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Research Article

Excavation Safety Modeling Approach Using BIM and VPL

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Soil excavation is a fundamental step of building and infrastructure development. Despite strong enforcement of construction best practices and regulations, accidents in construction industry are comparatively higher than other industries. Likewise, significant increase in injuries and fatalities are recently reported on geotechnical activities such as excavation pits and trenches. Academic researchers and industry professionals have currently devoted vital attention to acquire construction safety in preconstruction phase of the project. They have developed various algorithms to enhance safety in preconstruction phase such as automated generation of scaffolding and its potential risk analysis, checking BIM model for fall risks, and limited access zone allocation in wall masonry. However, safety in geotechnical works at preconstruction phase is yet unexplored. This paper proposed automatic safety rule compliance approach for excavation works leveraging algorithmic modeling tools and BIM technologies. The focused approach comprises of the following three modules: information extraction and logic design (IELD), information conversion and process integration (ICPI), and automodeling and safety plan generation (ASPG). Specifically, the scope of the paper is limited to major risks such as cave-ins, fall, safety egress, and prohibited zones risks. A set of rules-based algorithms was developed in commercially available software using visual programming language (VPL) that automatically generates geometric conditions in BIM and visualizes the potential risks and safety resources installation along with their quantity take-off and optimized locations. A case study has been presented to validate the proof of concept; automated modeling tool for excavation safety planning generated the required results successfully. It is anticipated that the proposed approach has potential to help the designers through automated modeling and assist decision makers in developing productive and practical safety plans compared to the conventional 2D plans for excavation works at the preconstruction phase. Moreover, it is realized that the same approach can be extended to other rule-dependent subjects in construction.

1. Introduction

Safety in construction is a major concern worldwide [1]. Recent studies reported a significant increase in excavation-related accidents [2] and could have been avoided with additional considerations. Soil excavation is an essential step of infrastructure development that includes removing of earth for the foundation installation, cut and fills to create usable lands, and landfill to construct embankments for flood mitigation [3]. In building construction, significance of the excavation works is eminent due to the ultimate base of entire construction. In general, construction projects such as building foundation, utility lines, tunneling, and underpasses require excavation in different makeup, e.g., open excavation, potholing, trenches, and shaft drives. According to safety and health agency in the United States, Occupational Safety and Health Administration, hereinafter referred to as OSHA, excavation typically refers to any man made cut, trench, cavity, or depression made by removal of earth [4]. Despite constant determination from safety professionals, researchers, and imposed safety regulations, injuries and fatalities in construction have not significantly dropped [5]. Unfortunately, geotechnical-related injuries and fatalities are incessantly growing [6]. Digging operations are one of the most challenging among other activities [7, 8], incorporating cave-ins, fall into the pit, working with machinery, deficiency of oxygen, flooding, and many more [6–10]. The unpleasant statistics from the United States (US) revealed the death of more than 30 workers per year in digging operation [11], cave-ins as a severe risk to the worker's life [12]. Likewise, in the private construction industry of US, statistics from 2003 to 2011 show the death of 287 workers caused by trench collapses [13]. These high numbers of accidents make serious contribution to time delays and cost overruns [14]. Earth excavation with a steep vertical or near vertical diggings needs to be protected by sloping, benching, shoring [4, 6, 12], and bracing system to avoid cave-ins or damage to the surroundings [8]. Evidence recorded by OSHA revealed more trench-related accidents in 2016 with the comparison of previous two years (2014 and 2015) combined [2]. Accordingly, OSHA considered pits and trenching hazards as a priority for 2018 [15], with the target of reducing accident rates by ten percent till SEP, 2019 [7]. The facts and indication presented to acknowledge the solemnity of the excavation safety and demand additional focus for proactive safety prevention methods.

In 1970, Occupational Safety Health Act laid the foundation for development of various strategies and safety standards in order to prevent accidents which show significant amelioration in construction safety management [16]. Construction safety performance has been significantly improved over the last four decades due to strong enforcement of these standards and strategies [17]. If these safety standards had not been provided and enforced, then the abovementioned statistics would have been higher than the current numbers [6]. The foundation of construction risks identification is safety standards and regulations [18]; enforcement of these regulations reported [17] in planning and monitoring could minimize the accidents in excavation-related tasks. Analysis of risks is crucial in planning phase to avoid misshapes in the execution and construction phase. Safety in construction was considered sole obligation of the constructor during execution phase of the project [19, 20]. Meanwhile, there is viable understanding about the mitigation of these risks that arise during construction, operation, maintenance, or repair works through proper consideration during design phase [1]. In the UK, establishment of Construction Design and Management (CDM) rules imposed health and safety considerations in the planning and design phase as an obligation [20]. Recently, different software tools are also developed rapidly for implementation of construction safety knowledge in the design phase, for example, "ToolBox" by Construction Industry Institute (CII) for identification of project-specific hazards along with improved design suggestions [21], web-based system by Dharmapalan et al. for quantification of safety risks based on design alternatives [22], and many more tools are proposed [23–25]. However, it is still interesting to note that construction safety planning is generally carried out separately from execution [18] which results in lack of communication and generates problems for safety manger in assessing (how, when, what, where, and why) safety measures needed for accident prevention [19]. It is further observed that traditional safety planning in construction has been infrequent, manual, time-consuming, labor-intensive, and prone to human error by using two-dimensional (2D) paper drawings and reports [5, 19, 21, 25] during the construction phase of the projects. On these grounds, advancement and automation are required for the improvement of the existing 2D drawing-based manual safety management processes as well as early prevention in the design phase by using technologies.

This paper proposed a unique approach for automated safety excavation modeling approach compliance with safety regulations and best practices, leveraging visual programming and BIM technologies for safety management process. To identify the benefits and limitations of the proposed approach, a system prototype is developed and verified through a case study. More specific objective of the study is to develop an automatic BIM-based safety planning tool specific to the excavation in construction that can identify potential hazards related to fall, cave-ins, and safety egress along with a visualized 3D model with built-in preventive solution for recognizing hazards. This research work does not consider the entire hazards related to geotechnical activities at this stage. Hence, the scope of the study is limited to the major types of potential risks, including but not limited to cave-in, fall, and safety egress risks.

2. Safety Planning Practices and BIM Applications

With regard to understanding the current safety planning status in focused area, a deep review of the previous research studies is summarized as safety planning practices related to pits and trenches in construction industry. Insufficiencies in contemporary safety planning were contemplated herein with BIM-based advanced design for safety concepts. Research works on rule-based safety planning and BIM are thoroughly reviewed, and necessity of the proposed safety rule-based automated excavation modeling approach is established.

2.1. Safety Planning Practices for Excavation in Construction. Despite extensive research and technological advancement in the construction industry, still it is considered as a hazardous industry that exposes workers to accidents. Safe environment is mandatory in all industries, while in construction, it is of particular importance compared to other industries because of four times higher fatality rate [26]. Accident statistics related to excavation revealed a relative increase in injuries and fatalities in the last years [2], which makes the excavation safety planning challenging. Execution of bad safety planning consumes the financial resources and time ineffectively and sometimes causes severe accidents [18]. In order to enhance safety at construction sites, companies have been establishing strategies and rectifying construction methods to ensure health and safety, such as toolbox talks, regular safety planning meetings, owner's involvement in safety planning, etc. [8]. Several rules and best practices have been developed since Occupational Safety Health Act 1970 [16, 17] that can be categorized under three general groups: (1) preexcavation—procedures required prior of any digging task; (2) excavation—safety during the activity execution; and (3) post-excavation—processes required after completion of excavation [6]. Safety planning based on these regulations in the design and planning phase is cumbersome owing to the dynamic nature of excavation activity. Construction companies depend on perpetual manual observations of the safety managers, which is requisite by OSHA; besides, a competent person with relevant safety skills [27] has to visit frequently and examine site condition. This requirement sometimes causes inconvenience due to economic and time constraint; consequently, safety managers are not present when obligatory and thus accidents occur [4]. Furthermore, safety knowledge such as safety regulations and experience integration with the design phase could reduce or even eliminate related risks by suggesting proper consideration or even changes in the design [28]. The analysis of 224 accident cases depicts that 42 percent of fatalities were linked to risks associated with design phase [29]. As manual detection of unsafe design is difficult due to scattered regulations and complex nature of construction projects [18], designers are mostly unaware of the activity conditions and associated physical constraint during construction; consequently, designers feel vexation in determining risks associated with their design components that may arise at construction phases of the project [1]. Correspondingly, communication gap and limited cooperation of the stakeholders regarding construction safety curtail the safety culture [30]. Even though trench collapse has a notable impact on safety and causes a major portion of accidents in the construction industry, it is still undiscovered. However, Literature revealed a lack of concentration towards workers safety aspect in the preconstruction phase of excavation works. Overcoming these limitations and challenges is extremely important in order to ensure a safe working environment with minimum accident possibilities in excavation-related activities.

2.2. Rule Compliance BIM-Based Safety Planning Approaches. Building information modeling (BIM) transformed the way of planning, designing, construction, operation, monitoring, and controlling for building and infrastructure [18, 31–39]. Several procedures have been recommended recently by extensive research employing BIM and other advanced technologies in order to figure out the problem of manual safety planning in the construction industry [1, 5, 23, 28, 36]. Zhang et al. [19] proposed an automated approach to safety planning by integrating fall prevention rules with BIM model. Feng and Lu [25] used algorithmic modeling tool (dynamo) to automate scaffolding planning and their risk analysis in construction sites. Existing construction best practices and rules can be used in convergence with three-dimensional (3D) model to engender an automated checking system for safety rule [38]. Automated workspace visualization method was established by Zhang et al. [40], which proactively improves safety during construction by using workspace modeling technologies and remote sensing. Wang et al. [6] also used safety rules and range point clouds as a modeling technology to control excavation-related hazards during construction phase. A tool called "See-BIM" has been developed by Belsky et al. [41] that tests topological relationship and embeds new knowledge details about the model through compiling a set of rules. Studies have considered risk factors in the design phase that could avert construction accidents and developed automated BIM and safety rule-based unsafe designs in construction [18]. In past few years, extensive research has been carried out focusing on rule-checking algorithms and BIM applications in order to enhance existing safety culture, its processes, and procedures [42, 43]. Studies have confirmed the use of programming to formalize the algorithms. Program developers have currently options to exploit various tools and techniques such as Open C, Java, Python, visual programming or visual algorithmic modeling, etc. To exercise the advantages of such tools, BIM users are trying to extend the use of BIM to the early design stages by connecting their product directly or indirectly [44].

2.3. Need for an Automated Rule Compliance Safety Modeling in Excavation. The literature review revealed that researchers have focused either on excavation's safety monitoring and inspections [6, 8, 27] or on trench-related hazard analysis and mitigation planning during the construction phase [6]. Nevertheless, few tools for incorporating safety rules in the preconstruction phase of the project are limitedly available, while safety planning for excavation works in preconstruction phase is yet unstudied and needs to be investigated. In addition, incredible improvements in excavation safety performance have been reported in recent years. Chi and Caldas recently developed image-based safety system for surface mining and earth moving activities [45], yet, automated hazard visualized excavation's safety planning in preconstruction phase is still lacking. To date, none of the existing studies currently provide evidence of safety rules integration through algorithmic modeling tool in a BIM model. Even though there has been few studies focusing on safety enhancement in preconstruction phase [18, 19, 25, 30, 36, 38, 46], none of them focuses on excavation-related safety management that can support automated modeling. Hence, significant attention is required to investigate better visualization techniques and safety process automation. Proactive elimination of hazards can be possible if safety regulations related to each activates are appropriately considered at preconstruction phase. Applications of advance techniques are inevitable to integrate concerned regulations to each hazard for the purpose to ensure safety in excavation works. Therefore, additional innovative algorithmic modeling approaches are needed to be explored for the integration of construction safety rules and best practices with the BIM 3D model in preconstruction phase. With these needs in mind, the next section will propose a unique approach for BIM-based excavation safety rule compliance modeling that can support automated 3D modeling with proactive visualization of potential hazards.

3. Research Design and Framework

In order to understand the nature of hazards related to excavation, the study was commenced with a detailed study of accident cases and previous literature. Thereafter, present status of safety management, related safety rules established by OSHA, and state-of-the-art of BIM technologies were reviewed. Initial investigation of excavation work hazards identified in accident cases motivated the development of a conceptual framework for automated safety excavation modeling. Subsequently, system prototype was developed and implemented on a real-world case study in order to test system's usability and effectiveness.

The proposed approach as depicted in Figure 1 reflects the conceptual framework that deals proactively with cave-in, fall, and safety egress risks. The conceptual framework for BIM-based excavation safety rule compliance modeling approach comprises three parts. First, the extraction of relevant rules from the pool of construction industry best practices and regulations along with the other process guidelines and information that includes field test and blueprints. Second part consists of visual programming and BIM. The former is used to convert the required safety rules information to graphical algorithms in a single scripting environment while latter one is used to integrate the process to a common place. Similarly, the third part is composed of automated modeling tool, which executes safety rule algorithms on the acquired information from two-dimensional (2D) data drawings in a BIM platform. Commercially available BIM tool (in our case Revit) is used for the ultimate model generation and visualized protection plan with its quantitative estimates and optimized locations as shown in Figure 1.

4. Proposed Prototype System Based on Framework

Based on the methodology and framework given above, a proposed automated excavation safety modeling system is developed as a tool for rule compliance automated safety planning. This system is named as Auto-Exca Safety Modeling System, which comprised of the following three modules, namely, (1) information extraction and logic design (IELD) module; (2) information conversion and process integration (ICPI) module; and (3) automodeling and safety plan generation (ASPG) module. The functions and systematic process of the prototype system in each module are detailed in the following sections.

4.1. Information Extraction and Logic Design (IELD) Module. As the name indicates, the function of this module is to extricate information from the raw data. The information extraction and logic design (IELD) module is initiated with the analysis of OSHA regulations. These rules provide best practices and lesson learned in the construction industry. The IELD module focuses on the extraction of relevant information from the pool of OSHA regulations. These ejected relevant rules are then manually converted to mathematical logics and then further into computer readable data in the next module. As illustrated in Figure 2, additional required guidelines is also considered in this module, such as soil type and actual excavation dimensions would be input from the soil report and excavation's blueprints, respectively.

4.1.1. Extracting Relevant Safety Rules. Causation of accidents provides vital information for safety planning; historical data related to trench excavation were reviewed and analyzed to find out the major risks and causes. Collapse cave-ins, safety egress, machinery and human fall into the trench, and humans hit by machinery were the major potential risks identified during the accident cases investigation. Apart from that, other risks like oxygen deficiency inside the trench, fire, and water leakage were also reported. Among them, collapse cave-ins pose the greatest potential risk to the workers in excavation. To limit the scope, this study only considers the top three potential risks (cave-ins, safety egress, and fall). The rest of the remaining associated risks to excavation works are out of scope at this stage of the research. Standard prevention methods applicable to associated risks minimization and mitigation were thoroughly studied in the context of regulations (OSHA).

The OSHA described the regulation in three parts beside the appendices (Table 1). First, scope and definitions (Subpart P-Excavation 1926.650) discusses the terminologies and its application with scope. Second, excavation specific requirements (Subpart P-Excavation 1926.651) illustrates hazard information and required measures specifically linked to the excavation. The third part is protective system requirements and criteria (Subpart P-Excavation 1926.652), which further explains the second part that determines prevention criteria and protective system to be used. Moreover, 1926 Subpart P-Excavations also include six appendices such as appendix A to appendix F. In 1926 Subpart P, appendix A focuses on soil classification while appendix B describes sloping and benching details. This study considered both appendices (A and B) for sloping method and soil classification. In addition to that, 1926 Subpart P appendix C, appendix D, appendix E, and appendix F show the detailed procedure along with scope for timber shoring, aluminum hydraulic shoring, alternative to timber shoring, and graphic summary of requirements in Subpart P, respectively. Applicable rules to the top three risks were extracted. Sloping, benching, and shoring are the methods advised by OSHA regulations and several best practices to protect workers from cave-ins in excavation trench. This paper considers merely sloping method (1926.652(b)) based on the soil classification available in the regulations (1926 Subpart P App A-Soil Classification).

Table 2 shows the detailed information specific to the intended risks from OSHA website. According to OSHA 1926.652 (a) (1), "each employee in an excavation shall be

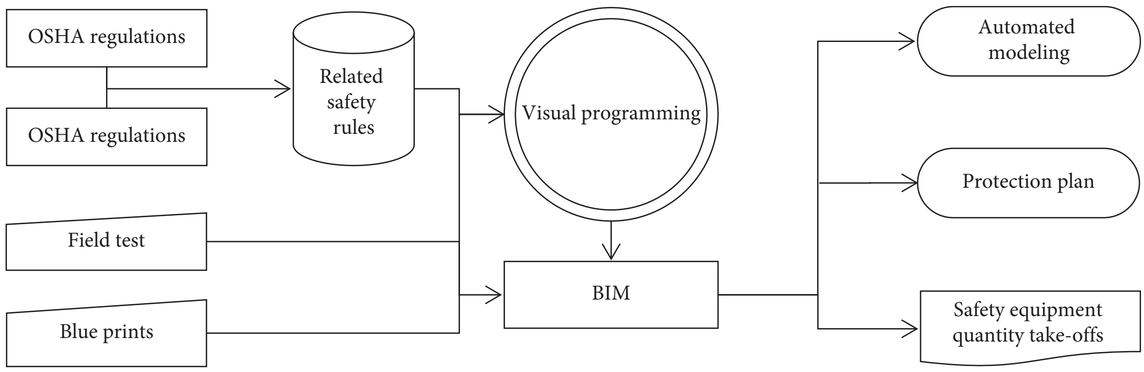


Figure 1: Conceptual framework for automated safety excavation modeling approach.

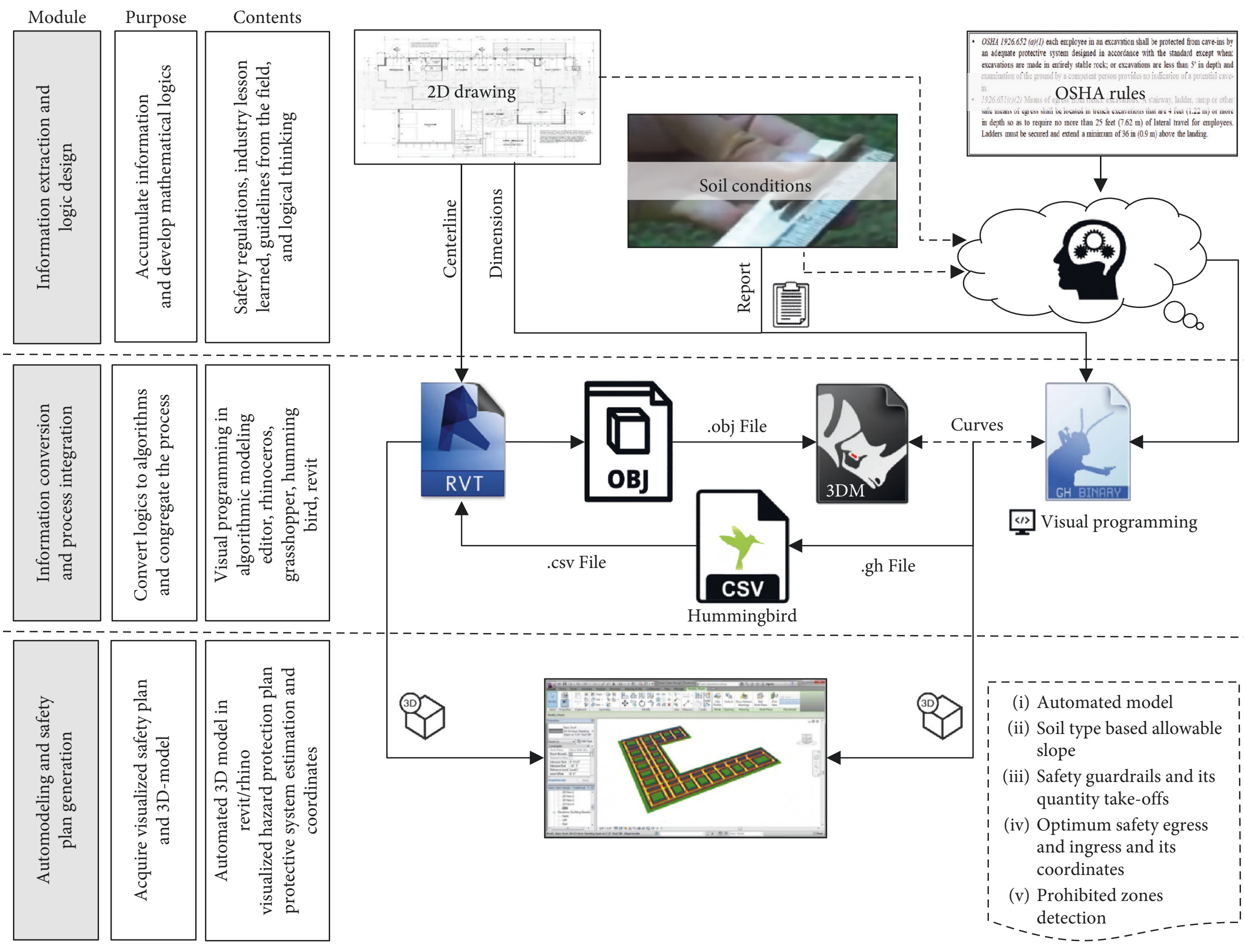


Figure 2: System architecture for auto-exca safety planning model approach.

protected from cave-ins by an adequate protective system designed in accordance with the standard except when excavations are made in entirely stable rock or excavations are less than 5′ in depth and examination of the ground by a competent person provides no indication of a potential cave-in." The standards state maximum allowable slope (horizontal to vertical ratio) for excavation pits considering the soil or rock properties (see Table 1).

Likewise, another rule 1926.651(j) (2) says workers will be protected from spoiled materials, excavated or other materials or equipments that could cause a hazard by rolling or falling into excavations. Protection shall be provided to the employees by placing that material and equipment at least 2 feet (0.61 m) away from the edge of excavation pits/trenches (Table 1), or by the using sufficient retaining devices that could prevent materials or equipment from falling or rolling into excavations, or combination of both conditions should be employed if necessary. Considering safe egress, the rule 1926.651(c) (2) clearly specifies the criteria for means of egress and ingress: stair, ramp, ladder, or other safe means of

Table 1: Excavation-related OSHA rules.

1926 Subpart P-Excavation		
No.	Standards	Explanation
1926.650	Scope, application, and definitions applicable to this subpart	Appraise terminologies and application guidelines
1926.651	Specific excavation requirements	Illustrates hazard information and required measures specifically linked to the excavation
1926.652	Requirements for protective systems	Further explains the second part that determines prevention criteria and system to be used
1926 Subpart P Appendix A	Soil classification	Focuses on soil and rock classification based on site, environmental conditions, and structural composition of the earth deposits
1926 Subpart P Appendix B	Sloping and benching	Describes sloping and benching if adopted as procedure to protect workers in excavations from cave-ins
1926 Subpart P Appendix C	Timber shoring for trenches	This appendix covers information if timber shoring is used as a method to protect employees from cave-ins
1926 Subpart P Appendix D	Aluminium hydraulic shoring for trenches	Appendix D contains information when aluminium hydraulic shoring is provided to protect workers against cave-ins
1926 Subpart P Appendix E	Alternatives to timber shoring	Alternative to timber shoring is illustrated in this appendix through figures
1926 Subpart P Appendix F	Selection of protective systems	This appendix explains the requirements for the protective equipment's used for less than 20 feet depth as summarized logical figures

Table 2: OSHA regulations related to excavation works.

Depth	Soil type	Slope ratio	Protection needed		
			Cave-ins	Safety egress	Fall
$D < 5$ ft	—	Vertical side 1 : 0	No	No	No
$5\text{ ft} < D < 20\text{ ft}$	Stable rock	Vertical side 1 : 0	No	Yes	Yes
	Type A	0.75 : 1	Yes	Yes	Yes
	Type B	1 : 1	Yes	Yes	Yes
	Type C	1.5 : 1	Yes	Yes	Yes
$D > 20$	—	Consult P.E	Yes	Yes	Yes

egress shall be provided in trench excavations that have depth equal to or more than 4 feet (1.22 m). Moreover, the location of that means of egress should be optimized in such a manner so that the employees require no more lateral distance than 25 feet (7.62 m). Ladders must be secured and extend a minimum of 36 in (0.9 m) above the landing. These rules provided knowledge for automation algorithms implemented in BIM. Specific steps taken for the automation are discussed in the next section.

4.2. Information Conversion and Process Integration (ICPI) Module. The information conversion and process integration (ICPI) module is the vital module of Auto-Exca Safety Modeling System. This module is devised to convert mathematical logics acquired through the IELD module into machine-readable format as revealed in Figure 2. To do this, visual programming techniques were employed. Commercially available tool, Grasshopper (a plug-in to Rhinoceros), which is a powerful tool for visual programming is selected for the development of visual scripts. This software is implemented in the study, mainly because it is relatively easy to use compared to other proprietary programming language software, is fast, and has diverse feature components required for this kind of programming. It is a platform that empowers designer to solve problems by visual programming and develop own tools. The humming bird was used for interoperability between the Grasshopper and other commercial BIM tool called Revit as delineated in Figure 2. It is used due to its broad functions and effectiveness for transferring more than one type of geometry. Functionality of Hummingbird plug-in covers a wide variety of different family types such as adaptive components, levels, walls, beams, lofts, and family instants and imports as CSV file to create geometry. A veritable tool file is developed from the algorithms created in a single scripting environment and then imported as CSV file to create geometry in a BIM (Revit) using Hummingbird available in both. The implementation of the prepared tool was executed in the next module.

4.3. Safety Rules-Based Visual Algorithms Development. This section focuses on the process details of the transformation of mathematical logics to algorithms through visual programming tool (Rhino Grasshopper). This commercial software provides visual scripting process in terms of predefine functionality components and wire connections for inputs and outputs data.

As noticed in swimlane diagram, Figure 3, there are four main portions that are cave-ins, prohibited zone, fall, and safety egress. First, in the cave-ins section, the system will convert logically designed rule for allowable slopes required for different types of soil. This is then ultimately liable to design proactive measure for cave-ins risk, in this case sloping base on soil types as shown in Figure 4. Second, with respect to prohibited zone, previous algorithm would be extended to figure out the danger zone near the edges. Third, with reference to the previous two algorithms, guardrail would be established for fall risk. Fourth, an additional algorithm for safety egress would be incorporated with the first section on the designated centerline.

4.3.1. Cave-In Hazard. As discussed earlier, cave-in is the major type of accident and usually happens in the excavation-related projects. Figure 5 deliberates the developed visual program to recognize the potential risks of cave-in and then suggests a preventive solution in 3D through slope ratio or angle based on the soil classification in OSHA standards. Figure 3 swimlane diagram shows the process flow of programming for cave-ins risk in the first column. To determine the bottom width, offset the centerline from inside and outside depending on the dimension input as shown in Figure 6 by using Voronoi logic tool imported to the Grasshopper canvas.

The offset curves inside and outside to the centerline at the specified distance and direction can be added by using Python Script Editor > import rhinoscriptsyntax as rs > a = rs.OffsetCurve(curve, dir, dis) in Grasshopper, where “rs” is the rhino-script and “a” refers to the output offset curves to the centerline at a given direction and distance.

In pursuit to understand the obligation of the excavation preventive procedures, the depth related OSHA rule 1926.652 (a) (1) (see Table 2) was translated through an algorithm. Afterwards, to detect the slope ratio or angle of the excavation, mathematical equation was generated and scripted as follows:

$$\mathrm{W.T} = (D * 2) * \mathrm{SR} + W, \quad (1)$$

where W.T is width at the top of the excavation, SR is a slope ratio of the soil type based on the classification, and D and W refer to the given depth and width for trench, respectively. The depth and width can be identified from the 2D blueprints, while the slope ratio can be extracted from the field test. Table 1 and Figure 4 describe four types of soil along with maximum allowable slope from regulations. Notice that angle (α) equal to 90° is allowed in excavation pit and safety prevention is not required in cases of stable rock. However, slope angle (α) equal to 53°, 45°, and 34° is required for rest of the remaining three types of soil, type A, type B, and type C, respectively. OSHA further clarifies that if the field test result of the soil type is absent, then soil type C will be used for further actions to ensure safe side [12]. The presented algorithm in Figure 5 will automatically visualize cave-in hazards determined by abovementioned soil type.

4.3.2. Fall Hazard. Falls from heights have received keen attention of health and safety management professionals and academic researchers. Currently, construction industry professionals are doing manual estimation and modeling of fall protections. This manual process needs a great deal of human inputs and cost and consumes time. However, some researchers used automated modeling for fall protection [19, 23, 38]. To automate and advance the safety management process with respect to fall risk in excavation works, an attempt was made to sort out the issue of automated modeling and estimation approach for fall preventions.

The programming process flow applied to detect edges where fall might happen and produce guardrails right there is depicted in Figure 3. The slope edges are defined in first column and are extended to the second column in the interest of prohibited zones; thereupon, guardrails are established in the process at third column of swimlane diagram. Previously stated fall hazard-related OSHA standards (see Table 2) are converted to graphical algorithms as illustrated in Figure 7. According to OSHA regulations, if the depth from the surface to the lower level exceeds than 6 feet, then fall protection system is needed. In addition, another vital rule for prohibited zone ascertaining to avoid overturning of the heavy construction machinery or human into the trench was also incorporated into the script (see Figure 7). That rule recommends that there will be prohibited zone for human, material, and machinery of at least 3 feet from the edge of the affected zone. Hence, the algorithm was set to allocate the fall prevention at the distance of 3 feet and visualize the prohibited zone along with the quantity of guardrails in running length.

4.3.3. Safety Egress. Numerous ways are currently used in the real construction excavation sites to ensure safe access. Apparent methods are providing slip-resistant ramps, use of stairs/ladders, and stepping back an excavation. OSHA standards endorse the provision of means of egress and ingress to the trench excavation if the depth is equal to or greater than 4 feet. The furthest lateral distance of the egress point from any worker inside the trench excavation should not be greater than 25 feet. Figure 8 demonstrates the algorithm for location optimization for means of egress and ingress.

The centerline of the excavation obtained from 2D blueprints (Figure 9(a)) was taken as a reference for optimized spot location as depicted in swamlane diagram in Figure 3. To calculate the most favorable points, a grid of 5 feet by 5 feet was positioned through a visual programming script as shown in Figure 9(b). Unique points of 25 intervals were picked through using the cull pattern for every five points (green points in Figure 9(c)). Next, the circles of 25 feet diameter were embedded on those unique points in order to trace the overlapping regions. The midpoints in overlapping regions of the two circles were then considered as an optimum location for means of

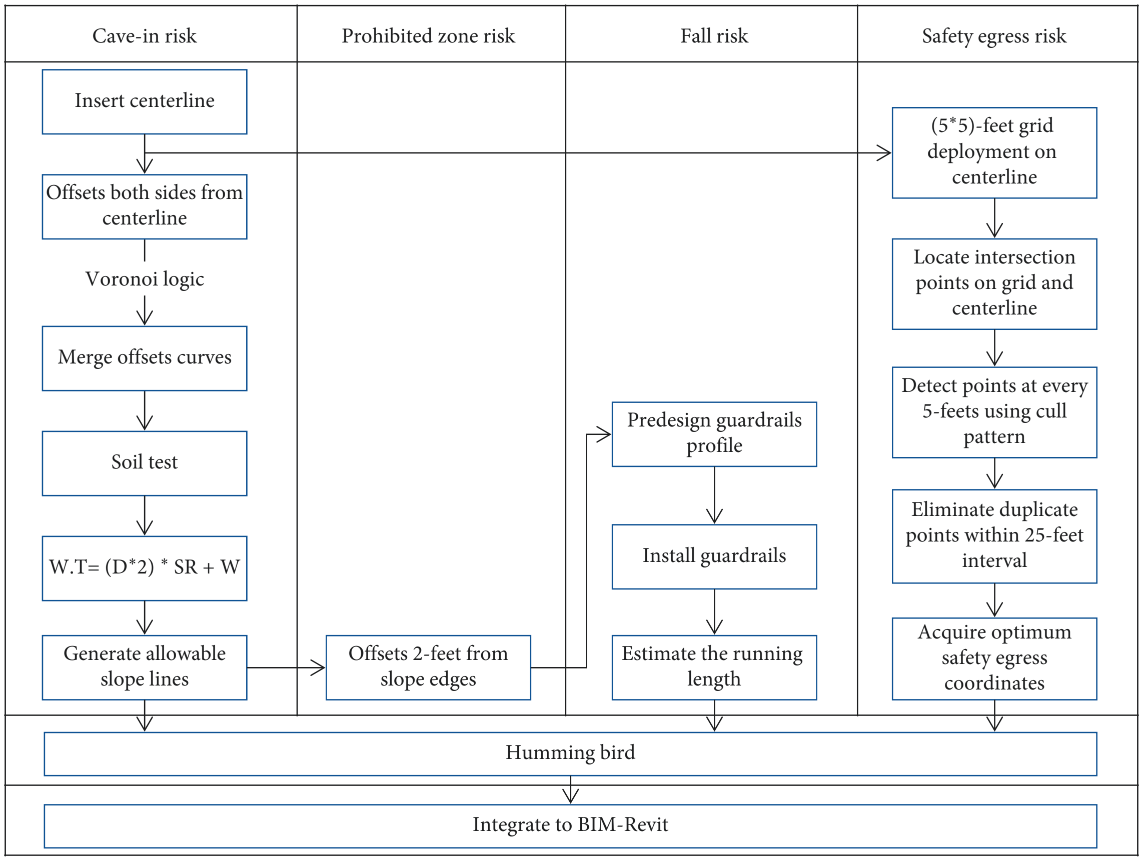


Figure 3: Visual algorithm development swimlane diagram.

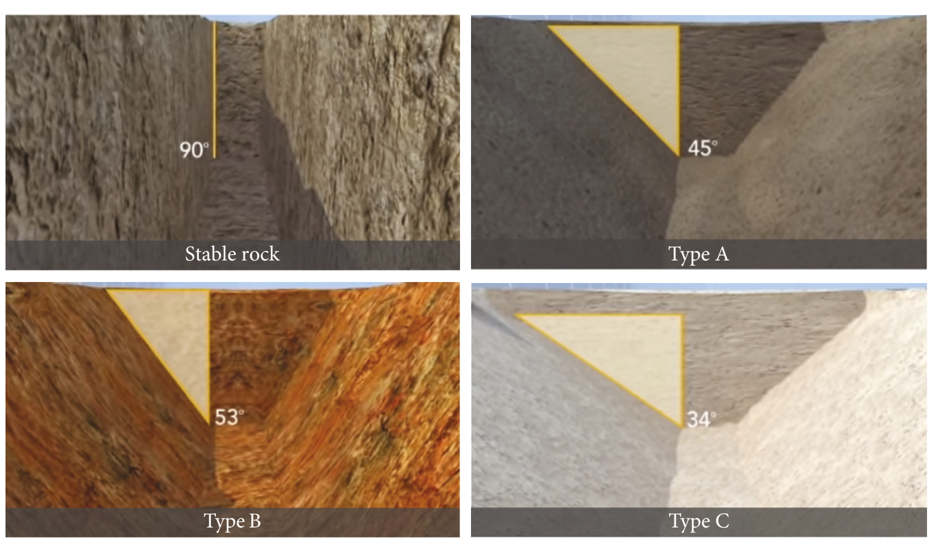


Figure 4: OSHA prevention videos (v-tools) for excavation.

safety egress and ingress. Finally, the system will provide a chart after simulation that shows the exit number of required safe access locations along with the position coordinates. The entire three portions of algorithm scripts were then connected to each other to make a complete, comprehensive visual program for Auto-Exca Safety Modeling System.

4.4. Automodeling and Safety Plan Generation (ASPG) Module. Lastly, the function of this module is to produce results after information extraction and logic design (IELD) and information conversion and process integration (ICPI) modules. The automodeling and safety plan generation (ASPG) module is designed to give users the visualized outcomes, produce an automated safety plan, and determine

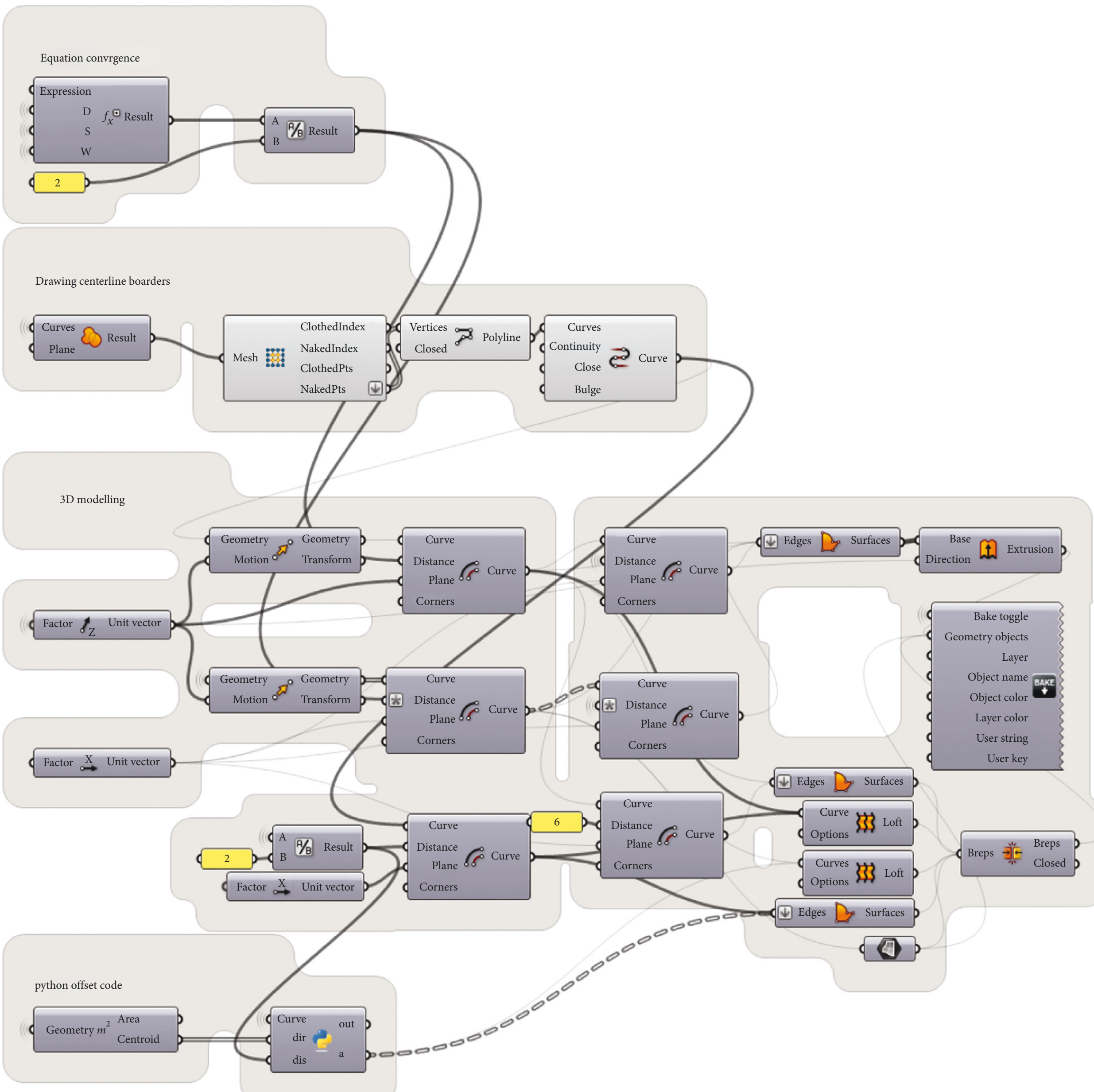


Figure 5: Cave-in hazard identification and preventive measure algorithm.

hazard response strategies. The principal emphasis of this module is to execute the developed tool on any centerlines of a given excavation 2D plan, which could be obtained from the excavation blueprints. The users select the soil types and feed the actual required width and depth, and then the simulation is conducted. The potential of this module is the rule compliance 3D model automatic safety plan for possible hazards. Detailed functions and results of the ASPG module are categorically illustrated in the discussion section.

5. Case Study

This section demonstrates a case study conducted to validate the prototype system by using a real-world excavation project. The aim was to apply Auto-Exca Safety Modeling System tool developed for automated safety planning and modeling with regard to excavation pits on a practical building project. This project uses excavation trenches for making the foundation of the typical school building (Figure 10).

The 2D drawing made in Revit for foundation excavation was used for experiment (Figure 10). The centerline length, width, and depth of the foundation were obtained from the 2D drawings as shown in Figure 11.

The soil test from the field was assumed as type C soil. The acquired centerlines of foundation were then imported into Rhinoceros as object file (obj). With noticing that the location/scale of the file imported as .obj file should remain as default in Rhinoceros because the coordinates (x, y, z) of each vertex (points) are matching between Rhinoceros and

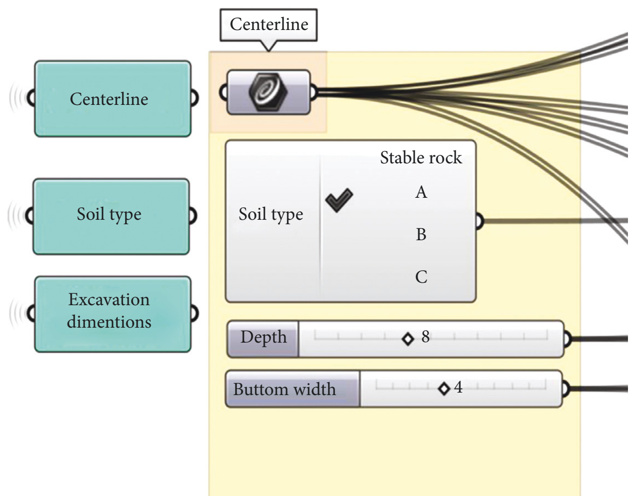


FIGURE 6: Soil classification and dimension constraint algorithm.

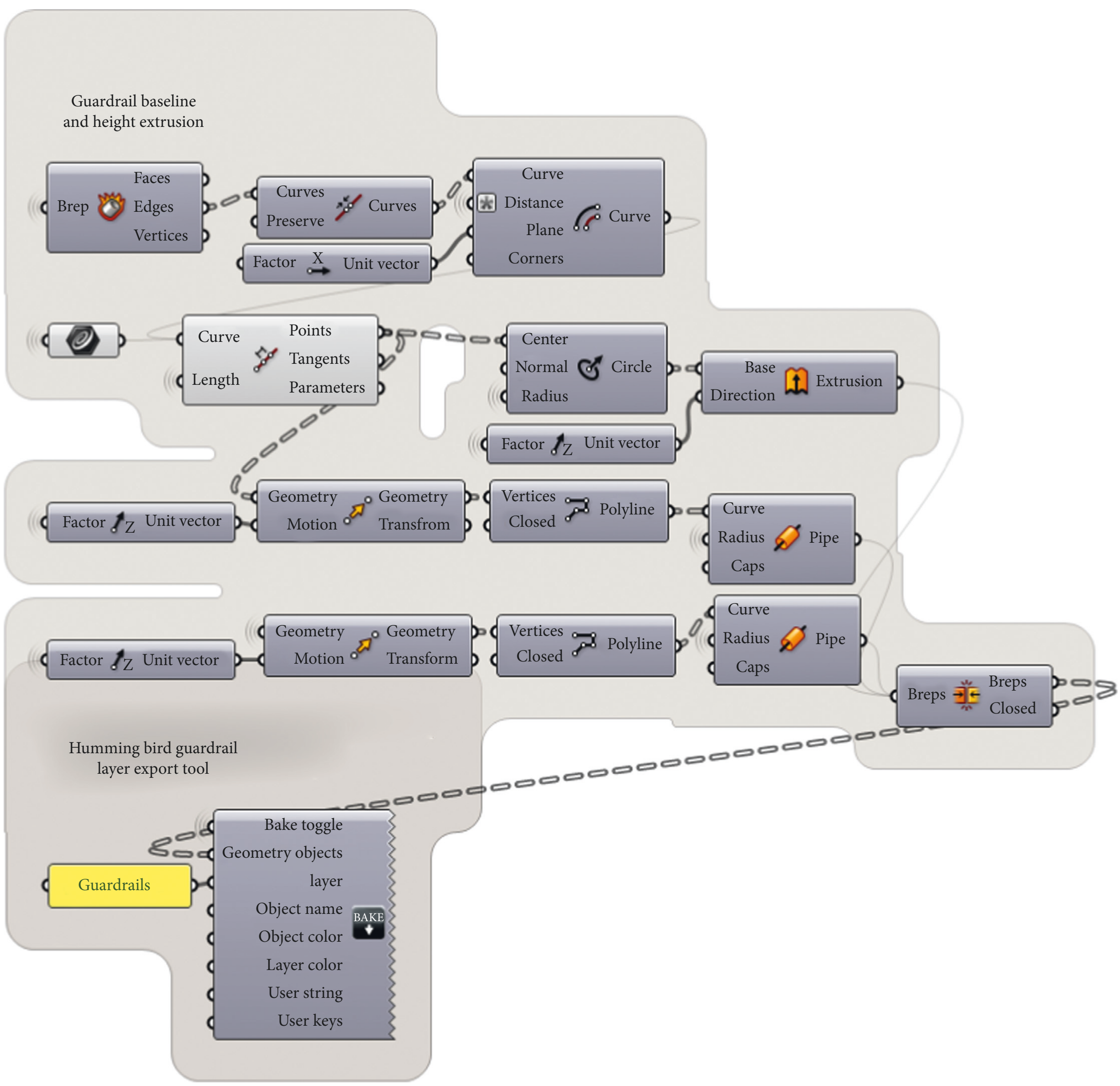


FIGURE 7: Algorithm for detecting fall hazards and required preventive solution estimation.

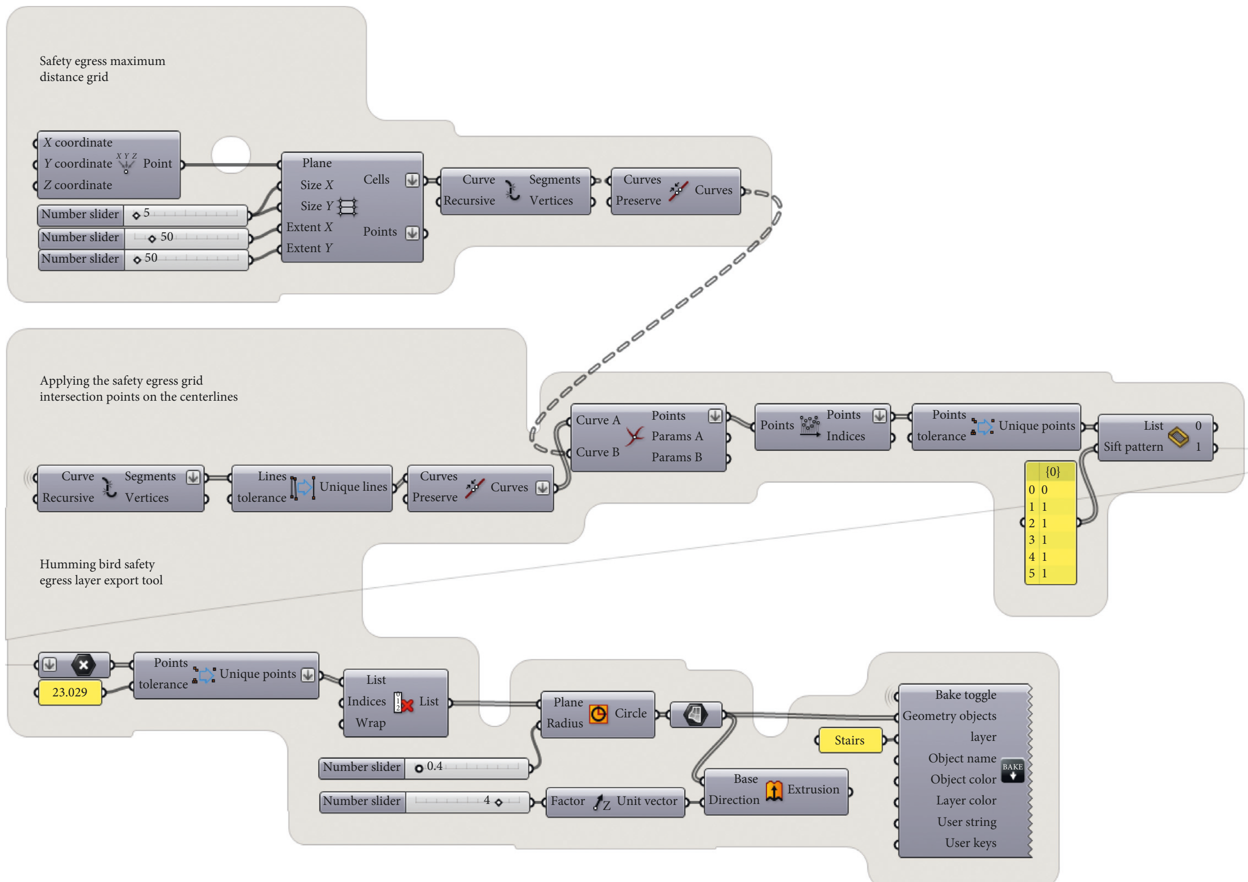
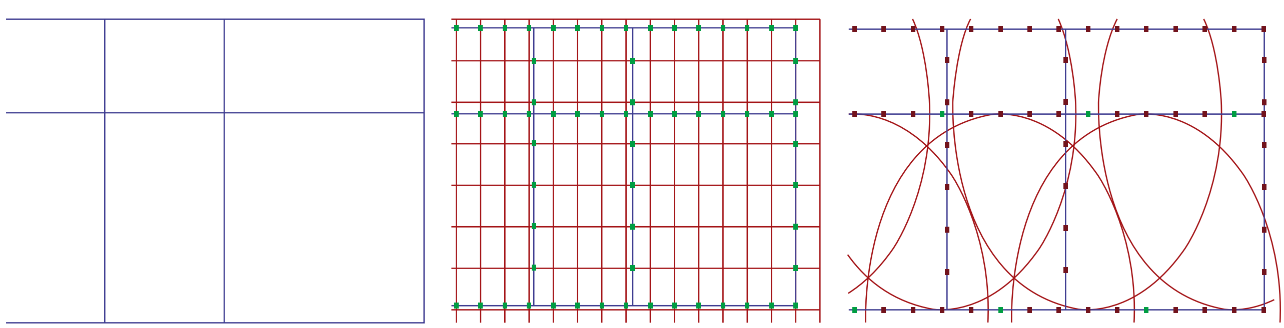


Figure 8: Algorithm for detecting optimized safety egress locations.



(a) (b) (c)

Figure 9: Safety egress algorithm process logics: (a) centerline from the 2D blueprints; (b) grid of 5 feet by 5 feet; (c) cull pattern for every five points and circle of 25 feet diameter.

Revit. If the coordinates (x, y, z) change, then as a result, the location/scale of the simulated foundation excavation model will not match with original 2D foundation layers. Formerly prepared graphical computational algorithms in grasshopper canvas were then simulated on the loaded data from the Revit into the Grasshopper. It was observed that the system produced the results successfully as expected for cave-ins, prohibited zone, fall and, safety egress risks. The brief result of the case study can be depicted in Figure 12. A 3D model was generated automatically with the appropriate allowable slope angle of 34° recommended by OSHA standards for type C soil. The generated allowable slope for the foundation trench can be seen through a cross section in Figure 12. In addition, the system automatically established guardrail system at the distance of 3 feet from the trench edges along with the estimated running length report (see Figure 13). The 3 feet distance between the guardrail system and the excavation trench edges are identified as a prohibited zone for machinery, spoil materials, and humans. Identification of this zone at this stage can decrease the occurrences of accidents due to the overturning of heavy construction machinery falling into the trench. In a similar manner, the

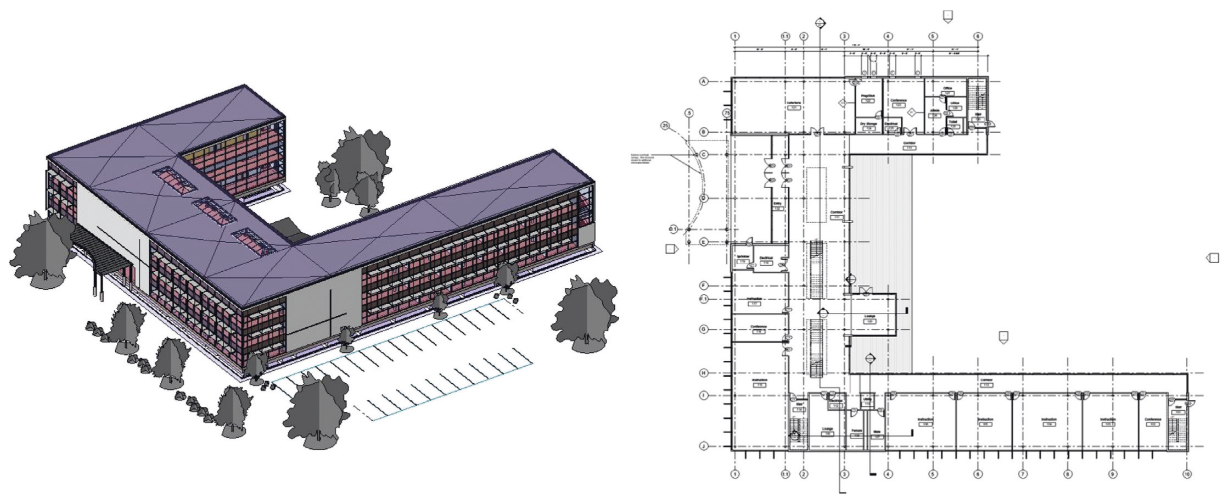


Figure 10: Isometric view and foundation plan of school building.

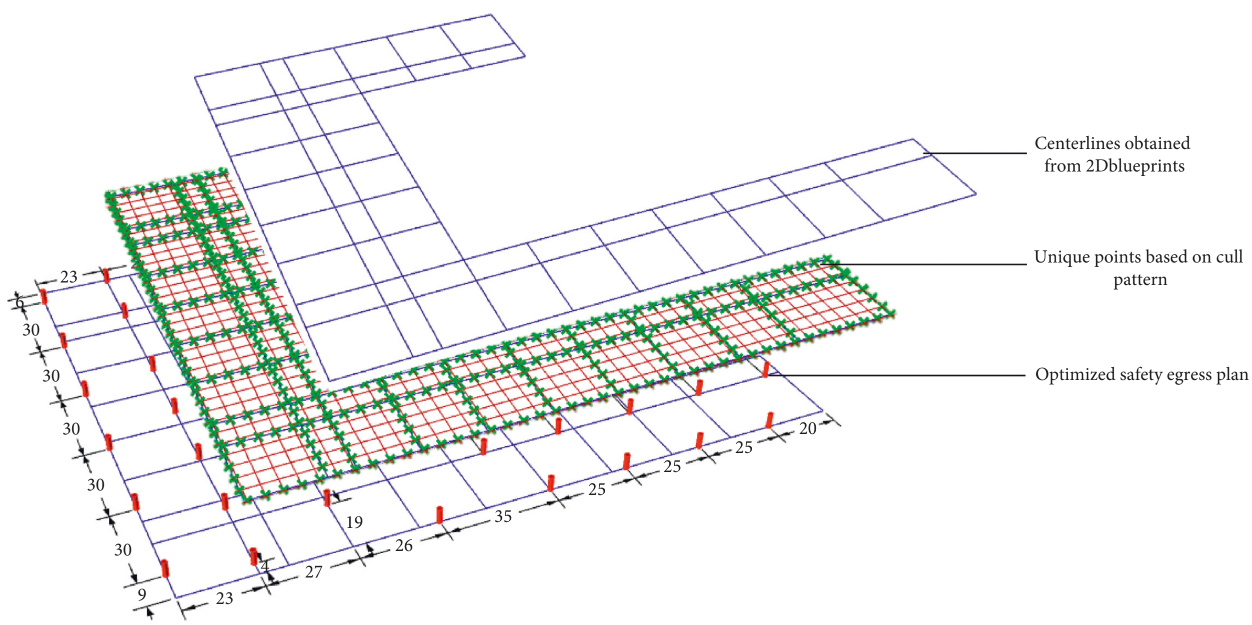


Figure 11: Automated excavation safety planning simulation.

automatically created 3D model correspondingly visualized an optimum safety egress plan for employees working inside the trench.

6. Discussion

The case study test of building foundation excavation revealed that the proposed system leveraging BIM technology could support more advanced and comprehensive excavation pits and trench safety planning. The tool has automatically and successfully designed the excavation slope according with the OSHA guidelines in order to prevent the cave-ins risk. The system produces more practical results when it comes to the contiguous trench; if the nearest alongside trench is close enough so that the slope lines intersect each other, in that case, the system generates more practical 3D model by visualizing both the trench as one pit. Notice that when this case happens in real construction site, the decision makers recommend excavating both the adjacent trench completely to avoid a potential collapse. The developed tool further detects vulnerable edges that could lead to fall risk and installed guardrails around the perimeter of the trench or pit. In addition to detection of edges and installation of guardrails, quantity take-off report list can be easily obtained by using its built-in function. OSHA made videos for education and training for concerned stakeholders in order to make the excavation works possible without accidents. The screenshots of the video made by OSHA for allowable slopes based on soil types can be seen in Figure 4. The framework for experiential safety education utilizing mobile-based virtual reality and augmented reality [47] can be extended to a comprehensive excavation safety training and education by integrating 3D model of the proposed system.

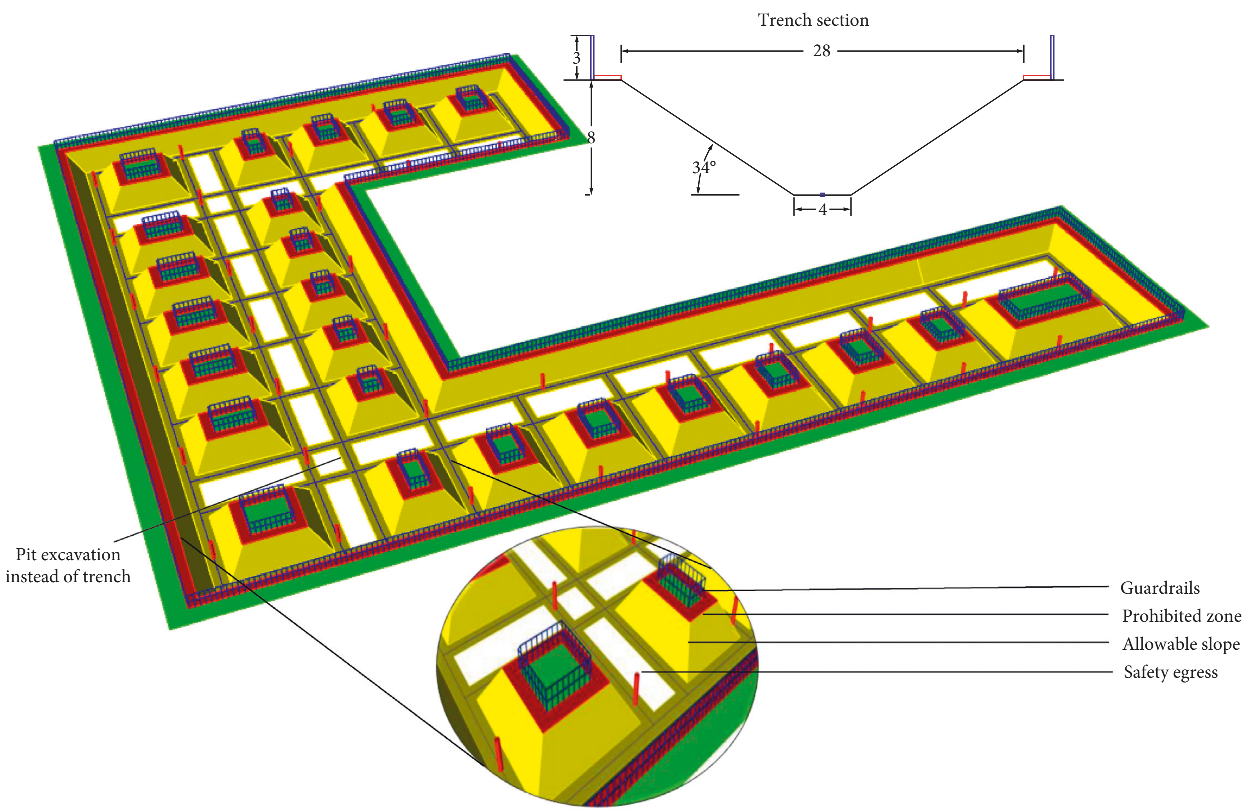


Figure 12: Automated safety planning model.

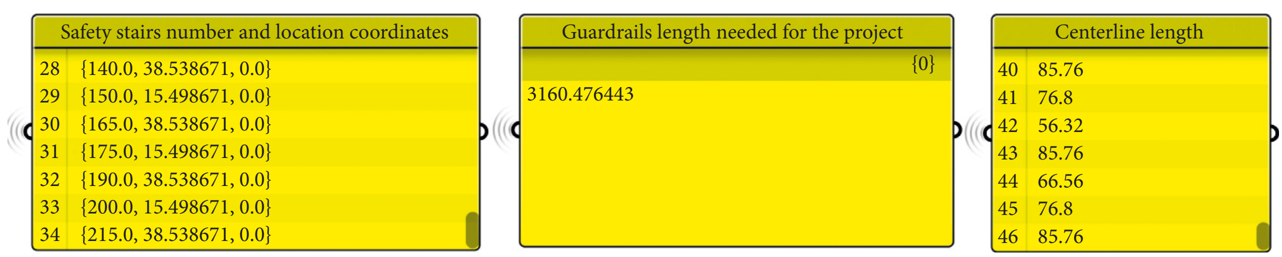


Figure 13: Quantity take-offs statistics chart.

The construction excavation is a dynamic activity that relies on different external factors such as weather (rain and hot temperature) and internal factors, for example, suffocation, toxic gases, water leakage, and underground services. Hence, representation of all unsafe conditions related to excavation pits and trenches in BIM at this level is not possible. Nonetheless, human hit by heavy machinery risk in construction excavation could be dealt with using 4D-BIM and sequencing the work path for both human and machinery considering their work schedule. Various limitations of the excavation's safety planning tool were observed through a building foundation case study. Several limitations of the system found were (1) that it might not be possible to generate required rule compliance 3D model for distinct layer of soil, since the layer of soil can vary based on the depth and width and (2) that as a construction site needs walkways crossing and pedestrian overpasses on trenches, this system does not specify crossings at current extent of study; however, users can modify the 3D model manually to overcome this limitation.

7. Conclusion

Despite the vital development of building information modeling (BIM) technologies for construction safety planning, current excavation safety planning practice is still manual and relies on conventional methods. To address the issue, an automated excavation safety planning tool was developed and tested. Based on the findings, the vital benefits are summarized as follows:

(a) The study depicted that the developed tool has ample potentials to enhance excavation-related safety planning, which is inevitable to cope with the recently reported significant increase in injuries and fatalities. It is found that the system automatically identifies and visualizes cave-ins, fall risks, and prohibited zone risks and optimizes the planning for ingress and egress based on OSHA rules.

(b) Automatic 3D model generation and more practical safety planning is another major contribution of this study. It is expected that the proposed approach would help the designers through automated modeling and assist decision makers in developing practical safety plans compared to the conventional 2D plans for excavation works at preconstruction phase. This unique approach of automatic modeling can be extended to other rule-dependent subjects and infrastructure work like bridges, pipelines, and additional works as parametric designs.

(c) Safety resources installation along with their quantity take-off and optimized locations were also witnessed in the case study. Hence, the system can predict the location coordinates and required preventive resources in advance.

To sum up, the potential of the VPL and BIM for the excavation safety planning and modeling at the preconstruction stage has been ascertained and confirmed with a real case study. In the future, this tool can be developed as a tab plug-in to commercial software applications that will enhance the entire safety planning process. Another future consideration is to simplify this tool to an app that can assist and guide field workers to execute safety plans in a more accurate and efficient way. Also, integrating the presented work with augmented reality could provide new direction for execution of planned excavation work in the real site. Moreover, this can be used to guide and educate the workers during the excavation execution phase.

Data Availability

The data generated or analyzed during the study are available from the corresponding author upon request.

Disclosure

The authors are solely responsible for the content.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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