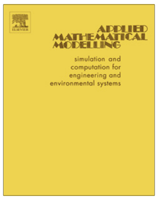
ARTICLE IN PRESS

Applied Mathematical Modelling xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm



Evaluating risks using simulated annealing and Building Information Modeling [☆]

Dong-Woo Ryu [a], Jung In Kim [b,*], Sunduck Suh [c], Wonho Suh [c]

[a] *Korea Institute of Geoscience and Mineral Resources, Deajeon 305-350, South Korea*
[b] *Center for Integrated Facility Engineering (CIFE), Department of Civil and Environmental Engineering, Stanford University, Y2E2 Building, 473 Via Ortega, Room 292, Stanford, CA 94305, USA*
[c] *Department of Transportation and Logistics Engineering, Hanyang University, 55 Hanyangdaehak-Ro, Sangnok-Gu, Ansan 426-791, South Korea*

ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 1 March 2015
Accepted 24 April 2015
Available online xxxx

Keywords:
Risk analysis
Tunnel construction
Simulated annealing
Building Information Modeling

ABSTRACT

Tunnel construction involves significant uncertainties in ground conditions, often causing cost overruns and schedule delays. To mitigate these risks, general contractors (GCs) should predict varying ground conditions based on information regarding ground conditions acquired before construction (i.e., borehole and geophysical investigations). Subsequently, GCs should also evaluate excavation costs and durations of their schedule based on predicted ground conditions; however, this is challenging because in current practice, GCs lack a method to incorporate these required processes into their existing evaluation process in a structured manner. To overcome this limitation, we developed a methodology to predict multiple sets of ground conditions by using simulated annealing (SA), which is a geo-statistical method, and then evaluate excavation costs and durations of a tunneling schedule via Building Information Modeling (BIM). For integration of SA and BIM, we extended existing BIM to accept multiple sets of ground conditions. To validate the effectiveness of our methodology, we applied it to a tunnel in Korea. Based on the application, we highlight that our methodology enables GCs to formally evaluate risks in excavation costs and durations of tunnel construction with complete information about ground conditions acquired before construction.

1. Introduction

Tunnel construction involves significant uncertainties in ground conditions that affect both tunnel design (e.g., support systems) and excavation productivity. Although various geotechnical (e.g., borehole and geophysical) investigations are performed before actual construction, there is often a certain degree of deviation between predicted and actual ground conditions. Panthi et al. [1] compared the predicted and actual rock mass conditions for four recently-constructed hydro-tunnels in Nepal Himalaya: the Khimti 1, the Kaligandaki “A”, the Modi Khola, and the Middle Marsyangdi headrace tunnels [1]. They found that considerable differences existed between predicted and actual rock mass conditions for all four tunnels. In particular, although Class 3 (i.e., middle ground condition) was dominant in the predicted condition for the Kaligandaki

---

[☆] 2013 International Applied Science and Precision Engineering Conference, October 2013 NanTou, Taiwan.

[*] Corresponding author. Tel.: +1 650 723 4945; fax: +1 650 723 4806.
E-mail addresses: dwryu@kigam.re.kr (D.-W. Ryu), jikim07@stanford.edu (J.I. Kim), sunduck@hanyang.ac.kr (S. Suh), wonhosuh@hanyang.ac.kr (W. Suh).

http://dx.doi.org/10.1016/j.apm.2015.04.024
0307-904X/© 2015 Elsevier Inc. All rights reserved.

Please cite this article in press as: D.-W. Ryu et al., Evaluating risks using simulated annealing and Building Information Modeling, Appl. Math. Modell. (2015), http://dx.doi.org/10.1016/j.apm.2015.04.024

“A” tunnels, Class 6 (i.e., poor ground condition) was dominant in the actual conditions. Due to these uncertainties in ground conditions, general contractors (GCs) often encounter difficulty completing their projects on time and within budget.

To mitigate the risks caused by these uncertainties, GCs should conduct two required processes in preconstruction. First, GCs should predict varying ground conditions with complete information about ground conditions (i.e., borehole and geophysical investigations) acquired before construction. In addition, when predicting ground conditions, GCs should take into account spatial relationships among ground conditions because the ground conditions are spatially correlated with each other. Next, GCs should also evaluate the excavation costs and durations of their schedules based on the varying ground conditions predicted.

Recently, ground conditions such as Rock Mass Rating (RMR), which was developed in 1973 requiring only a few basic parameters relating to the geometry relating to the geometry and mechanical conditions of the rock mass to improve the quality of site investigations by calling for the minimum input data as classification parameters, provide quantitative information for design purposes and enable better engineering judgment and more effective communication on a project, and Rock Quality Designation (RQD) have been estimated in unsampled areas based on the given data using geostatistical methods such as kriging and conditional simulation, which take into account geospatial relationships among sampled and unsampled areas [2–4]. Although kriging methods have been regarded as a good predictor from the viewpoint of specific statistical criteria such as minimum variance and unbiasedness, kriging methods have a serious shortcoming in that their resulting maps cannot reproduce a predefined spatial variability or other statistical models [5]. Thus conditional simulation methods can be considered as a remedy for the shortcomings of kriging and have been used in the prediction of geotechnical attributes that are spatially distributed; however, existing studies about conditional simulation methods cannot provide a formal reasoning mechanism appropriate for tunnel construction to reduce the uncertainty that is due to deficiency of borehole data and to exploit other types of information regarding ground conditions (e.g., geophysical investigation).

Building Information Modeling (BIM) supports decisions about construction plans (e.g., schedules) by utilizing digital representations of the building process [6]. Because BIM allows GCs to facilitate the exchange and interoperability of information in digital format, it allows GCs to rapidly and formally evaluate direct costs and durations of construction schedules; however, existing studies on BIM are limited in cost and duration evaluation of excavation schedules for tunnel construction with varying ground conditions because each component in product models (i.e., designs) accepts only one material. Furthermore, the construction method models used in existing BIM are not specialized for tunnel construction. Consequently, GCs have difficulty evaluating risks in excavation costs and durations of tunneling schedules with complete information about ground conditions acquired before construction, because GCs lack a method to incorporate the two required processes into their existing evaluation process in a structured manner.

To overcome these limitations, we developed a methodology by integrating geostatistical methods and BIM. We first specialized simulated annealing (SA), one of the conditional simulation methods, in the prediction of ground conditions for tunnel construction with complete information acquired before construction. We also specialized BIM-based evaluation processes of costs and durations for tunnel excavation. To integrate SA and BIM, we extended the existing BIM to accept multiple sets of ground conditions. After that, we applied the methodology to a tunnel in Korea to validate the effectiveness of our methodology.

2. Literature review

This section describes the advantages and limitations of existing studies in facilitating the two required processes explained in the previous section. This section first introduces geostatistical methods for predicting ground conditions and then presents BIM for evaluation of costs and durations for construction schedules.

2.1. Geostatistical methods

Geostatistical methods have been widely applied to predict ground conditions in a way that takes into account spatial relationships among sampled and unsampled areas. Kriging has been used to sketch the trend of georeferenced variables, and conditional simulation adopts the theory of regionalized variables based on the idea of kriging. Since different kriging and conditional simulation methods have different objectives, we investigated the characteristics of kriging and conditional simulation methods in order to select appropriate methods to facilitate our first required process.

Over the past several decades kriging, which was first introduced by Krige [7], has become a fundamental tool in the field of geostatistics [7]. Kriging is based on the assumption that the parameter being interpolated can be treated as a regionalized variable. A regionalized variable is an intermediate between a truly random variable and a completely deterministic variable in that it varies continuously from one location to the next. Therefore, points that are near each other have a certain degree of spatial correlation, whereas points that are widely separated are statistically independent. This kriging minimizes estimation variance from a predefined covariance model that takes into account functions of distance. Thus, the kriging makes locally optimal predictions about ground conditions. However, because the kriging variance does not fully measure spatial uncertainty, the smoothing effect is detrimental if kriging predictions are used as parameters in a non-linear multiple-cell model (e.g., cost and duration evaluation).

Please cite this article in press as: D.-W. Ryu et al., Evaluating risks using simulated annealing and Building Information Modeling, Appl. Math. Modell. (2015), http://dx.doi.org/10.1016/j.apm.2015.04.024