A Selection Model for Soil Retaining Walls in Construction Projects

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Abstract

Recently, there has been an increase in the size, diversification, and specialization of the construction methods of underground sites, particularly due to the need for more efficient utilization of underground spaces in downtown sites where space is limited and land prices high. This study presents a number of procedures that can be used to review site constraints and constructability, and to evaluate the economic efficiency and safety of soil retaining walls in order to select the optimum wall for the given site conditions. Furthermore, this study presents a quantitative analysis model to determine whether the selected soil retaining wall is able to deal with the site risks by using the forced decision method and binary weighting analysis. The study also presents a process model in order to select the optimum soil retaining wall for the given site conditions through the analysis of constructability, economic efficiency, stability and risk factors.

Keywords: construction management; construction method; construction planning; decision making

1. Introduction

1.1 Background and purpose

Due to limited space and high downtown land prices, the size of underground constructions has increased in order to make use of underground space for parking or commercial facilities, while the related construction methods have become more diversified and specialized. In particular, underground construction, which has a high impact on the whole project because it accounts for 20% to 40% of the total construction cost, is an important element of a successful project (e.g., Jung, K. J *et al.* 2003), and it requires careful planning and selection of the optimum method. However, there are no quantitative criteria concerning the selection of the soil retaining construction method, and it is mostly selected by the intuition of related engineers after simple data comparisons and review. As a result, the optimum soil retaining wall for a site cannot be selected, causing such problems as design changes, increased construction costs, delays, and soil collapse. Therefore, this study presents a quantitative soil retaining wall selection model that enables objective decision making and the systematic reflection of the experience and knowledge of staff.

1.2 Scope and methods

The scope of this study concerns the selection process for soil retaining walls in underground construction planning. The related literature as well as the existing underground construction method selection processes were reviewed, while the forced decision method (J. Fasal 1965) and binary weighting analysis (Oh, S. J 2004) to be applied in this study were examined. A selection process model was presented for the optimum soil retaining wall for the given site conditions based on safety, constructability, economic efficiency, and risks during construction planning. The process and main contents of this study are listed in Fig.1.

Fig.1. Study Procedure and Methodology

2. Theoretical Review

2.1 Soil retaining wall

The purposes of a soil retaining wall include safety, prevention of heaving (swelling of the excavated ground because the soil outside the retaining wall flows inside during soil retaining or excavation work),

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prevention of boiling (soaring of back sand to the excavated ground during the excavation of sandy ground), countermeasures regarding groundwater, and prevention of other damage.

2.2 Conventional selection process for soil retaining walls

While the conventional selection process for a soil retaining wall varies according to the site conditions, based on the author's past experiences, this was determined in most cases by the subjective judgment of the site staff. In the case of small projects, the soil retaining wall was selected by a simple comparison of different walls as shown in Table 1.

Table 1. Conventional Analysis for Selection of Soil Retaining Walls

Conditions	Factors	Soil Retaining Walls			
		H-pile + soil wall	Soil Cement Wall (SCW)	Cast In concrete Pile (CIP)	Dia-phragm Wall
Ground Condition	Soft rock story	B	A	A	A
	Hard rock story	B	B	B	B
	Ground water story	B	B	B	B
Size	Deep	B	A	A	A
	Wide	B	A	A	A
Rigidity	Wall bending rigidity	B	A	A	A
Pollution	Noise, Vibration	B	B	B	B
	Surrounding land settlement	B	A	A	A
	Backwater Treatment	B	C	C	A
Construc-tion Period	Construc-tion Period	A	C	C	C
Cost		A	C	C	C
Stagnant Water		B	B	B	A

Note: A - Possible, B - Average, C - Difficult

2.3 Forced decision method

While preparations for various risks concerning underground construction must be made, it is difficult to plan perfect countermeasures for every expected risk. Therefore, the major risks that must be considered according to site conditions were identified and the forced decision method was used to determine the priority of each risk. The forced decision method involves evaluating the importance of a risk through pair-wise comparison between risks in order to determine the priority of each risk (Lee, D. H 2006). Specifically, the relative priority of each function is given a score of either '1' or '0' in comparison to another risk, and the scores are summed up for each function. The forced decision method enables a decision to be made about which risks in a specific site must be given higher priority when selecting a soil retaining wall.

2.4 Binary weighting analysis

This selection method evaluates each soil retaining wall to determine whether it is able to deal with each risk. If the soil retaining wall is appropriate for a given risk, Yes is assigned to the method concerning the risk; otherwise, No is assigned as shown in Table 2. The value 1 is then given for Yes and 0 for No. The final value is then converted to a binary number, which is converted to a decimal number again to determine the evaluation result as in Eq. (1), (2) and (3). The more satisfactory the review factors are, the larger the Equivalent Decimal Value is and according to the formula (3), the Rating Value is between 0 and 1. If the method satisfies every factor, the Rating Value becomes 1. If not, it becomes 0. In other words, the larger the Rating Value is, the more suitable the method is.

Table 2. Binary Weighting Analysis (Example)

Factor	Yes	No
A	•	
B		•
C	•	
D		•
E		•

$$EDV = \sum_{i=1}^n (w_i \cdot 2^{i-1})$$

$$= 1 \cdot 2^{5-1} + 0 \cdot 2^{4-1} + 1 \cdot 2^{3-1} + 0 \cdot 2^{2-1} + 0 \cdot 2^{1-1} = 20$$

..... Eq. (1)

$$MEDV = \sum_{i=1}^n (1 \cdot 2^{i-1})$$

$$= 1 \cdot 2^{5-1} + 1 \cdot 2^{4-1} + 1 \cdot 2^{3-1} + 1 \cdot 2^{2-1} + 1 \cdot 2^{1-1} = 31$$

.....Eq. (2)

$$RV = EDV / MEDV = 20 / 31 = 0.645$$

.....Eq. (3)

Where

RV : Rating Value

MEDV : Maximum Equivalent Decimal Value

EDV : Equivalent Decimal Value

w_i : The value en-downed to the i factor, Value 1 given for 'Yes' and 0 for 'No'

i : The arranged location of the factor

3. Process Model for Selection of Soil Retaining Walls

Using the process model for the selection of soil retaining walls used in this study, the optimum soil retaining wall for a site was selected through a review of the constraints of the site and ground, a review of the economic efficiency and safety of the soil retaining wall, and a review of the risks. Fig.2. shows a summary of the review details in each step of the selection process for the optimum soil retaining wall for a site, which is proposed by this study and the applied theory.

(1) Constraints review

In the constraints review, which is the first step in the soil retaining wall selection process, the

Fig.2. Selection Model for Soil Retaining Walls

Table 3. Review Factors for Project Constraints (Partial)

	Factor
1	Client requirements
2	Local districts
3	Construction period
4	Building structure
5	Surrounding environment
6	Underground structure
7	Foundation excavation depth
8	Foundation excavation area
9	Construction size
10	Building area
11	Land area
12	Groundwater contamination problems
13	Neighboring structures
14	Notable surrounding structures
15	Difference of elevation
16	Surrounding roads
17	Underground utilities
18	Important neighboring facilities
19	Surrounding environmental pollution problems
20	Existence of underground structures
21	Distance to neighboring buildings
22	Surrounding road surface condition

Fig.3. Constraints Review for Ground Conditions (Example)

Table 4. Constructability Review Factors

Category	Review Factors
Topography	Is there a difference of elevation in and around the site?
	Does the rock condition need to be considered?
	Does the transportation path for construction equipment and materials need to be considered?
	Does sequential load according to traffic need to be considered?
	Does the general topography around the site need to be considered?
Influence on neighboring structures	Does the foundation penetration depth need to be considered?
	Are there neighboring structures that need to be considered?
	Does the foundation type need to be considered?
	Does the influence of noise and vibration to neighboring structures need to be considered?
	Does the distance between temporary structures and existing structures need to be considered?
	Do the properties of the ground in the area affect the safety of temporary facilities and need to be considered?
	Does the degree of consolidated settlement of the ground around the site need to be considered?
Location conditions	Is the site in a downtown area?
	Does the site boundary need to be checked?
	Do the neighboring structures interfere with clearance?
	Are there structures that require caution? (e.g., subways)
	Is there a concern about damage due to noise during construction?
	Is there a concern about damage due to vibration during construction?
Underground utilities and obstacles	Do they affect the foundations of existing structures?
	Were there wells in the past?
	Were there riverbanks in the past?
	Do the location, size, structure, and deterioration of gas pipes need to be investigated?
	Do the location, size, structure, and deterioration of water supply pipes need to be investigated?
	Do the location, size, structure, and deterioration of sewer pipes need to be investigated?
	Do the location, size, structure, and deterioration of electric cable pipes need to be investigated?
Seasonal weather	Are preparations for rainfall and local downpour necessary?
	Does the existence of wells need to be checked?
Road and traffic conditions	Does the road type need to be considered?
	Does the road structure need to be considered?
	Does the restriction of traffic need to be considered?
Others	Is a review of related laws or preparation for restrictions necessary?

project constraints were included, such as the client requirements, construction size, neighboring structures, elevation differences, surrounding road surface conditions, and ground conditions, including soil quality. Table 3. and Fig.3. provide lists of the constraints review items.

(2) Constructability review

In this step, the ease of construction of the soil retaining wall is evaluated as well as the factors that may affect the constructability on the site, including the location of the site, elevation differences, rock conditions, ease of operation of the construction equipment, conditions of structures close to the site and surrounding ground, buried utilities, expected weather during the construction period, and road and traffic conditions. Table 4. lists the items for a constructability review for an underground wall retaining construction.

(3) First selection of soil retaining walls

Based on the results of constraints and constructability reviews, the first selection of soil retaining walls that can be applied to the given site is made using Tables 5. and 6., which were reorganized from the related research and practical data.

Table 5. Applicable Quality of Soil for Retaining Wall

Method	Applied Soil
H-pile + Soil wall	All geological strata
CIP	All grounds excluding boulder and rock layers
SCW	Ground with clay and sand of N-value < 50
Diaphragm wall	All geological strata

(4) Stability review

For a stability review of a soil retaining wall, this study used the SUNEX (elasto-plastic analysis of Step Underground Excavation) method, a soil retaining wall structure calculation program with expanded functions and improved usability while considering both the Yamagata expansion method and the Morishige method among the elasto-plastic beam methods (Seo, J. H 2000).

(5) Economic review

The economic review of each soil retaining wall calculates the schematic construction cost of the walls,

and uses the comparison of costs for selection of the final wall.

(6) Risks review and selection of soil retaining wall

The possible risks that may occur during an underground construction are classified as design conditions, structural conditions, ground conditions, site conditions, economic conditions, and environmental conditions. The forced decision method is then used for a comparative analysis of the risks. On the basis of the comparative analysis results, the priorities of risks that must be managed during construction are determined, and the binary weighting analysis is carried out with the priorities of the selected soil retaining walls.

① Risk review;

While it is difficult to predict which site conditions will act as risks during construction, the review and preparation for risks is a critical task. This review of risks is an important activity used to select the optimum construction methods that can be applied to each step of the selection process. Thus, through an analysis of related literature and case studies, in this study the risks that may occur in the soil retaining wall construction site for a building are classified into: design conditions, ground conditions, site conditions, environmental conditions, construction conditions, structural conditions, and economic conditions. The risk review items proposed in this study are summarized in Table 7.

② Application of the forced decision method to derive risks;

The forced decision method used to determine which risks must be considered before other construction conditions, is managed in a focused manner. The priorities of risks provide the criteria for determining the optimum soil retaining wall for the site by weighting each risk, and the priorities determined by the forced decision method are unique for each site and can be used as case data (N. Yau and J. Yang 1998) for the selection of a soil retaining wall for similar sites in the future. Table 8. shows an example of the determination of risk priorities using the forced decision method in which the risks, ranging from design conditions to economic conditions, are compared with each other,

Table 6. Selection Criteria for Soil Retaining Walls According to Ground Conditions

		Depth (m)	Water shielding performance	Vibration & Noise	Soil Quality					
					Rocks	Boulder	Gravel	Sand	Clay	
									Soft	Hard
H-pile + Soil Wall	Conventional type	20	C	C	C	B	A	A	A	A
	Auger-combined press-in	25	C	A	C	C	A	A	A	A
	Field mortar piles	36	C	A	A	B	A	A	A	A
CIP	Conventional type	36	B	A	A	A	A	A	A	A
	Impermeable type	30	B	A	A	B	A	A	A	A
SCW	Shape steel	30	A	A	C	B	A	A	A	A
	Steel pipe	30	A	A	C	C	A	A	A	A
Diaphragm Wall	Field concrete wall	Drill	100	A	A	C	A	A	A	A
		Bucket	50	A	A	C	A	A	A	A

Note: A - Possible, B - Average, C- Difficult

Table 7. Risk Review Factors

Review Factor	Details
Design conditions	Applied load, soil parameters, reliability of soil retaining model, reliability of subsidiary methods.
Ground conditions	Ground property (e.g., soft layer, conglomerate layer), groundwater condition, support layer condition, support layer depth.
Site conditions	Difference of elevation in the site, planar shape (standard/nonstandard), site size, relationship with neighboring land.
Environmental conditions	Noise, vibration, settlement of surrounding land, treatment of discharged muddy water, contamination of groundwater.
Construction conditions	Ground collapse, change of applied load, earthquake, neighboring constructions, water leakage, failure of excavation base.
Structural conditions	Bending rigidity of soil retaining wall, stagnant water, properties of structures.
Economic conditions	Construction period, construction cost, material management, productivity.

Table 8. Priority of Risk Review Factors using the Forced Decision Method (Example)

Review Factor	1	2	3	4	5	6	7	Total	Priority
Design conditions		0	1	1	1	0	1	4	2
Ground conditions	1		1	1	1	1	1	6	1
Site conditions	0	0		1	0	0	0	1	5
Environmental conditions	0	0	0		1	1	1	3	3
Construction conditions	0	0	1	0		1	0	2	4
Structural conditions	1	0	1	0	0		0	2	4
Economic conditions	0	0	1	0	1	1		3	3

and either '0' or '1' is assigned to each to indicate importance. If the design conditions are more important than the ground conditions for a risk, 1 is assigned to the design conditions and 0 is assigned to the ground conditions. In this way, each item is compared with another item. The values in each row are then summed up, and the priority is determined for each risk.

③ Selection of soil retaining wall using binary weighting analysis;

The priorities of risks determined by the forced decision method are factors for the selection of the optimum soil retaining wall for a site. As shown in Table 9., each wall is weighted and quantified by binary weighting analysis to determine the risk correspondence, which determines the degree of correspondence for each wall to the risk. This result is then combined with the stability review and economic

Table 9. Evaluation using Binary Weighting Analysis

	Risk Review Items	Yes	No
Ground conditions	Is the wall restricted by ground conditions, including soil quality, groundwater level, and coefficient of hydraulic conductivity?		
Design conditions	Are the water discharge and water shielding plans appropriate?		
Environmental conditions	Can the surrounding structures cope with the influences (e.g., settlement of surrounding ground, noise, vibration)?		
Economic conditions	Is the economic efficiency (construction period, construction cost) excellent?		
Construction conditions	Can you cope with work area limitation and failure of excavation base?		
Structural conditions	Are the structural conditions such as rigidity, properties of structures, and connections of structures excellent?		
Site conditions	Is the wall appropriate for the size, difference of elevation, and configuration of the site?		

review in the previous steps to select the optimum soil retaining wall for the site. The priorities determined by the forced decision method become the criteria for allocating weights in the binary weighting analysis.

④ Correlations between forced decision method and binary weighting analysis;

For a combination of the forced decision method and binary weighting analysis in sites that have different constraints, the priorities determined by the forced decision method provide the basis for weights in the binary weighting analysis, as shown in Fig.4. Specifically, the risks that are determined by the forced decision method should be considered before others are positioned at a higher level on the list and are given higher weights in the binary weighting analysis.

4. Case Study

The case study for this research was a commercial building with 8 floors underground and 16 floors above ground. The building was to be newly constructed on a 6,950m² site located in downtown Seoul, which is Korea's capital. The constraint was to construct a subway passage that was close to the first and second underground floors of the building, and the client demanded that the construction be completed six months earlier than planned as shown in Table 10.

Table 10. Results of Constraints Review

Factor	Review
Client requirements	Shorten the construction duration (36 months → 30 months)
Local districts	General commercial district, aesthetic area
Construction period	-
Building structure	Steel frame, reinforced concrete
Surrounding environment	Low-story housing, subway.

Underground structure	Reinforced concrete
Foundation excavation depth	35m
Foundation excavation area	6,139m ²
Building size	8 floors underground, 16 floors above ground
Building area	4,072.85m ²
Land area	6,950.70m ²
Groundwater contamination problem	Concern for contamination of groundwater when ground reinforcement method is used
Neighboring structures	Low-story housing
Notable surrounding structures	Subway line 3 (Located 25m to the west of the site)
Difference of elevation	Relatively flat
Surrounding roads	Trunk road 25m in front to the northwest
Underground utilities	None
Important neighboring facilities	Subway
Surrounding environmental pollution problems	Noise and vibration
Existence of underground structures	None
Distance to neighboring buildings	Close
Surrounding road surface condition	Good

After understanding the soil quality and rock conditions of the case site as in Table 11.

Table 11. Results of Ground Conditions Review

	Layer thickness (m)	Com-ponents	Stand-ard pene-tration test (N value)	Relative density and softness/hardness	Rocks
Buried layer	1.4~4.1	Sand with gravel and silt	2/30~50/10	Very loose - Very dense	-
Transported soil layer	3.3~8.9	Gravel with silt and sand	2/30~50/16	Very weak - Solid, Loose - Very dense	-
Decomposed soil layer	0.6~11.5	Gravel with silt	17/30~50/11	Average dense - Very dense	-
Weathered rock layer	0.8~9.9	-	50/10~50/3	Very hard	-
Soft rock layer	1.5~13.0	-	-	-	Gneiss
Ordinary rock layer	2.0~6.0	-	-	-	Gneiss
Hard rock layer	3.0~21.4	-	-	-	Gneiss

Review Results

Finally applied soil quantity; Understanding of rock conditions

Joints and cracks are developed / $q_u \geq 147.10$ Mpa

Note: q_u -Unconfined compression strength

The authors chose H-pile + soil wall, CIP, SCW, and Diaphragm Wall as the primary soil retaining walls that could be applied. After stability and economic

efficiency reviews were carried out on each wall, it was found that the selected walls had no stability problems when they were correctly designed. In terms of the economic efficiency review, the Diaphragm Wall was more expensive than other walls when only construction costs were considered. However, when it was considered that the structure can be permanent after construction and that the construction period can be shortened, the Diaphragm Wall demonstrated high economic efficiency, as shown in Table 12.

Table 12. Stability Review for Soil Retaining Walls

	H-pile + Soil Wall	CIP
Body (mm)	H-pile: 400×300×10×16	CIP : Ø400, H-pile: 300×300×10×5
Brace (mm)	H-pile: 300×300×10×15	H-pile: 300×300×10×15
Maximum displacement	101.3mm	52.6mm
	SCW	Diaphragm Wall
Body (mm)	H-pile: 400×300×13×21	Iron bar: SD 40, $f_y=392.27$ Mpa, $f_{ck}=29.42$ Mpa
Brace (mm)	H-pile: 300×300×10×15	SLAB thickness: 300
Maximum displacement	149.3mm	15.6mm

Note: Ø- Diameter, SD-Steel bar Diameter, f_{ck} -Compression strength, f_y -Yield strength

In order to identify the risks in the site and the importance of the risks, the risks were analyzed using the forced decision method, with five specialists both inside and outside the company, as shown in Table 13. A risk analysis was conducted and it was found that the risks that must be considered to have a higher priority than others were weighted in the following order: environmental conditions, ground conditions, design conditions, construction conditions, structural conditions, and economic conditions. It was considered that this result was due to the increasing interest in the environment among people, and the consideration of disputes due to civil complaints.

Table 13. Result of Risk Priority

	A	B	C	D	E	F	G
Specialist 1	0	2	1	3	4	5	6
Specialist 2	2	4	0	3	1	6	5
Specialist 3	1	5	2	6	3	4	0
Specialist 4	1	3	5	0	4	2	6
Specialist 5	1	0	2	4	3	5	6

Group weight (Average of weights)	1	2.8	2	3.2	3	4.4	4.6
Ranking	7	5	6	3	4	2	1

Note: A-Economic conditions, B-Structural conditions, C-Site conditions, D-Design conditions, E-Construction conditions, F-Ground conditions, G-Environmental conditions

Fig.4. Correlation of Forced Decision Method and Binary Weighting Analysis

Based on the risk priority analysis shown above, an analysis was carried out of the risk correspondence of the multiple walls that were first selected. The risk priority was highest for the Diaphragm Wall, at 0.937, followed by the Soil Cement Wall, the H-pile + Soil Wall, and Cast In concrete Pile, as shown in Table 14.

Table 14. Evaluation Process and Result

Ranking	Method				
	Review Factor	I	II	III	IV
1	A	1	1	1	1
2	B	1	0	1	1
3	C	0	1	1	1
4	D	1	1	0	0
5	E	1	1	0	1
6	F	0	1	1	1
7	G	1	0	1	1
Rating Value		0.858	0.740	0.906	0.937

Note: A-Environmental conditions, B-Ground conditions, C- Design conditions, D-Construction conditions, E-Site conditions, F-Structural conditions, G-Economic conditions, I- H-pile + Soil Wall, II-Cast In concrete Pile, III-Soil Cement Wall, IV-Diaphragm Wall

* Evaluation

$$MEDV = 1 \cdot 2^6 + 1 \cdot 2^5 + 1 \cdot 2^4 + 1 \cdot 2^3 + 1 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 = 127 \quad \text{.....Eq. (4)}$$

(1) H-pile + Soil Wall

$$EDV = 1 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 109 \quad \text{.....Eq. (5)}$$

$$RV = 109 / 127 = 0.858 \quad \text{.....Eq. (6)}$$

(2) Cast In concrete Pile

$$EDV = 1 \times 2^6 + 0 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 = 94 \quad \text{.....Eq. (7)}$$

$$RV = 94 / 127 = 0.740 \quad \text{.....Eq. (8)}$$

(3) Soil Cement Wall

$$EDV = 1 \times 2^6 + 1 \times 2^5 + 1 \times 2^4 + 0 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 115 \quad \text{.....Eq. (9)}$$

$$RV = 115 / 127 = 0.906 \quad \text{.....Eq. (10)}$$

(4) Diaphragm Wall

$$EDV = 1 \times 2^6 + 1 \times 2^5 + 1 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 119 \quad \text{.....Eq. (11)}$$

$$RV = 119 / 127 = 0.937 \quad \text{.....Eq. (12)}$$

5. Conclusion

This study presented a model to review the constraints, constructability, stability, and economic efficiency in the planning stage for the selection of the optimum soil retaining wall for a given site. Recently, there has been an increase in the size of underground construction in order to more efficiently use underground spaces in expensive, limited and densely populated areas. Soil retaining walls are consequently diversifying and specializing, and a quantitative analysis model is necessary to determine whether a soil retaining wall can cope with the site risks through the forced decision method and binary weighting analysis.

This model was then applied to the construction planning stage for a new commercial building in order to verify the possibility of its practical application. This was a basic study to select the optimum soil retaining wall for underground construction in the construction planning stage. In the future, continuous studies are needed to computerize this process model and to develop it into a case-based reasoning process model through many case applications.

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