properties are defined as parameters in the Rhino software. Data type and category were assigned to each of the parameters. Each voxel is facilitated with the geotechnical properties that can be seen in Fig. 8.

Two tests were conducted to validate the proposed method: a correction and a speed test. The correction test evaluates the accuracy of the proposed method. In the earthwork design, the volume of quantities should be accurate for accurate project cost estimation. In this study, the earthwork model is divided into small voxels that require verification in terms of volume. A speed test determines the effect of the size of the voxels and the number of voxels on the performance in terms of the simulation time.

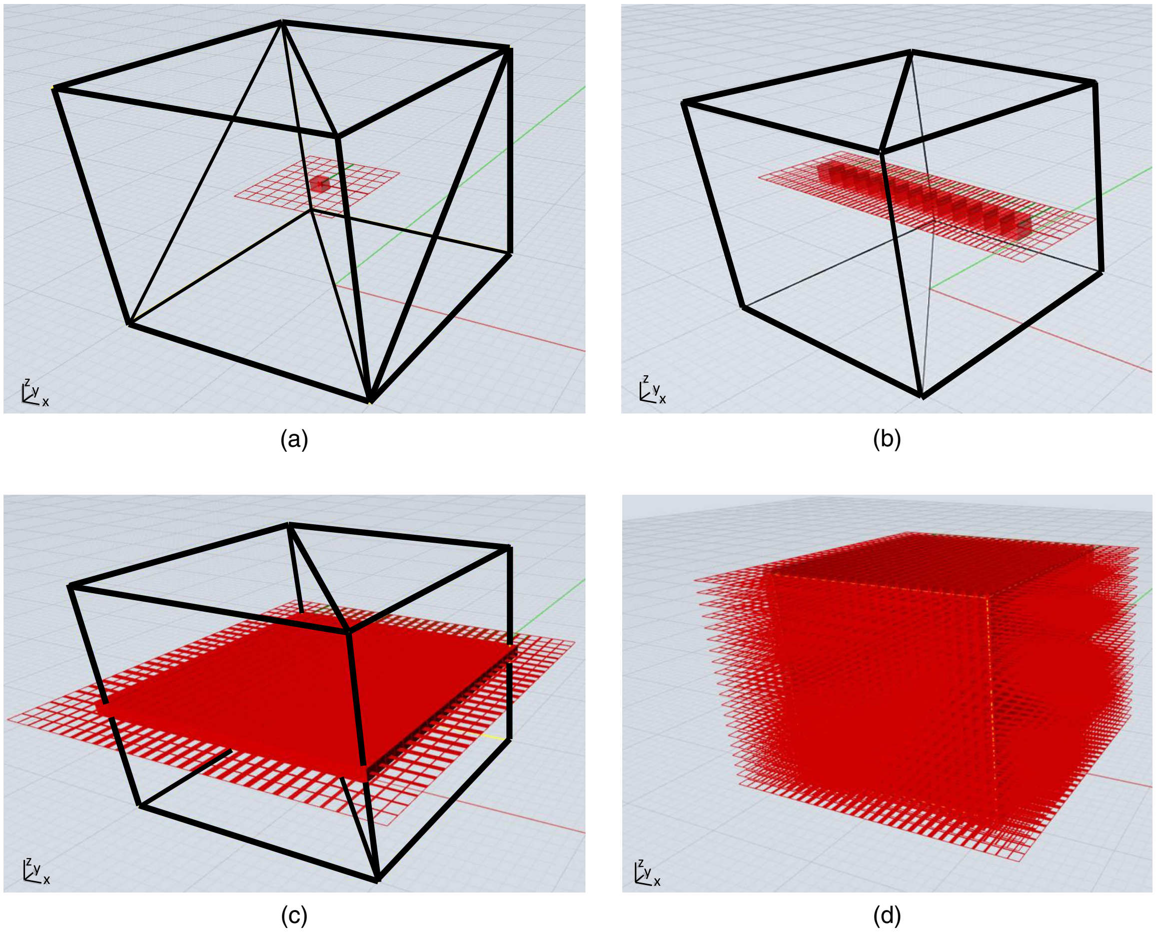


Fig. 3. Bounding box voxelization: (a) center voxel creation; (b) voxels in U-direction; (c) voxels in U- and V-directions; and (d) voxels in U-, V-, and W-direction.

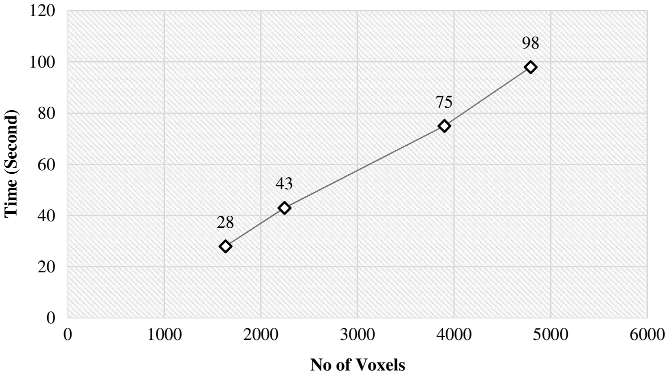


Fig. 4. Experimental result depicting time complexity of algorithm (x-axis: number of voxels, y-axis: time).

Results and Discussion

The voxelized model of earthwork is presented in Fig. 8, where all properties are stored with each voxel. The design in this workflow is such that when a voxel is selected, all attributed properties are listed. The tools used in the experiment for this study were Civil 3D 2020, Rhinoceros 6, and Grasshopper. Civil 3D was used for designing the earthwork model, which has the functionality of grading surfaces to the target, which are required for earthwork modeling. Additionally, quantities of earthwork were evaluated in Civil 3D. Civil 3D has an extension of the Geotechnical module that can integrate the soil type with the earthwork model. However, the problem with this module is that it only shows the soil type in layers. Further, it does not include the functionality for the segmentation of earthwork in voxelization. Rhinoceros is a CAD software program that has various functions for modeling; however, it does not have grading and daylighting functions, which are available in Civil 3D for the earthwork model. Therefore, an integrated workflow that combines the earthwork model, divides the earthwork model into voxels, and associates geotechnical attributes for each voxel is proposed and validated in this study. Civil 3D and Rhino are interoperable, and the earthwork model created in Civil 3D was imported into Rhino, and a triangular mesh was created. The design algorithm implemented in Grasshopper uses Rhino geometry as the input. Parametric voxelization was completed by running the developed algorithm.

Tests results are presented in Fig. 9 (both test results are shown in one figure). These tests are run on a PC with an Intel i5-4460 CPU (two cores, 3.20 GHz) with 8 GB RAM. The correctness test shows the volume accuracy of the model after voxelization. The correctness test is determined by calculating the error and voxel volume. The earthwork volume was calculated before voxelization as a theoretical volume. The voxels and number of voxels are determined to achieve the actual volume after voxelization. The error is determined by subtracting the actual volume from the theoretical volume. The test for each voxel size is performed 10 times and the average is used to reduce occasional errors (Wang et al. 2019, 2020)

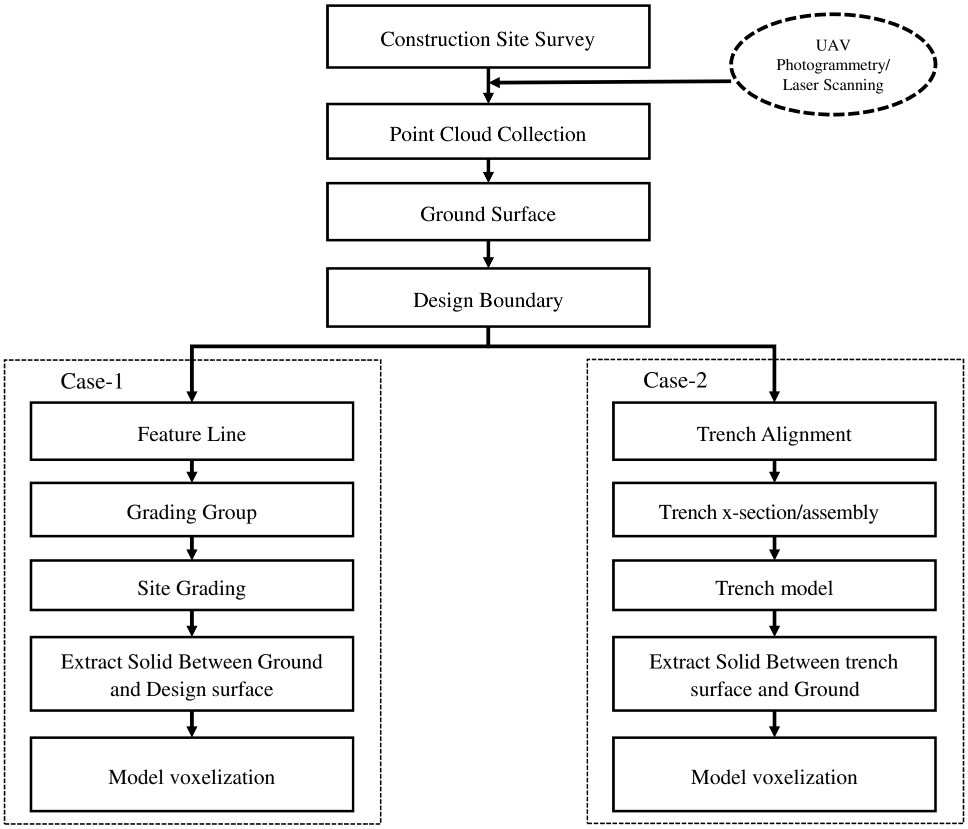


Fig. 5. Earthwork design process for Cases 1 and 2.

$$\text{Error}(\%) = \frac{\text{Volume of voxels} - \text{Volume of earthwork in Civil 3D}}{\text{Volume of voxels}} \times 100 \quad (1)$$

The earthwork volume was calculated using the Civil 3D surface-to-surface method. This research is based on the identically sized voxelization strategy. Therefore, the total volume of voxels generated from the earthwork design solid is calculated from the volume of one voxel multiplied by the number of voxels. The error in the volume was calculated using Eq. (1). Keeping the earthwork design, the voxel volume was varied to check the effect of voxel size on the accuracy and simulation. As shown in Fig. 9, as the volume of a voxel decreases, the error in the model decreases, thereby decreasing the difference between the actual volume of the earthwork model and the theoretical model. From the speed test result, it is shown in the figure that, as the volume decreases, the elapsed time increases. By decreasing the volume of a voxel, the number of voxels increases and the time elapsed for voxel generation increases with the number of voxels. Finally, a voxel size in the range of 2.5–3 mm^3 is considered as the optimal size that gives us an error in the range of 2%–4% with a simulation time of less than 30 s. The error range calculated using the voxel-based method is within the acceptable range for earthwork projects. In this way, practitioners can easily choose the feasible size voxel according to the design requirements.

Case 2

To spread smart construction technology to demonstrate onsite smart construction utilizing advanced technologies, a contest was arranged by the Ministry of Land, Infrastructure, and Transport and the Korea Land & Housing Corporation. The site of the contest is located in Sejong Metropolitan Autonomous City, South Korea. The earthwork design data used in this construction site were used as a study for the demonstration of the proposed method. Moreover, the soil type and conditions of the contest site are also known in this study.

To form the earthworks automation site, a coordinate system was first set up. Site calibration was performed using the total station survey equipment. Then the site coordinate system was developed from four nationally authorized reference points near the competition field. The coordinate system was calibrated at the GRS80 (Korean 2000/Central Belt 2010) and Geoid KN13. It is important to accurately depict the existing ground conditions because the construction process is affected by that data. The site of the area 105 × 35 m for the earthwork automation contest was scanned with the laser scanner equipment shown in Fig. 10(a). Civil 3D was used to convert the scanned data into a TIN surface.

Based on this, three excavation trenches were designed as a target model. The trenches were developed for three different excavators of different companies. The target model was made using CAD software according to the design criteria. However, the design model is the same for all three trenches. Therefore, one model is selected in this study to check the proposed method applicability on the actual design data. The trench is modeled using a subassembly composer. The procedure adopted for the trench design is presented in Fig. 5 (Case 2). The subassembly composer can be used to create subassemblies according to design requirements. Subassembly has points, links, and shapes that carry different information. These features are used to make a surface model and for volume calculation for the earthwork. The assembly is created and combined with the trench alignment to make the final trench corridor model. The trench target

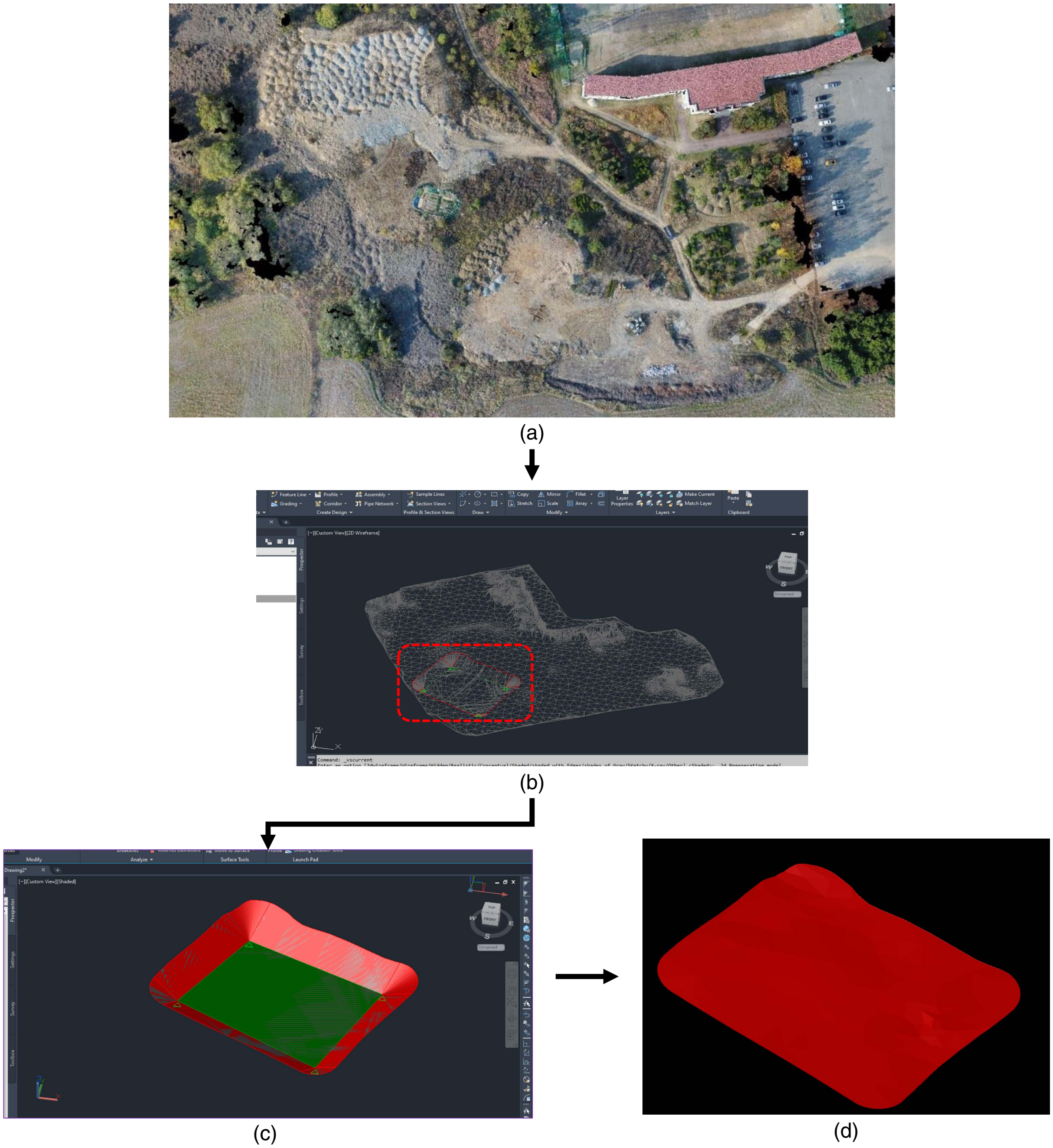


Fig. 6. (a) UAV photogrammetry results showing site aerial view (image by authors); (b) ground surface created in Civil 3D using point cloud; (c) 3D design surface of proposed excavation; and (d) extracted solid between ground surface and design surface (this solid will be used for the voxelization).

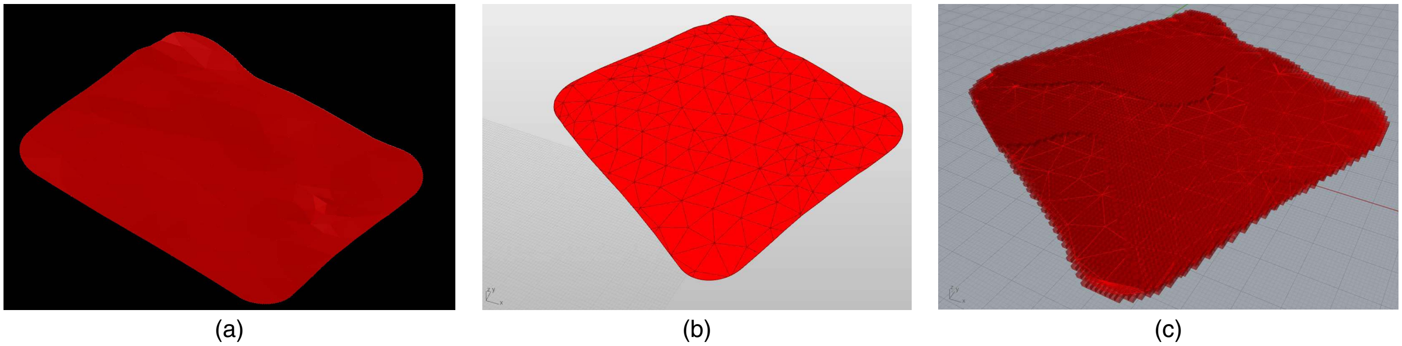
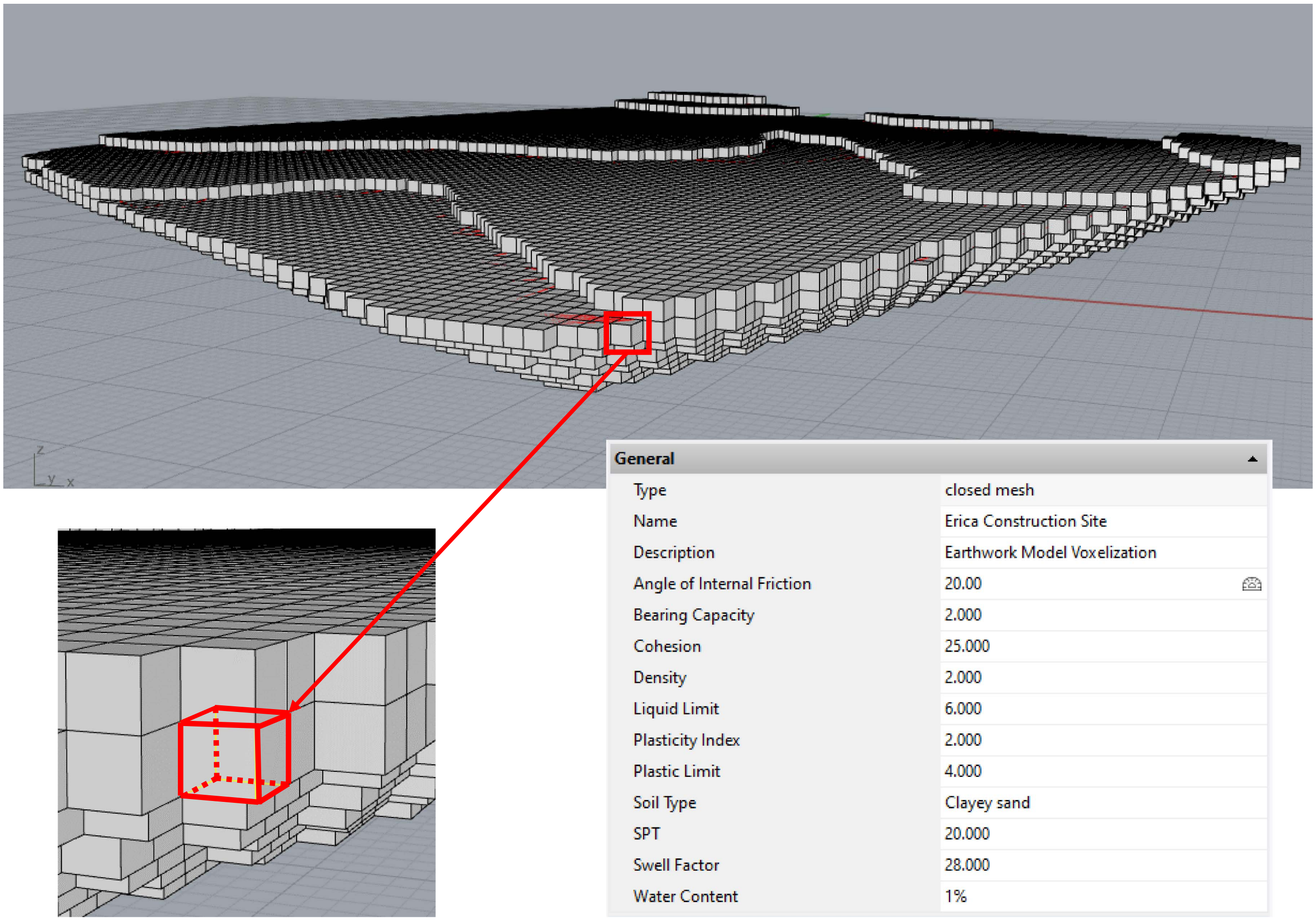


Fig. 7. Voxelization process for earthwork design: (a) earthwork solid model (Civil 3D); (b) triangular mesh (Rhino 6); and (c) voxelized earthwork model.



General	
Type	closed mesh
Name	Erica Construction Site
Description	Earthwork Model Voxelization
Angle of Internal Friction	20.00
Bearing Capacity	2.000
Cohesion	25.000
Density	2.000
Liquid Limit	6.000
Plasticity Index	2.000
Plastic Limit	4.000
Soil Type	Clayey sand
SPT	20.000
Swell Factor	28.000
Water Content	1%

Fig. 8. Voxelization of earthwork design with geotechnical properties.

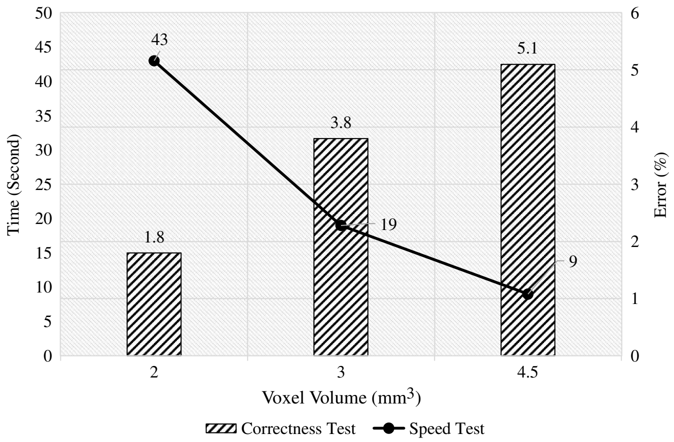


Fig. 9. Correctness and speed test results.

model was illustrated using a surface representation, as shown in Fig. 10(d). Another surface was created using the top corner of the trenches. The target to surface function was used to obtain the solid between the trench surface design and the ground surface. The solid is extracted between the surfaces that can be used for the voxelization of the trenches. The ground model and trench model visualization can be seen in Figs. 10(a and b). The trench models are voxelized using the voxelization algorithm. Figs. 10(e and f) present the voxelized models of the trenches in the sectional and perspective views.

Results and Discussion

Autodesk Civil 3D was used for the trench design. The trench subassembly was modeled in the subassembly composer. However, the information contained in the subassembly is limited. Furthermore, the 3D trench model generated in Civil 3D was not partitioned into small segments. The 3D trench model was segmented using a developed voxelization algorithm. The models are compared using cross-sectional images, shown in Figs. 10(c and e). The soil properties in this case study were known. Therefore, the geotechnical properties of the site were attributed to the voxel model. The final model is segmented where each voxel has its properties as presented in Fig. 11.

The correctness test and the speed test were conducted for this case. The values for these tests were obtained with the same method adopted for Case 1. The earthwork trench volume was calculated using Civil 3D and was compared with the volume of the earthwork after voxelization. Voxel volume was varied for the same earthwork design to check the effect of voxel size on the model accuracy. The volume difference was calculated from Eq. (1) using the average value. Furthermore, the time taken by the algorithm to convert the earthwork model into the voxelization model was noted for each case. The test results are shown in Fig. 12. The results show behavior similar to that in Case 1. The reason behind the error in the

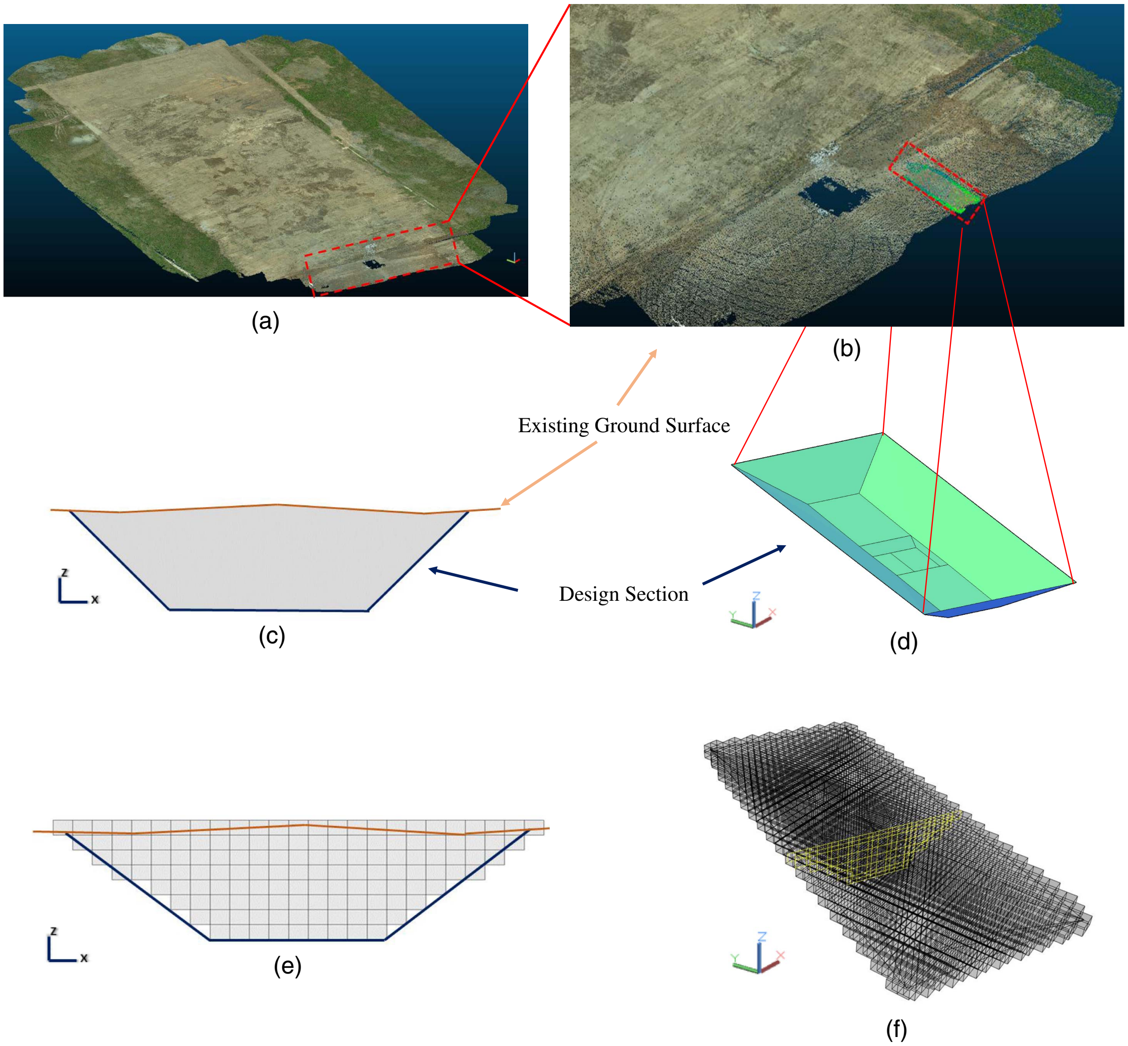


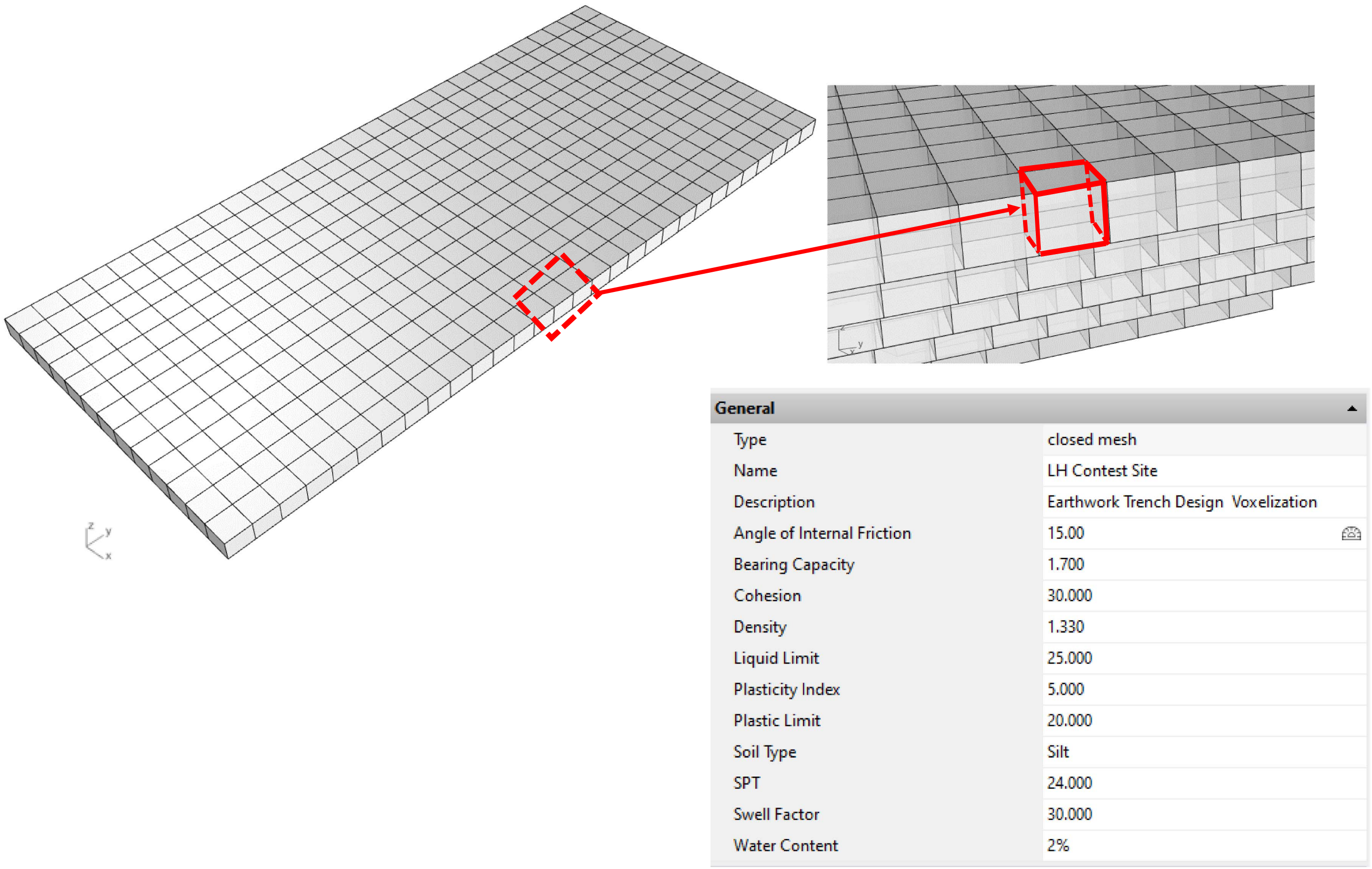
Fig. 10. (a) Site laser scanner photogrammetry (image by authors); (b) area of trench design models (image by authors); (c) section design showing design level and existing ground surface; (d) proposed 3D trench model created in Civil 3D using subassembly composer; (e) design section voxelized representation; and (f) results of voxelization of whole 3D trench model.

volume of the earthwork from Civil 3D (surface-to-surface) and the voxel-based volume is that elements are not fully covered by voxels that can be seen in the cross-sectional shape comparison Figs. 10(c and e). The shape consistency acquired by voxels increases with the decrease in the size of the voxels, however, there will always be voxels not fully covering the design (Shapira 1993). Furthermore, the elapsed time increases with the reduction in the voxel size. A voxel size of 3–4 mm^3 is considered optimal for such designs that give errors in the range of 2%–3% with a simulation time of less than 30 s. The error range in this type of earthwork project is acceptable; however, it varies from site to site and depends on the type of earthwork project. The error range for optimal voxel size is different from Case 1 because the design data are changed in both cases. Moreover, the size and type of earthwork design are changed. The application of a voxel-based method to actual site data shows that this method can provide a better opportunity for designers and researchers to segment earthwork models into 3D cells with geotechnical information more quickly with a smaller error range.

Advantages and Benefits

The application of the proposed method and developed algorithm in two case studies with different shapes, sizes, and properties successfully created a cell-based environment along with the geotechnical information. Furthermore, the accuracy of the proposed method is convenient according to the earthwork design. The main advantage of voxel-based representation is the creation of the cell-based environment. Voxelization is the segmentation of 3D objects into voxels (cubes), which are 3D analogs of pixels. The faces of voxels may create a cell-based environment. In addition, the earthwork design is represented in the surface graphics, which is not suitable for rendering volumetric objects. The voxel created after voxelization from surfaces and meshes contains volumetric data. In the earthwork construction process, planning is crucial for equipment and material movement. It involves cutting and filling earthwork volumes, which then have to be moved using heavy equipment such as excavators and dumpers. In some scenarios, cut and fill volumes are mostly balanced, and excavators are used to move the cut materials to the filling place. If the quantity of the cut material is more than that of the fill material, some cuts are moved to the fill locations, and the rest are dumped at a planned site, and vice versa.

A 3D volumetric representation, such as a voxel-based environment, can help in this process because it provides a cell-based representation that enables easy planning of construction equipment



General	
Type	closed mesh
Name	LH Contest Site
Description	Earthwork Trench Design Voxelization
Angle of Internal Friction	15.00
Bearing Capacity	1.700
Cohesion	30.000
Density	1.330
Liquid Limit	25.000
Plasticity Index	5.000
Plastic Limit	20.000
Soil Type	Silt
SPT	24.000
Swell Factor	30.000
Water Content	2%

Fig. 11. Voxels local view on trench surface with geotechnical information.

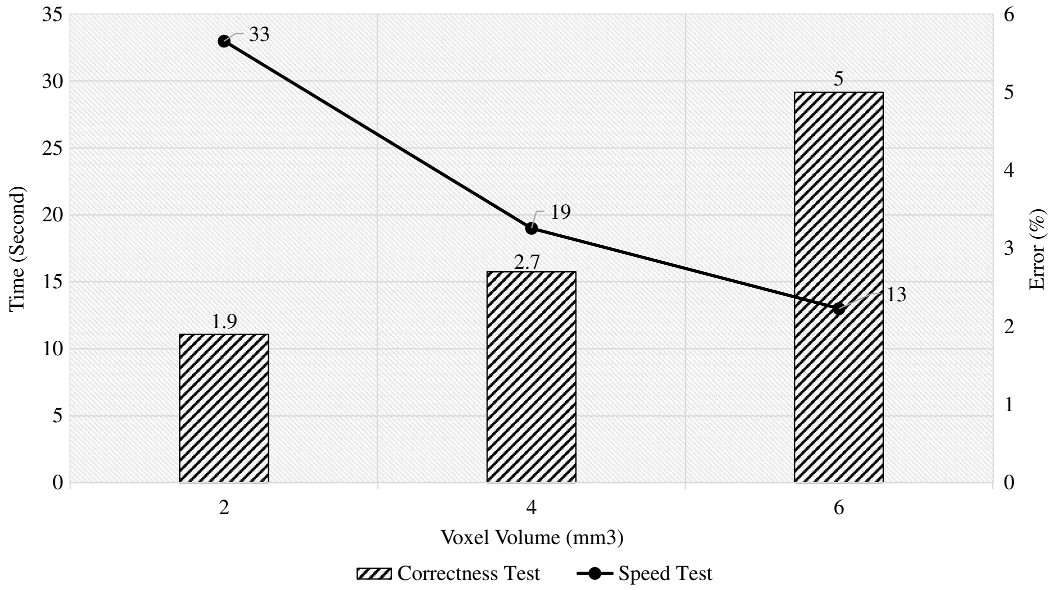


Fig. 12. Correctness and speed test results for Case 2.

and materials (Kim and Russell 2003a; Pradhananga and Teizer 2015; Seo et al. 2011). Tasks and resources can be assigned to each cell, which will allow a construction manager to handle cells easily. In addition, assigning properties to each cell is important role because these cells could be associated with each other based on their characteristics, such as soil properties, tasks, or resources assigned. Also, knowing the properties of soil during the earthwork process is essential for the productivity of machines, such as excavators and bulldozers because the soil type effects the penetration of excavator buckets during cutting (Parsakho et al. 2008).

Construction managers can use such cell-based environment for path planning purposes, such as construction equipment moving path simulation (Zhang et al. 2007), visualizing real-time location data from construction equipment for construction site simulation (Pradhananga and Teizer 2015), congestion analysis for construction site layout planning (Pradhananga and Teizer 2014), and material transport planning at construction sites (Park et al. 2012). The most significant characteristic of the cell-based representation is that spatial relationships and spatial distributions can be assigned to each cell. The spatial relationships among cells enhance their capability and produce efficient work-space plans, whereas traditional techniques, such as Gantt charts, network diagrams, and critical path techniques, are unable to account for spatial relationships (Choi et al. 2014). The graphical control interfaces developed for construction equipment, such as machine guidance and machine control, are becoming common (Seo et al. 2000). A voxel-based representation can contribute significantly to the creation of an efficient graphical interface. Cell-based representations can be used for efficient resource planning and construction site management.

Conclusion

This study details the development of an algorithm to segment an earthwork model into voxels. The research contributes to the existing body of knowledge by providing a voxel-based earthwork model that generates a cell-based environment because the upper face of voxels is treated as a cell. The proposed method has more advantages over traditional methods because it provides a parametric 3D cell-based environment with customized geotechnical information. Moreover, the algorithm generates parametric voxels rapidly and intelligently because when the parameters of a model change, all voxels change and are updated with new information. The most challenging aspect of adopting such a model lies in integrating other information with the model. The voxel-based model in this method is flexible enough to assimilate geotechnical information linked to each voxel. The appropriateness of the method and algorithm for earthwork voxelization was therefore verified using actual design data. Two cases with different design data, types, and properties used for the demonstration and verification of the method showed satisfactory results. Practitioners and researchers can easily convert earthwork BIM models to create a model with feasibly sized voxels producing the desired accuracy using the proposed method. This study focused on voxel-based earthwork representation, and future studies could extend the algorithm to scheduling and path planning. To increase the robustness of the developed algorithm, a quantitative comparison with other algorithms, such as that in Solihin (2015), must be performed.

Appendix. Pseudocode of Developed Algorithm

```
Start
Step 1: Earthwork surface-based design
Select
      Surfaces for voxelization (1, 2, 3 . . . n)
Step 2: Extract solid between surfaces
Step 3: Generate mesh model
Create bounding box
Step 4: Define steps for the division
      Parametric division into x, y, and z components
            Create voxel at the center of bounding box
      Cross reference x, y, and z in each direction of bounding box
      Translate center voxel in each created x, y, and z component
      If earthwork design shape is not same as bounding box Then
            Collision test
      Else
            Okay
      If size is not within optimal range Then
            Change steps for division
      Else
            Design is final
      End
End
```

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restriction. The available items are data models used in the case studies with the restriction of the algorithm generated.

Acknowledgments

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References

Akinci, B., M. Fischer, and J. Kunz. 2002. “Automated generation of work spaces required by construction activities.” *J. Constr. Eng. Manage.* 128 (4): 306–315. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(306).

Cai, L., F. Jiang, W. Zhou, and K. Li. 2018. “Design and application of an attractiveness index for urban hotspots based on GPS trajectory data.” *IEEE Access* 6 (Sep): 55976–55985. https://doi.org/10.1109/ACCESS.2018.2869434.

Castellazzi, G., A. M. D’Altri, G. Bitelli, I. Selvaggi, and A. Lambertini. 2015. “From laser scanning to finite element analysis of complex buildings by using a semi-automatic procedure.” *Sensors (Switzerland)* 15 (8): 18360–18380. https://doi.org/10.3390/s150818360.

Cheng, J., and L. Jiang. 2013. “Accuracy comparison of roadway earthwork computation between 3D and 2D methods.” *Procedia Soc. Behav. Sci.* 96 (Nov): 1277–1285. https://doi.org/10.1016/j.sbspro.2013.08.145.

Choi, B., H. S. Lee, M. Park, Y. K. Cho, and H. Kim. 2014. “Framework for work-space planning using four-dimensional BIM in construction projects.” *J. Constr. Eng. Manage.* 140 (9): 04014041. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000885.

Dawood, N., R. Chavada, C. Benghi, and R. Sanches. 2010. “Interactive visual lean system for resource planning of earthwork operations.” In *Proc., 18th Ann. Conf. of the Int’l. Group for Lean Construction*, 652–661. Trondheim, Norway: International Group for Lean Construction.

Dong, Z., W. Chen, H. Bao, H. Zhang, and Q. Peng. 2004. “Real-time voxelization for complex polygonal models.” In *Proc., 12th Pacific Conf. on Computer Graphics and Applications, 2004. PG 2004*, 43–50. New York: IEEE. https://doi.org/10.1109/PCCGA.2004.1348333.

Hinks, T., H. Carr, L. Truong-Hong, and D. F. Laefer. 2013. “Point cloud data conversion into solid models via point-based voxelization.” *J. Surv. Eng.* 139 (2): 72–83. https://doi.org/10.1061/(ASCE)SU.1943-5428.0000097.

Jakobsen, L. S., J. Lodewijks, P. N. Gade, and E. Kjems. 2018. “Visualizing earthwork and information on a linear infrastructure project using BIM 4D.” In *eWork and eBusiness in architecture, engineering and construction*, 177–183. London: CRC Press.

Jrade, A., and N. Markiz. 2012. "A decision-support model utilizing a linear cost optimization approach for heavy equipment selection." In *Proc., Construction Research Congress 2012: Construction Challenges in a Flat World*, 100–109. Reston, VA: ASCE. https://doi.org/10.1061/9780784412329.011.

Khan, N., A. K. Ali, M. J. Skibniewski, D. Y. Lee, and C. Park. 2019. "Excavation safety modeling approach using BIM and VPL." *Adv. Civ. Eng.* 2019: 15. https://doi.org/10.1155/2019/1515808.

Kim, J., H. Kim, W. A. Tanoli, and J. Seo. 2019. "3D earthwork BIM design and its application in an advanced construction equipment operation." *Archit. Eng.* 4 (2): 22–26. https://doi.org/10.23968/2500-0055-2019-4-2-22-26.

Kim, S. K., and J. S. Russell. 2003a. "Framework for an intelligent earthwork system: Part I. System architecture." *Autom. Constr.* 12 (1): 1–13. https://doi.org/10.1016/S0926-5805(02)00034-1.

Kim, S.-K., and J. S. Russell. 2003b. "Framework for an intelligent earthwork system: Part II. Task identification/scheduling and resource allocation methodology." *Autom. Constr.* 12 (1): 15–27. https://doi.org/10.1016/S0926-5805(02)00033-X.

Kim, S.-K., J. Seo, and J. S. Russell. 2012. "Intelligent navigation strategies for an automated earthwork system." *Autom. Constr.* 21 (1): 132–147. https://doi.org/10.1016/j.autcon.2011.05.021.

Lee, H. C., H. S. Gwak, J. Seo, and D. E. Lee. 2018. "Eco-economic excavator configuration method." *Autom. Constr.* 86 (Jul): 138–149. https://doi.org/10.1016/j.autcon.2017.11.006.

Lee, S. S., K. T. Kim, W. A. Tanoli, and J. W. Seo. 2020. "Flexible 3D model partitioning system for nD-based BIM implementation of alignment-based civil infrastructure." *J. Manage. Eng.* 36 (1): 04019037. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000725.

Min, K., C. Park, H. Yang, and G. Yun. 2018. "Legorization from silhouette-fitted voxelization." *KSII Trans. Internet Inf. Syst.* 12 (6): 2782–2805. https://doi.org/10.3837/tiis.2018.06.019.

Nourian, P., R. Gonçalves, S. Zlatanova, K. A. Ohori, and A. Vu Vo. 2016. "Voxelization algorithms for geospatial applications: Computational methods for voxelating spatial datasets of 3D city models containing 3D surface, curve and point data models." *MethodsX* 3: 69–86. https://doi.org/10.1016/j.mex.2016.01.001.

Park, M., Y. Yang, H.-S. Lee, S. Han, and S. Ji. 2012. "Floor-level construction material layout planning model considering actual travel path." *J. Constr. Eng. Manage.* 138 (7): 905–915. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000493.

Parsakho, A., S. Ataollah Hosseini, H. Jalilvand, and M. Lotfalian. 2008. "Physical soil properties and slope treatments effects on hydraulic excavator productivity for forest road construction." *Pakistan J. Biol. Sci.* 11 (11): 1422–1428. https://doi.org/10.3923/pjbs.2008.1422.1428.

Pradhananga, N., and J. Teizer. 2014. "Congestion analysis for construction site layout planning using real-time data and cell-based simulation model." In *Computing in civil and building engineering*, 681–688. Reston, VA: ASCE.

Pradhananga, N., and J. Teizer. 2015. "Cell-based construction site simulation model for earthmoving operations using real-time equipment location data." *Vis. Eng. Visualization Eng.* 3 (1): 1–16. https://doi.org/10.1186/s40327-015-0025-3.

Raza, H., W. Tanoli, S. Lee, and J. Seo. 2017. "Flexible earthwork BIM module framework for road project." In *Proc., Int. Symp. on Automation and Robotics in Construction: ISARC 2017*, 410–415. Oulu, Finland: International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2017/0056.

Seo, J., C. T. Haas, K. Saidi, and S. V. Sreenivasan. 2000. "Graphical control interface for construction and maintenance equipment." *J. Constr. Eng. Manage.* 126 (3): 210–218. https://doi.org/10.1061/(ASCE)0733-9364(2000)126:3(210).

Seo, J., S. Lee, J. Kim, and S. K. Kim. 2011. "Task planner design for an automated excavation system." *Autom. Constr.* 20 (7): 954–966. https://doi.org/10.1016/j.autcon.2011.03.013.

Shah, R. K., and N. Dawood. 2011. "An innovative approach for generation of a time location plan in road construction projects." *Constr. Manage. Econ.* 29 (5): 435–448. https://doi.org/10.1080/01446193.2011.563785.

Shah, R. K., N. Dawood, and S. Castro. 2008. "Automatic generation of progress profiles for earthwork operations using 4D visualisation model." *Electron. J. Inf. Technol. Constr.* 13: 491–506.

Shapira, A. 1993. "Octree subdivision of building elements." *J. Comput. Civ. Eng.* 7 (4): 439–457. https://doi.org/10.1061/(ASCE)0887-3801(1993)7:4(439).

Shirowzhan, S., S. M. E. Sepasgozar, H. Li, and J. Trinder. 2018. "Spatial compactness metrics and constrained Voxel automata development for analyzing 3D densification and applying to point clouds: A synthetic review." *Autom. Constr.* 96 (Dec): 236–249. https://doi.org/10.1016/j.autcon.2018.09.018.

Solihin, W. 2015. *A simplified BIM data representation using a relational database schema for an efficient rule checking system and its associated rule checking language*. Atlanta: Georgia Institute of Technology.

Stolte, N., and A. Kaufman. 2001. "Novel techniques for robust voxelization and visualization of implicit surfaces." *Graph. Models.* 63 (6): 387–412. https://doi.org/10.1006/gmod.2001.0559.

Sun, X., Q. Li, and B. Yang. 2018. "Compositional structure recognition of 3D building models through volumetric analysis." *IEEE Access* 6: 33953–33968. https://doi.org/10.1109/ACCESS.2018.2842721.

Tanoli, W. A., J. W. Seo, A. Sharafat, and S. S. Lee. 2018. "3D design modeling application in machine guidance system for earthwork operations." *KSCE J. Civ. Eng.* 22 (12): 4779–4790. https://doi.org/10.1007/s12205-018-0309-y.

Truong-Hong, L., D. F. Laefer, T. Hinks, and H. Carr. 2012. "Flying voxel method with Delaunay triangulation criterion for façade/feature detection for computation." *J. Comput. Civ. Eng.* 26 (6): 691–707. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000188.

Vaha, P. K., A. J. Koivo, and M. J. Skibniewski. 2017. "Excavator dynamics and effect of soil on digging." In *Proc., 8th Int. Symp. Automation Robotics Construction*, 297–306. Oulu, Finland: International Association for Automation and Robotics in Construction. https://doi.org/10.22260/isarc1991/0030.

Wang, Q., Z. Guo, K. Mintah, Q. Li, T. Mei, and P. Li. 2019. "Cell-based transport path obstruction detection approach for 4D BIM construction planning." *J. Constr. Eng. Manage.* 145 (3): 04018141. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001583.

Wang, Q., W. Zuo, Z. Guo, Q. Li, T. Mei, and S. Qiao. 2020. "BIM voxelization method supporting cell-based creation of a path-planning environment." *J. Constr. Eng. Manage.* 146 (7): 04020080. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001864.

Yuan, W., and M. Schneider. 2010. "Supporting 3D route planning in indoor space based on the LEGO representation." In *Proc., 2nd ACM SIGSPATIAL Int. Workshop Indoor Spatial Awareness ISA 2010*, 16–23. https://doi.org/10.1145/1865885.1865890.

Zhang, C., A. Hammad, T. M. Zayed, G. Wainer, and H. Pang. 2007. "Cell-based representation and analysis of spatial resources in construction simulation." *Autom. Constr.* 16 (4): 436–448. https://doi.org/10.1016/j.autcon.2006.07.009.

Zhang, Y., S. Garcia, W. Xu, T. Shao, and Y. Yang. 2018. "Efficient voxelization using projected optimal scanline." *Graph. Models* 100 (Nov): 61–70. https://doi.org/10.1016/j.gmod.2017.06.004.