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Urban Tunneling Risk Management: Ground Settlement Assessment through Proportional Hazards Modeling

Ali Kazempour Osalou[1], Sayfoddin Moosazadeh[1]*, Ali Nouri Qarahasanlou[2], Mohammad-Reza Baghban Golpasand[3]

1. *Department of Mining Engineering, Faculty of Engineering, Urmia University, urmia, Iran*
2. *Faculty of Science and Technology, UiT, the Arctic University of Norway, Tromsø, Norway*
3. *Department of Civil Engineering, Seraj Institute of Higher Education, Tabriz, Iran*

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Abstract

Nowadays, tunnel excavation plays a major role in the development of countries. Due to the complex and challenging ground conditions, a comprehensive study and analysis must be done before, during, and after the excavation of tunnels. Hence, the importance of study and evaluation of ground settlement is dramatically increased since many tunnel projects are performed in urban areas, where there are plenty of constructions, buildings, and facilities. For this reason, the control and prediction of ground settlement is one of the complicated topics in the field of risk engineering. Therefore, in this paper, the proportional hazard model (PHM) is used to analyze and study the ground settlement induced by Tabriz Metro Line 2 (TML2) tunneling. The PHM method is a semi-parametric regression method that can enter environmental conditions or factors affecting settlement probability. These influential factors are used as risk factors in the analysis. After establishing a database for a case study and using a proportional hazard model for surface settlement analysis, and then by evaluating the effect of environmental conditions on the ground surface settlement, it has been found that the risk factors of grouting pressure behind the segment, the ratio of tunnel depth to groundwater level, and drained cohesion strength at a significant level of 5% have a direct effect on the probability of settlement. The results also showed that the effect of grout injection pressure on ground subsidence is more than other parameters, and with increasing injection pressure, the probability of exceeding safe subsidence values decreases. In addition, it has been found that increasing the risk factor for the ratio of tunnel depth to groundwater level reduces the probability of exceeding the safe ground settlement. Finally, increasing the number of risk factors for drained cohesion strength increases the probability of exceeding safe settlement.

1. Introduction

The *in-situ* stresses are disturbed after the excavation of tunnels, which creates a new stress condition called induced stress. The horizontal component of total displacements causes tensile and compressive stresses on the ground surface, and the vertical component of the mentioned displacements causes ground settlement. If these ground movements exceed limiting ranges in urban areas, the surrounding buildings will be damaged. Therefore, the ground movements and displacements created by tunnel excavation, especially urban subways, should be investigated in detail in order to decrease the risks [1-3]. In recent decades, many studies have been conducted to predict movements and displacements, which can be classified into two main categories: deterministic and probabilistic approaches. In deterministic methods, the uncertainty of geological data is ignored; therefore, the results of the mentioned method are always accompanied by some errors that must be validated with instrumentation data.

For this reason, statistical methods are highly suggested to investigate the behavior of surface

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✉ *Corresponding author: s.moosazadeh@urmia.ac.ir (S. Moosazadeh)*

subsidence by considering it as random variables and exhibiting it by probability functions. This approach can be useful for the analysis and evaluation of geotechnical data based on the uncertainties' point of view [4, 5]. Molon et al. (2013) carried out the first comprehensive study to evaluate the effect of uncertainty of soil parameters on ground displacement due to tunneling operations by using the CSRSM (Collocation-based Stochastic Response Surface Methodology) approach [6, 7]. Lai et al. (2017) proposed a new method for predicting ground settlement by classification of the influence zone of the twin tunnels under-passing existing tunnel based on analysis of the coupling effects of new tunnels in-between soil and the existing tunnel. Gong et al. (2014) have used both Loganathan-Polus and closed-form analytical methods to predict ground surface settlement induced due to the excavation of tunnels in clay soil [8]. Miro et al. (2015) have modeled the tunneling process using FEM PLAXIS 3D modeling in the slurry tunnel boring machine; however, they have used probabilistic approaches to reduce numerical modeling costs [9]. Powers (2017) has obtained the probable range of exceeding settlement with regard to maximum settlement by using reliability analysis [10]. Cheng et al. (2019) present a study of ground surface settlement induced by large shield EPB tunneling that provides important insights into the values of settlement trough parameters of empirical methods [11]. Wei and Yang (2018) have also proposed a reliability analysis method based on related data to model ground settlement because of mining activities [12]. In 2018, Yang et al. developed the upper bound solutions in the form of reliability analysis to determine the block failure mode in rectangular tunnel shapes, which are influenced by the water table [13]. [14] Most of the proposed methods for the prediction of ground surface settlement are classified into the deterministic category since the input and output parameters are defined as deterministic and unique values in these methods.

In deterministic models, the values of dependent variables are entirely determined by the parameters of the model. However, in probabilistic models, the random results are represented as probability distributions and not as unique values [4, 15].

A deterministic model is a model in which the state variables are determined uniquely by the parameters of the models and the previous state. Thus, all the parameters, including governing equations, conditions, and model solutions, are unique in deterministic models. This limitation brings some fundamental problems due to the heterogeneous essence of nature because, in geotechnical problems, the system is measured only in the limited number of interrupted places by a set of boreholes [5]. In the deterministic approach, since the environment of the model can be anisotropic, the model's input and output parameters can have some ambiguity, which means that we cannot say a particular value is correct for the input or output parameter.

As has been mentioned in the above paragraphs, another difficulty of deterministic model results is that these results need to be validated, which means that the researchers must validate their results with the value of instruments or other deterministic approaches. The other negative point of deterministic models is the implementation of this model in various situations, which would be costly. For example, by changing engineering geological properties, governing equations of problems are also changed so that the new sections need to be produced again to simulate the required conditions. On the other hand, probabilistic model parameters are determined based on random variables and probability distributions, which do not have a unique value compared to the deterministic model parameters. Therefore, probabilistic models result in multiple solutions; for example, this advantage allows the researchers to perform modeling regardless of the essence of geological problems. Based on what has been written above, although the physics of the system is simple to deterministic equations, it is not easy to count on the results from deterministic models. For this, in most cases, the results need to be validated because the input parameters, model geometry, and initial boundary conditions are not known, and they have never been identified comprehensively. Hence, probabilistic models can be a tool for combining physics, statistics, and uncertainties (probability theory) with a coherent theoretical framework [5, 9]. For this reason, an appropriate model considers the uncertainty of geotechnical parameters and can also be applied to various conditions, which shows a fast and cost-effective response for the prediction of settlement.

In this regard, the researchers can use the reliability and proportional hazards model (Cox regression) as robust statistical and mathematical methods, which have been recently proposed. These models define random events based on probability [16, 17]. In the reliability model, the ground surface settlement is calculated regardless of environmental conditions, and the occurrence of different ground surface settlements is obtained based on probability. The main advantage of the proportional hazards model, which is rooted in the classical reliability model, is to consider the environmental conditions and estimate its effect in the form of risk factors on the occurrence of the objective function, i.e., ground surface settlement.

This research work is carried out to investigate the effect of all important parameters on the probability of ground surface settlement in the entire tunneling path, considering the uncertainty of the environment which is very rarely seen in previous studies. The results of the current study can be a reasonable basis for predicting settlement with appropriate control and measures to prevent the occurrence of unpleasant accidents.

This research work consists of 5 main sections. In the first part, as described, the literature is reviewed with a focus on the nature of the uncertainty of geotechnical conditions. In the second, the reliability and its application in tunneling projects are introduced, and then basic reliability concepts are explained. Following the second part, the effect of environmental conditions on ground surface settlement in the PHM model is reviewed, and the concepts, characteristics, and conditions are explained. In the third part, Tabriz Metro-Line 2 will be introduced. In the fourth part, statistical modeling of a case study based on the PHM model is performed by considering the effect of risk factors. In the last section, the research results are summarized.

2. Reliability Analysis of Ground Settlement

The value of ground surface settlement in various geological conditions and excavation methods is one of the most critical issues that has always attracted experts' attention. In this research work, due to the unknown and uncertain parameters in tunnel excavations, the probability of ground settlement domain and allowed magnitudes are assessed using both reliability models and proportional hazards models. The outcome of this research work is presented as criteria for assessing the quality of the tunnel project, which helps the supervisor to make the necessary adjustments and insights to control ground settlement [18-20].

Reliability is a part of engineering sciences that evaluates various engineering problems to increase the performance of systems. The most common definition of reliability is a subsystem's ability to perform a required task under certain conditions in a given time [21, 22]. Reliability can be defined as the right function of a component, system, or machine in a specified time interval under certain conditions [23]. The engineers have defined reliability to determine the longevity of the system based on its components. Based on a theoretical point of view, reliability can be defined as the probability of failure of industrial equipment or the probability of an individual or patient's lifetime [24-27].

In Equation 1, the reliability function is shown as:

$$\text{Reliability} = 1\text{-probability of failure} \qquad (1)$$

This way, if survival time is denoted by a random variable T, based on probability theory, the reliability function is shown by R(t) and calculated by Equation 2:

$$\mathrm{R(t) = Pr\{T > t\}} = \int_{t}^{+\infty} \mathrm{f(x)dx} \qquad (2)$$

In Equation 2, f(x) is the Probability Density Function (PDF), and t is the failure time. The PDF indicates the random variable distribution, and its general form can be obtained by drawing the frequency of variables. The sub-curved area of PDF is equal to "1" [21]. Since the Cumulative Probability Distribution Function (CDF) of T indicates the probability of survival time is smaller than t, and the reliability function indicates the probability of survival time is larger or equal t, CDF complements the reliability function. This matter can be shown as an equation, which is the function of F(t) is CDF:

$$\mathrm{R(t) = P(T > t) = 1\text{-}P\ (T \leq t) = 1\text{-}F(t)} \qquad (3)$$

The concept of reliability can be used for the topic of ground settlement and shows the probable nature of subsidence, which is one of the important aspects of failure and uncertainty in tunneling projects, providing an indicator to assess the project's safety and reliability. Therefore, the probability of ground surface settlement can be verified by reliability analysis.

Regarding the phenomenon of settlement due to mechanized tunneling operations, the same time perspective can be used. In this case, the initial event is the settlement before the tunneling operation, which is equal to zero millimeters. By tunnel excavation, the settlement increases over time and finally converges to a maximum value. The maximum settlement value can be assumed as a representative of the duration of the maximum settlement and as a final event. In other words, the amount of settlement in different areas is considered a random variable.

If settlement value is shown with symbol "s" and is taken in millimeters, in this state, the probability of a ground surface settlement can be analyzed as follows:

1- The probability of ground surface settlement larger than s (mm), which is expressed using the reliability function in Equation 4**Error! Reference source not found.**:

$$\mathrm{R(s) = Pr(S{>}s)} = \int_{s}^{+\infty} \mathrm{f(s)ds = 1\text{-}F(s)} \qquad (4)$$

2- The probability of ground surface settlement smaller than s, which is expressed using CDF in Equation 5:

$$\mathrm{F(s) = Pr(S \leq s)} = \int_{0}^{s} \mathrm{f(s)ds} \qquad (5)$$

2.1. Approach based on the impact of environmental conditions (risk factors)

Reliability is based on failure time and environmental conditions. In general, the investigation of reliability should include technical, operational, business, management, and overall risk factors. In the 1970s, the use of regression models was suggested for better evaluation due to their ability to incorporate risk factors. Risk factors are accidentally changed and may affect ground surface settlement [28]. For this reason, The Cox regression model, which considers the environmental conditions in association with the reliability function, is investigated in the following parts.

2.1.1. Proportional hazards model

The Proportional Hazards Model (PHM) is a standard model that various scientists use to analyze survival data [29-31]. The PHM model is a non–non-parametric or semi-parametric model (does not consider a specific distribution function to data), which was first introduced in 1972 by David Roxbee Cox for survival analysis in the field of medical sciences. Hence, this model is known as the Cox regression model. The Cox model can be applied for tunneling projects to estimate ground surface settlement's risk since, as has been mentioned, the survival analysis is part of the reliability theory. Therefore, all relationships and concepts that are related to reliability theory can be generalized to analyze the Cox model and use it for further investigation [32]. The reliability relation of ground surface settlement is based on the PHM model as Equation 6:

$$\mathrm{R(s.X)} = (\mathrm{R_0(s)})^{\exp(\sum \beta_i X_i)} \qquad (6)$$

In Equation (2-6), $R_0(s)$ is the reliability function of ground surface settlement, which is calculated based on monitoring data, and $\exp\left(\sum \beta_i X_i\right)$ involves the impact of risk factors. The important feature of this Equation, which expresses the assumption of proportional hazards, is that the baseline reliability is defined as a function of monitoring data, and the X value is not considered. In contrast, the exponential term contains the values of X and does not consider the values of settlement. Another reason why the Cox mode is called semi-parametric is that the explanatory variables are formulated in a parametric form. In this case, the values of X are independent of the settlement. However, it can be defined as values of X to include values of settlement. In that case, X will be dependent on the settlement, and it can still be defined as the Cox model using settlement-dependent variables. However, under these conditions, the assumption of proportional hazards is not validated, and then, this model is called the extended Cox model [33, 34].

2.1.2. Assumption of proportional hazards

The Cox model can be used if the risk ratio for the two groups of study is independent of the settlement values because if this ratio is formulated, it can be shown in Equation 7:

$$\mathrm{HR} = \frac{\mathrm{h(s,X^*)}}{\mathrm{h(s,X)}} = \frac{\mathrm{h_0(s)}\exp(\sum \beta_i X_i^*)}{\mathrm{h_0(s)}\exp(\sum \beta_i X_i)} = \exp\left(\sum_{i=1}^{p} \beta_i (X_i^* \text{-} X_i)\right) \qquad (7)$$

In this Equation, HR is called the hazard ratio. This ratio is independent of settlement, and it has a constant value. HR shows the hazard of a particular group, which is formulated as X^* is the proportion of hazard of another group, which is formulated as explanatory variable X, and this ratio is independent of the settlement. Being independent of settlement for two groups of explanatory variables is called the assumption of proportional hazards. For this reason, The PHM can be used if the assumption of proportional hazards is validated [33].

Investigation of the hypothesis of proportional hazards

For investigation of the hypothesis of proportional hazards, the first and second types of graphical methods, the Goodness of fit test and time-dependent variables, are used and explained in the following paragraphs.

Graphical method: In the first-type graphical method, the natural logarithm of values of reliability function for each group of variables are calculated two times, and then the graph is plotted for each group. If log-log plots are parallel to each other, the PH assumption is established [33]. In the second type graphical method type, firstly, all variables must be classified. Then, the graph of Cox's reliability model function is plotted for each group of variables as expected values. Finally, the observed and expected diagrams of each group are compared with each other. If the observed and expected diagrams of all groups of variables match and are identical, then the PH assumption is established [31, 33].

Schoenfeld residuals as Goodness of fit (GOF) test: this test lets the researcher make a better decision compared to the graphical method because it makes statistical test and p-value for evaluating PH assumption. If Schoenfeld residuals are independent of a variable's settlement, the main idea of this method is that if the PH assumption is valid for a variable, Schoenfeld residuals are independent of a variable's settlement [31, 33].

Settlement dependent variables: in this method, the generalized Cox model is used to evaluate the PH hypothesis. A settlement-dependent variable is defined for each random variable, and the PH assumption is checked as one or more variables. In contrast, other methods, such as the stratified Cox regression model (SCRM) or extended Cox regression model (EPHM), should be used if the risk assumption is not appropriate for several variables [31, 33].

3. Case Study: Iran, TML2 (TML2)

The length of TML2 is 22 kilometers, and the diameter is 9.49 meters (Figure 2). This metro line has three main parts and 20 stations, and it has been excavated using by Earth pressure machine (EPBM). The support system is segmental, and four completed rings are excavated and installed in each shift of work. Ground leveling instrument is utilized for monitoring of ground surface settlement points for this project.

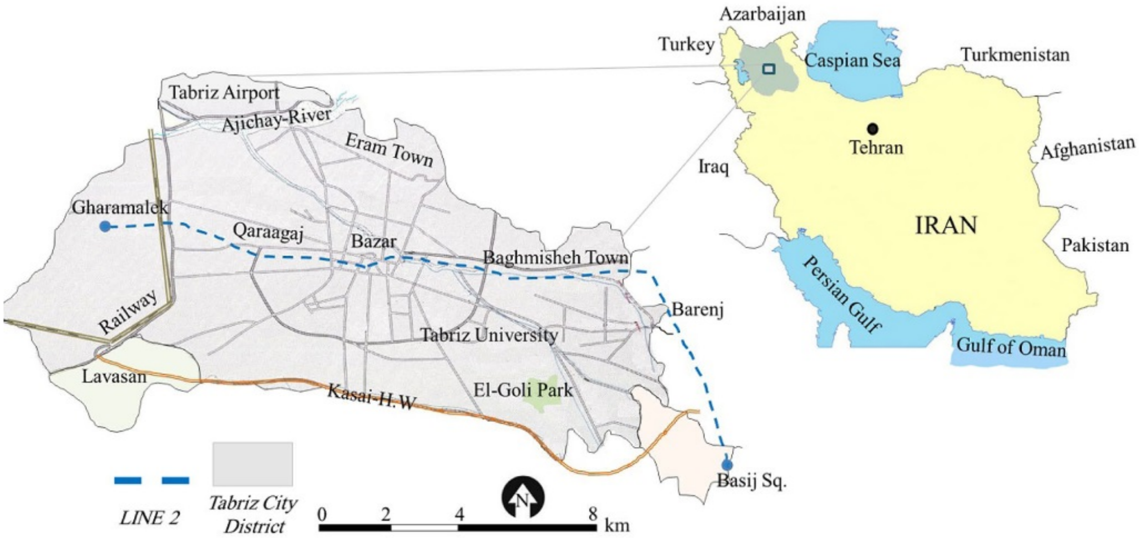

Figure 1. General layout of Tabriz Metro Lines (Alizadeh, A. et al., 2021).

According to Figure 2, firstly, monitoring data of ground surface settlement and information relating to risk factors are collected. Then, the effects and transactions of risk factors are investigated to mitigate risk factors, if necessary. In addition, the PHM model is fitted to the database with the assumption that hazards are proportional and the coordinates of the model are obtained. Finally, the assumption of proportional hazards is evaluated in GOF test format to evaluate fitting accuracy. [35, 36] (Barabadi et al., 2015; Zamani Arabshah et al., 2019).

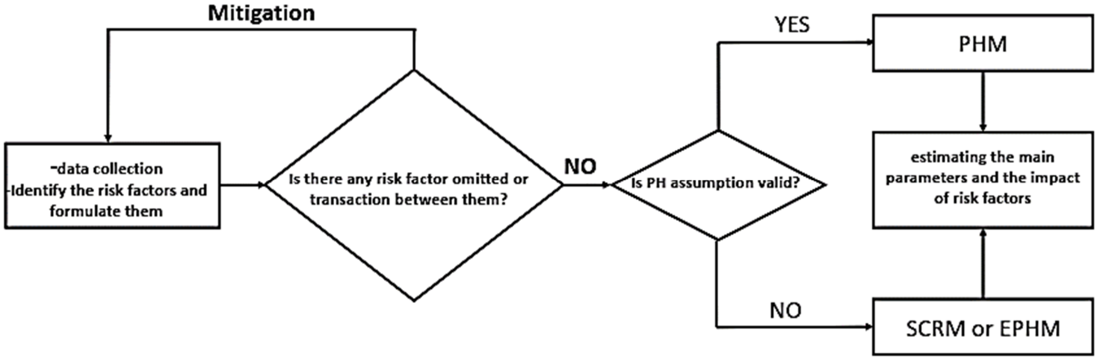

Figure 2. Choosing the appropriate regression model for analysis [35, 36](Barabadi et al., 2015).

3.1. Settlement analysis of TML2

In this section, the reliability of ground surface settlement is calculated using the proportional hazards model, which involves environmental conditions on the probability of ground surface settlement.

After collecting environmental conditions data based on the risk factors, risk factors should be identified and classified. The interactions of risk factors, transactions, and elimination of some of them should be investigated [28, 37].

In this paper, the risk factors database is extracted from the geological engineering profile, which was prepared based on experimental laboratory and *in-situ* tests. The following principles are taken into account to identify and characterize risk factors [28]:

- Principle 1: Mutual effects of risk factors: mutual effects of two or more risk factors can be modeled by introducing a new risk factor.
- Principle 2: Remove influential risk factors: this may lead to inaccurate analysis.
- Principle 3: Settlement dependency of risk factor: this issue must be considered as settlement dependency of risk factors

In the first step, data for 31 risk factors (Table 1) are collected at intervals between 2+000 and 5+700 at a period of 50 meters. It is worth mentioning that the modulus of elasticity, Poisson's ratio, horizontal pressure of soil layers, and cohesive strength are calculated by weighted averaging (thickness of soil layers is considered as weight).

Table 1. The first step of the database's compilation.

No.	Name of risk factor	Type	No.	Name of risk factor	Type
1	Underground water level from the axis of the tunnel	Continues	16	SPT	Continues
2	Tunnel depth of	Continues	17	Dry unit weight	Continues
3	The thickness of the filling soil	Continues	18	Saturated unit weight	Continues
4	The thickness of TG-1 layer in the overburden	Continues	19	Drained cohesion strength	Continues
5	The thickness of TG-2 layer in the overburden	Continues	20	Undrained cohesion strength	Continues
6	The thickness of TG-3 layer in the overburden	Continues	21	Drained friction angle	Continues
7	The thickness of TG-4 layer in the overburden	Continues	22	Undrained friction angle	Continues
8	The thickness of TG-1 layer in the tunnel face	Continues	23	Modulus of elasticity	Continues
9	The thickness of TG-2 layer in the tunnel face	Continues	24	Poisson's ratio	Continues
10	The thickness of TG-3 layer in the tunnel face	Continues	25	Coefficient of lateral earth pressure	Continues
11	The thickness of TG-4 layer in the tunnel face	Continues	26	Grout injection pressure	Continues
12	The consistency index of layers, which includes tunnel	Continues	27	Tunnel face's applied support pressure	Continues
13	Permeability of layers, which include tunnel	Continues	28	Potential of clogging	Categorical
14	Percentage of refined grains in tunnel face	Continues	29	The hazard of abrasive ground	Categorical
15	Qanat[1]	Categorical	30	Tunnel face's designed to support pressure	Continues
			31	|*No. 27-No. 30*|	Continues

Table 2. An example of the data analyzed in the settlement.

Kilomerage	Settlement	Status	Tunnel depth/Underground water level	Consistency_index	Permeability (10^7)	Qanat	k0	c_drained	phi_drained	Elastic	Poisson	Grout_pressure	Face_pressure
2000.00	21.00	1.00	4.62	-0.38	55.00	1.00	0.54	13.51	30.98	28.02	0.32	2.20	0.60
2050.00	18.00	1.00	4.86	-0.38	55.00	1.00	0.54	13.60	29.20	27.98	0.32	2.00	0.70
2100.00	25.00	1.00	5.00	-0.38	55.00	1.00	0.53	13.46	29.58	28.35	0.32	1.80	0.65
2150.00	23.00	1.00	5.50	-0.38	55.00	1.00	0.54	13.55	29.12	28.10	0.32	2.10	0.60
2200.00	20.00	1.00	5.38	-0.38	55.00	1.00	0.53	12.87	31.37	29.35	0.32	2.50	0.50
2250.00	19.00	1.00	6.77	-0.38	55.00	1.00	0.54	13.65	29.00	27.73	0.32	0.75	0.40
2300.00	35.00	1.00	7.79	-0.38	55.00	2.00	0.54	13.68	28.65	27.50	0.32	0.40	0.60
2350.00	18.00	1.00	9.02	0.00	302.50	2.00	0.54	13.04	28.12	27.85	0.32	0.60	0.50
2400.00	8.00	1.00	10.41	0.00	550.00	2.00	0.53	12.20	27.84	28.34	0.32	0.80	0.35

Finally, by observing the mentioned principles, 11 risk factors are selected according to Table 2 for the PHM model. Table 3 shows an example of the analyzed data for ground settlement.

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[1] Qanat is a system for transporting water from an aquifer or water well to the surface, through an underground channel.

Table 3. Selected risk factors.

No.	Name of risk factor (symbol)	Type	No.	Name of risk factor (symbol)	Type
1	The ratio of the depth of the tunnel to underground water level (D/W)	Continues	7	Modulus of elasticity (E)	Continues
2	Consistency index of layers, which include tunnel (Ci)	Continues	8	Poisson ratio (Po)	Continues
3	Permeability of layers, which include tunnel (P)	Continues	9	Coefficient of horizontal pressure (K0)	Continues
4	Qanat (Q)	Continues	10	Grout injection (G) pressure	Continues
5	Drained cohesion strength (C)	Continues	11	Tunnel face applied support pressure (F)	Continues
6	Drained friction angle (ϕ)	Continues			

3.1.1. Fitting appropriate model

In this section, the reliability of ground surface settlement is calculated using PHM, which involves environmental conditions on the probability of different values of ground surface settlement. According to Equation 8), the PHM model consists of two functions; the first function ($(R_0(s))$) is calculated based on ground surface settlement's monitoring data, and the second function (exp ($\sum \beta_i X_i$)) consists of the impact of risk factors.

In this study, to determine the distribution shape of ($R_0(s)$) and also to obtain a vector of regression coefficients (β_i), the SYSTAT 13 software is used. For this purpose, the estimation of regression coefficients is determined by the step-by-step backward method. For this, all variables are entered into the model, and then, in each step, the least important risk factor with the least effect on the objective function is excluded from the calculation process based on the Wald statistical method and the P-value. A significant regression coefficient test is performed for each of the risk factors, and the P-value and Wald statistics for each risk factor are calculated and compared with the exclusion criterion (significance level of 0.05). In the last step, residual risk factors are introduced as affecting factors on the probability of ground surface settlement [28, 38-39].

It is worth mentioning that according to Equation 8, Weibull distribution is applied for($R_0(s)$) [28].

$$\mathrm{R_0(s)=exp} -(\frac{s}{\lambda})^{k} \tag{8}$$

In Equation 8, λ is the scale parameter, and k is the shape parameter.

Finally, the regression coefficients, parameters of shape, and scale of baseline reliability function are calculated (Table 4).

Table 2 Results of estimating parameters of ($R_0(s)$) and regression coefficients of influential risk factors (β_i).

parameter	The regression coefficient of risk factor (β_i)	Standard error	Wald statistic	P-value	The average amount of risk factor
shape	2.699	0.241	11.211	0.000	-
scale	43.613	28.551	1.528	0.127	-
D/W	0.053	0.025	2.088	0.037	6.471
C	-0.116	0.037	-3.156	0.002	14.266
G	0.248	0.121	2.051	0.040	1.3

The ground surface settlement's reliability function is calculated by applying the factors of risk effects to consider environmental conditions (Equation 9). The modeling results show that the ratio of the depth of the tunnel to underground water level (D/W), drained cohesion strength (C), and Grout injection pressure (G) are meaningful at the significance level of 0.05, which indicates the importance of these risk factors as an influential parameter for the probability of ground surface settlement occurrence. Finally, the general function of the ground surface settlement will be shown as follows based on the data obtained from the case study:

$$R(s.X)=Pr(S>s)=\left[\exp\left(-\left(\frac{s}{43.613}\right)^{2.699}\right)\right]^{\exp\left(\frac{D}{W}0.053-C0.116+G0.248\right)} \tag{9}$$

Using Equation 9, the probability of ground surface settlement occurrence is predicted using risk factors of D/W, C, and G.

An important point about the analysis of settlement by the reliability model is that the time-dependent data is related to lifetime industrial components, which means the optimal state is directly related to the length of system life. However, in the analysis of settlement, measured data represent vertical displacement values of the ground surface, which is induced by tunneling, and optimal mode is when vertical displacement values are smaller; therefore, in settlement analysis, when the probability of being exceeded values of settlement, which is equal to reliability function (R(s.X)), is smaller; it can be called the desirable state.

The reliability function graph is obtained by considering the effects of risk factors and their values according to Table 4 and Equation (0). Based on Figure 3 and considering the PHM model[40][2-3, 6], the probability of being exceeded values of ground surface settlement (20 & 30 millimeters) is externally increased (Table 5). The main reason can be explained by inappropriately applied values of grout injection pressure. According to the results, the grout injection pressure is meaningful at the significance level of 0.05; however, its effect on ground surface settlement is obvious. Hence, at sections where ground surface settlement exceeds the safe value, operators could reduce ground surface settlement value by increasing grout injection pressure because the impact of injection pressure has a direct effect on the probability of the occurrence of different ground surface settlement values so that by increasing grout injection pressure, the probability of being exceeded ground surface settlement values is reduced.

Table 3. The probability of exceeding safe settlement values by using the PHM model.

Safe settlement	Probability of exceeding safe settlement values by using PHM
20 mm	95
30 mm	87

Figure 4 shows the ground settlement reliability for different grout injection pressure values, and for two other risk factors (D/W, C), average values are taken into account.

As shown in Figure 4, the probability of exceeding safe ground surface settlement (20 and 30 millimeters) is reduced with increasing grout injection pressure. According to regression coefficients, the effect of grout injection pressure on the probability of different ground surface settlement values is higher than other risk factors. The injection pressure is also introduced as a parameter that plays a significant role in the probability of occurrence of different ground surface settlement values. Applying appropriate injection pressure makes it possible to prevent severe ground surface settlement.

Based on Figure 5, variations of the ground surface settlement's reliability function are plotted for various values of risk factors to the ratio of tunnel depth to underground water level. The average values are considered for two other risk factors (G, C) in the plot mentioned above. As values of D/W increase, it is obvious that the probability of exceeding safe values of ground surface settlement (20 and 30 millimeters) is reduced.

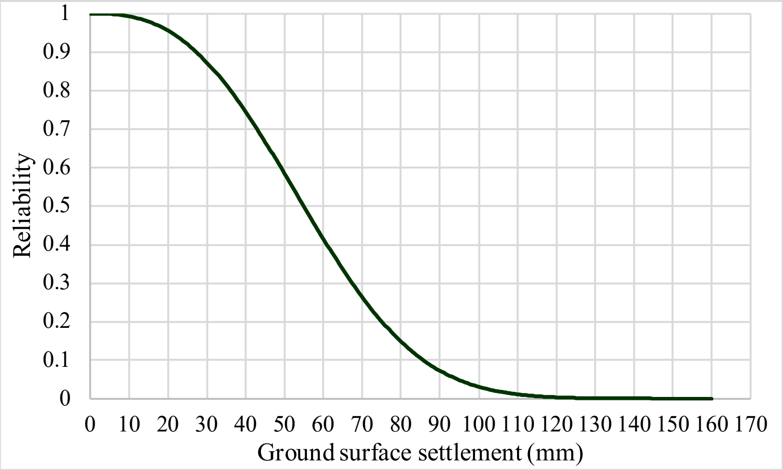

Figure 3. Reliability diagram of ground surface settlement about the impact of risk factors.

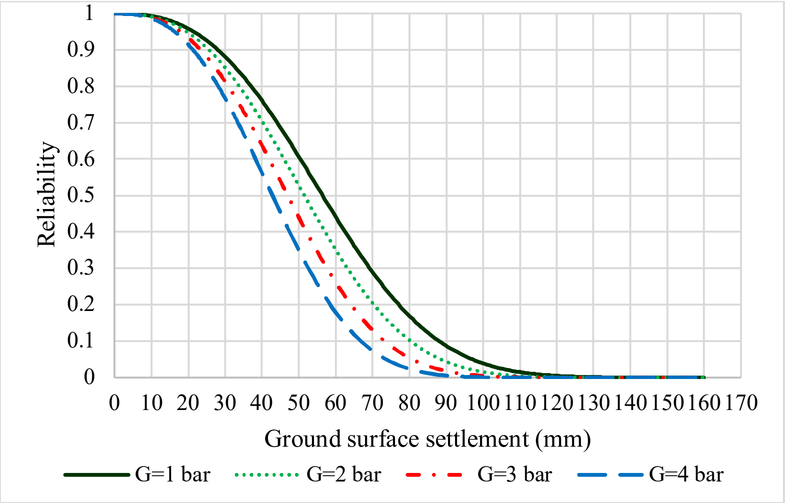

Figure 4. Reliability of ground surface settlement for varying values of grout injection pressure.

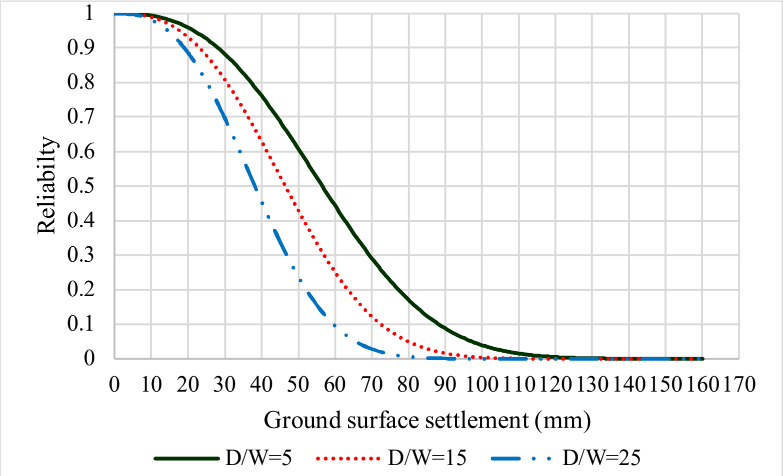

Figure 5. Reliability of ground surface settlement for varying values of depth of tunnel to underground water level.

Figure 6 exhibits the effects of drained cohesion strength on ground surface settlement reliability. Based on Figure 6, increasing drained cohesion strength increases the probability of being exceeded safe ground surface settlement (20 & 30 millimeters). This increase means that in sections where the amount of equivalent drained cohesion strength increases compared to the previous section, the probability of exceeding the allowable subsidence increases compared to the previous section. By taking a close look at the final database, the drained cohesion strength has increased compared to the previous section in the sections where the ground subsidence has exceeded 30 mm.

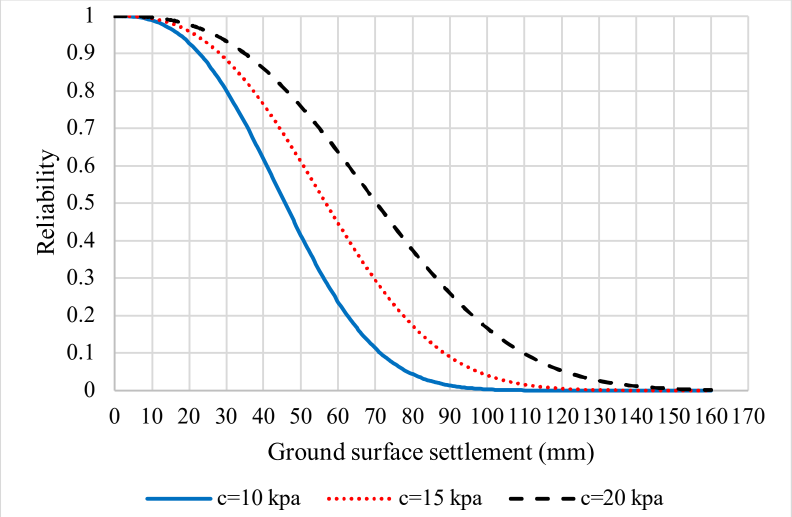

Figure 6. Reliability of ground surface settlement for varying values of drained cohesion strength.

3.1.2. Investigation of proportional hazards hypotheses

As it has been discussed before, if the proportional hazard hypothesis is valid, we can use the PHM. Based on the Cox model's formulation, when two groups' hazard ratio is calculated, the mathematical function is independent of the settlement value. In fact, proportional hazards hypotheses state that variables entered in the model are independent of settlement, and the main purpose for the assumption of proportional hazards is to determine whether risk factors are dependent on the settlement or not. If all risk factors are independent of settlement value, the proportional hazards hypotheses are valid, and the Cox model is correct; otherwise, other models that take settlement-dependent risk factors, like SCRM and EPHM, are used. In this study, Schoenfeld residuals as GOF test are used. Based on the Schoenfeld residuals test, the null hypothesis is meaningful if the proportional hazards assumption is valid; then, Schoenfeld residuals are independent of the settlement. If the null hypothesis is rejected, then the proportional hazards hypothesis is invalid. In the current study, SPSS 26 is used to test proportional hazard hypotheses. (Table 6).

Table 4. The results of the proportional hazards assumption test.

Risk factor (symbol)	The correlation coefficient of Schoenfeld residuals to settlement	P-value
The ratio of the depth of the tunnel to underground water level (D/W)	-0.089	0.487
Consistency index of layers, which include tunnel (Ci)	a	-
Permeability of layers, which include tunnel (P)	0.026	0.841
Qanat (Q)	a	-
Drained cohesion strength (C)	a	-
Drained friction angle (ϕ)	0.081	0.526
Modulus of elasticity (E)	0.063	0.622
Poisson ratio (Po)	a	-
Coefficient of lateral earth pressure (K0)	a	-
Grout injection pressure (G)	0.219	0.084
Tunnel face applied support pressure (F)	a	-

In Table 6, “a” indicates that the correlation coefficient cannot be calculated because at least one of the risk factors is constant. All risk factors are not meaningful at the significance level of 0.05; therefore, proportional hazards hypotheses are valid for all risk factors.

4. Conclusions

In the realm of mechanized tunneling within urban landscapes, a paramount concern is the occurrence of ground settlement. Hence, a meticulous evaluation of this phenomenon becomes imperative for tunnel construction projects, necessitating both estimation and prediction. Numerous factors exert a direct influence on the magnitude and progression of ground settlement. To gain a more profound understanding, it becomes imperative to meticulously identify and comprehensively examine the singular impact of these risk factors. Employing the Proportional Hazard Model (PHM), this study delves into the investigation of the influence of environmental conditions on ground surface settlement induced by mechanized tunneling. Notably, the PHM identifies the ratio of tunnel depth to underground water level, drained cohesion strength, and grout injection pressure as statistically meaningful risk factors at a 0.05 significance level, each possessing regression coefficients of 0.053, -0.116, and 0.248, respectively. Intriguingly, grout injection pressure emerges as the most influential factor affecting the probability of ground surface settlement occurrence, with drained cohesion strength exhibiting a notable impact among the remaining factors. The PHM model facilitates the prediction of probable values of ground surface settlement in yet-unexcavated sections, further enabling the extension of short-term monitoring data to predict long-term settlement trends due to soil consolidation parameters. Conclusively, the application of the PHM in analyzing ground settlement induced by tunnel excavation, particularly within urban projects, signifies a comprehensive and quantitative paradigm. Despite the inherent limitations, such as assumptions of proportional hazards, sensitivity to model assumptions, and reliance on data quality, the PHM proves instrumental in prioritizing risk factors and guiding effective mitigation strategies. The model's project-specific nature necessitates cautious consideration in generalization to other tunneling projects, while the dynamic nature of urban environments underscores the ongoing validation and adaptability required to enhance its reliability across diverse tunneling scenarios.

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مدیریت ریسک تونلسازی شهری: ارزیابی نشست سطح زمین با روش مدلسازی مخاطرات متناسب

علی کاظم‌پور اوصالو[۱]، سیف‌الدین موسی زاده[۱*]، علی نوری قراحسنلو[۲]، محمد رضا باغبان گلپسند[۳]

۱. گروه مهندسی معدن، دانشکده فنی و مهندسی، دانشگاه ارومیه، ایران
۲. پستداک، دپارتمان ایمنی و تکنولوژی، دانشگاه شمالگان نروژ، ترومسو، نروژ
۳. گروه مهندسی عمران، موسسه آموزش عالی سراج، تبریز، ایران

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* نویسنده مسئول مکاتبات: s.moosazadeh@urmia.ac.ir

چکیده:

امروزه حفاری تونل نقش اساسی در توسعه کشورها دارد. با توجه به شرایط پیچیده و چالش برانگیز زمین، باید مطالعه و تحلیل جامعی قبل، حین و بعد از حفاری تونل‌ها انجام شود. بنابراین، اهمیت مطالعه و ارزیابی نشست سطح زمین از آنجایی که بسیاری از پروژه‌های تونلسازی در مناطق شهری انجام می‌شود که در آن سازه‌ها، ساختمان‌ها و تأسیسات فراوانی وجود دارد، به طور چشمگیری افزایش می‌یابد. به همین دلیل، کنترل و پیش‌بینی نشست زمین یکی از موضوعات پیچیده در زمینه مهندسی ریسک است. در این مقاله از مدل مخاطرات متناسب (PHM) برای تحلیل و بررسی نشست زمین ناشی از عملیات تونلسازی خط ۲ مترو تبریز (TML2) استفاده شده است. روش PHM یک روش رگرسیون نیمه پارامتریک است که می‌تواند تاثیر شرایط محیطی یا عوامل مؤثر را بر احتمال وقوع نشست وارد کند. از این عوامل تأثیرگذار به عنوان فاکتورهای ریسک در تحلیل استفاده می‌شود. پس از ایجاد پایگاه داده برای مطالعه موردی و استفاده از مدل مخاطرات متناسب برای تحلیل نشست سطح زمین و سپس با تحلیل و ارزیابی میزان تأثیر شرایط محیطی بر نشست زمین، مشخص شد که فاکتورهای ریسک فشار تزریق دوغاب پشت سگمنت، نسبت عمق تونل به تراز آب زیرزمینی و مقاومت چسبندگی زهکشی شده خاک در سطح معنی داری ۵ درصد تأثیر مستقیمی بر احتمال نشست زمین دارد. همچنین نتایج نشان داد که تأثیر فشار تزریق دوغاب بر نشست سطح زمین بیشتر از سایر پارامترها است و با افزایش فشار تزریق، احتمال تجاوز از مقادیر نشست ایمن کاهش می‌یابد. علاوه بر این، مشخص شده است که افزایش فاکتور ریسک نسبت عمق تونل به تراز آب زیرزمینی، احتمال تجاوز از نشست ایمن زمین را کاهش می‌دهد. در نهایت، افزایش فاکتور ریسک مقاومت چسبندگی ذهکشی شده، احتمال تجاوز از نشست ایمن را افزایش می‌دهد.

کلمات کلیدی: نشست سطح زمین، مدل مخاطرات متناسب، قابلیت اطمینان، احتمال، تونلسازی.
