Study on the Optimal Digging Range for Intelligent Excavation

Jeonghwan Kim[a], Joonhyun Jang[b], Leeho Lee[c], and Jongwon Seo[d]
[a]Dept. of Civil Environmental Engineering, Hanyang University, Korea
[b]Korea Construction Engineering Development Collaboratory Program, Korea
[c]Dept. of Civil Environmental Engineering, Hanyang University, Korea
[d]Dept. of Civil Environmental Engineering, Hanyang University, Korea (Corresponding Author)
E-mail: kimjh0418@gmail.com, jang1013@koced.net, leedon62@naver.com, jseo@hanyang.ac.kr,

Abstract -
Excavators play an important role at construction sites owing to high application and economic advantages, but the number of skilled operators of the excavator decreased because young operators do not like to enter to construction business. Research on automation of excavator and earthwork equipment was actively done such as IES (Intelligent Excavating System) in Korea. Much of research relied upon skilled worker's heuristics at making decision of minimum working unit without considering the conditions of the ground and excavator load, and it exposed to fall down of excavator at collapse of the ground and difficult to improve working efficiency. This study suggested optimal digging range considering heuristics of skilled workers, ground of various kinds of working areas and excavator specification to supplement existing methods and to improve safety and performance.

Keywords -
Automated Excavation; Geotechnical Conditions; Culmann’s method; Optimal Digging Range

1 Introduction

The earthwork at construction sites produces basic ground to build up facilities at natural land. Earthwork project occupy about 20% of construction project cost and it has great influence upon construction project and to rely upon construction machinery more than other civil engineering businesses do [1]. The productivity, quality and safety, etc. may vary depending upon use and operation of construction machinery [2].

Nowadays, on-the-spot construction work has become particularly difficult at large-scaled and complicated construction projects, and these include a variety of construction businesses. Consequently, risks in handling heavy weight machines and a much higher rate of negligence-related accidents have created a situation where many young labourers do not feel motivated to work at construction sites. As a result, the number of skilled operators of construction machinery is likely to decrease day by day: Nonetheless, the construction business has relied upon machinery and equipment. Recently, Studies on construction machines and equipment can prevent negligent accidents from happening in the absence of skilled operators, as well as prevent productivity and quality from being lowered. In other words, it creates a decision-making system of not only operators but also managers of construction machines to make operation plans of construction machines and to put them into practice using a full automation system. In light of this, the Ministry of Land, Infrastructure and Transportation supported R&D project of Intelligent Excavating System (IES) to improve conditions and environment at construction sites. The development of IES expanded the applications and use of excavation machines, providing an automation system of simple and repeated excavation.

The system adopted the digging range of excavators as basic operation unit of excavated area. Size of digging area or range can be varied based on the depth and length of excavation work. Increasing the excavation depth and length seem to good for excavation in terms of productivity, it may also cause an critical incident, such as overturn, by making an unstable ground condition due to excessive excavation. Therefore, we need to find a balance point between two things; maximizing the volume of excavation area and guaranteeing a safety work condition (e.g. soil collapse).

At the initial stage of IES development, digging range relied upon information of skilled excavator operator's heuristics. In other words, excavator operators' experience and knowledge were generalized to apply them into the system. However, that approach had always been applied in the same way, neglecting current ground conditions and weight of excavators. In fact, this implied exposing the machines to collapse or accidental falls due to possibilities of unexpected ground settlement, thus leading to lower levels of operation efficiency. In this study, the optimal digging range of IES that reflects ground condition and excavator specifications (e.g. weight) at various kinds of operation areas was suggested to assure of safety and performance for intelligent excavation.

The goal of the IES was not to produce excavating robots with new types of specifications but to perform excavation effectively by using current excavators. That did not make any great changes on the existing specifications, its focus was to remodel some organs and add communications equipment, such as posture and positioning sensors, as well as laser scanners and cameras. 13-ton caterpillar type excavator (Model No. DX140, supplied by Doosan Infracore Co., Ltd.) were investigated in IES development, which is often used at local construction sites to develop prototype. In this study, modules for optimal digging range of each excavator were developed to expand use. This study suggested Vertical Excavation Depth (H_v), Safety Length (L_s) and Horizontal Excavation Length (L_{opt}) of digging range as shown in figure 1, minimum working unit of excavation, to let IES excavate effectively in several steps; First, the study investigated IES and task planning system development to find out problems of IES digging range generation as well as needs of new optimal digging range generation.

Second, as mentioned before, the study investigated specifications of excavators of Doosan Infracore to examine excavator movement depending upon operations and specifications that made change in accordance with environment of earthwork, and to discover parameters of modules of optimal digging range generation.

Third, the study investigated alternatives for the production of optimal digging range generation module to suggest optimal alternative and to give development method of modules and to set up optimal digging range generation algorithm.

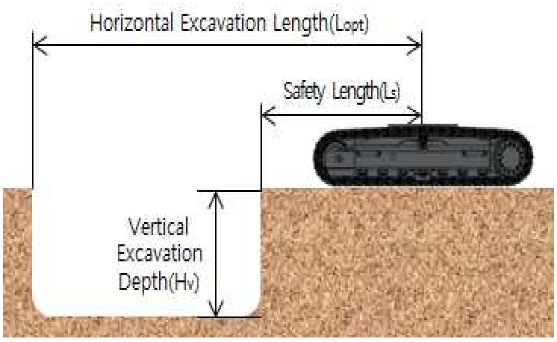


Figure 1. Configuration of digging range

2 Optimal Digging Range

2.1 Definition of digging range

The digging range that an excavator excavates without rotation is the minimum task unit of the task planning system as figure 2. In other words, the size of the digging range has great influence upon efficiency and safety of IES task plan.

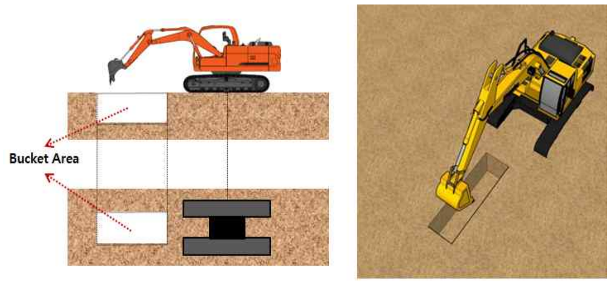


Figure 2. Digging range

Excavated amount of dirt and cycle time determines the productivity of excavation task. Wide digging range for quick operation can increase excavating task excessively, and deep digging depth without considering physical properties of the soil and safety (buffer) area around the excavator could destroy slopes to overturn excavator. Smaller size of digging range that stabilizes ground can lower excavation efficiency so that optimal digging range size is needed to assure of safety and efficiency of excavation.

The digging range cross section consists of H_v (vertical excavation depth), L_s (safety length) and L_{opt} (horizontal excavation length in optimal) as shown in figure 1. L_s includes distance from center of excavator to start point of the slope to apply bucket width of excavator specification to the digging range. And, H_v is 2 to 2.5 m at earthwork site: In this study, heuristics of skilled excavation operator who did not excavate more than 2.5 meters was reflected.

The failure surface can be made by using critical break angle based on angle of internal friction. At this time, the study has inspected slope stability considering downward moving force of earth along the failure surface, resistance and weight of the excavator.

2.2 Slope Stability Analysis Theory

The methods of slope stability analysis for development of digging range generation algorithm of soil properties includes not only straight line but also curve of failure surface (Table 1).

Table 1 Analysis of Slope Safety

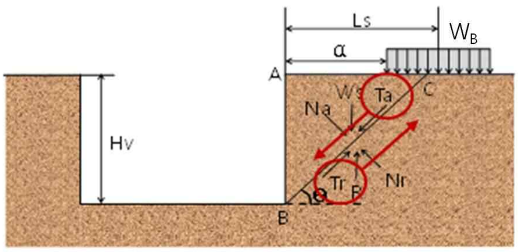
	Straight Failure Surface	Curve Failure Surface
Failure Surface		
Analysis Method	Culmann method	Fellenius method, Bishop method, Spencer method, etc

These days, the limit equilibrium method (Bishop's section method) that is similar to failure surface has been often used, and curve of failure needs to reflect variables that can be produced at many complicated environments of calculation. Also, break without enough depth can be close to plane break, and Culmann method that is subject to plane of failure surface can produce satisfactory results [3]. That is, the digging range generation algorithm was designed based on Culmann method subject to plane of failure.

The steep slope with H_v of excavating depth has failure surface ($\overline{AB}$) with critical break angle (θ) as shown in Fig 3. Equation 1 is used to estimate weight of earth on the failure surface (ΔABC).

$$W_s = \frac{1}{2}(\overline{AC})(H_v)(\gamma) = \frac{1}{2}(H_v \cot\theta)(H_v)(\gamma) = \frac{1}{2}\gamma H_v^2 \cot\theta \quad (1)$$

Where,
W_S: Soil weight on the failure surface
H_v: Excavation depth (vertical)
γ: Unit weight of soil



Where,
W_B: Excavator weight
K: Including the percentage in Surface AC(%)
FS: Safety factor
L_t: Excavator track length
L_{tw}: Excavator track width
W_{BK}: Part of excavator weight ($=W_B/L_{tw}*K$)
α: Free distance of excavator front
$L_{opt} - L_s$: Excavation length

Figure 3. Culmann-type failure

Weight of earth (W_s) of failure surface ($\overline{BC}$) has normal and tangent Equation (2):

$$\text{Normal of } W_s = N_a = W_s \cos\theta = \frac{1}{2}\gamma H_v^2 \cot\theta \cos\theta \quad (2)$$

$$\text{Tangent of } W_s = T_a = W_s \sin\theta = \frac{1}{2}\gamma H_v^2 \cot\theta \sin\theta \quad (3)$$

Equation 3 makes change with tangent of earth weight (W_s) and excavator's partial weight (W_{BK}):

$$N_a = (W_s + W_{BK})\cos\theta = (\frac{1}{2}\gamma H_v^2 \cot\theta + W_{BK})\cos\theta \quad (4)$$

$$T_a = (W_s + W_{BK})\sin\theta = (\frac{1}{2}\gamma H_v^2 \cot\theta + W_{BK})\sin\theta \quad (5)$$

$$*W_{BK} = \frac{\text{weight of the excavator}}{\text{total width of excavator}} = \frac{\text{total weight of excavator} \times \text{degree of } \overline{AC}(\%)}{\text{total width of excavator track}} = \frac{W_B \cdot K}{L_{tw}}$$

$$*K = \frac{\text{weight of the excavator at AC area}}{\text{Total weight of the excavator}} \times 100(\%)$$

Not only normal stress on average but also shear stress on average (τ_a) is applied to failure surface ($\overline{BC}$):

$$\acute{\sigma} = \frac{N_a}{A} = \frac{N_a}{(\overline{BC})(1)} = \frac{N_a}{(\frac{H_v}{\sin\theta})} = (\frac{\sin\theta \times \cos\theta}{H_v})(\frac{1}{2}\gamma H_v^2 \cot\theta + W_{BK}) \quad (6)$$

$$\tau_a = \frac{T_a}{A} = \frac{T_a}{(\overline{BC})(1)} = \frac{T_a}{(\frac{H_v}{\sin\theta})} = (\frac{\sin^2\theta}{H_v})(\frac{1}{2}\gamma H_v^2 \cot\theta + W_{BK}) \quad (7)$$

The shear strength on average of failure surface ($\overline{BC}$) can be obtained by using normal stress on average Equation (6) Equation (8):

$$\tau_r = c + \acute{\sigma}\tan\varnothing = c + (\frac{\sin\theta \times \cos\theta}{H_v})(\frac{1}{2}\gamma H_v^2 \cot\theta + W_{BK})\tan\varnothing \quad (8)$$

The study obtains not only shear stress on average (τ_a) but also shear strength on average (τ_r) on failure surface ($\overline{BC}$) by using partial load (W_{BK}) of failure load ($\overline{AC}$) of total excavator load on ground surface as well as weight (W_s) of the earth (ΔABC): The shear stress on average (τ_a) can be compared with shear stress strength on average (τ_r) to judge break of steep slope.

Safety factor shall be applied to shear stress on average (τ_a) considering risks Equation (9). The regulation of road design of Korea Expressway Corporation [4] adopted FS of more than 1.5 at cutting of soil layer as well as weathered rock that did not consider underground water level at dry season. This study supplemented special situation that slope stability analysis did not consider not only continuous change of weight center of the excavator but also vibration at movement of the excavator, and it adopted factor of safety of 1.6:

$$F_s\,\tau_a < \tau_r \qquad (9)$$

$$F_s \frac{\sin^2\theta}{H_v}\left(\frac{1}{2}\,\gamma\, H_v^2 \cot\theta + W_{BK}\right) < c + \left(\frac{\sin\theta \times \cos\theta}{H_v}\right)\left(\frac{1}{2}\,\gamma\, H_v^2 \cot\theta + W_{BK}\right)\tan\emptyset \qquad (10)$$

So, shear stress strength on average that resists break more than 1.6 times than shear stress on average of break of failure surface ($\overline{AC}$) is thought to be safe.

2.3 Horizontal Excavation Length

L_{opt} (Horizontal Excavation Length) on which size of digging range relies shall be decided before making not only H_v but also L_s.

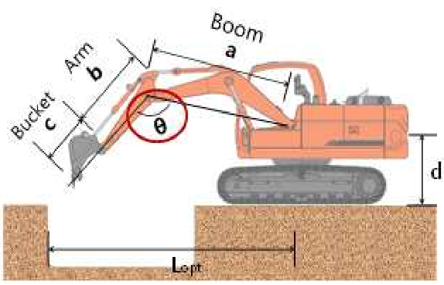


Figure 3. Horizontal digging distance (L_{opt})

The excavator can often reach a distance of maximum arm length and boom, and skilled excavator operators excavated earth surface with 130˚ to 135˚ of boom and/or arm angle of the excavator (θ of fig 18): L_{opt} that reflected the experience and knowledge of excavator operators based on Equation (11):

$$L_{opt} = \sqrt{a^2 + (b+c)^2 - 2a(b+c)\cos\theta} \qquad (11)$$

2.4 Vertical Excavation Depth and Safety Length

The initial process of discovery of both H_v (Vertical Excavation Depth) and L_s (Safety Length) starts from H_v and specification of the excavator. A slope stability analysis is to be done from 0 ton having no effect of W_{BK} to 13 ton of total weight of the excavator subject to 1 meter of H_v and 13 ton of excavator total weight to find out excavator W_{BK} at critical break point that the slope broke down. L_s can be estimated with 1 meter of H_v with Lt being total excavator weight versus track length (L_t) Equation (12).

$$L_s = H_v \cot\theta - \mathrm{K}\,L_t + \frac{1}{2}\,L_t \qquad (12)$$

In essence, after the first process is done, the second process is carried out by increasing H_v gradually from 1 meter, and the process is repeated for every H_v. Earth-work sites often have 2.5 meters or less of H_v considering drainage at excavation, dump loading and connections with other types of constructions which have up to 2.5 meters of H_v. At both the first process and the second process, each H_v is to be obtained for L_s of W_{BK} at critical break point, and the area of cross section of digging range is used to decide upon both H_v and Ls. The length of excavation can be obtained by deducting L_s from L_{opt} to estimate cross section of digging range by using H_v and length of the excavation. When excavation length exceeds three times of bucket length, excavation can be done smoothly. Optimum H_v and L_s have been set at three times or more of excavation length than bucket length as well as the largest area of cross section of digging range.

2.5 Optimal Digging Range Generation Algorithm

Figure 4 shows an optimal digging range generation using the algorithm mentioned above.

The process of determination of both H_v and L_s is the most important at optimal digging range algorithm

First, standard of H_v is to be set with IES specifications as well as soil parameters. The example has 1 meter of H_v as well as 3 meters of L_s (length from excavator center to end of the excavation) as shown in figure 5. 14.4-ton excavator on firm and stable ground may collapse slope of more than 1-meter of excavation depth according to skilled excavator operators: Consequently, 1 meter H_v has been set. L_s has been set considering length of excavator boom and front side.

Second, slope stability analysis is done with reference condition of H_v and L_s. In the example, reference condition is safe. Third, L_s decreases at the reference condition. In the example, L_s decreased by 0.5 meters. Basically, with a smaller Ls, W_{BK} of the excavation can be added to weight of the earth on failure surface to increase break force.

Fourth, slope stability analysis is to be done at less L_s. In the example, given L_s is safe even at 2.5 meter. And the same process has been repeated until break of the slope. In the example, the slope was broken down at 1.5 meter of L_s. Fifth, aforementioned process is to be repeated with deep H_v.

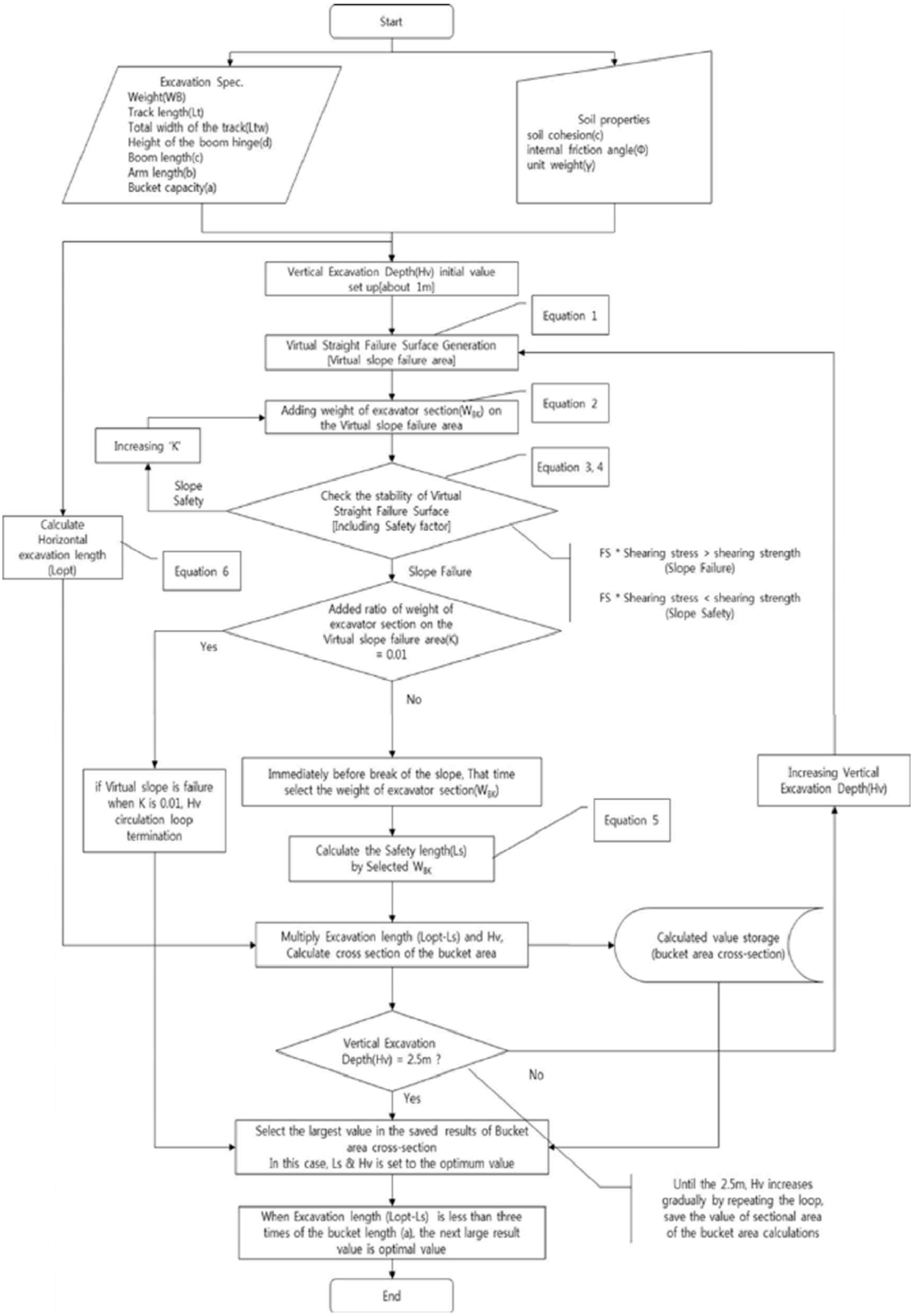


Figure 4. Optimal digging range generation algorithm

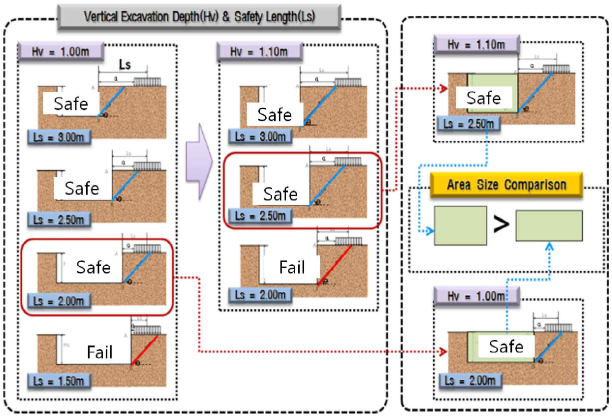


Figure 5. Processes of cross section of digging range (H_v) and safety length (L_s)

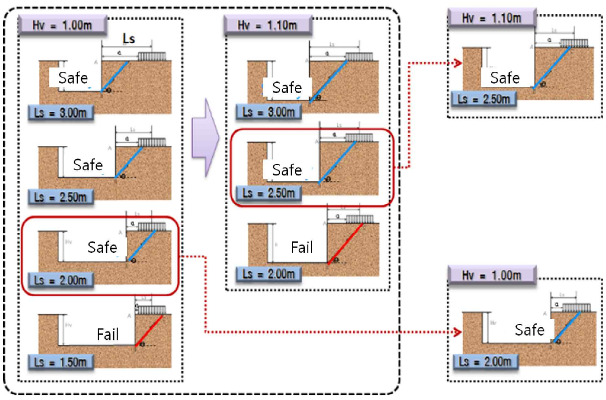
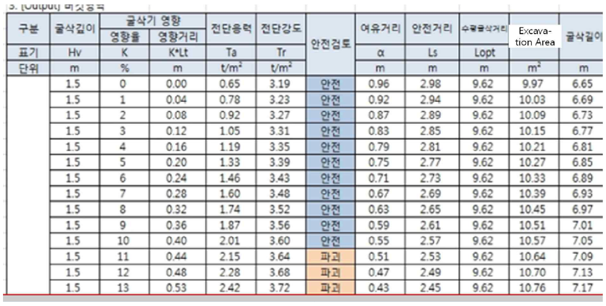


Figure 6. State immediately before Destruction of the Slope

Sixth, 1 meter of H_v and 1.1 meter of H_v have 2.0 meter and 2.5 meter of L_s respectively immediately before break of the slope (Fig 6). Seventh, the most spacious one of both ones based on L_{opt} is to be selected by comparing area of the digging range. Eighth, the aforementioned process is repeated with up to 2.5 meter of H_v. The most spacious area can be optimal to have final values of both H_v and L_s.

2.6 Algorithm Test before Module Production

We conducted the test by using spreadsheet of MS Office Excel before producing modules with optimal digging range generation algorithm. The spreadsheet for testing consisted of input of both excavator specifications and soil parameters, calculation of slope stability depending upon place of the excavator, and output showing optimal digging range to check results by applying soil quality that can be found out at common earthwork sites (Fig. 7).



구분	굴삭길이	굴삭기 영향		전단응력	전단강도	안전검토	여유거리	안전거리	수평굴삭거리	Excava-tion Area	굴삭길이
		영향율	영향거리								
표기	Hv	K	K*Lt	Ta	Tr		α	Ls	Lopt		
단위	m	%	m	t/m²	t/m²		m	m	m	m²	m
	1.5	0	0.00	0.65	3.19	안전	0.96	2.98	9.62	9.97	6.65
	1.5	1	0.04	0.78	3.23	안전	0.92	2.94	9.62	10.03	6.69
	1.5	2	0.08	0.92	3.27	안전	0.87	2.89	9.62	10.09	6.73
	1.5	3	0.12	1.05	3.31	안전	0.83	2.85	9.62	10.15	6.77
	1.5	4	0.16	1.19	3.35	안전	0.79	2.81	9.62	10.21	6.81
	1.5	5	0.20	1.33	3.39	안전	0.75	2.77	9.62	10.27	6.85
	1.5	6	0.24	1.46	3.43	안전	0.71	2.73	9.62	10.33	6.89
	1.5	7	0.28	1.60	3.48	안전	0.67	2.69	9.62	10.39	6.93
	1.5	8	0.32	1.74	3.52	안전	0.63	2.65	9.62	10.45	6.97
	1.5	9	0.36	1.87	3.56	안전	0.59	2.61	9.62	10.51	7.01
	1.5	10	0.40	2.01	3.60	안전	0.55	2.57	9.62	10.57	7.05
	1.5	11	0.44	2.15	3.64	파괴	0.51	2.53	9.62	10.64	7.09
	1.5	12	0.48	2.28	3.68	파괴	0.47	2.49	9.62	10.70	7.13
	1.5	13	0.53	2.42	3.72	파괴	0.43	2.45	9.62	10.76	7.17

Figure 7. Algorithm implementation

The Road Design Manual [4] gives soil parameters of natural specimen of the design to classify SM and SC into 1.7tf/m^3 of unit weight, 30 degree of angle of internal friction and 3tf/m^3 or less of adhesiveness. The author increased adhesiveness from 1tf/m^3 to 3tf/m^3 to estimate optimal digging range by using the spreadsheet for the test. Two types of excavator (Table 2) were used and results are shown in Figure 8 and 9.

Table 2. Specifications of excavator

	13.3 ton Excavator (Doosan DX 140)	21.5 ton Excavator (Doosan DX 220)
Weight (ton)	13.30	21.50
Track length (m)	2.78	3.65
Total width of the track (m)	1.20	1.20
Height of the boom hinge (m)	1.51	1.87
Boom length (m)	4.00	5.70
Arm length (m)	1.90	2.90
Bucket capacity (Cu. m)	0.59	0.82

3 Case study

In this study, IES with task planning system having digging range generation module was used to conduct test at earthwork site by many IES technicians and professionals who are experienced in earthwork. The purpose of the test was to inspect H_v, L_{opt} and L_s and to verify exactness and stability by testing sizes of digging range of excavation of IES: An earth-work site was chosen at Hanyang University's Erica campus at Ansan, where banking with 15 meters in width, 15 meters in length and 1.5 meter in height was made to demonstrate

IES in operation and to conduct tests after skilled operators excavated several times (Fig. 10).

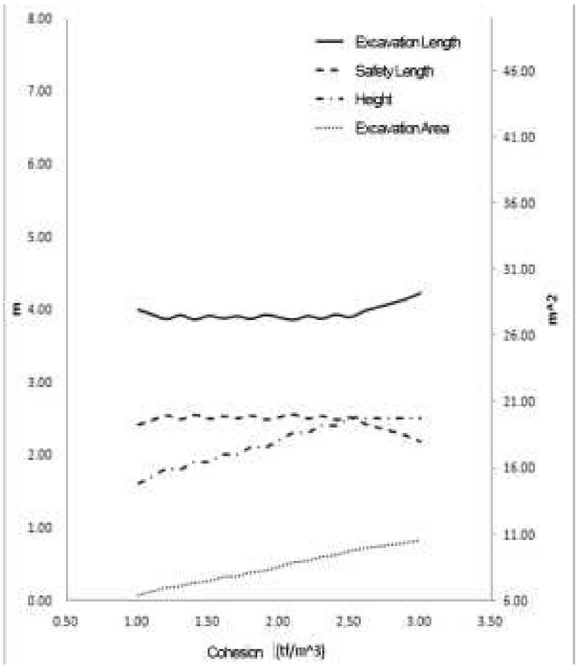


Figure 8. Result of optimal digging range generation algorithm test of DX 140

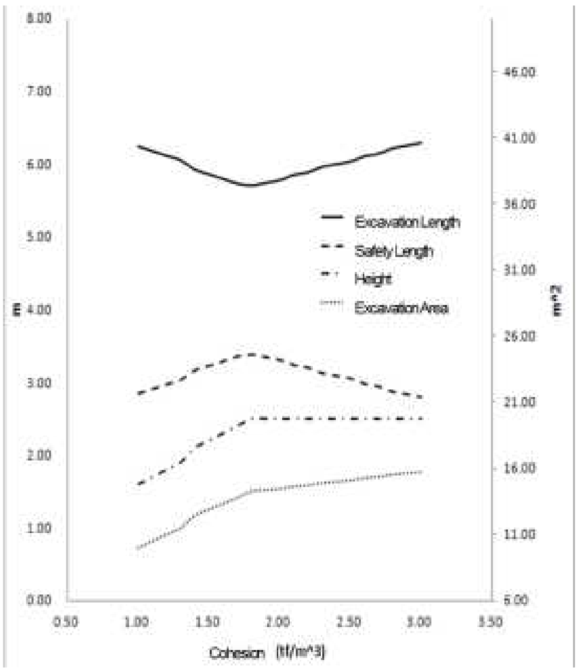


Figure 9. Result of optimal digging range generation algorithm test of DX 220

Figure 10. Construction Sites for IES Test

The findings are as follows: H_v had an error of about ±6.45cm, and L_{opt} had an error of about ±7.93cm and L_s had an error of about ±13.23cm. The information of digging range generation module differed a little from the results of actual excavation. Nonetheless, we admitted of the existence of errors because effects of posture and position sensor exactness as well as mechanical errors could not be removed completely.

On top of that, some professionals said that the size of the digging range had conservative values from the point of view of ground properties at earthwork site. The digging range generation module gives enough digging range information for IES to excavate safely without collapse of excavating slope, and the digging range size is smaller than when compared to operations conducted by skilled excavator operators.

Skilled excavator operators, however, mentioned that they could not take immediate and flexible actions against working environment when they took on an excavator, and that they needed to keep stability relying upon conservative values. Therefore, the excavation amount of the digging range generation model was a little smaller than that of skilled excavator operators which increase excavation efficiency considerably, with stability of the excavator. Also, not only digging range information of the modules but also errors of actual IES task results could be used to improve sensors and mechanical parts.

4 Conclusion

This study has improved conventional method that decided upon size of digging range, minimum task unit of Intelligent Excavation System (IES) that relied upon skilled operator's heuristics being development factor of IES and it developed auto generation module of optimal digging range size by using soil strength properties at earthwork sites and IES specifications. The slope stability analysis was done repeatedly subject to plane of hypothetical break surface and load of the excavator to give optimal digging range for better IES performance and to improve safety and productivity in simple and prompt way. Further studies were needed to protect excavators from risks that were not acknowledged prior to application to actual earthwork sites, and to inspect various kinds of ground environments, and to examine not only static factors but also dynamic factors

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