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Development of 3D Geo BIM Framework for Optimizing Pile Lengths in Large-scale Structures

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ABSTRACT: Large-scale structures, such as high-rise residential complexes, typically require a significant number of piles to efficiently transfer superstructure loads to the bearing stratum. However, even with extensive geotechnical investigations, it remains challenging to accurately characterize subsurface conditions and determine the depth of the bearing layer at every pile location. To address this issue, GS E&C has developed an advanced program that calculates the capacity of each pile within large structures using a three-dimensional subsurface model (3D Geo-BIM). The 3D Geo-BIM model integrates both stratigraphic data and key soil parameters—such as groundwater level, unit weight, cohesion, friction angle, and SPT-N values—required for pile capacity evaluation. These parameters are automatically extracted from geotechnical investigation reports within minutes using AI-based tools. Although 3D Geo-BIM is still relatively new to geotechnical engineers due to the inherent uncertainty of subsurface conditions, this integration represents a significant step toward overcoming ambiguities in geotechnical design. By implementing three-dimensional kriging of AI-extracted soil parameters, the platform enables accurate estimation of pile resistances at every location and depth, thereby supporting data-driven and optimized pile foundation design.

KEYWORDS: Pile resistance, 3D Geo-BIM, Kriging, AI tool.

1 INTRODUCTION

Large-scale structures, such as high-rise apartment buildings and mixed-use complexes, require numerous piles to support heavy superstructure loads. In Korea, excavation is typically required to create underground parking spaces, and the resulting rigid parking structures can effectively resist horizontal loads. Consequently, the majority of the loads transferred to the piles are vertical. Pile foundations are therefore designed to resist vertical loads through a combination of shaft friction and end bearing to ensure structural stability. In practice, pile design is completed by determining the pile length based on the estimated bearing capacity at each pile location. Although geotechnical investigations are performed at multiple locations to evaluate the bearing capacity of piles, it is practically impossible to conduct borehole drilling at every pile location.

As a result, pile designs are typically based on ground conditions inferred from the investigation points, and pile lengths for large structures are often grouped into a few categories. However, this grouping process is inherently subjective, as it relies on the engineer's judgment to define the boundaries of subsurface layers. Consequently, ensuring that the pile bearing capacity at each location is accurately assessed becomes challenging.

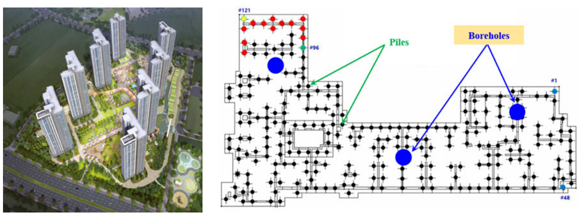

Figure 1. Pile Layout of a Building within Apartment Complex

In large-scale project sites where geotechnical investigations are performed at only a limited number of locations, subsurface conditions at uninvestigated areas are often inferred using simple two-dimensional linear interpolation between adjacent boreholes. However, in regions with high spatial variability, this approach may lead to significant discrepancies from the actual subsurface conditions. To ensure a more reliable prediction of ground stratigraphy and properties, it is therefore essential to construct a three-dimensional ground model that incorporates all available investigation data across the entire site.

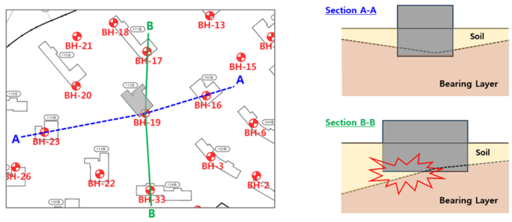

Figure 2. Potential Errors from 2D Interpolation of Ground Data

Constructing a 3D ground model necessitates the integration of a substantial volume of geotechnical investigation data, a process that can be time-intensive due to the complexity of data handling and entry. Moreover, manual data input is prone to human error, often requiring repeated verification of records and resulting in reduced efficiency. By employing AI-based techniques to standardize and structure geotechnical investigation data into a uniform format, both the speed and accuracy of data processing can be significantly enhanced.

For large-scale structures containing over 200 or 300 piles, essential design information—such as pile coordinates and lengths—is typically provided as numerical data within engineering drawings. Converting this data into actionable construction information demands considerable time and effort from site engineers. To overcome this challenge, we propose a three-dimensional pile design and construction system that integrates pile design outputs with the 3D Geo-BIM model, enabling intuitive visualization and facilitating the practical application of pile data in the field.

2 BACKGROUND FOR PILE DESIGN IN KOREA

The scope and extent of geotechnical investigations are determined by the subsurface conditions of the project site and the characteristics of the target structure. In South Korea, apartment construction projects are predominantly located in urban or peri-urban areas. Except for certain coastal regions, soft ground is rarely encountered; instead, weathered rock layers are typically present at depths of approximately GL(-)20 to (-)30 meters, where most piles are designed to bear on these strata.

Accordingly, geotechnical investigations primarily focus on the surficial sedimentary layers—generally composed of silty sand with minor occurrences of sandy silt and silty clay—and the underlying weathered residual soil, which is predominantly silty sand. Owing to the structural characteristics of apartment buildings in Korea, which commonly incorporate large underground parking structures, foundation design is governed by vertical loading. As lateral behavior is rarely critical, PHC (Pretensioned spun High strength concrete) piles are typically selected for their efficiency in sustaining vertical loads.

To mitigate noise and vibration complaints from neighboring communities during pile installation, piles are generally not driven directly into the ground. Instead, a pre-bored method is commonly employed: the ground is pre-drilled, the pile is placed, and the annular space between the pile and surrounding soil is filled with cement grout. In South Korea, extensive construction experience and load test data have confirmed that the Standard Penetration Test (SPT) N-value is the primary design parameter for cast-in-place piles. Notably, even within the weathered rock layer serving as the bearing stratum, the pile end-bearing capacity correlates more strongly with SPT N-values than with initial or ultimate stresses derived from pressuremeter tests

Table 1. Ultimate Pile Resistance in the Pre-drilling method

Pile	Soil Type	Value (kPa)	Remark
Skin Friction	*Sand*	2N	N≤50
	Clay	0.8Su	
Toe Resistance	*Sand*	250N	N≤60
	Clay	9Su	
	Weathered Rock	15,000~21,000	

* N : Blow Numbers per 300mm penetration in the SPT
** Su : Undrained strength
*** Weathered Rock : N=50/100~50/10

Given these structural characteristics, ground conditions, and construction practices, geotechnical investigations for apartment construction projects in Korea primarily rely on SPT data. While this reliance introduces certain limitations in accurately evaluating pile capacity, the results of both dynamic and static load tests have shown good agreement with empirical design formulas, suggesting that current design practices are reasonably reliable. Consequently, geotechnical investigations for pile design in apartment construction projects typically include the following types of information:

Geotechnical Investigation Items:

- Stratigraphic composition and layer thickness
- Basic index properties and grain-size distribution of soils
- Standard Penetration Test(SPT) N-values across all soil layers
- Undrained shear strength of cohesive soils (primarily obtained from triaxial compression tests)

3 PROCESSING INPUT DATA USING AI-BASED TECHNIQUES

For the design of large-scale apartment complexes, geotechnical investigations are typically conducted at approximately 20 to 30 locations, generating a substantial volume of data. To build a three-dimensional ground model, the following geotechnical information must be input into the modeling software:

- Borehole coordinates and groundwater levels
- Soil layer composition, unit weight, and top/bottom elevations for each stratum within each borehole
- Standard Penetration Test (SPT) N-values at all depths
- Shear strength parameters of soils (specified by borehole location and depth)

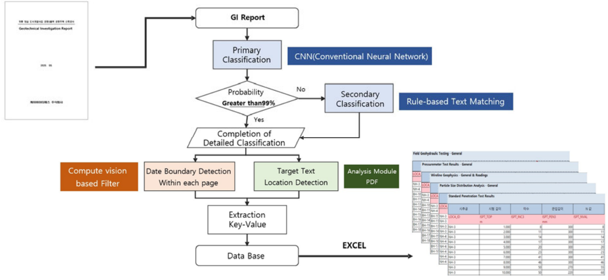

Figure 3. Flow Chart of the Data Extraction Algorithm

To efficiently manage and utilize these datasets, we developed a program capable of automatically extracting the aforementioned information from approximately 50 types of geotechnical investigation reports in diverse formats. The extraction process follows a two-stage approach. First, a Convolutional Neural Network (CNN) identifies and classifies the pages containing specific geotechnical items based on visual patterns. Subsequently, a rule-based text-matching algorithm is applied to extract the numerical values associated with each item. Through this combined approach, the system achieved a data-extraction accuracy exceeding 99.9%.

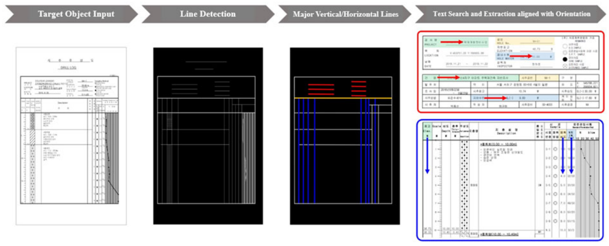

Figure 4. Illustration of the Data Extraction Algorithm for Boreholes

To ensure compatibility with other engineering software platforms, the extracted geotechnical data were stored in the AGS (Association of Geotechnical and Geo Environmental Specialists) format—a standardized, text-based file format designed to facilitate reliable data exchange within the site investigation industry, independent of software, hardware, or operating systems.

4 KEY TECHNOLOGY COMPONENTS OF 3D GEO BIM FOR PILE DESIGN

4.1 *Investigation of Design and Construction Practices*

We began by examining conventional practices in pile design and construction for large-scale apartment complexes, identifying the core technologies requiring development, and evaluating their significance. Due to the limited number of geotechnical investigations, it was observed that, in apartment buildings with 200–300 piles, pile lengths were often designed to be uniform or grouped into only two or three categories, despite significant variations in the actual constructed pile lengths. Consequently, we concluded that the number of borehole investigations should be flexibly adjusted during the design phase to account for ground variability. Specifically, in the initial phase of site investigation, a borehole should be drilled at each structural location to obtain an overview of soil stratification. In the subsequent phase, areas exhibiting high ground variability should be targeted for intensive investigations to accurately determine the detailed subsurface conditions of the project site.

During the design phase, information on the locations of 200–300 piles is typically presented in CAD-based plans and cross-sectional drawings. However, interviews with contractors revealed that predicting the pile bearing layer during construction is often challenging, as pile coordinates and lengths must be reprocessed into digital data based only on approximate stratification information. Therefore, if all pile-related data from the design phase were visualized in a 3D BIM model and digitized for each pile, construction engineers could initiate pile installation with reliable information. This would minimize variations in pile length and construction methods caused by ground variability and reduce the risk of construction delays.

The critical pile data to be digitized and visualized include:

- Pile coordinates (X,Y,Z of pile head and tip)
- Pile length
- Target soil layers for pre-boring and their respective thicknesses
- Preliminary selection of drilling bits for pre-boring (e.g., auger or air hammer)

4.2 *Procedure for Geotechnical Data input*

As described in Section 3, to minimize human errors and accelerate the processing of extensive geotechnical data, we developed a program that utilizes AI techniques to extract design-relevant parameters from text-based geotechnical investigation reports and convert them into the AGS standard format. The extracted data are first saved in Excel format and subsequently imported into the 3D GEO BIM module in CSV format, forming the core data pipeline of the developed program.

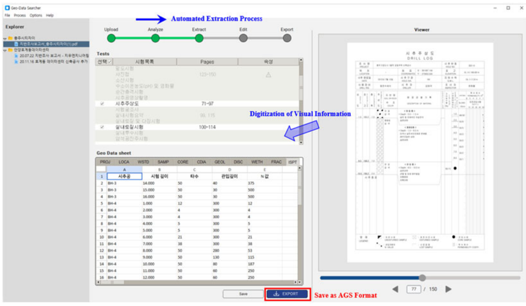

Figure 5. User Interface for Geotechnical Data Extraction and Storage

4.3 *Data Acquisition for Non-bored locations*

The most common approach for predicting geotechnical conditions at locations without borehole investigations is the use of the ordinary kriging method. This technique, widely implemented in commercial software such as Surfer, is regarded as highly reliable. By utilizing borehole data, including the top surface level of each soil layer and SPT N-values at all depths, a 3D Geo-BIM model can be constructed by generating a three-dimensional layer network for each stratum.

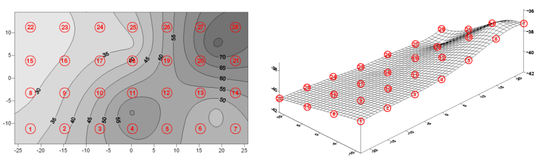

Figure 6. Example Output of 2D Surfer Program (Ground Surface)

Typically, 3D subsurface models accurately represent only the ground surface using kriging, while underground layers are approximated through linear interpolation. In contrast, a key feature of the developed program is that the surfaces of all subsurface layers are generated using ordinary kriging, thereby enhancing the overall precision of the model.

SPT N-values, measured at 1-meter intervals from all boreholes, are critical design parameters for pile foundation design. Accordingly, a three-dimensional kriging approach was implemented to generate depth-dependent N-value profiles at every pile location. Additional design parameters, such as shear strength constants, were assigned by soil layer and incorporated into the 3D geotechnical model, enabling the calculation of both shaft friction and end-bearing capacity for piles across the entire site.

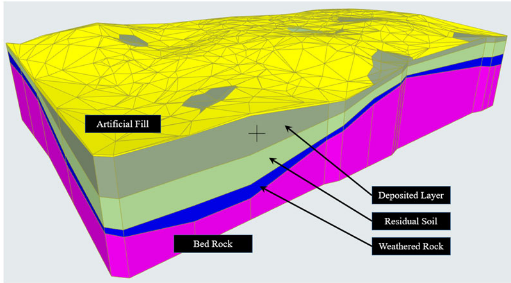

Figure 7. 3D Geo BIM Model

4.4 *Calculation of Pile Resistance and 3D Visualization*

When the 3D Geo BIM model—containing soil layer classifications, shear strength parameters, and SPT N-values at 1-meter depth intervals—is supplemented with the diameter, head coordinates (X, Y, Z), and required design bearing capacity of each pile, the pile length at every location is determined using the bearing capacity equations summarized in Table 1. The R programming language was employed to calculate design bearing capacities for various pile lengths and to identify the optimal pile length that meets the target bearing capacity.

In large apartment complexes, multiple buildings and variations in topography often result in differences in pile head elevations. To address these conditions, the program allows users to define multiple zones and conveniently assign pile head elevations and target design capacities for each zone.

To enhance accessibility for both designers and field engineers, the system was developed as an add-on to ArchiCad software provided by GRAPHISOFT**,** a widely used BIM platform in architecture. The system is structured into the following modules:

- **3D Geo BIM module** for visualizing geotechnical data
- **Pile design module** for calculating optimal pile lengths and visualizing all piles within the 3D Geo BIM model
- **Data management Module** for digitizing pile design results and providing construction-related information

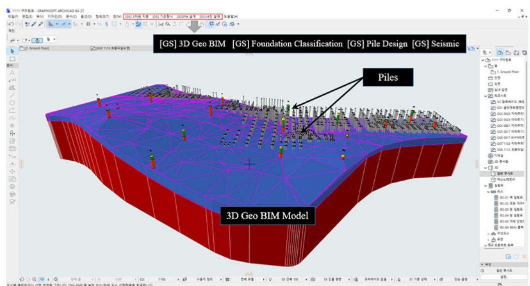

Figure 8. Add-on Modules and Output Display

4.5 *Comprehensive Construction Information Management*

As outlined in Section 4.1, a BIM-based dataset integrating both pile and subsurface information was developed to assist construction engineers in understanding pile design details. All construction-related pile data were delivered in Excel format, eliminating the need for additional documentation. The dataset also contains information on the number of pile splices and locations where the bearing layer emerges at shallow depths, resulting in shorter pile lengths and enabling engineers to anticipate potential challenges arising from subsurface variability. Furthermore, by incorporating data on hard strata—such as sand–gravel layers and weathered soils containing rock fragments—into the 3D Geo BIM model, the system supports the pre-planning of drilling bit types (e.g., auger or air hammer) required for pre-boring operations.

■ Building No.101

No	X-coord	Y-coord	Pile Dia. (m)	Pile Tip Level (m, A)	Pile Head Level (m, B)	Pile Length (m, D-A)	Pre-Drilling Depth (m, C-A)						Pile Resistance (tonf)	Number of Pile Splices	Short Pile 0 : No 1 : Yes
							Filled Layer	Deposited Soil	Residual Soil	Weathered Rock	Bed Rock	Total Length			
1	238814.065	521794.374	0.500	61.500	75.390	15.390	0.000	0.000	7.179	6.475	0.236	13.890	203.778	1	0
2	238814.998	521793.441	0.500	61.500	75.390	15.390	0.000	0.000	7.247	6.493	0.150	13.890	203.911	1	0
3	238816.296	521792.483	0.500	61.500	75.390	15.390	0.000	0.000	7.297	6.485	0.108	13.890	204.278	1	0
4	238817.229	521791.549	0.500	61.500	75.390	15.390	0.000	0.000	7.365	6.503	0.022	13.890	204.345	1	0
5	238810.303	521790.619	0.500	60.000	75.390	16.890	0.000	0.000	7.887	7.151	0.352	15.390	210.045	1	0
6	238818.163	521790.616	0.500	61.000	75.390	15.890	0.000	0.000	7.433	6.522	0.436	14.391	207.211	1	0
7	238811.237	521789.686	0.500	60.000	75.390	16.890	0.000	0.000	7.955	7.169	0.265	15.389	210.178	1	0
8	238819.096	521789.683	0.500	61.000	75.390	15.890	0.000	0.000	7.501	6.540	0.349	14.390	207.445	1	0
9	238820.030	521788.749	0.500	61.000	75.390	15.890	0.000	0.000	7.569	6.558	0.263	14.390	207.411	1	0
10	238807.945	521788.261	0.500	59.000	75.390	17.890	0.000	0.000	8.332	7.575	0.483	16.390	214.111	1	0

Figure 9. Sample Construction Data following Pile Resistance Analysis

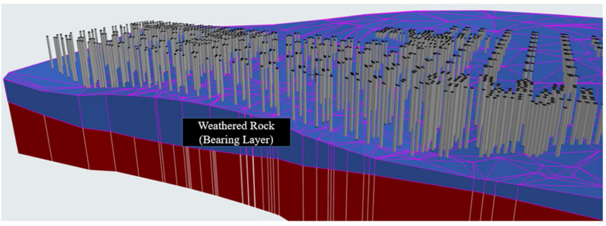

Figure 10. Pile BIM Integrated within 3D Geo BIM Model

5 CONCLUSION

Large-scale structures, such as apartment complexes or mixed-use buildings, require a substantial number of piles. However, pile design is typically based on geotechnical investigations conducted at only a limited number of discrete points, which introduces subjectivity and increases the risk of unsafe design in areas with high ground variability. In this study, geotechnical investigation data from the project site were processed using AI techniques to automatically extract key engineering parameters, which were then stored in AGS format for seamless integration with other software applications. Using these data, a three-dimensional Geo BIM model incorporating geotechnical information for pile design was developed.

Moreover, by integrating the pile layout into the BIM model, we developed an add-on feature for commercial software that calculates pile bearing capacities and visualizes the design results within the 3D Geo BIM environment as part of an in-house software tool. The pile design outcomes are provided to construction engineers via a BIM viewer, along with essential construction data—such as pile lengths and layer-specific drilling depths—enabling them to anticipate ground variability and respond flexibly to site conditions.

6 ACKNOWLEDGEMENTS

This study originated from GS E&C's initiative to optimize pile foundation design for apartment complexes. We sincerely thank the Department of Civil and Environmental Engineering at Yonsei University for their pioneering contribution to developing, for the first time in Korea, an AI-based technique for extracting and storing geotechnical information tailored to on-site requirements. We also acknowledge the Department of Civil and Environmental Engineering at Seoul National University for their development of the three-dimensional ordinary kriging method. Lastly, we extend our gratitude to DoallTech for creating add-on modules that seamlessly integrated these technologies into the commercial ArchiCad platform.

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