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Application of an interval wear analysis method to cutting tools used in tunneling shields in soft ground

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ABSTRACT

The replacement of cutting tools is important when shield tunneling in abrasive soils. The task is performed based on an assessment of the degree of cutting tool wear. The wear of cutting tools is influenced by many factors, such as the soil abrasiveness, shield machine operational parameters, and tool sliding distance. The representation of the uncertainty in these factors is the primary problem in the evaluation of tool wear. Instead of real variables, interval variables are employed to represent the uncertainty in the influencing factors, and the interval of the tool wear amount is attained based on interval arithmetic operations. With the calculated interval for the amount of tool wear and the dimensionless indices η and ξ, the feasibility of completing shield tunnel construction with tool wear within a predefined tolerance is quantitatively evaluated. Measures and countermeasures can be implemented based on the results of the evaluation. A five-step process for conducting an evaluation is described and explained using an example application. The suggested methodology can help realize active tool replacement and obtain cost-effective and less-disruptive solutions for shield cutting tool wear in tunnel construction.

1. Introduction

The soft ground shield tunneling method is common in construction of subway tunnels as well as road, railroad, water, utility tunnels and etc. throughout the world. The cutting tools of shield machines endure substantial wear when tunneling in abrasive soils, and this wear significantly impacts the operation, schedule and cost of tunnel construction. Planning tool replacement based on an assessment of tool wear is indispensable for rapid construction. Assessment of the wear amount of tools, which is primarily dependent on two types of factors—geological and technical—is critical. The former type of factor refers to the soil abrasiveness, whereas the latter is associated with the shield machine operational parameters, the tool sliding distance, and the shape and materials of tools. These factors serve different roles in controlling the wear of shield cutters. For a subway tunnel construction project, the shield machine and cutting tools are usually specific to the project. The configuration of the cutter head and the layout of the cutting tools remain unchanged during the entire tunneling process, with the exception of cutter head innovation and adjustment of tools, which are performed in the case of excessive primary and secondary wear of the tunneling shield. Selection of reasonable shield operational parameters is important for reducing wear of the cutting tools. Reasonable characterization of the soil abrasiveness and the operational parameters is critical for prediction of the shield cutting tools wear.

Recently, attempts to describe and quantify the wear of tools have been made. Indoor tests to connect the abrasivity of soils with a limited array of essential soil properties—namely, the mineralogy, angularity of soil grains, and grain size distribution—have been devised by many researchers [1–16]. Zhang et al. [17] monitored the wear of cutting tools that were employed during construction of a shield tunnel of line 4 of the Beijing subway and established the relation between the wear coefficients of the tools and the shield tunneling parameter. DiPonio et al. [18] discussed the factors that affect the wear and breakage of ripper cutters during construction of the BWARI Project for the City of Columbus; the distance that a cutter travels and the soil conditioning were highlighted. Kawashima et al. [19] predicted the wear of cutter bits based on data that were collected by cutter bit wear detectors during the boring of a 3400-m tunnel through boulder and alluvial sand formations. They determined that the subsequent wear could be predicted using detector-measured data and that the wear of the bits was proportional to the sliding distance of the tools. Walter et al. [20] suggested some novel techniques for measuring the physical wear of

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Fig. 1. Cutting tools used in soils.

cutting tools and conferred the integration of sensors and acquisition devises. Frank et al. [21] and Gharahbagh et al. [22] developed a novel approach to monitor gauge cutter wear by considering the relationship between the overcut length and the length of the gauge cutters. Using this testing system, continuous monitoring of the gauge cutter length is possible while excavation is in progress. Gharahbagh et al. [23] discussed the anticipated tool wear and the major parameters that influence tool wear in several projects and introduced a new method for the prediction of tool wear in the U230 project, which is based on data from the Beacon Hill and Brightwater projects. Köppl and Thuro [24] employed an empirical approach to model tool wear in soft ground by performing a detailed data analysis of 18 mix-shield drives and presented a prognosis model for cutter life and tool wear based on empirical correlations with soil parameters and machine design and advance parameters. Rahm et al. [25] presented an approach that is based on fuzzy logic to integrate the performance-related influence of the wear of cutting tools on the advance rate and illustrated the influence of wear on the advance rate in the context of disturbances. However, the majority of these methods consider the geological and technical factors that influence the wear of tools to be real variables and disregard spatial variability in the soil properties and the characteristics, which vary within certain ranges, of the shield operational parameters. Despite a lack of in-depth knowledge regarding the uncertainty of soil abrasiveness, the use of a certain interval to represent the variation in soil abrasiveness may be a potential solution. This approach is valid for the shield operational parameters. Considering the factors that influence tool wear to be interval variables, a practical and realistic approach for estimation of tool wear amount is proposed. This approach is based on the theory of interval analysis, which is a means of representing uncertainty by replacing single values with intervals. A quantitative analysis of tool wear is conducted after the interval of the tool wear amount and the two dimensionless indices are defined. The results of the evaluation are helpful for planning tool replacement, which is a cost-effective and less-disruptive solution for rapid shield tunnel construction.

2. Tool wear amount prediction model based on interval arithmetic

2.1. Basic operations of interval arithmetic

Interval arithmetic defines a set of operations on intervals, whereas classical arithmetic defines operations on individual numbers, which is a powerful technique for bounding solutions under uncertainty that was developed by mathematicians in the 1950s and 1960s. This concept is suitable for a variety of purposes and is extensively employed to solve various uncertainty problems.

Let $[a] = [\underline{a}, \bar{a}]$ and $[b] = [\underline{b}, \bar{b}]$ be real compact intervals. Using one of the basic operations '+', '−', '·'and '/', the following rules for the corresponding operations for the intervals $[a]$ and $[b]$ hold [26,27]:

$$[a] + [b] = [\underline{a} + \underline{b}, \bar{a} + \bar{b}] \tag{1}$$

$$[a] - [b] = [\underline{a} - \bar{b}, \bar{a} - \underline{b}] \tag{2}$$