Application of BIM Technology to Soil Layer Risk Analysis for Enhanced Accuracy and Informed Decision-Making in Geotechnical Engineering

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Abstract –

While BIM technology is widely used for designing and managing above-ground construction, its applicability in representing underground soil distribution and properties is limited, which can increase risks during planning and construction. This study integrates Dynamo with on-site drilling data to automatically generate underground soil models, which incorporates key attributes such as moisture content, liquid limit, and N-value. This approach provides engineers with a clear and intuitive representation of soil conditions. The core value of the soil model lies in enhancing safety assessment capabilities, enabling engineers and designers to identify potential foundation construction risks, such as diaphragm wall mud inclusion, in advance. This facilitates optimized designs and reduces hazards during construction. Additionally, the model supports the estimation of excavation volumes for reuse, such as utilizing sandy soil for concrete and asphalt concrete production and clay soil for backfilling, ensuring efficient resource allocation. By integrating BIM technology with geological information, this study not only improves the visualization of soil layers but also enhances the safety analysis of foundation engineering and the efficiency of earthwork applications.

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Keywords –

BIM Model; Risk Analysis; Geotechnical Engineering; Borehole; Dynamo; Automation;

1 Introduction

The construction industry is mainly divided into two key fields: Structural Engineering (SE) and Geotechnical Engineering (GE). In recent years, BIM methods have been extensively developed and applied in the SE field [1]. However, their adoption in geotechnical engineering has been limited, largely because of inherent uncertainties associated with soil and geotechnical parameters, making the modeling process more challenging.

To reduce risks in underground foundation projects, a geological survey is typically the first step [2]. However, when dealing with complex geological conditions, traditional 2D workflows are often insufficient to fully capture geological details [3]. BIM offers a significant advantage, providing a clear visual representation of the entire strata. By doing so, it helps reduce risks, optimize foundation construction, and significantly improve both efficiency and safety [4].

Applying BIM technology to visualize soil layers using integrated data and 3D visualization can considerably improve the clarity of subsurface understanding and enable more precise engineering planning. During the design phase, a visualized soil model can effectively illustrate stratigraphy, groundwater distribution, and variations in soil properties, providing designers with a more reliable and scientific reference. This approach helps prevent design errors or construction challenges arising from insufficient information [5]. BIM technology is intended for use throughout a structure's entire lifecycle, from design and construction to operation and maintenance. Among these stages, understanding soil conditions is crucial, considering that every structure depends on the stability of its foundation [6]. Traditional geotechnical software primarily focuses on soil modeling and analysis but often operates in isolation from broader engineering workflows. In contrast, this study leverages Dynamo to automate soil layer modeling, ensuring that geotechnical data is not only visualized within a BIM environment but also actively utilized for risk assessment. By integrating geotechnical information directly into BIM workflows, engineers can systematically identify potential hazards such as soil instability, excavation risks, and foundation settlement before construction begins. Using an automated bounding box approach, the system detects critical soil layers with unfavorable properties, enabling a structured and data-driven risk evaluation process. This approach goes beyond merely using BIM for modeling; it establishes BIM as a decision-support tool, enhancing risk assessment accuracy, optimizing construction planning, and improving safety management through automation.

Moreover, specialized geotechnical software such as Plaxis, FLAC, and GeoStudio provide advanced 3D soil modeling capabilities with integrated physical parameters. However, these tools often function as standalone applications, primarily focused on geotechnical analysis. This study utilizes Dynamo and Revit for geotechnical modeling due to their seamless integration with architectural and structural design workflows. By generating soil models directly within the Revit environment, this approach minimizes the need for software transitions, streamlining the modeling process throughout the engineering lifecycle.

Based on these considerations, this study developed a Dynamo-based soil model generation program. The resulting BIM model emphasizes soil layer definitions and properties by integrating the digital terrain model and borehole data. This approach integrates scattered geological data into 3D models that incorporate both geometry and soil parameters. These models provide designers and construction teams with a clear and intuitive visualization of the underground structure and its characteristics.

2 Methodology

Accurate geotechnical risk assessment is challenging due to the complexity and variability of subsurface conditions. Traditional methods rely on borehole data, but inconsistencies in data quality and fragmented soil layers often lead to uncertain risk evaluations. Without a structured approach, these uncertainties can result in inaccurate estimations of soil stability, increasing the risk of ground movements, excavation failures, or foundation settlement. The key issue is not merely generating a 3D soil model but ensuring that it systematically identifies and assesses geotechnical risks before construction. However, due to the variability of soil layers, the flexibility of automated modeling is limited [8], making it challenging to standardize risk assessment and reliably detect hazardous zones, particularly in projects with heterogeneous or discontinuous soil formations.

To address these challenges, this study develops a systematic risk identification framework that integrates borehole data into a BIM-based workflow. By analyzing key parameters such as the liquid limit, N-value, and moisture content, the framework enhances risk assessment by identifying potential instability zones.

The system framework (Figure 1) illustrates the integration of geotechnical data with BIM-based risk assessment. The process begins with field drilling data to obtain borehole depth and soil layer information, while InfraWorks and Civil 3D are used to acquire surface elevation data, generating a digital elevation model (DEM) for an accurate representation of terrain conditions. These data are then imported into Dynamo to automatically generate soil surfaces. However, due to the variability in soil layer structures, the modeling process may fail, resulting in errors or incomplete models. To address this issue, the system utilizes error data from Dynamo for corrections. Excel is used as a data processing tool to filter and adjust abnormal points, ensuring that elevation values align with surrounding soil layers and maintaining model stability and accuracy. The corrected data are then re-imported into Dynamo to generate the final 3D soil model.

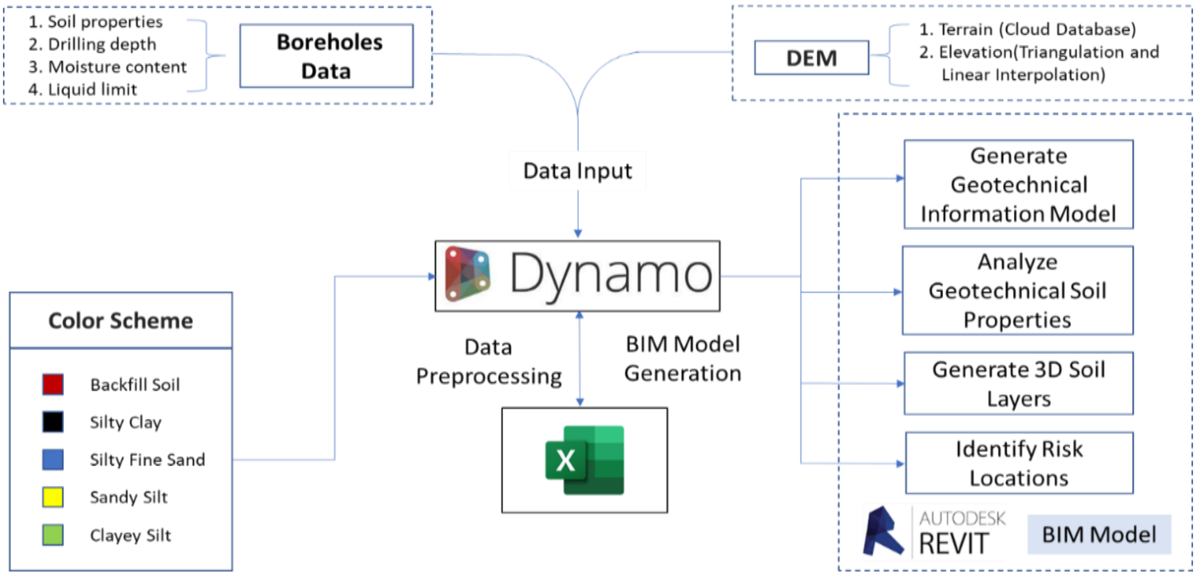

Figure 1. System framework

Once the model is established, a risk identification algorithm embedded in Dynamo is used for automated risk detection. Using the bounding box method, the identifies high-risk zones based on predefined criteria, such as the liquid limit, N-value, and moisture content, and automatically generates bounding boxes around them. These risk zones are then visualized in Revit, providing engineers with an intuitive, data-driven geotechnical risk assessment.

3 Soil BIM Model Generation

3.1 Digital Elevation Model

Before establishing a 3D soil model, accurate surface elevation data must be collected. This data represents ground variations and serves as the foundation for modeling subsurface conditions. It is also essential for calculating earthworks, such as excavation or filling. In this study, tools such as InfraWorks and Civil 3D are used to generate elevation models, automatically generating surfaces from survey data for further analysis.

First, the geographic data in InfraWorks primarily originates from various data platforms and formats, such as Bing Maps and GIS files. This data is used to generate accurate surface models and present detailed surrounding terrain features. InfraWorks can efficiently integrate these data types and automatically generate 3D terrain models. The data obtained in this study using InfraWorks includes elevation points (X, Y, Z coordinates), contour lines, and a triangulated irregular network (TIN) surface.

Second, after obtaining the terrain surface from the InfraWorks model generator, the terrain data is imported into Civil 3D in IMX format. In Civil 3D, the terrain surface is represented as a TIN, which consists of a series of triangles defined by elevation points, where the X and Y coordinates correspond to the planar position and the Z coordinate represents the elevation value of each point. This structure accurately describes the undulations and details of the terrain surface.

In this study, a point set is created using a 20 × 20 grid, generating 20 rows and 20 columns of points with equal spacing across the terrain surface. Civil 3D calculates the Z value (elevation) for each point based on the imported TIN model. The software automatically detects each point’s location on the terrain and applies an interpolation algorithm using the Z values of the three points in the surrounding triangle. This assigns an accurate elevation value to each point, ensuring that the terrain's details are accurately represented.

Once the point set is generated, the points are exported as a DEM file in ASCII format, serving as the data foundation for generating points in Dynamo. This process ensures terrain data accuracy and provides the flexibility to adjust grid density based on specific engineering design and data analysis requirements. The result is shown in Figure 2. This terrain model serves as an essential foundation for the automated soil modeling process.

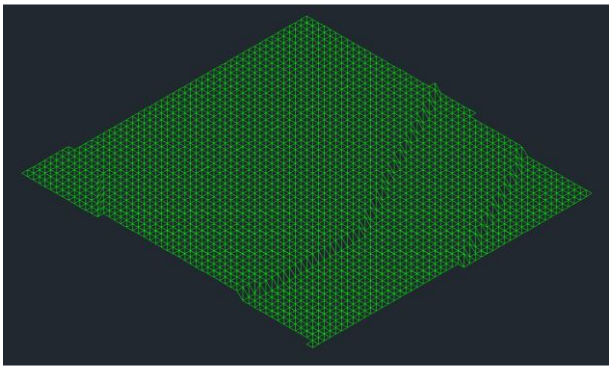

Figure 2. DEM in Civil 3D

3.2 Borehole and Soil Layer Model

After importing the terrain survey data into Dynamo, the data is cleaned by removing invalid characters, extra spaces, and other errors. The goal is to ensure accuracy and consistency, preventing issues in later modeling and analysis stages. Once cleaned, the data is converted into a standardized format, preparing it for subsequent steps.

3.2.1 3D Borehole Generation

The 2D profiles from borehole reports provide detailed soil classification information, including soil types, physical properties, and depth ranges for each soil layer. This data is essential for visualizing the underground soil structure and plays a crucial role in risk assessment and construction planning. In Dynamo, this soil classification data is used to generate depth points, with each point representing the location of a specific soil layer, as indicated in the borehole report.

By identifying these depth points, Dynamo is used to generate a 3D borehole model that illustrates the distribution of different soil layers. This enables clear visualization of the soil structure beneath the excavation area using a color scheme, as shown in Figure 3.

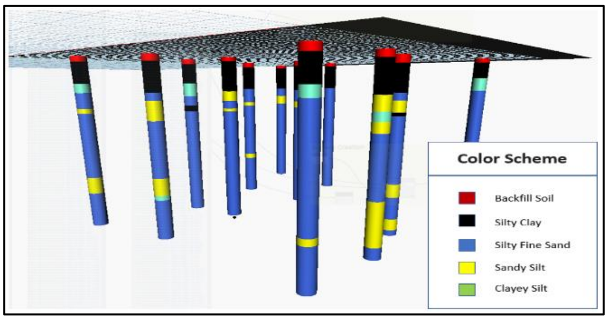

Figure 3. 3D borehole model

3.2.2 Soil Layer Creation

Using color-coded soil classifications and depth information, the distribution of different soil layers can be easily visualized. In Dynamo, soil layers are generated based on depth points from borehole data. These points are connected to form surfaces that represent the structure of the soil layers. The color coding clearly defines the boundaries between different layers, ensuring the model is accurately constructed. The results are shown in Figure 4.

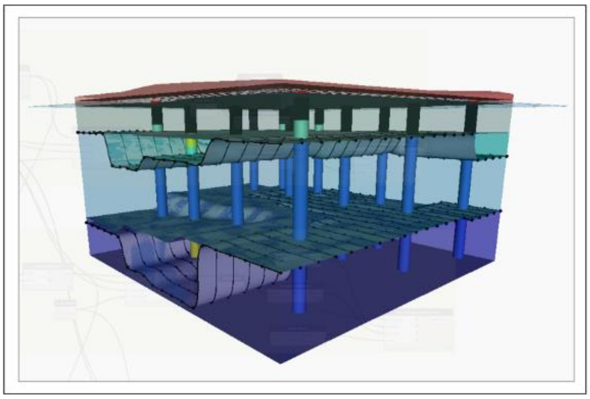

Figure 4. Soil layer model in Dynamo

However, uneven geological data and fragmented soils pose challenges to automated modeling. In some areas, depth points from borehole data may not align properly, resulting in gaps, distorted layers, or unrealistic features in the model. These inconsistencies can cause modeling failures in Dynamo, preventing the successful generation of soil surfaces. To address this issue, error messages from Dynamo are first analyzed to identify problematic data points. When irregular surface formations are detected, the corresponding surface points are extracted and processed in Excel for correction. Using Excel as a preprocessing tool, elevation anomalies are filtered and adjusted by referencing nearby depth values, ensuring smooth transitions between layers. The corrected points are then re-imported into Dynamo, where they form a continuous and stable soil surface. This iterative correction process ensures that fragmented soil layers are more accurately represented and prevents interruptions in the modeling workflow. Once these corrections are made, the final soil layers more accurately reflect the true subsurface, making them useful for further engineering analysis and applications.

3.3 Soil Properties Assignment

In foundation construction, soil properties are critical for ensuring engineering stability and construction efficiency. Parameters such as moisture content, liquid limit, and standard penetration test (N-values) serve as essential indicators for evaluating soil characteristics and potential construction risks. These parameters help identify potential excavation challenges and provide reliable decision-making support before construction begins. Accurately assigning these parameters to the 3D soil layer model significantly enhances the realism and practical value of the model.

Using Dynamo, soil parameters from borehole data are seamlessly integrated into the 3D model through an automated process that matches layer depths and local features, as shown in Figure 5. By assigning soil attributes and incorporating construction data, the model enhances pre-construction decision-making efficiency, reduces risks during construction, and improves project safety and execution. In addition to providing a clear visual representation of the soil structure, the model enables precise volume calculations for land leveling, facilitating the estimation of earthwork quantities.

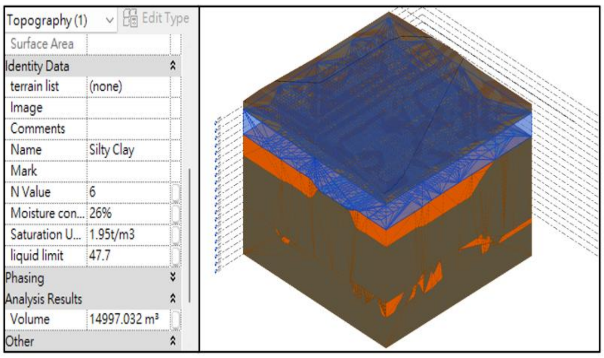

Figure 5. Soil properties assignment

4 Soil Layer Risk Analysis

Integrating geotechnical engineering with BIM technology improves risk assessment and construction management, particularly in addressing soil-related issues that may affect the stability of building foundations. If these problems are not identified and addressed early, they can significantly impact construction safety. Therefore, it is crucial to assess and evaluate these risks at an early stage to ensure a safe construction process.

This study applies BIM technology to soil risk assessment by using 3D models to visualize the underground environment. This approach enables designers to identify potential risks early in the design phase, thereby reducing uncertainty and mitigating risks during construction. Although this method remains in the exploratory stage, it has already demonstrated the potential of BIM technology to enhance risk management and improve construction safety in geotechnical engineering.

This section focuses on the preliminary risk assessment of parameters such as soil moisture content (w), liquid limit (LL), and the standard penetration test (N-value) to identify potential construction risks. These key parameters are used to assess the soil's consistency, stability, and mechanical properties, helping to determine potential challenges during construction.

4.1 Soil Consistency Classification Standards

During construction, potential issues can be estimated by classifying soil hardness using indicators such as the standard penetration test (SPT) N-value, moisture content (W), and liquid limit (LL). This classification provides a solid foundation for assessing construction risks. These indicators help evaluate soil stability and strength, facilitating the prediction of potential problems and the implementation of preventive measures. For example, softer soil layers may require additional support structures, whereas harder layers may necessitate adjustments in construction methods or techniques.

To improve risk identification, this study developed a simplified soil layer table that organizes key characteristics of different soil layers, serving as a quick reference for the on-site construction team. This table enables the team to quickly estimate the properties of various soil layers, reducing the uncertainties caused by soil variations and ensuring improving the flow of the construction process. Additionally, it serves as a reference for the automated modeling in this study, supporting the automation of risk assessment and soil modeling by digitizing and simplifying soil layer characteristics. The classification criteria for clay and sandy soils are as follows:

- Clay Silt (CL, CL-ML)
  $N \leq 4$ (±2), $W \geq LL$: Soft clay sediments
  $N \leq 2$, $W \geq LL$: Very soft clay sediments
  $N \leq$ 4-15: Medium hard clay
  $N \geq 15$: Hard clay
- Sandy Soil (SM)
  $N \leq 10$: Loose sand (from GL-0m to GL-10m)
  $N \leq 15$: Loose sand (below GL-10m)
  N = 10-30: Medium dense sand
  $N \geq 30$: Dense sand

4.2 Relationship Between Soil Properties and Engineering Issues

In foundation engineering construction, the soil characteristics of a site directly influence the stability of construction methods and the quality of the work. Due to variations in soil hardness, moisture content, and stratification, different construction techniques are associated with various engineering risks. Common methods such as diaphragm walls, bored piling, and steel sheet piling may encounter issues such as soil disturbance, leakage, or soil liquefaction under different ground conditions, potentially leading to settlement, tilting, or structural damage to nearby buildings, among other problems.

This section examines the specific problems caused by geological conditions during the construction of diaphragm walls, bored piling, and steel sheet piling. By analyzing case studies, it explores how soil characteristics contribute to engineering issues such as soil disturbance, leakage, and liquefaction.

Studying these cases allows engineers to better understand potential challenges associated with different construction methods in various geological conditions. This insight serves as a valuable reference for both design and construction.

(1) Diaphragm Wall

During diaphragm wall construction in soft clay and silt layers where $N \leq 4$ and $W \geq LL$, or in loose sandy soils where $N \leq 10$, the loose and highly fluid nature of these soils often leads to soil displacement and intrusion into the excavation zone. This can result in the mixing of soil with the diaphragm wall concrete, leading to defects such as soil inclusion, mud contamination, sand infiltration, or large soil lumps. These conditions compromise the structural integrity and load-bearing capacity of the diaphragm wall, degrade construction quality, and may ultimately lead to engineering failures or instability.

(2) Pre-packed Pile

In excavation projects with depths of up to 10 meters, the pre-bored piling method is commonly used for support. However, when constructing in soft soil layers, the cement grout used for the piles—often mixed with fly ash—provides excellent water tightness and high fluidity. While this is beneficial, its high fluidity can also delay the initial setting time, resulting in insufficient early strength. In such conditions, particularly in weak soil layers, the cement grout may leak, leading to a problem known as "Grout Leakage."

(3) Steel Sheet Piles

In excavation projects with depths of up to 15 meters, the steel sheet pile method is commonly used as a retaining structure. However, soil properties play a crucial role in determining both project quality and the safety of nearby structures. Two key issues related to this study are discussed below.

First, when the ground consists of relatively hard layers, such as clayey silt with $N \geq 15 \pm 2$ or sandy soil with $N \geq 20 \pm 2$, driving steel sheet piles becomes significantly more difficult. Forcing the piles into such hard ground may induce large-scale ground vibrations. In stratified ground conditions, if the overall geological formation is predominantly hard, vibration waves can propagate over a wider range, potentially causing structural cracks in nearby buildings. The impact may extend to a radius of more than 100 meters.

Second, when the ground exhibits a soft upper layer and a hard underlying layer—such as weak clay or silt with N ≤ 4(±2) or W ≥ LL, or loose sandy layers with N ≤ 10—pile driving may trigger ground liquefaction. In such cases, the localized loss of ground strength may lead to settlement, tilting, or structural cracking in nearby buildings [7].

4.3 Application of Soil Layer Models in Risk Assessment

In this project, a total of 12 boreholes were drilled. For the risk assessment, boreholes located near roadsides or buildings were prioritized, as these areas are more susceptible to external forces and require greater ground stability. Additionally, the borehole with the lowest N-value (indicating the loosest soil) was selected from the drilling data to evaluate ground risks.

As a result, Borehole B9 was chosen as the reference point for risk assessment in this study, with its findings representing the soil conditions beneath the entire excavation surface. While localized variations in soil distribution may exist across the excavation site, selecting the borehole with the lowest N-value provides a worst-case scenario for assessment, facilitating early predictions of potential engineering risks.

This section examines ground behavior during construction using different methods and analyzes the engineering issues that may arise. Particular attention is given to mud-wrapping phenomena in weak soils, sand-wrapping issues caused by sand displacement, and the potential impacts of ground vibrations or liquefaction on nearby structures. These factors can significantly affect construction safety and efficiency, making comprehensive risk assessment essential.

To improve risk evaluation, data is first organized and verified in Excel. After processing, soil layer parameters are imported into Dynamo and assigned corresponding soil properties. Evaluation formulas are then embedded within Dynamo, enabling the automatic generation of bounding boxes to enhance risk identification. Excel was chosen for its compatibility with Dynamo, facilitating efficient data processing and supporting automated risk assessment. The following outlines the methods used for risk evaluation, as shown in Figure 6:

1. For diaphragm walls encountering soft soil with N<4 and similar saturated unit weights, the soil layers are nearly identical.
2. Soft clay is characterized by N ≤ 4 and W ≥ LL. Therefore, soil with the highest water content and lowest liquid limit is identified as the potential mud-wrapping zone.
3. During diaphragm wall construction, Masako excavation may cause sand to fall, leading to sand-wrapping formation, However, dense sand layers with N≥30 are less susceptible to this issue due to their high relative density.
4. Driven steel sheet piles with N > 15±2 for clay and N > 20±2 for sand may generate vibrations that could damage nearby structures.
5. When using driven steel sheet piles, soil liquefaction may occur if the strata consist of soft upper layers and hard lower layers.

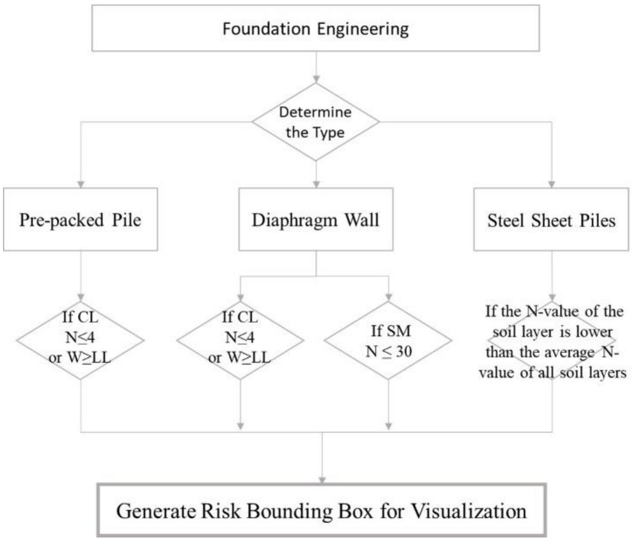

Figure 6. Workflow for generating risk bounding boxes for visualization

This assessment process has been integrated into Dynamo, enabling the automated generation of risk indicators through visual programming. By providing a systematic approach to identifying potential risk areas, this method serves as a reference for engineers in geotechnical risk assessment, design, and construction planning.

In Dynamo, bounding boxes are used to identify risk layers, which are then integrated with the Revit model for automatic generation. This process helps categorize potential risks for each construction method and marks hazardous soil areas with different colors. The visual display enables the project team to identify issues in specific soil layers, such as looseness, leakage risks, or liquefaction, while also providing clear risk indicators. This approach simplifies geological data, allowing the design and construction teams to address key challenges early, plan preventive measures, and reinforce structures. Ultimately, it reduces construction risks and enhances both project quality and safety. The results are shown in the following figure.

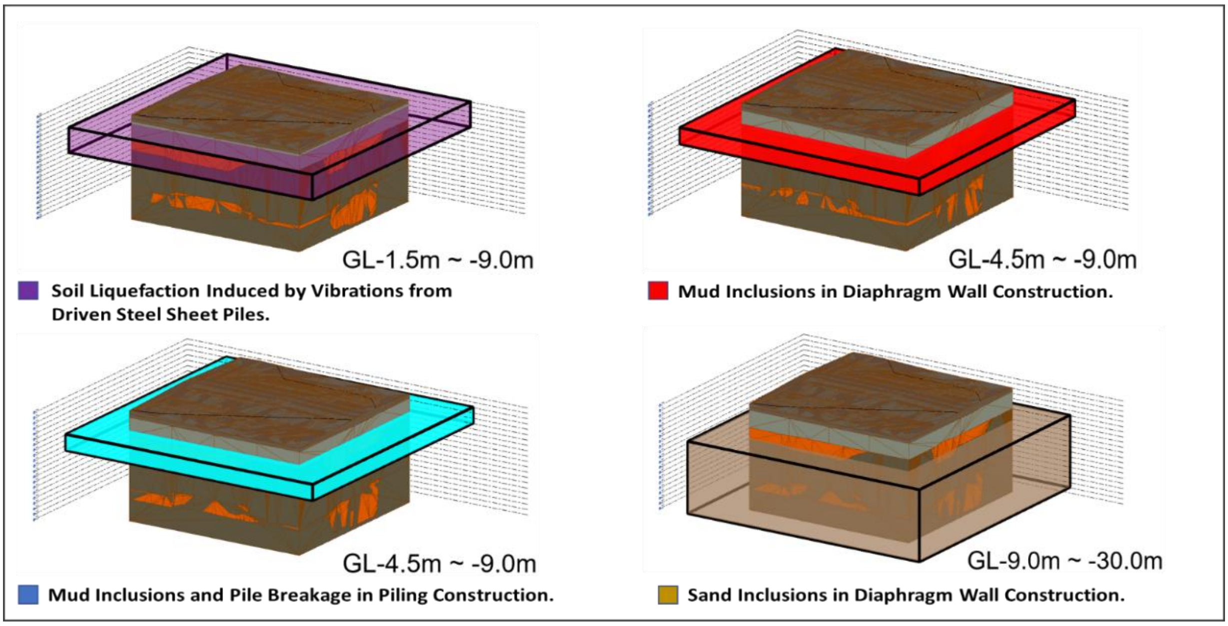

Figure 7. The results of Soil layer risk assessment

Borehole reports indicated that the excavation area primarily consisted of weak clay ($N \leq 4$ (± 2), $W \geq LL$) and loose sand layers ($N \leq 10$ (± 2)), both of which posed a high risk of instability due to clay inclusion and sand pockets. These unfavorable soil conditions made the site highly susceptible to settlement and collapse, likely contributing to the failure. Had an automated soil risk identification method been applied, these hazardous zones could have been clearly identified before excavation, enabling the project team to implement appropriate mitigation measures and reduce the risk of failure.

This case highlights the practical necessity of integrating automated soil risk assessment methods. By leveraging bounding box analysis in Dynamo, hazardous zones can be detected before excavation, allowing engineers to visualize soil risks directly within the BIM model. This automation improves geotechnical risk visibility, reduces reliance on manual interpretation, and provides a structured framework to prevent similar failures in future construction projects.

5 Conclusion and Future Work

Integrating BIM technology with soil characteristics and risk assessment in geotechnical engineering can enhance the predictability of soil-related issues and the effectiveness of corresponding mitigation measures during construction. Through 3D modeling and data analysis, designers can identify potential soil problems during the design phase and assess risks based on key parameters such as soil stiffness, liquid limit, and SPT N-values. This approach reduces construction risks associated with soil-related challenges and facilitates the development of appropriate strategies for varying soil conditions.

While current methods demonstrate the potential of BIM technology in geotechnical engineering, further improvements are needed to automate the modeling process. For instance, existing risk identification models require validation through additional real-world cases to ensure accuracy. Moreover, these models must be continuously refined to maintain precision as geological conditions evolve, making this an important focus for future research. Additionally, integrating BIM technology with existing soil analysis data remains challenging. In many cases, manual judgment is still required to identify risk areas before computational processing, reducing efficiency and potentially affecting the accuracy and timeliness of data analysis.

Future research may leverage existing soil data for computational analysis to gradually establish an automated system for soil risk assessment and retaining structure modeling. Currently, this study primarily focuses on automating soil layer generation and risk assessment by identifying potential hazards based on soil properties, while groundwater variations are beyond its scope. However, future studies may explore incorporating groundwater level fluctuations into simulations to provide a more comprehensive understanding of subsurface conditions and improve the safety and reliability of both geotechnical risk assessment and automated retaining structure modeling.

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