RISK ASSESSMENT OF RAILROAD FOR THE PRESENCE OF UNDERGROUND CAVITIES BASED ON A STATISTICAL APPROACH

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ABSTRACT
Collapses due to underground cavities have been drastically increasing in urban areas of South Korea. This article establishes a statistical model to assess the risk potential of railroads with respect to underground cavities. The authors first identified the risk factors of the event based on case studies where the collapses of underground cavities took place. The database was then established, taking into account the risk factors, to come up with a statistical model that estimates the risk level. In this study, the maximum likelihood estimation (MLE) method was employed to estimate the parameters in a statistical model. Thorough the statistical analysis, the probability of underground cavity occurrences was found to be expressed in terms of the depth of alluvial layer, groundwater level, water and sewage utilities, and their age. Consequently, an attempt was made to generate a preliminary hazard map for a specific railway route by employing the statistical model.
Keywords: database, maximum likelihood estimation, railroad statistical model, underground cavities.

1 INTRODUCTION

The numbers of occurrences of underground cavities have been dramatically increased in South Korea, particularly in metropolitan areas. The sudden nature of this phenomenon can be very detrimental for the various types of infrastructures and for the residences. It should be noted that the sinkhole is different from underground cavities, dealt with in this article. Several researches have reported that sinkhole hazard is common in limestone karst, associated with subcircular surface depression or collapse structure formed by the collapse of small subterranean karst cavities [1, 2]. Therefore it is deemed more likely a natural phenomenon.

An extensive effort has been made to identify the causes of underground cavities by the Seoul metropolitan government in conjunction with engineers in academic and industry fields [3]. The findings of this research can be summarized as follows:

I. Since 2010, around 600 events per year have mainly taken place in pavements, sidewalks and vicinities of underground construction areas.
II. Around 40% of events occurred during summer season, which has frequent heavy rainfalls.

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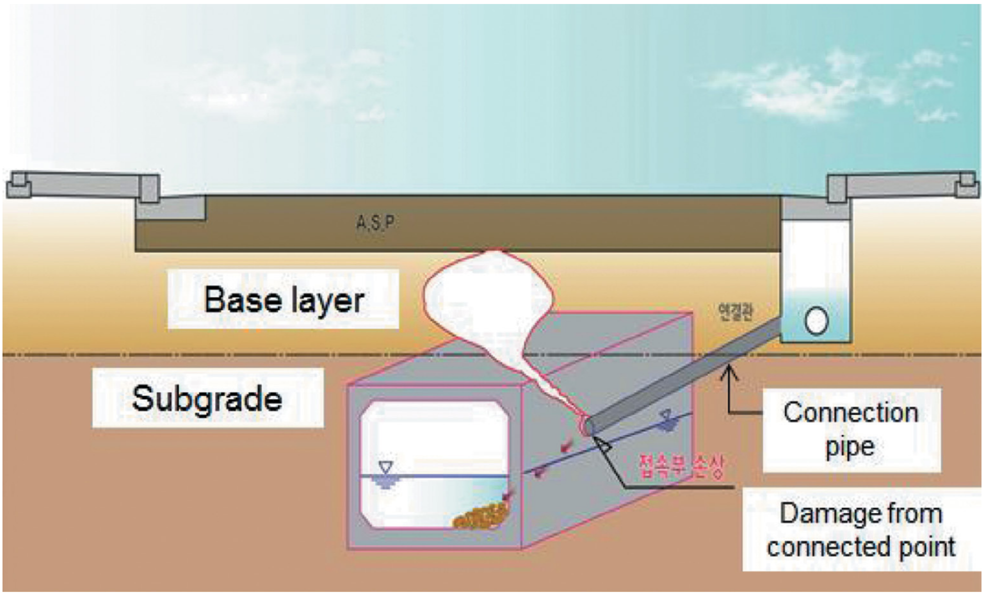

Figure 1: Illustration of the development of underground cavity.

III. The causes of the events have been categorized as:
  - Damage of water and sewage utilities, which allows surrounding soil loss through the holes made as illustrated in Fig. 1;
  - Inappropriate backfill compaction during excavation activities that include open-cut construction and installation of underground utilities;
  - Sudden drop of groundwater table due to pumping activities.

In this article, the author focused on conducting risk assessments of railroads that are being operated throughout metropolitan areas with respect to underground cavities in spite of such events rarely occurring in railroads of South Korea. In order to conduct the risk assessment, the following works have been performed consequently:

I. Identify the critical factors based on numerical analysis
II. Establish database of critical factors
III. Develop a statistical model to assess the risk of underground cavity
IV. Apply the model for a preliminary risk assessment

2 NUMERICAL ANALYSIS

Numerical analysis was employed to identify the critical factors associated with the development of underground cavities. Since this study focuses on railroad structure, the following numerical model was tested. With respect to loading condition, 50 kPa of distributed load was applied at the surface of layer #1 (Figs. 2 and 3).

Table 1 presents the material properties that were used for this analysis. Finite element modelling was utilized along with Mohr Coulomb's failure theory, which is widely adopted for analysing granular or soil material behaviour.

With a given of a 3 metre diameter of underground cavity located along the central line at a depth of 1.5 metre from the top of layer #3, vertical settlement at the top of layer #1 was evaluated along with variation of N-value, which represents the bearing capacity of layer, depth of alluvial layer and groundwater level. The results revealed that vertical settlement tends to increase as the N-value decreases, depth of alluvial layer increases and groundwater level lowers.

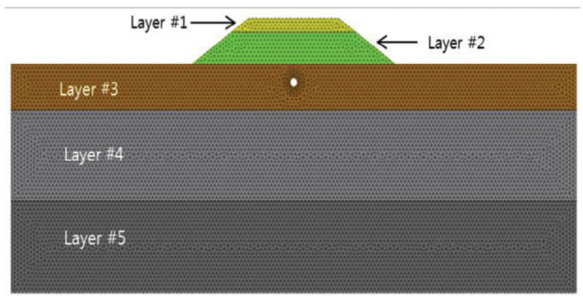

Figure 2: Railroad modelling structure along with underground cavity.

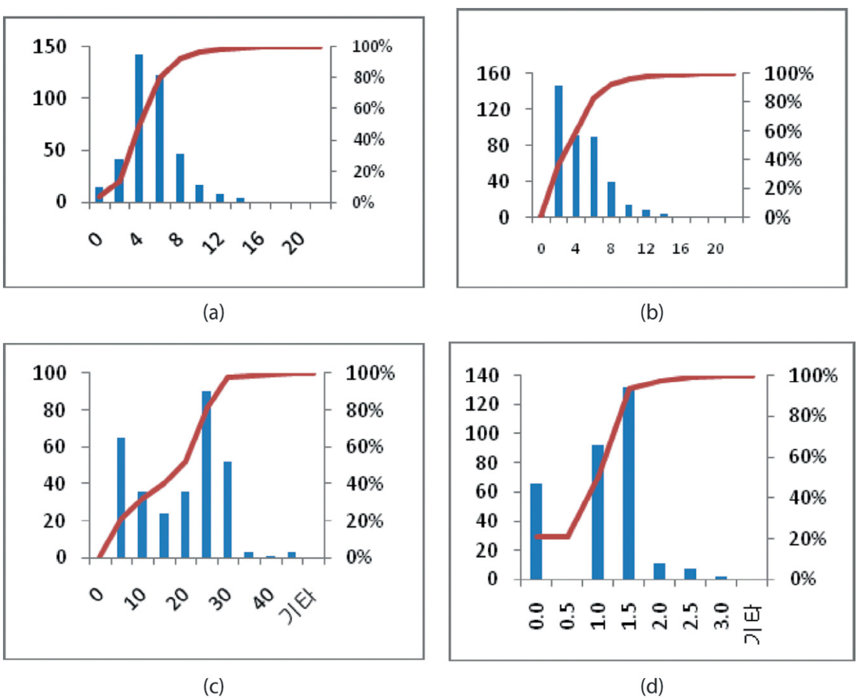

Figure 3: Histogram of each dataset: (a) groundwater table depth (m), (b) depth of alluvial layer (m), (c) age of water pipelines, (d) cover depth of water pipelines.

Table 1: Geometric and material properties used.

Property	Layer #1	Layer #2	Layer #3	Layer #4	Layer #5
Elastic modulus (MPa)	80	60	20	300	2000
Poisson's ratio	0.3	0.3	0.32	0.29	0.28
Unit weight (kN/m^3)	18	18	18	20	23
Cohesion (kPa)	15	15	1	50	150
Internal friction angle (°)	25	25	28	33	35
Thickness (m)	1.5	3.5	5.0	10.0	10.0

3 ESTABLISHMENT OF DATABASE

Based on previous research findings and numerical analysis results, the authors made an attempt to establish database in order to develop a statistical model that assesses the risk of underground cavity around railroads. First of all, all of the locations where the event took place were identified, and geotechnical and underground utility information at the vicinity of the site was extracted using existing database systems. Here are examples of database analysed as follows.

4 DEVELOP A STATISTICAL MODEL

The purpose of developing a statistical model is to generate a hazard map that shows the level of risks, taking into account various critical factors identified. Several researches have established sinkhole hazard models incorporating various data interpretation techniques [1, 4, 5]. The sinkhole hazard models, suggested from previous studies, highly depend on the degree of event occurrences. However, as stated earlier, since there have not been such cases where the underground cavities have been detected at the vicinity of railroads, a rational statistical model that can assess the risk of the event using only the critical factors needs to be developed for the generation of a hazard map.

4.1 Application of maximum likelihood estimation

There are two general methods of parameter estimation: least-squares estimation (LSE) and maximum likelihood estimation (MLE) [6]. While LSE has been widely applied to numerous statistical approaches such as linear regression, sum of squares error and root mean squared deviation, MLE is regarded as a standard method to parameter estimation and inference in statistics [6]. MLE is feasible to have many optimal properties in estimation compared to LSE. Due to the uncertainty of dependent variable, MLE seems to be more appropriate to apply in this study. Using a logistic regression model incorporating MLE, the following eqn (1) can now be written as follows:

$$p \equiv P\left(Y = 1 \middle| \overline{X}\right) = \frac{e^{b_0 + \sum_{i=1}^{m} b_i \overline{X}_i}}{1 + e^{b_0 + \sum_{i=1}^{m} b_i \overline{X}_i}} \quad . \tag{1}$$

In this equation, p is the level of risk, Y is an indicator (when underground cavity occurs, Y=1, otherwise, Y=0), $\overline{X}$ is an average of each dataset (which is regarded as an individual critical factor), m is number of dataset, and b_0 and b_i are MLE coefficients.

Table 2: Results of statistical test.

Variable	b	S.E.	Walls	D.O.F	P-value	Exp (b)
Alluvial layer depth	1.536	0.734	4.379	1	0.036	4.644
Cover depth of sewage	–0.280	0.131	4.592	1	0.032	0.756
Cover depth of water pipelines	–7.134	2.762	6.671	1	0.010	0.001
Intercept	8.430	3.663	5.295	1	0.021	4581.263

For the development of an MLE-based statistical model, six variables were first considered: groundwater table depth, alluvial layer depth, age of sewage, cover depth of sewage, age of water pipelines and the cover depth of water pipelines. The statistical model accounting for all the variables was found to be ineffective due to multi-collinearity among independent variables. After the completion of statistical tests, as presented in Table 2, the following model is tentatively suggested in this study.

$$p = \frac{\exp(8.430 + 1.536x_1 - 0.280x_2 - 7.134x_3}{1 + \exp(8.430 + 1.536x_1 - 0.280x_2 - 7.134x_3}, \quad (2)$$

where x_1 is alluvial layer depth, x_2 is the cover depth of sewage and x_3 is the cover depth of water pipelines.

4.2 Preliminary risk assessment

A preliminary risk assessment was conducted using a statistical model proposed. The authors selected a railroad that travels 11.9 km as denoted by five arrows, representing the location of station. There are five stations, so four segments were evaluated using obtained database along with the statistical model. For the evaluation, the database was used along the railroad which covers 100 metres with respect to the centre of the route. Figure 4 shows the results of

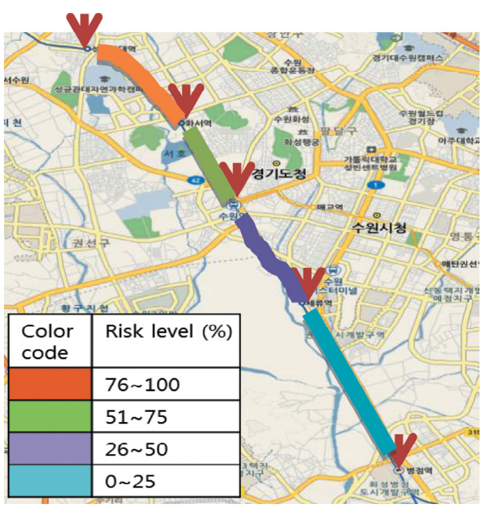

Figure 4: Results of preliminary risk assessment.

the preliminary risk assessment. Further efforts are being conducted to upgrade the statistical model, such as incorporating artificial neural network to improve its efficiency.

5 CONCLUSION

This study aimed to develop a statistical model to generate a hazard map with respect to underground cavities along the railroads in metropolitan areas of South Korea. Employing a numerical model was successfully conducted to evaluate the impact of critical factors on vertical settlements of the railroad structures. Extensive efforts are going on to establish a database of critical factors that entails geological properties and underground utility information at the vicinity of actual underground cavities that have taken place. Based on analysing database, a tentative statistical model incorporating the MLE method was applied to a preliminary risk assessment on a selected railroad segment. As a result, four different risk levels were identified by taking into account critical factors. Further efforts are being conducted to improve the statistical model by employing artificial neural network technique. In addition, field experimental programmes have been planned to verify the hazard map.

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