Equipment Combination Model for Effective Excavation Work for Urban High Rise Buildings

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Abstract
The excavation work for constructing urban high-rise buildings is narrow and deep, limiting the mobility of equipment. In addition, the productivity of excavation work varies according to the type and amount of equipment used. Therefore, a combination of excavation and rock breaking equipment is needed to maximize productivity while minimizing the cost of excavation work.

Simulation of various cases is needed to draw optimum plans for variables that can greatly affect the productivity of excavation work, but that is not an easy task. Furthermore, a great deal of information and time are necessary for engineers or technicians to review the combination of equipment. For these reasons, most engineers or technicians are unable to accurately predict construction duration or the cost of using a particular equipment combination, based on their experience. The objective of this paper is to propose an efficient equipment combination model for effective excavation work for urban high-rise buildings. In the test case project, applying the proposed model reduced the equipment rental cost about 3% compared with the method relying on experience. The results of this study will be useful in establishing earthwork plans by taking into consideration the productivity of equipment per type and combination.

Keywords: earthwork; excavation; combination model; equipment; high-rise buildings

1. Introduction
Excavating for a building construction project in a downtown area can limit the amount of equipment that can be used because the site is both narrow and deep. Therefore, the interference and movement of equipment is quite sensitive to the limits of the area, as shown in the analysis of project excavator productivity (Table 1.). In addition, the efficiency of different equipment varies according to the type and amount of other equipment used. Engineers or technicians who can devise an efficient equipment combination can enhance productivity and reduce construction duration and cost. Here, 'equipment combination' refers to the combination of the types of equipment and the number used. However, determining an efficient combination requires more time and information than engineers and technicians usually have. Therefore, they generally dispatch equipment based on their own experience, which leaves them unable to accurately predict the construction duration or cost. To address this problem, studies have examined the distribution of earthwork quantity (Easa, 1988; Easa 1987; Jayawardane and Harris, 1990; Moreb, 1996) and the combination of excavation equipment, but they were based on mining equipment or roadwork. No studies have examined narrow and deep excavation in downtown areas. Therefore, this study intends to develop a combination model to improve the efficiency of earthwork equipment.

The first stage of the model is to divide the work into sections and limit the types of equipment used. The second stage is to combine the equipment for the excavation of each section, review its productivity and estimate the cost. Lastly, the cost of the equipment used in every section is calculated to find the minimum cost combination. The procedure adopted in developing this model is described below.

1) Analyzing productivity changes based on equipment combinations by looking into past cases;
2) Drawing a cost estimation method for simulation;
3) Building a combination model to compute the minimum cost;
4) Developing an equipment combination simulation for the excavation of soil and rock; and
5) Verifying the simulation based on a case study.
2. Theoretical Consideration

Marzouk & Moselhi (2004) and Zhang (2008) utilized simulations and genetic algorithms for equipment combination. Furthermore, Moselhi & Alshibani (2009) and Markiz & Jrade (2015) applied genetic algorithms to find an optimized simulation for equipment combination, taking into account geological strata. However, this differs from an optimization study based on original project data, which requires a thorough analysis of various factors that may impact the productivity of earthwork. Also, simulation results should be assessed based on the analysis results. However, in reality, it is difficult to consider all of the numerous factors that may impact productivity. We feel that the statistic-stochastic analysis method of the study may be more accurate than other methods. In addition, we considered that the same combination in probabilistic reflection of productivity may lead to different results. It is believed that such differences have study implications.

Easa (1987) conducted a study on the distribution of earthwork quantity for roadwork and estimated the cost of earthwork. In addition, Easa (1987) proposed a plan to reduce costs by increasing the efficiency of excavating and back-filling. Shah (2014) automated location-based earthwork scheduling in road construction. However, those studies did not consider efficiency based on the amount of equipment in a narrow space or optimize the horizontal location and movement of equipment. Several other studies with a different scope considered similar ideas. Jayawardane (1990) studied methods for planning an efficient operation when the soil differs in road construction. Sthapit et al. (1994) presented an earthwork quantity estimation model for highways. Ahmad A. Moreb (1996) improved Easa’s (1988) study to propose a linear plan model to minimize the costs related to earthwork in road construction. Easa (1988), Jayawardane (1990), Sthapit (1994) and Moreb (1996) all established plans to reduce the cost and duration of excavation and backfill, but they failed to draw an equipment combination.

Swamee et al. (2001) performed a study on earthwork planning to minimize the cost of a canal, but it differs from the scope of this study. Also, Mawdesley et al. (2002) devised a model for the automatic creation of earthwork plans based on the main balance line, but it was a model for the distribution of earthwork quantity and order that made it impossible to reduce costs based on equipment combination and analyses of productivity. Kim et al. (2012) developed an intelligent earthwork system planning and resource allocation method, but it was focused on the horizontal alignment of equipment for earthwork, making it unusable for finding new combinations that need to consider productivity and the cost of equipment.

Göktepe et al. (2003) implemented a study on the geometric design of highways; however, efficient equipment combination was not taken into consideration. Other studies include an optimization plan considering the effect of soil quality on the geometric design of highways by Göktepe et al. (2004) and an inaccurate fuzzy optimization model for earthwork quantity allocation developed by Mohamad Karimi et al. (2007). In addition, Göktepe et al. (2008) proposed a fuzzy decision-making model for road earthwork, and You et al. (2009) built a digital earthwork model for the automation of excavators. None of those studies found the equipment combinations considering efficiency and productivity.

Ji et al. (2010) and Moon et al. (2007) proposed a mathematical model for optimization of earthwork, and Hare et al. (2011) conducted a study applying a design algorithm linear plan to road construction, establishing a plan for excavation and backfill, and improving efficiency in terms of cost and construction duration. Also, Kim (2003) proposed system architecture for an intelligent earthwork system. However, those studies did not consider interference among pieces of equipment. Naoum & Haidar (2000) proposed an integrated information system and genetic algorithms for equipment selection, and Cheng et al. (2011) proposed a simulation model for virtual construction of earthmoving operations. However, their plan did not take into account that the productivity of equipment can vary according to the situation. And those studies did not consider interference of equipment. In addition, it did not consider changes in the geological stratum and rocks that can occur with deep excavation. Thus, this study develops an equipment combination model per stratum for excavation work in downtown areas.

3. Cost Estimation for Excavation

3.1 Excavation Work Type

Construction conditions should be analyzed to estimate the time and cost of excavation. The construction conditions refer to the width and depth of the excavation and the stratum composition. Thus, the earthwork quantity should be estimated depending on the earth, sand and rock types. Excavation sections should be classified based on the soil quality and the construction duration (time), and cost should be calculated per section. The work per section can thus be classified depending on the soil and rock by stratum, as shown in Fig.1., and each section should have plans for excavation and removal. When soil is to be excavated, the excavator, loader and truck should be combined, and for rocky strata, rock-breaking equipment should be used. In addition, when the excavation work is completed and the removal work is in progress, as shown in combination case 2 of Fig.1., the number of excavators, loaders and trucks is determined considering efficiency.

![Fig.1. Concept of Work Type Per Section](image)

Combination case 1

Excavate (soil) : Excavator
Remove (soil) : Excavator, loader, truck

Case 2

Excavate (rock)

Case 3

Remove (rock)
3.2 Cost Estimation

A model for selecting earthwork equipment needs to determine the combination with the minimum total cost. The cost per section should be estimated using a method with a simulation structure. For cost estimation, the number of strata, quantity per stratum and maximum daily productivity of the excavator should be identified. Furthermore, cost is divided per section for estimation, and depending on the work type, the cost is classified by excavation, loading, disposal and rock breaking. General parameters and cost parameters for estimation are described below.

- **General parameters**
  
  \[ n = \text{Number of strata} \]
  \[ Q_i = \text{Amount of soil and rock in section } i \]
  \[ N_{i,k} = \text{Number of excavators for section } i \text{ (EQD)} \]
  \[ N_{i,k} = \text{Number of loaders for section } i \text{ (EQD)} \]
  \[ N_{i,k} = \text{Number of trucks for section } i \text{ (EQD)} \]
  \[ q_{i,k} = \text{Daily productivity of excavator } k \]
  \[ q_{i,k} = \text{Daily productivity of loader } k \]
  \[ q_{i,k} = \text{Daily productivity of truck } k \]
  \[ q_{i,k} = \text{Daily productivity of rock breaking equipment } k \]

- **Cost parameters**
  
  \[ C_i = \text{Earthwork cost of section } i \]
  \[ C_{\text{total}} = \text{Total earthwork cost} \]
  \[ C_{i,2} = \text{Excavation cost of section } i \]
  \[ C_{i,3} = \text{Loading cost of section } i \]
  \[ C_{i,4} = \text{Disposal cost of section } i \]
  \[ U_C = \text{Unit rental cost of equipment } k \text{ (USD/EQD)} \]

To estimate the cost per section, the earthwork quantity of each section should be identified. As shown in Equation 1, the total quantity of earthwork \((Q_{\text{total}})\) is calculated by adding up the earthwork quantity \((Q_i)\) of each section \(i\). As shown in Equation 2, the total cost \((C_{\text{total}})\) is calculated by adding all of the section costs \((C_i)\). The section costs \((C_i)\) are the sum of the cost per equipment type used \((C_{i,1} - C_{i,4})\), as shown in Equation 3. The cost is estimated by reflecting the quantity for each unit cost per equipment type, as shown in Equation 4.

\[
Q_{\text{total}} = \sum_{i=1}^{n} Q_i \quad (1)
\]
\[
C_{\text{total}} = \sum_{i=1}^{n} C_i \quad (2)
\]
\[
C_i = C_{i,1} + C_{i,2} + C_{i,3} + C_{i,4} \quad (3)
\]
\[
C_i = \sum_{k=1}^{a}(U_C \times N_{i,k}) + \sum_{k=1}^{b}(U_C \times N_{i,k}) + \sum_{k=1}^{c}(U_C \times N_{i,k}) + \sum_{k=1}^{d}(U_C \times N_{i,k}) \quad (4)
\]

The quantity of work (excavation) performed by the equipment should be larger than the volume of soil or rock. Equations 5–8 express such conditions as formulae. Also, the earthwork equipment combination model simulates the amount of equipment using these 4 different equations.

\[
Q_i \leq \sum_{k=1}^{a}(q_{i,k} \times N_{i,k}) \quad (5)
\]
\[
Q_i \leq \sum_{k=1}^{b}(q_{i,k} \times N_{i,k}) \quad (6)
\]
\[
Q_i \leq \sum_{k=1}^{c}(q_{i,k} \times N_{i,k}) \quad (7)
\]
\[
Q_i \leq \sum_{k=1}^{d}(q_{i,k} \times N_{i,k}) \quad (8)
\]
Simulation 1 checks the excavation quantity, the work space and the truck paths, to see whether particular pieces of equipment can be used. At this point in the process, engineers or technicians should review the work space and truck paths.

3.4 Simulation for Soil and Rock Excavation

Excavation of soil and rock are not the same. An equipment combination can be created without reviewing the use of rock breaking equipment for a stratum filled with soil. Fig.4. illustrates the simulation algorithm for a combination that determines the maximum amount of equipment, reviewing the available machines and the work space. The algorithm reviews the available equipment and decides the maximum number of pieces of equipment considering the space. The equipment combination should be within the range that satisfies Equations 5-6. After creating all possible combinations, the algorithm saves them and is completed.

4. Quantity of Excavation Equipment & Productivity

Excavation of soil and rock are not the same. As with simulation model 2, it determines the maximum amount of equipment for the work space, considering the equipment available. The equipment combination should be within the range that satisfies Equations 5–7. After creating all the possible combinations, the algorithm saves them and is completed.
For this project, an excavator with a 1-m$^3$ bucket was used for excavation, and excavators with 0.2-m$^3$ and 0.6-m$^3$ sized buckets were used for work other than the excavation. Fig.7-(a) shows the daily excavation volume of the 1-m$^3$ sized excavator, expressed in a scatter diagram. The data were classified based on the amount of equipment used per day to determine changes to productivity caused by interference. The excavators with bucket capacities of 0.2 m$^3$ and 0.6 m$^3$ were not used for excavation, but because they were within the work space, they could have interfered with the operation. The excavators used in the project operated for 11 hours a day.

The 'H' project spent 82 days purely on excavation. Excluding 6 days when the weather was not good, data were collected for the remaining 76 days. The excavation volume was estimated using the amount of soil carried out per day. As demonstrated in Table 1., when 3 pieces of equipment were used for the work, the daily average (mean) excavation volume was 746.5 m$^3$; with 4 pieces, the daily average was 641.9 m$^3$; with 5 pieces, the daily average was 583.4 m$^3$.

To investigate differences in productivity among the 3 groups, the null hypothesis (H$_0$), 'There is no difference in productivity among the 3 groups,' was used. An ANOVA test was conducted with the case site with a 95% confidence level to see whether the productivity changed according to the number of equipment. Table 2. shows the results of the ANOVA test: the f value is 5.41, and the p value is 0.006. The null hypothesis (H$_0$) can be rejected within the confidence level. Therefore, the 3 groups had differences in productivity.

Because most geological strata in this project were composed of soil, changes to productivity according to the amount of equipment can be said to be caused by limited space and interference among pieces of equipment. Interference was proven by analyzing the route of the excavators and trucks during project implementation. As observed on site (Fig.7.-a), a truck should load soil next to an excavator, and when the excavator was nearby, the route of (1) and (2) overlapped. Also, small equipment unrelated to the excavation work operated within the truck's route. (1)–(4) of Fig.7.-b show the places where a small
excavator was under operation for drain work and surplus soil cleaning. (3) and (4) did not affect the excavation work, but (1) and (2) changed the truck’s waiting spot and movement.

Such productivity decreases in a narrow work space can be expressed as the relationship between construction cost and working hours. Without a decrease in productivity, cost would not change when the amount of equipment increases and the construction duration decreases. Productivity can change not only with the amount of equipment, but also with equipment type. The amount and type of equipment used simultaneously is called an equipment combination.

The combinations that can be applied to projects vary widely. Fig.8. is a conceptual graph of cost and time for a wide range of equipment combinations. Productivity, cost, and construction time vary with the equipment combination, and the combinations (case 1) that do not exceed the time (a) and or cost limitations (b) become candidates. The objective of the simulation model proposed in this study is to find the combination(s) with the highest productivity among those in case 1.

5. Case Study

This study verifies its model by choosing a case project, checking the productivity and searching for an optimal equipment combination. The case project is an earthwork that extends to 4 underground levels, as shown in Fig.9., with CIP (Cast-in-concrete pile) used for sheathing and trench excavation performed twice. In addition, the space near the temporary office is narrow, so small equipment should be used. In light of the characteristics, the volume of sand and earth per section was calculated, and the maximum number of excavators used simultaneously was limited to four or less. The total excavation quantity is approximately 171,000 m$^3$, and it is simulated in 6 steps (Fig.9.), depending on the work type.

In this case, the rocks discovered upon excavation could be easily removed using an excavator or crushed using an excavator's breaker. So, a breaker was installed on an excavator for rock breaking. The simulation was implemented for 3 types of equipment based on the bucket capacity (BH06W, BH08W and BH10W).

It was assumed that a loader was not used, a truck could transport materials sufficiently, and the combination of equipment was optimized (the core of the simulation). Also, there were no data on using loaders in narrow places, so the case study was conducted assuming that loaders were not used. The simulation found a combination that satisfies the limited time shown in Fig.10. The combinations labeled (a) in Fig.10., which do not meet the time and cost constraints, are excluded from the candidate values.

A Monte Carlo model was used for random-number generation when creating the simulation combinations, and the average (mean) productivity shown in Table 1. was applied to create candidates. The generation used OracleTM Crystal ball v.11. The construction duration (time) was set at 76 days, which was the same as the excavation time. The number of variables created per simulation was 1,000, and after implementing the simulation 3 times, the results were drawn as shown.
The lowest value of the first simulation used 192 pieces of equipment and cost 168,132 USD. The third and fourth simulations would have spent 167,631 USD and 167,702 USD, respectively. Thus, those combinations reduced the cost by 5,000 USD or more compared to the actual cost input for the project, which was equivalent to 174,581 USD. When the simulation was conducted by limiting the construction time to 70 days, the cost was 173,094–180,528 USD, as shown in Table 4. Cost was not reduced, but the time was reduced by 6 days.

The values drawn from the second simulation, which had the lowest cost, have the statistical characteristics shown in Table 5. The average (mean) was 92,762 USD, and the standard deviation was 3,541 USD. Considering the simulation characteristics, it is difficult to obtain the same value every time it is conducted. Nonetheless, this model would have allowed engineers or technicians to find relatively efficient equipment combinations for the project. After applying the combination algorithm, it is clear that engineers or technicians missed the chance to reduce their costs by 5,000 USD or more by relying on their experience.

The differences in simulation results are probably caused by differences in equipment productivity and constraint conditions. Fig. 11 shows section A as excavated using 2 different sets of equipment, BH06W and BH10W. It takes 2.5 days to work on section A, and after it is completed, section B must also be excavated. Sections B and C can be excavated without using BH06W, which has relatively low productivity. However, because the simulation assumes that equipment is rented per day, after section A is completed, BH06W should be mobilized for section B. Thus, other equipment, such as the more efficient BH10W could be used for sections B and C.

The model proposed in this study establishes an operation plan that limits the time and minimizes the cost. The results of such a method cannot be taken as the best value because reducing the construction time could lead to positive results even when the cost increases. However, when various time ranges are applied to the model, the best result can be found. For instance, as illustrated in Fig. 12, among the combinations (a)–(f) that meet the cost and time limits, the best value in terms of cost is (f), and the optimum value in terms of time is (a). To identify which value is more suitable for the site, the construction time should be converted into cost by calculating all expenses arising from an increase of time. Therefore, a line that represents the equivalent value of time and cost can be drawn, and the optimum value (d) can be found.

6. Conclusion

This study developed a combination model to improve the efficiency of excavation equipment in deep, narrow spaces. The model is organized using a combination algorithm, and its efficiency was verified through a case study. The combination model is composed of a combination model and 3 simulation models. Simulation 1 determines whether a loader is to be used, and Simulation 2 creates equipment combinations for soil excavation. Simulation 3 creates equipment combinations for rock excavation.

a) The simulation algorithm proposed in this study draws the equipment combinations to enhance the efficiency of earthwork equipment. As a result of the case study, the algorithm found an alternative that could reduce the cost by around 5,000 USD compared to the actual cost for model project.

b) Productivity varies by the amount and type of equipment. When equipment is combined considering constraints such as soil quality,
volume and work conducted simultaneously, productivity can be improved.

c) Simulation models should be able to create all combinations within the constraint conditions. The total cost can change according to the type of earthwork, the excavation volume and pre/post-operations.

d) Productivity should be taken into consideration to obtain the best equipment combination. The work section should be split, and the sequence based on time flow should be reviewed. To do so, it is necessary to review the equipment combination continually without reference to the work sections.

e) In the case of excavator–truck combinations, the path of the truck could be altered or its movement postponed, a representative cause of productivity change.

f) Any change to the total cost depending on the equipment combination should be checked. Using large equipment is not necessarily a good combination, and various simulations should be conducted to find the best combination.

These study results will be useful in establishing earthwork plans by taking into consideration the productivity of equipment per type and combination. By constantly collecting data on the productivity of a wide range of equipment, the reliability of the proposed model can be improved. In addition, further studies should subdivide the steps (sections) of the earthwork and measure productivity changes by step for earthwork planning in downtown areas.

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