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Optimal cut-fill pairing and sequencing method in earthwork operation

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ABSTRACT

Earthwork operations consist of repeated cycles of excavating, moving, and backfilling processes, in which rock-earth block is excavated from its cut pit, moved to a fill pit, and then backfilled into its corresponding fill prism. An efficient earth allocation plan reduces the total earthwork cost. This paper presents a computational method called Optimal cut-fill Pairing and Sequencing (OPS) which identifies the most economical EAP. It identifies the optimal cut-fill pairs and their sequence which minimizes the total earthwork cost by hybridizing the mixed integer linear programming (MILP) and evolutionary algorithm (i.e., harmony search). The proposed method is of value to earthwork managers because it identifies the most favorable EAP by accounting for the rock-earth type of each and every prism, the series of prisms occupying each and every cut and fill pits, and the moving directions (i.e., the order of cut-fill prism pairs), expeditiously. This study is also of relevance to researchers because it provides a white box which defines the mathematical formula and computational procedures to identify the global solution in detail. Two test cases confirm the usability and validity of the computational method.

1. Introduction

An earthwork site consists of many cut pits (i.e., stations, cells, areas, or grids) and/or fill pits, regardless of whether it is a linear project (i.e., road or highway) or planar project (i.e., housing, residential, or industrial complex, etc.). Its planned ground elevation may be achieved by performing repeatedly an engineered earthwork operation in which an earth unit is excavated from its corresponding cut pit, moved to a fill pit, and backfilled into its corresponding fill prism which minimizes the expenditure. Previous studies use various terminologies to denote a segment of land under earthwork operation at a specific distance, such as station [1,2], cell [3,4], pit [5], and grid [6]. A pit or cell is sliced into a series of prisms or earth units, each of which has the same horizontal slice height. The unit of earth with a special quantity and material type is called either an "earth unit" [4] or "earth block" [7]. Instead of using these terms, the term prism is used in this study because "earth block" may refer to a soil block cylinder used for geotechnical tests. A cut pit or cell may contain a series of cut prisms or earth units to be excavated from top to bottom, and a fill pit may have a series of fill prisms to be backfilled from bottom to top. A prism contains a volume of rock-earth with a special type of material in a square column, which has the same width (w) and length (l) but may or may not have the same height (h). It may correspond to the earthmoving production unit [1].

The earthmoving operation utilizes large pieces of heavy equipment (e.g., excavators for cutting, trucks for loading and moving, dozers for spreading, and compactors for ramming, etc.) that incur high hourly owning and operating cost [8]. This represents the highest percentage of the total construction budget, because it is one of the most equipment-intensive and expensive operations [9,10]. Earthwork allocation planning requires all facets of the earthwork operational information under study. This information may be obtained by two types of investigation. The first is studying the contract documents (i.e., engineering drawings, project manuals, and ground investigation reports, geological columnar sections, soil sampling data, etc.); the second is conducting a rigorous job site investigation to handle the job site constraints and productivity correction factors which include the soil properties, the locations of the borrow pit(s) and disposal pit(s) and their capacities, historical target weather information, etc. These two types of investigation enable the earthwork manager to obtain a better understanding of the operation in order to minimize the uncertainty involved in the earthwork productivity estimation.

Existing earthwork optimization methods are classified into equipment fleet planning (EFP) and earth allocation planning (EAP). EFP identifies the most favorable equipment type, computes the optimal number of equipment, calculates the anticipated earthwork productivity, and allocates equipment at the right time and place on schedule [11,12]; EAP identifies the optimal cut-fill pairs and their

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sequence to minimize the total earthmoving cost by assigning cuts to fills economically, that is, by identifying what amount of earth should be moved from which cut pits to which fill pits in which order [10,24,39]. An erroneous EAP leads to moving nonconforming cut prism(s) which may not conform to the rock-earth quality required by their corresponding fill prism(s), thereby unbalancing the cut pits and fill pits, desynchronizing the prism moving with the earthwork schedule, hence, causing unnecessary expensive corrective actions [13]. Indeed, EAP is a sophisticated engineering problem having a large solution space.

Various EAP methods, which are based on either linear programing (hereafter, called LP-based EAP) or evolutionary algorithms (hereafter, called evolutionary-based EAP), have been introduced into the earthwork community to identify favorable cut-fill pairs and their sequence [9,14,15]. However, very few of them provide a mathematical formula and computational procedure that identifies the optimal solution (i.e., cut-fill prism pairs and their sequence) by considering the rock-earth types of each and every cut prism and fill prism, thereby enabling an earthmoving truck to move a cut prism to its corresponding fill prism by taking the current best route, and reducing an excavator's repositioning time between cut pits by digging out as many cut prisms as possible, once the cut pit is positioned. It is certain that none of the existing EAP methods offer the earthwork community a computational method coupled with automated software that identifies the exact global solutions by considering these issues comprehensively. A new computational method which handles these issues with the least cost is presented in this paper. Integrating this method into the earthwork management arsenal would be beneficial by allowing for effective cost saving.

The research was conducted in six steps. First, the performance of the existing EAP methods was investigated by reviewing previous studies. Second, the major issues which limit the existing EAP were identified. Various strategies were implemented to complement the deficiencies of the existing methods. Third, a new computational method, which identifies the optimal solution (i.e., cut-fill prism pairs and their sequence) by considering the issues mentioned in the previous section is implemented. This new method identifies the time at which a cut prism should be excavated from which cut pit, moved to which fill pit, and backfilled into which fill prism. Fourth, this new method was coded into a system to make it practical for handling the real-world earthwork frequently encountered in practice. Fifth, the computational method was illustrated in detail using a small linear road construction project to confirm that it moves the appropriate cut prisms, which satisfy the rock-earth quality required by their corresponding fill prisms, located in subgrade or road-bed positions. In addition, its validity as an efficient EAP tool for planar project was verified by testing it on a real world earthmoving project for a commercial complex. The computational performance, practicality and usability of the new method were verified by performing these case studies. Finally, the contributions, limitations, and suggestions relative to this method were discussed. The material in this paper is organized in the same order.

2. Current state of earth allocation planning methods

An EAP aims to minimize the total earthmoving cost by computing the volumes of cuts and fills, and identifying the optimal cut-fill pairs and their sequence, which result in the most economical operation execution. A mass haul diagramming method, which measures the haul distance graphically, is useful for the EAP tool of linear earthwork. It provides the essential information (i.e., the volume of rock-earth, the average haul distance, the terrain, etc.) for selecting the most economical equipment type [16]. However, it does not lend itself to handling the unit moving cost, identifying the cut-fill prism pairs by considering their rock-earth types, and handling overcut or overfill to sequence the cut-fill pairs in such a way as to keep this process in line with the top-down excavating and bottom-up backfilling rules, etc. ([16,17,39]).

After the linear programing (LP) method was introduced by Stark and Nicholls [18] to complement the limitations of the mass haul diagram, the deterministic LP based EAP method was expanded to incorporate the earthwork productivity variables comprehensively ([39]), to optimize the earthwork allocation schedule [14,19–22], and to minimize earthmoving cost by identifying the optimal cut-fill pit pairs [23]. Its determinism was replaced by a fuzzy linear programing (FLP) model [16] that computes the variability of the earthwork productivity by handling the uncertainty of the input variables (i.e., the maximum capacities of the borrow pits and disposal pits, the unit earthmoving costs of a cut prism and fill prism, etc.) using fuzzy numbers. After mixed integer linear programming (MILP) model was introduced to consider the path accessibility constraints attributed to obstacles (i.e., such as creeks, groups of trees, or rock-bed, etc.) [9], the supply of different rock-earth types (e.g., crushed stone, soil, etc.), and the rock-earth mixing plant's location [17], the deterministic method was hybridized with the Floyd-Warshall algorithm to identify the optimal temporary road network that maximizes the earthmoving productivity [24]. In addition, it is expanded to handle the variability of the unit moving cost by considering the terrain changes and the rock-earth types of the cut prisms [13], etc.

Evolutionary based EAP methods were introduced in recent years [7,10]. They include a least-cost route cut and fill model (LCRCFP) that minimizes the earthmoving cost given a fixed equipment operation by hybridizing the particle swarm optimization (PSO) and branch and bound algorithm [10]. A new version called the shortest path/least cost route model, which calculates the earthmoving cost by updating the contour information, equipment specification, job site attributes, and rock-earth attributes in real time using simulated annealing, was recently released [7]. Recently, Li and Lu [4] proposed an automated earthwork scheduling method that generates a work breakdown structure (WBS) followed by a schedule network model by identifying the optimal earthwork volume allocation among cut and fill cells.

No clear depth mapping of the soil rock layers for a site is available in reality. The underground vertical layers may be soils or rocks with different classes or densities, and a series of prisms with different rock-earth types may be obtained from a cut pit. Very few EAP methods consider the rock-earth types of the cut prisms and those of fill prisms together. Existing methods assume that each prism has the same rock-earth type at best, and the 'bulky rock' prism is merely waste for disposal pit [13]. No study has provided mathematical methods that handle the following issues. First, the series of cut prisms that should be excavated in the top-down sequence from its corresponding cut pit may have different rock-earth types or soil classes. In addition, each fill prism that should be backfilled into its corresponding fill pit in the bottom up sequence may have different rock-earth types as well. For example, given a fill pit with a subgrade and a road bed, the subgrade that supports the asphalt paving layer of a fill pit accepts 'quality soil' only (i.e., less than 100 mm particle-size). Second, it would be desirable to minimize the excavator's repositioning time by minimizing its travel distance between two consecutive cut pits, as far as its digging depth permits, and to reposition it at the nearest new pit (or face), as long as its repositioning time is less than the truck's inter-arrival time. An economic operation may be achieved by constraining the excavator to dig out as many cut prisms as possible once it is positioned in the cut pit. Third, the series of cut prisms (i.e., the number of cut prisms and their soil types) in the cut pit and that of the fill prisms (i.e., the number of fill prisms and their soil types) in the fill pit should be considered when the cut-fill prism pairs and their sequence are searched. The series of prisms and their associated attributes may be obtained from the geological columnar sections which correspond to each and every pit. Fourth, the corrective action costs for secondary blasting, which are incurred due to the necessity to fix the nonconforming rock-earth prisms to satisfy the quality requirements of each fill prism (i.e., subgrade or road bed), should be considered. Given a nonconforming prism