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Geostatistical investigation of geotechnical and constructional properties in Kadikoy–Kartal subway, Turkey

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ABSTRACT

The Kadikoy–Kartal subway is a unique underground transit line in the Asian part of Istanbul, and has been in operation since August 2012. The 22 km underground subway line includes 16 stations and two main tubes. This study focuses on the last 13 km, where the excavation was performed by excavators and loaders, to obtain the distribution of geotechnical and construction parameters from geostatistical methods. Rock quality designation (RQD), geological strength index (GSI), uniaxial compressive strength (UCS), elasticity modulus of intact rock (E_m), and rock mass elastic modulus (E_r) were determined from laboratory and site studies as geotechnical parameters. The daily advance rate (AR) for the excavation of underground tubes was collected as a construction parameter. Geostatistical methods were applied to estimate the magnitude of the unsampled points from sampled points. The validity of the proposed methodologies was confirmed by the previous researches, working with site specific parameters, determining the regional dependence functions, and applicability of kriging matrices. After regionalization of the parameters, semivariograms (SV) and crossvariograms (CSV) were determined to run kriging and cokriging techniques that were used to estimate the magnitude of regionalized variables (ReV). Cokriging is used to estimate the magnitude of E_r, which has scarce data, from UCS, which is highly correlated to E_r. The effect of areas that are changing between 49 m and 212 m for geotechnical and construction parameters were determined by SVs. This is important to show the applicability of the geostatistical methodologies prior to the construction stage for tunnel projects especially to prepare a well-organized drill hole program. Distribution maps for each parameter were then determined. The distribution of E_r was obtained from cokriging technique that was not possible to determine from classical statistical and geostatistical techniques because of the insufficient number of data. Consequently, this research demonstrates that the application of kriging, cokriging techniques, and SV functions as geostatistical methodologies are usable for tunnel projects, therefore the techniques and interpretations based on the distribution maps can be used to assist the similar high budget subway projects.

1. Introduction

Investigation into the geotechnical properties of geological formations along a tunnel route is crucially important because of the economical and safety aspects of high budget tunnel projects. Excavation and support systems for underground openings are designed based on geotechnical properties. Laboratory and site investigations are carried out using samples taken from drill hole investigations. The results obtained from geotechnical studies as well as the tunnel construction parameters should be evaluated by statistical approaches. Geostatistical methodologies can be applied to estimate the magnitude of variables even for unsampled points based on spatial statistics methods that cannot be determined from conventional statistical approaches. The expected benefit from these applications is to obtain the distribution of data for each point in the study area in order to estimate the magnitude of parameters for construction and geotechnical properties.

Rosenbaum et al. (1997) used geostatistics as a tool to estimate lithology. Indicator kriging was used to obtain the distribution of regionalized variables (ReV) in the study area as a geostatistical tool. Ozturk and Nasuf (2002) proposed the use of geostatistical applications for tunneling to estimate rock quality designation (RQD), compressive strength (CS), Schmidt hammer hardness (SHH), and net cutting rate (NCR) for 800 m of the Eyup sewerage tunnel using kriging. Moreover, geostatistics were successfully used for rock mass rating (RMR) evaluation from borehole and MT resistivity data (Oh et al., 2004). Jeon et al. (2009) applied ordinary and indicator kriging and sequential indicator simulation to estimate RMR around the tunnel. The results in this study also

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support the use of geostatistics to estimate geotechnical properties as ReVs. Oh (2012) proposed the integration of seismic velocity and resistivity data for the evaluation of rock quality based on geostatistical methods. This study illustrates how to investigate geophysical surveys with geostatistics for the estimation of RQD. All of these studies are good examples of the use of geostatistics as a tool for estimating geotechnical parameter distribution that is also spatially correlated.

In this study, the Kadikoy–Kartal underground subway line is selected as the case study area to investigate geostatistical research alternatives of geotechnical and constructional parameters along the tunnel route. RQD, geological strength index (GSI), and rock mass elasticity modulus (E_r) as rock mass properties, uniaxial compressive strength (UCS) and elasticity modulus (E_m) as intact rock, and daily advance rate as construction parameters are used to estimate the magnitude of these variables for both sampled and unsampled points. The kriging technique was applied to determine the distributions of ReVs except for E_r. E_r as an output of in-situ testing reflects the properties of rock mass which is formed by discontinuities and intact rock material properties. Since the distribution of E_r could not be searched by classical geostatistical methodologies due to the insufficient number of data, the distribution of E_r was determined from cokriging. Not only the existence of a highly correlated relation between E_r and UCS but also the relation between intact rock material and rock mass elastic modulus relation proposed by several researches, such as the study of Palmström and Singh (2001), encourages making the investigation possible based on cokriging. The results are useful to understand the applicability of spatial investigations of geotechnical properties for geological formations along a tunnel route as well as the use of different geostatistical techniques for the assessment of rock mass zones for both geotechnical and constructional parameters.

2. Subway project and geology of the study area

The Kadikoy–Kartal underground subway line, which is used by approximately 1 million people each day, is becoming a part of the solution for Istanbul's heavy traffic problem. As shown in Fig. 1, there are 16 stations along the 22 km subway line.

The subway project consists of two underground main tunnels (tubes 1 and 2), 16 stations, shafts, shaft tunnels, switch tunnels, and connection tunnels. Simple demonstrations and details of these underground structures are given in Fig. 2 and Table 1. The geometry of the main tubes is also given in Fig. 3. The height of the overburden material ranges between 18 m and 44 m due to the topographical diversity. The horizontal distance between the tubes ranges between 12 m and 64 m (Ozturk and Simdi, 2012).

Total length of the underground tunnels is 56.10 km; 43.08 km were excavated by New Austrian Tunneling Method (NATM), while the rest of the underground openings were driven by tunnel boring machines (TBM) due to contractual obligations. Earth Pressure Balance (EPB) type TBMs from Kozyatagi to Kadikoy were used to overcome the difficulties of poor soil condition excavations. With an average of 10 m daily advance rates, TBMs were used to complete excavation, concrete lining, and grout injections between ground and lining. The excavations began in August 2007 from Kozyatagi with two EPB type TBMs and were completed in June 2010 for tube 1 and July 2010 for tube 2 in Kadikoy. The remaining excavations of the main tubes were completed by excavators with an average of 2 m daily advance rates. The number of working tunnel faces in other works excavation areas were arranged accompanied with the construction schedule. This study focused on the locations between 8+000 km and 21+000 km that were excavated by NATM.

Main geological formations in this 13-km tunnel route are Kartal, Kurtkoy, and Dolayoba formations. Aydos and Gozdagi formations also exist in this 13-km zone. A geological cross-section is given in Fig. 4 (Ocak, 2006), and brief descriptions of these geological formations are given below.

Kartal is the longest formation from 3.50 km to 11.75 km, and it is mainly formed by carbonate mudstone and limestone. According to the geotechnical investigation, the formation can be classified as poor and medium. The lithology of the Kurtkoy formation from 11.25 km to 16.20 km is pebbly sandstone, sandstone, and mudstone. This formation is also classified as poor and medium. Aydos is the shortest formation with very strong quartzite rocks from 16.40 km to 17.50 km. Although the intact rock material has strong strength values, the rock mass is classified as poor and medium due to the existence of discontinuities. The Dolayoba formation, which is classified as poor and medium, mainly consists of strong clay filled limestone in some places and stretches from 17.50 km to the end of the project area. The Karstic spaces in the formation caused issues during excavation and support of underground openings. The lithology of the Gozdagi formation is formed by laminated and lenticel quartzite shale. It is mainly formed between 17.60 km and 17.86 km. Only laminated shale (excluding quartzite) was found during the excavation of this formation. This formation is highly weathered due to the tectonic deformations; in some cases, the shale has turned into dark brown clay (Baykal and Kaya, 1963; Haas, 1968; Kaya, 1978; Onalan, 1982; Sayar and Sayar, 1962). Geotechnical properties of these formations are summarized in Tables 2 and 3 that provide RMR and GSI values determined for each geological formations (IBB, 2008, 2005, Ocak et al., 2008).

3. Methodologies

The aim of the geostatistical methodology is to estimate the magnitude of ReVs for unsampled locations in any given spatial. The semivariogram (SV) function can be used to measure the dependency of an ReV according to the distance and magnitude defined in Eq. (1), where $\gamma_{(h)}$ is the semivariogram; N is the number of pairs; and $Z_{(x)}$ magnitude of the ReV, $Z_{(x+h)}$ magnitude of the ReV that is away from the $Z_{(x)}$ by distance h. An experimental SV function can be determined from the equation defined below (Journel, 1989; Ozturk, 2001)

$$\gamma_{(h)} = \frac{1}{2N}\sum_{i=1}^{N}[Z_{(x+h)} - Z_{(x)}]^2 \qquad (1)$$

Theoretical SV function must fit the experimental SV function in order to make the function applicable to the estimation problem via the kriging matrix, which provides the best linear unbiased estimator (blue) of unknown characteristics. An unsampled location can be estimated by Eq. (2), where $Z_{(x0)}$ is the magnitude of the unsampled site, $Z_{(xi)}$ is the sample point's magnitude, and w_i is the weight coefficient.

$$Z_{(x_0)} = \sum_{i=1}^{m} w_i Z_{(x_i)} \qquad (2)$$

A problem with two unknown parameters in the above equation can be solved using the kriging matrix given in Eq. (3). The required data for this kriging matrix can be determined from the theoretical SV, where γ_{ii} is the value of SV between every sampled point; w_i is the value of the weight coefficient for the desired points; γ_{vi} is the value of SV between unknown point and other points; and μ is the Lagrange parameter. Determination of w_i from the matrices below makes it possible to estimate the magnitude of the unsampled location.