

# Ground Surface Settlement Evaluation by Proportional Hazards Model in Tunneling Projects

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## Research Article

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# Ground Surface Settlement Evaluation by Proportional Hazards Model in Tunneling Projects

## ABSTRACT

Nowadays, tunnel excavation plays a major role in development of countries. Due to the complex and challenging ground conditions, a comprehensive study and analysis must be done before, during and also after the excavation of tunnels. Hence, the importance of study and evaluation of ground settlement are dramatically increased, since many tunnel projects are performed in the 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 topic in the fields of risk engineering. Therefore, in this paper, 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 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.

**Keywords:** Ground surface settlement, Proportional hazard model, Reliability, Probability, Tunneling

## 1-Introduction

The in-situ stresses are disturbed after the excavation of tunnels, which creates a new stress conditions called induced-stresses. The horizontal component of total displacements causes tensile and compressive stresses on the ground surface, and the vertical component of 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 (Dindarloo and Siami-Irdemoosa 2015; Fang et al., 2016; Qods et al., 2016). In recent decades, many studies have been conducted to predict movements and displacements which can be classified into two main categories of 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, the statistical methods are highly suggested to investigate the behavior of surface subsidence by considering it as random variables and exhibiting it by probability functions. This approach can be useful for analysis and evaluation of geotechnical data based on the uncertainties' point of view (Renard et al., 2013; Rey 2015). 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 CSRS (Collocation-Based Stochastic Response Surface Methodology) approach (Mollon et al., 2013; Grasmick Jacob and Mooney Michael 2017). 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 excavation of tunnels in clay soil (Gong et al., 2014). 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 (Miro et al., 2015). Powers (2017) have obtained the probable range of exceeding settlement with regard to maximum settlement by using reliability analysis. Cheng et al. (2019) presents a study of ground surface settlement induced by large shield EPB tunnelling that provides important insights into the values of settlement trough parameters of empirical methods. Wei and yang (2018) have also proposed a reliability analysis method based on related data to model ground settlement because mining activities. In 2018, Yang et al have 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 water table (Yang et al., 2017). Most of the proposed methods for 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 model. However, in probabilistic models, being random of results is represented as probability distributions and not as unique values (Rey 2015; Franco et al., 2019).

A deterministic model is a model that the state variables are determined uniquely by parameter of models and 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 (Renard et al., 2013). In the deterministic approach, since the environment of 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 it has been mentioned in above paragraphs, another difficulty of deterministic models results is that these results need to be validated, which means researchers must validate their results with the value of instruments or other deterministic approaches. The other negative point of deterministic models is implementation of this model in various situation 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 have written above, although the physics of the system is simple to deterministic equations, it is difficult 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 (Renard et al., 2013; Miro et al., 2015). For this reason, an appropriate models considers the uncertainty of geotechnical parameters, and also can be applied for various conditions, which shows a fast and cost-effective response for the prediction of settlement.

In this regard, 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 the random events based on probability (Tian and Liao 2011; Chen et al., 2012). In the reliability model, the ground surface settlement is calculated regardless of environmental conditions and the occurrence of different ground surface settlement are 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 estimating its effect in the form of risk factors on occurrence of objective function, i.e., ground surface settlement.

This research 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 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 measure to prevent the occurrence of unpleasant accidents.

This research 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 is introduced, and then, basic reliability concepts are explained. Following of the second part, the effect of environmental conditions on ground surface settlement in the PHM model is reviewed, which 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 method is one of the most critical issues that is always attracted experts' attention. In this research, due to the unknown and uncertainty parameters in tunnel excavations, the probability of ground settlement domain and allowed magnitudes are assessed using both reliability models and proportional hazards model. The outcome of this research is presented as criteria for assessing the quality of the tunnel project which helps supervisor to make the necessary adjustments and insights to control ground settlement (Jallow et al., 2019; Jia et al., 2020; Guo et al., 2021).

Reliability is a part of engineering sciences which 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 (Luxhoj and Shyur 1997; Ahmadi 2017). Reliability can be defined as the right function of a component, system, or machine in a specified time interval under certain conditions (Mirmojarabian 2013). The engineers have defined reliability to determine the longevity of system based on its components. Based on theoretical point of view, the reliability can be defined as the probability of failure of industrial equipment or probability of individual or patients' life time (Modarres et al., 1999; Stapelberg 2009; Wessels 2010; Raybod 2019). The equation of reliability is shown:(1)

$$Reliability = 1 - Probability\ of\ failure \quad (1)$$

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

$$R(t) = Pr\{T > t\} = \int_t^{+\infty} f(x)dx \quad (2)$$

In equation (2) f(x) is Probability Density Function (PDF) and t is 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" (Ahmadi 2017). Since the Cumulative Probability Distribution Function (CDF) of T indicates the probability of survival time is smaller than t, and reliability function indicates the probability of survival time is Larger or equal t, CDF complements the reliability function. This matter can be shown as equation, which is the function of F(t) is CDF (3):

$$R(t) = P(T > t) = 1 - P(T \leq t) = 1 - F(t) \quad (3)$$

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. 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 reliability function in equation (4):

$$R(s) = Pr(S > s) = \int_s^{+\infty} f(s)ds = 1 - F(s) \quad (4)$$

- 2- Probability of ground surface settlement smaller than s, which is expressed using CDF in equation (5):

$$F(s) = Pr(S \leq s) = \int_0^s f(s)ds \quad (5)$$

## 2.1 The 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 1970 s, 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 (Nouri Qarahasanlou 2017; Wang 2020). 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 (PHM)

The Proportional Hazards Model (PHM) is a standard model that is used for various science to analyze survival data (Seetharaman and Chintagunta 2003; Sankaran and Sreeja 2007; Aramesh et al., 2016). PHM model is a non-parametric or semi-parametric model (does not consider a specific distribution function to data), which was firstly 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 project to estimate ground surface settlement's risk since as it has been mentioned, the survival analysis is part of reliability theory. Therefore, all relationships and concepts which are related to reliability theory can be generalized to analyze the Cox model and use it for further investigation ( Kumar and Klefsjö 1994; Wei 1984). Reliability relation of ground surface settlement is based on PHM model as equation (6):

$$R(s, X) = (R_0(s))^{\exp(\sum \beta_i X_i)} \quad (6)$$

In Eq.(2-6)  $R_0(s)$  is the reliability function of ground surface settlement which is calculated based on monitoring data and  $\exp(\sum \beta_i X_i)$  involves the impact of risk factors. The important feature of this Eq., 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 (Kleinbaum and Klein 2012; Ranger and Ortner 2013).

### 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: Eq. (7)

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

In this equation: HR is called 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 are called assumption of proportional hazards. For this reason, The PHM can be used if the assumption of proportional hazards is validated (Kleinbaum and Klein 2012).

### Investigation the hypothesis of proportional hazards

For investigation the hypothesis of proportional hazards, the first and second type 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, PH assumption is established (Kleinbaum and Klein 2012). 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 group of variables are match and identical, then, PH assumption is established (Sankaran and Sreeja 2007; Kleinbaum and Klein 2012)

**Schoenfeld residuals as Goodness of fit (GOF) test:** this test lets the researcher make a better decision compared to 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 (Sankaran and Sreeja 2007; Kleinbaum and Klein 2012).

**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 PH assumption is checked as one or more variables. In contrast, the 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 (Sankaran and Sreeja 2007; Kleinbaum and Klein 2012).

### 3-Case study: Iran, TML2 (TML2)

The length of TML2 is 22 kilometers and the diameter is 9.49 meters. 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 ring is excavated and installed in each shift of work. Ground leveling instrument is utilized for monitoring of ground surface settlement points for this project.

According to Figure 1, firstly, monitoring data of ground surface settlement and information relating to risk factors are collected. Then, 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. (Barabadi et al., 2015; Zamani Arabshah et al., 2019)

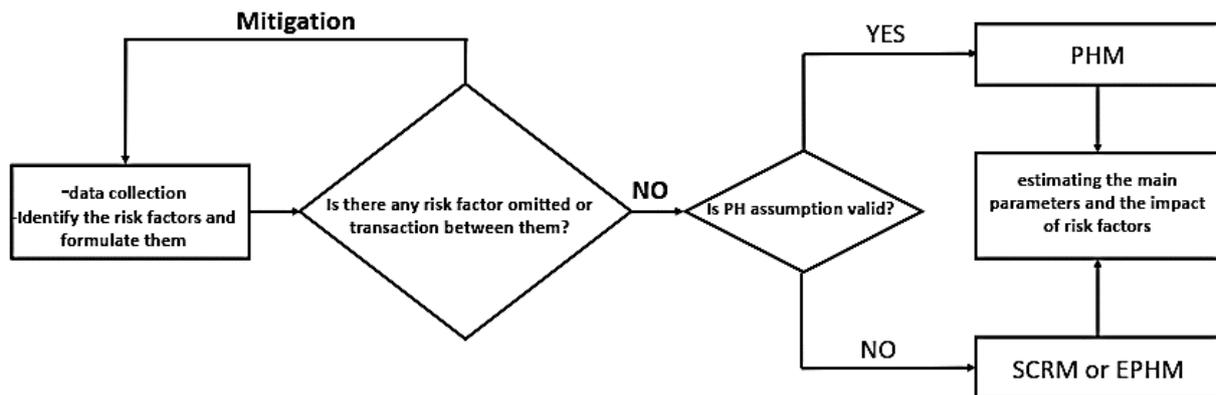


Figure 1- Choosing appropriate regression model for analysis(Barabadi et al., 2015)

### 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 (NASA 2008; Nouri Qarahasanlou 2017).

In this paper, the risk factors database is extracted from the geological engineering profile which was prepared based on experimental and laboratory and in-situ tests. The following principles are taken into account to identify and characterize risk factors (Nouri Qarahasanlou 2017):

- 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 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 tunnel face	continues	23	Modulus of elasticity	continues
9	The thickness of TG-2 layer in tunnel face	continues	24	Poisson's ratio	continues
10	The thickness of TG-3 layer in tunnel face	continues	25	Coefficient of lateral earth pressure	continues
11	The thickness of TG-4 layer in tunnel face	continues	26	Grout injection pressure	continues
12	Consistency index of layers which include 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	Categorical	30	Tunnel face's designed to support pressure	continues
			31	No. 27 – No. 30	continues

Finally, by observing the mentioned principles, 11 risk factors are selected according to Table 2 for the PHM model.

**Table 2 -selected risk factors**

No.	Name of risk factor (symbol)	Type	No.	Name of risk factor (symbol)	type
1	The ratio of the depth of 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 ( $\phi$ )	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 value of ground surface settlement. According to Eq. (6) PHM model consists of two functions; the first function ( $(R_0(s))$ ) is calculated based on ground surface settlement's monitoring data and 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 ( $\beta_i$ ), 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 is 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 (Sodeir Abedy 2011; Nouri Qarahasanlou 2017; Barabadi et al., 2019).

It is worth mentioning that Weibull distribution is applied for  $(R_0(s))$ . Finally, the regression coefficients, parameters of shape and scale of baseline reliability function are calculated (Table 3)

**Table 3- Results of estimating parameters of  $(R_0(s))$  and regression coefficients of influential risk factors ( $\beta_i$ )**

parameter	The regression coefficient of risk factor ( $\beta_i$ )	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 (Eq. (8)). The modeling results is shown the ratio of the depth of 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:

$$R(s, X) = \Pr(S > s) = \left[ \exp\left(-\left(\frac{s}{43.613}\right)^{2.699}\right) \right]^{\exp\left(\frac{D}{W}0.053 - C0.116 + G0.248\right)} \quad (8)$$

Using Eq.(8), 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 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.

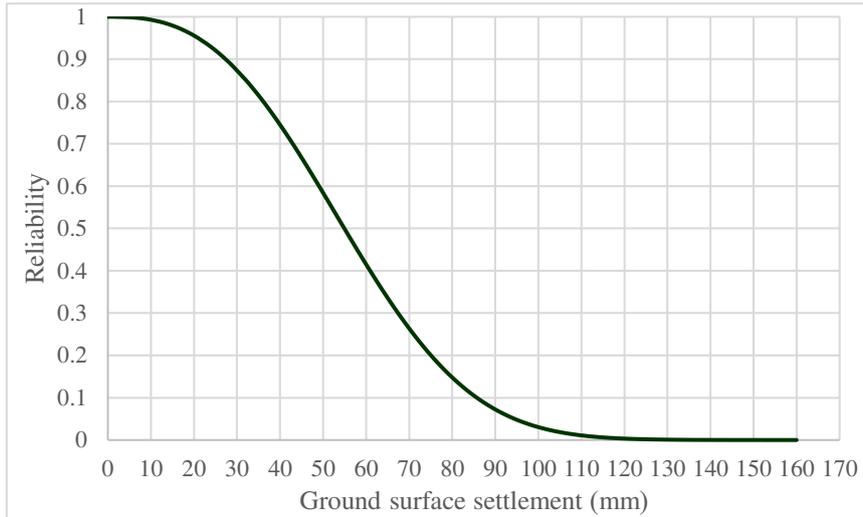
The reliability function graph is obtained by considering the effects of risk factors and its values according to Table 3 and equation (3-1). Based on figure 2 and considering the PHM model, the probability of being exceeded values of ground surface settlement (20 & 30 millimeters) is externally increased (Table 4). 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 is exceeded 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 4- The probability of being exceeded safe settlement values by using the PHM model**

<b>Safe settlement</b>	<b>probability of being exceeded safe settlement values by using PHM</b>
20 mm	95
30 mm	87

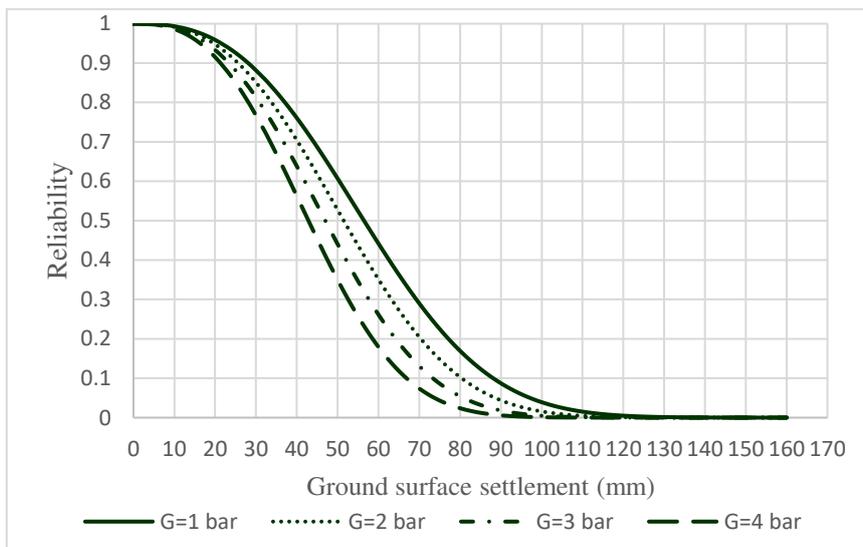
Figure 3 shows the ground settlement reliability for different grout injection pressure values, and for two other risk factors (D/W, C), average values are taken into account.

As shown in Figure 3, the probability of being exceeded safe ground surface settlement (20 & 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.

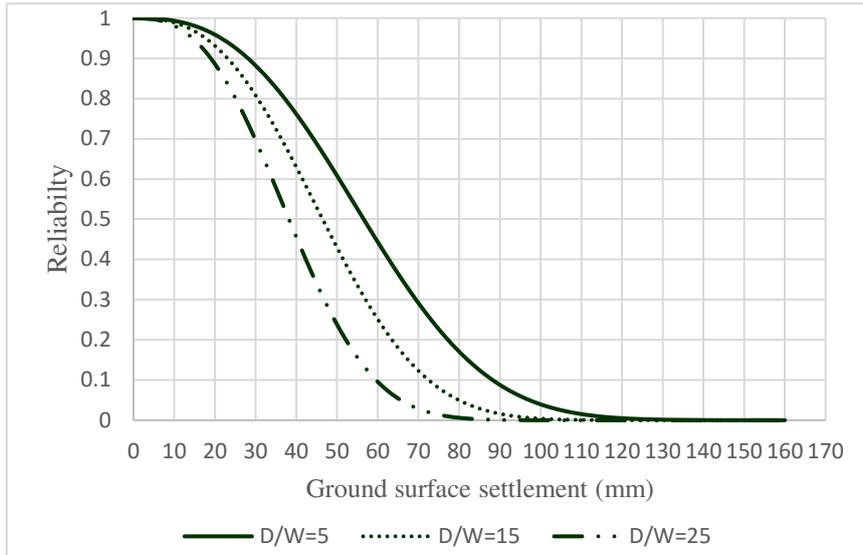


**Figure 2- reliability diagram of ground surface settlement about the impact of risk factors**

Based on the figure 4, 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 above-mentioned plot. As values of D/W increase, it is obvious that the probability of being exceeded safe values of ground surface settlement (20 & 30 millimeters) is reduced.

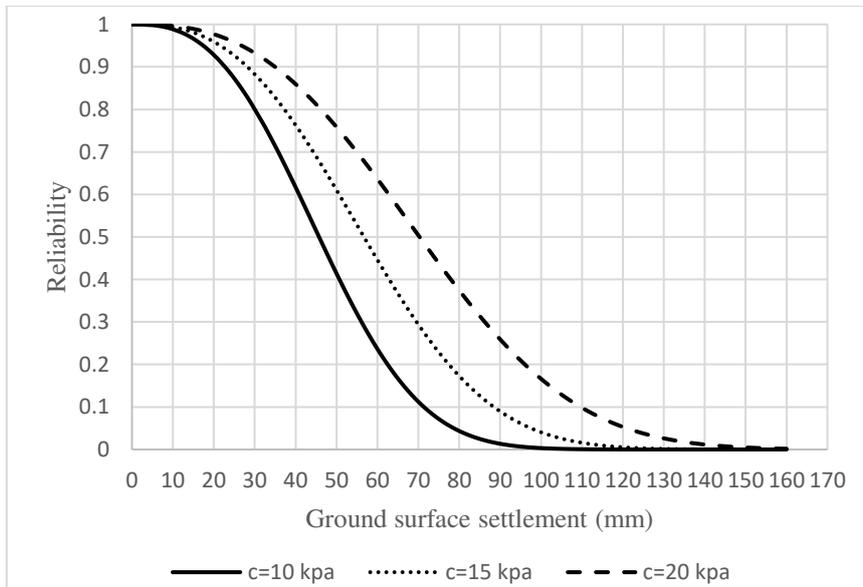


**Figure 3- Reliability of ground surface settlement for varying values of grout injection pressure**



**Figure 4- Reliability of ground surface settlement for varying values of depth of tunnel to underground water level**

Figure 5 exhibits the effects of drained cohesion strength on ground surface settlement reliability. Based on Figure 5, 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 5- 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 hypotheses 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, which take settlement-dependent risk factors, like SCRM and EPHM are used. In this study, Schoenfeld residuals as GOF test is used. Based on the Schoenfeld residuals test, 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 5).

**Table 5- The results of proportional hazards assumption test**

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

Table 5 “a” indicates that 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-Conclusion

One of the most critical issues in mechanized tunneling in urban areas is the ground settlement. Therefore, to evaluate the risk of this phenomena, its estimation and prediction are necessary for tunnel construction projects. Many factors have a direct effect on the amount of ground settlement and its curve. In order to have better understanding, the single impact of the risk factors need to be identified and examined comprehensively. To investigate the impact of environmental conditions on ground surface settlement induced by mechanized tunneling, the PHM model is utilized. Based on the result of this model, the relation of risk factors to underground water level, drained cohesion strength, and grout injection pressure are meaningful at the significance level of 0.05, and the regression coefficient of these risk factors is 0.053, -0.116, and 0.248, respectively. According to regression coefficients, grout injection pressure has the highest impact on the probability of ground surface settlement occurrence. Among the two remaining factors, drained cohesion strength has more effect. By analyzing

the settlement data and using risk factors and their impact in the form of the PHM model, it is possible to predict the probable values of ground surface settlement in the sections that have not been excavated yet. In addition, the results of one-month monitoring of ground surface settlement data can be extended to long-term settlement due to the consolidation parameters of soil. Because, based on monitored data, settlements that are occurred in 3 and 6 months, are mostly more than the exceeded allowed values. Therefore, in sections where the probability of one-month exceeding safe settlement values is calculated too high, the settlement will exceed beyond safe values for the long period of time.

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