Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-412
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 14 December 2017

Stability assessment of roadbed affected by ground subsidence adjacent to urban railways

Ki-Young Eum[1], Young-Kon Park[2], Sang-Soo Jeon[3]

[1]Advanced infrastructure research team, Korea Railroad Research Institute, Chuldobakmulgwan-Ro 176, Uiwang City, Gyeonggi-Do 16105, South Korea

[2]Smart station research team, Korea Railroad Research Institute, Chuldobakmulgwan-Ro 176, Uiwang City, Gyeonggi-Do 16105, South Korea

[3]Department of Civil and Urban Engineering, Inje University, Inje-Ro 197, Gimhae City, Kyungsangnam-Do 50834, South Korea

Correspondence to: Sang-Soo Jeon (ssj@inje.ac.kr)

Abstract. In recent years, leakages in aged pipelines for water and sewage in urban areas have frequently induced ground loss resulting in cavities. One third of the pipelines buried in Seoul city in South Korea are more than fifty years old. Train loadings and change in groundwater levels in the undiscerned development of urban areas induce roadbed settlements. Train derailment may occur as the roadbed exceeds the allowable settlements associated with location and size of the cavity adjacent to the roadbed. In this study, FLAC3D, which is a three-dimensional finite-difference numerical modeling software, is used to do stability and risk level assessment for the roadbed in adjacent to urban railways with respect to various groundwater levels and the geometric characteristics of cavities. Numerical results show that the roadbed settlements in simulated ground conditions in South Korea, that satisfy the allowable values for a cavity of diameter of 10 m exists adjacent to the roadbed. The distance between the center of the roadbed and the center of the cavity should be greater than 25 m and the groundwater level should be greater than 22 m below the ground surface.

1 Introduction

Urban railways in South Korea have been initiated from the Seoul subway 1st line in1974 and have been operating in Seoul city and several metropolitan cities. The number of passengers using urban railway are being increased and it has played a significantly important role in public transportation for urban development. Urban railway is defined as transportation facility and method for smooth transportation in the city and includes light rail transit and subway as indicated in the law of urban railway (Ministry of land, 2017). As roadbed settlements exceed the allowable limits, it may result in track irregularity and derailments of trains causing heavy loss of life. Therefore, methods to secure the stability of roadbeds have been examined.

Research on stability assessment and reinforcement of railway roadbeds has been actively carried out, but the effect of the cavity adjacent to urban railways on roadbed behavior has rarely studied. In recent years, the number of accidents induced by cavities larger than 2-m in diameter has increased especially in highly populated cities in South Korea. Therefore, the residents in these cities were terrified of cavities after the accidents (Shin and Roh, 2006). Especially, ground subsidence near subways due to self-weight and/or surcharge loading was around 60% (Lee and Kang, 2014). Changes in groundwater levels may cause increased occurrences of ground subsidence because the lowering of groundwater levels lead to ground settlement (Lee et al., 2015). Groundwater level influences both ground settlement and stability of underground structures. Deep excavation of the ground adjacent to urban railways has a significance influence on the allowable tensile strength of underground structures (Lee at al., 2017). If large underground cavities are located at nearby roadbeds, there is a high potential of ground subsidence.

80% of the ground subsidence occurred from 2010 until the beginning of 2014 in Seoul City (Fig. 1) was induced by aged pipelines for water and sewage (Oh et al., 2015). Since 48% and 30% of sewage pipelines in Seoul city were constructed more than thirty and fifty years ago, respectively. Aged pipelines for water and sewage pipelines cause numerous cavities in the near future (The Segye times, 2016).

As a cavity exists at the center of the railway track in the box structures of urban railways, its influence on box structures and roadbed settlements has been examined to observe the effects of cavities adjacent to the roadbeds of urban railways (Lee at al., 2015). A method to establish a data-base was proposed to prevent and manage the disasters (Choi et al., 2007).

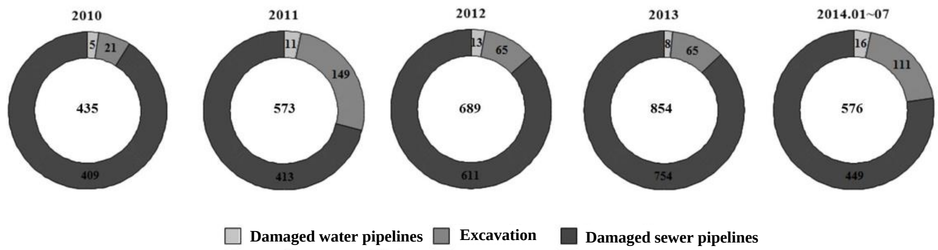


Figure 1. Frequency and cause of ground subsidence in urban areas

As a cavity exists adjacent to the roadbed, in this study, a three-dimensional numerical analysis is carried out to assess both roadbed stability and risk level with respect to the distance between the center of the roadbed and the center of the cavity, diameter of the cavity, and groundwater levels.

2 Case studies of ground subsidence

2.1 Ground subsidence in South Korea

The ground subsidence (Fig. 2) occurred at nearby urban railways most recently (Kyunghang times, 2016). The ground subsidence (Fig. 2a) occurred with a cavity of depth 5 m, width 8 m, and length 80 m near the Seokchon subway station in Seoul City. The accident was induced by the inappropriate deep excavation near the subway. The ground subsidence (Fig. 2b) was caused by the leakage of a water pipeline with a large-scale cavity of depth 21 m, width 11 m, and length 12 m near Bakchon subway station in Incheon City (Newshankuk, 2016). The ground subsidence (Fig. 2c) occurred near Samseongjungang subway station. Six cavities were found almost simultaneously in Seoul City (Kyunghang times, 2016). A small-scale cavity of depth 2.2 m (Fig. 2d) occurred near Janghanpyeong subway station in Seoul City, but the cause of this accident has not been clarified. The accident was assumed to be caused by inappropriate recovery construction near subway extension. Ground subsidence, as described above, occurred at nearby urban railways.

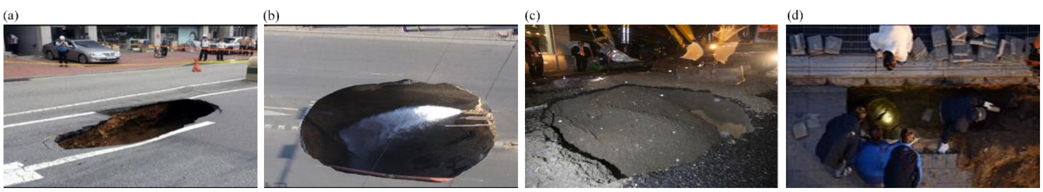


Figure 2. Ground subsidence nearby subway of urban railway in South Korea. Seokchon subway station **(a).** Bakchon subway station **(b)**. Samseongjungang subway station **(c)**. Janghanpyeong subway station **(d)**.

2.2 Representative ground subsidence in the US, Canada, Japan, and China

Ground subsidence (Fig. 3) has occurred at nearby urban railways most recently [10]. Ground subsidence with a cavity having depth 3.6 m (Fig. 3a) occurred as the replacement work of a sewage pipeline was carried out at Texas in the US (Wikitree, 2016). Ground subsidence with a cavity having a width of 15 m (Fig. 3b) occurred as tunnel excavation work for subway extension was carried out at Fukuoka in Japan (Chosun Ilbo, 2016). Ground subsidence with a cavity of width 25 m (Fig. 3c) occurred as a 50-m tunnel excavation near the light rail transit was carried out at Ottawa in Canada (Yonhap news, 2016). Ground subsidence with a cavity of depth 10 m (Fig. 3d) occurred as subway construction was carried out near Guangzhou in China (Sisa china, 2016). Ground subsidence with a large-scale cavity in urban areas is highly correlated with the undiscerned development of urban areas, abuse of groundwater and inappropriate underground construction.

Figure 3. Ground subsidence nearby subway of urban railway in the US, Canada, Japan, and China. Texas in the US **(a)**. Fukuoka in Japan **(b)**. Ottawa in Canada **(c)**. Guangzhou in China **(d)**.

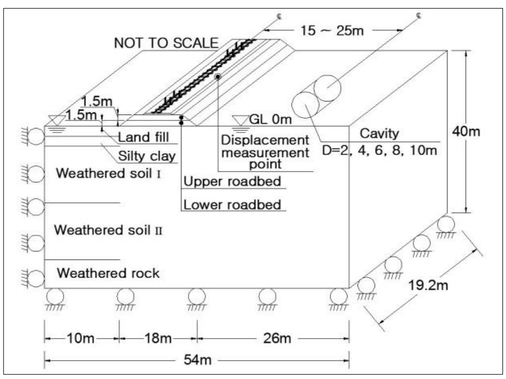
3 Numerical analysis

3.1 Conditions for numerical analysis

In this study, FLAC3D, which is a three-dimensional finite-difference numerical code, is used to conduct stability and risk level assessment for roadbeds associated with various groundwater levels and the geometric characteristics of cavities adjacent to urban railways. The Mohr-Coulomb failure model has been used for the analysis (Itasca Consulting Group Inc., 2015). Since there are various causes and sizes of the cavity of ground subsidence occurring near urban railway, it is very difficult to simulate the process of cavity generation. A circular cavity below the ground surface has been modelled with respect to diameters (D) of 4-10 m at distances of 15-25 m from the cavity to the center of the roadbed associated with various groundwater levels. The analysis is performed based on the configuration and numerical model of the analysis, respectively (Figs. 4 and 5).

3.1.1 Ground conditions

An embankment consists of the lower roadbed, upper roadbed, and gravel ballast. The roadbed width at the bottom of the ballast is 8m. The widths of its bottom and top are 5.1 m and 3.3 m, respectively, and its slope is 1:1.8. In-situ soil consists of reclaimed soil, silty clay, weathered soil, and weathered rock. Its physical properties listed in Table 1 are obtained from lab experiments of soil sampled at a construction site.



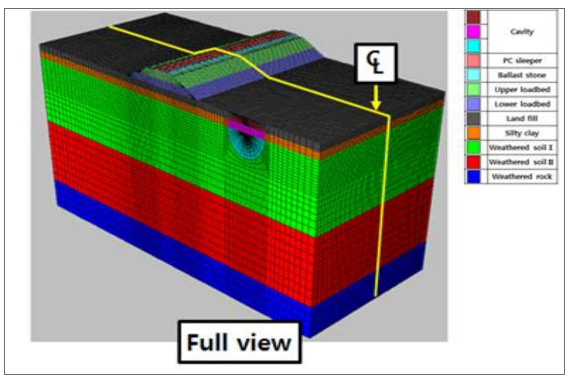


Figure 4. Configuration of the railway roadbed and cavity

Figure 5. Three-dimensional view of the numerical model

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-412
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 14 December 2017

3.1.2 Physical properties of rail, rail pad, and prestressed concrete (PC) sleeper

KS60 rail and prestressed concrete (PC) sleeper commonly used in gravel ballast have been used for the numerical analysis. A rail pad, which is widely used to minimize vibration and impact loading during train operation is made of ethylene vinyl acetate (EVA). However, in this study, a thermoplastic polyurethane (TPU) rail pad, which is more economical and has higher tensile strength has been used for the numerical analysis. Its properties are listed in Tables 2, 3, and 4. The beam element is used for the rail and rail pad.

Table 1. Physical properties of soil

	Height (m)	Unit Weight (kN/m^3)	Elastic modulus (kPa)	Poisson's ratio (υ)	Cohesion (kPa)	Friction angle (°)	Coefficient of permeability (cm/s)	K_o
Ballast stone	0.3	19.0	133,900	0.30	-	35	-	0.43
Upper roadbed	1.5	18.0	81,600	0.20	3.0	32	-	0.47
Lower roadbed	1.5	18.0	51,000	0.30	10.0	30	-	0.50
Land fill	1.5	17.0	30,000	0.35	5.0	24	1.0×10^{-3}	0.59
Silty clay	1.5	17.0	20,000	0.35	5.0	25	5.0×10^{-4}	0.58
Weathered soil Ⅰ	15.0	19.0	75,000	0.33	10.0	30	1.0×10^{-4}	0.50
Weathered soil Ⅱ	15.0	19.0	70,000	0.33	10.0	33	1.0×10^{-4}	0.46
Weathered rock	7.0	20.0	110,000	0.31	60.0	42	1.0×10^{-5}	0.33

Table 2. Physical properties of the rail

	Area (mm^2)	Unit weight (kN/m^3)	Elastic modulus (kPa)	Moment of inertia(m^4)	
				I_{XX}	I_{YY}
KS60 rail	7,741	77.5	$21,000\times10^4$	$30,820\times10^{-9}$	$5,120\times10^{-9}$

Table 3. Physical properties of the PC sleeper

	Length (m)	Width (m)	Height (m)	Interval between sleepers (m)
PC sleeper	2.45	0.28	0.20	0.58

Table 4. Physical properties of the rail pad

	Thickness (mm)	Unit weight (kN/m^3)	Vertical spring coefficient of rail pad (kPa)
Rail pad	5	11.5	15.3×10^7

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-412
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 14 December 2017

3.1.3 Applied train loading

An axial load of the urban railway train (16 tons) is applied for the numerical analysis. The effective loading is estimated by multiplying 1.2 with half of the axial load considering a wheel loading increment of 20% and a marginal safety of deficiency of the cant. Dynamic loading to reflect dynamic impact ratio (Fig. 6) was estimated by multiplying 1.2 with the effective loading (Ministry of land, 2013).

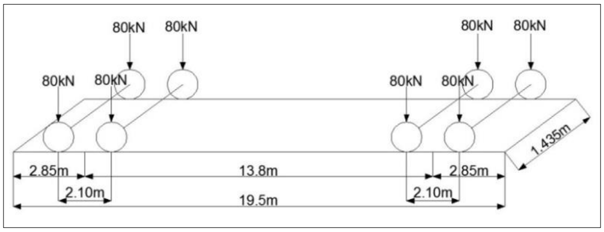


Figure 6. Configuration of the train load

3.2 Allowable settlement of the roadbed

In general, an allowable settlement of 10 mm has been recommended in South Korea. The vibratory loading induces the gravel to be in a loose state, and frequent repairs of ballasts are required. Therefore, an allowable settlement of 2.5 mm is used to attain additional marginal safety considering the compressive displacement of both the rail pad and ballasts, settlement of rail, ride quality, and both water inflow and cracks in the pavement surface of roadbeds (Jeon, 2014).

4 Roadbed Settlement and Stability

4.1 Roadbed settlement

The contours of ground settlement are presented for how the roadbed (Fig. 7) is influenced by a cavity adjacent to the urban railways. The contours of ground settlement are presented for cavities with diameters of 8 m and 10 m, respectively, at a distance of 20 m between the center of the roadbed and the center of the cavity. As shown in the figures, ground settlement increases as the diameter of the cavity increases. As a cavity is generated on the right side of the roadbed, the right end of the roadbed is significantly settled down.

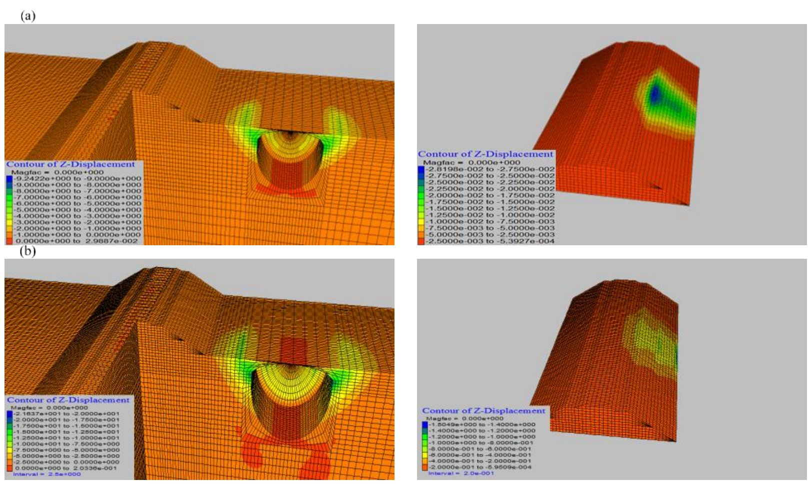


Figure 7. Vertical displacement contour of the roadbed at a distance of 20 m between the center of roadbed to the center of the cavity=20 m with respect to diameter of the cavity. Diameter = 8 m **(a)** and Diameter = 10 m **(b)**

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-412
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 14 December 2017

Natural Hazards and Earth System Sciences
Open Access
Discussions

The analysis results (Fig. 8) are presented for cavities with diameters of 4-10 m. As the variation from 15 to 20 m in the distances between the center of the roadbed and the center of the cavity is applied to the 10-m cavity, roadbed settlements are calculated with respect to various diameters of the cavity. The cavity with a diameter of 10 m at a distance of 20 m has little influenced on the roadbed. However, as the diameter of the cavity at the same distance exceeds 10m, the roadbed settlement exceeds the allowable value. As cavities with diameters of 8 m and 6 m are generated, at distances less than 18 m and 15 m, it exceeds the allowable settlement and may result in an accident

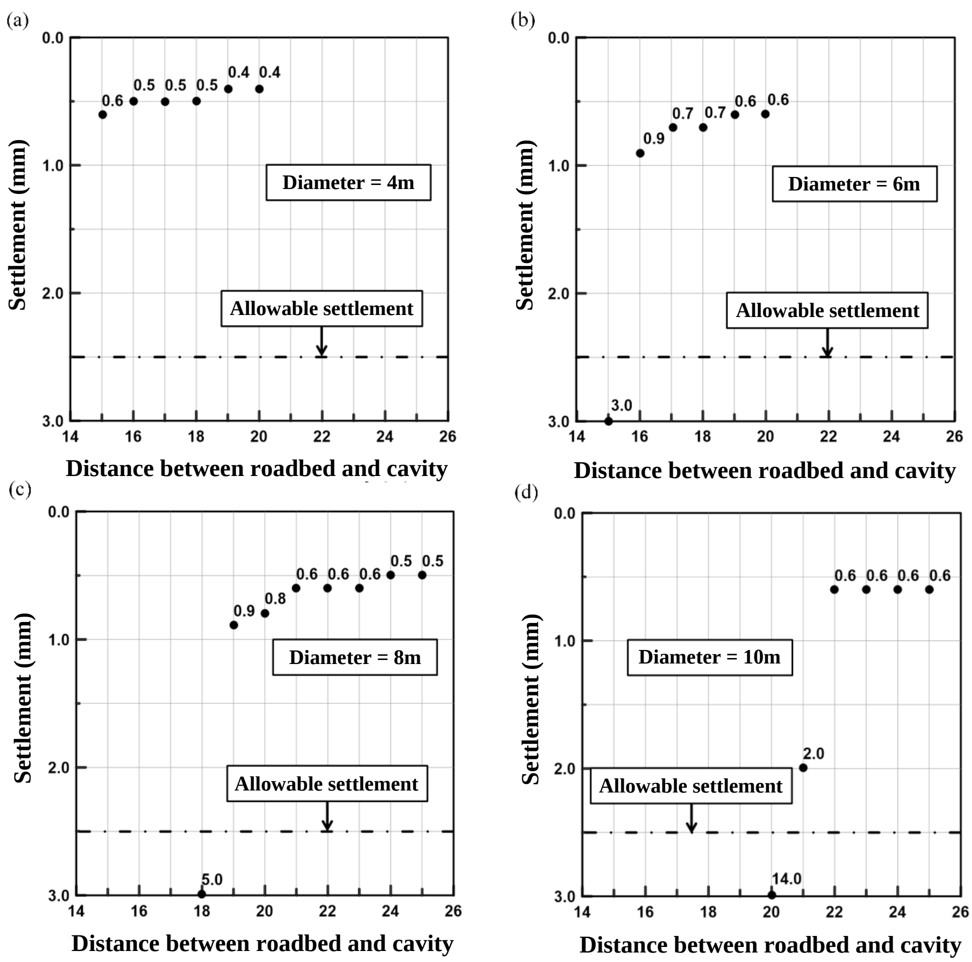


Figure 8. Roadbed settlement with respect to distance between roadbed and cavity. Diameter = 4 m **(a)**. Diameter = 6 m **(b)**. Diameter = 8 m **(c)**. Diameter = 10 m **(d)**.

4.1.1 Regression analysis of roadbed settlement

The regression analysis results (Fig. 9) are presented for the roadbed settlement with respect to the distance (d) between the roadbed and the cavity and diameter (D) of the cavity shows high correlations of r^2=0.72 and substantial increment as D/d exceeds 0.35.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-412
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 14 December 2017

4.2 Effects of groundwater level

In this study, the effects of groundwater level on the roadbed settlement are examined and it is lowered until the allowable settlement value of the roadbed is satisfied. The maximum distance between the roadbed and the cavity for the analysis is determined as the maximum value for the satisfied allowable settlement with no groundwater condition. A stability assessment of the roadbed has been carried out at the distance of 20 m for both 4-m and 6-m diameter cavities and at 25 m for both the 8-m and 10-m diameter cavities.

The contours of ground settlement (Fig. 10) are presented to examine the groundwater level (GWL) effects in the case of the 8-m diameter cavity located at a distance of 25 m from the roadbed to cavity. The contours of ground settlement are presented with GWL on the ground surface and 20 m below it, respectively (Figs. 10a and 10b). The settlement of the roadbed is highly subject to groundwater levels.

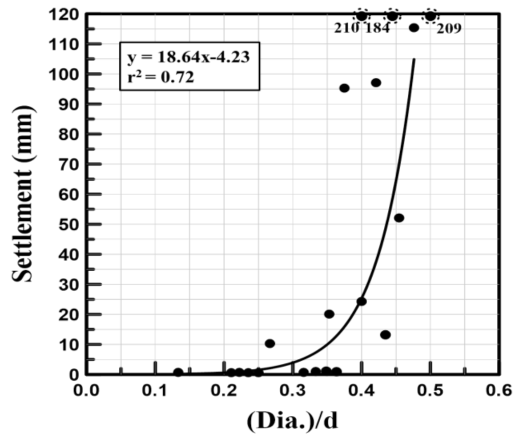


Figure 9. Regression analysis of roadbed settlements with respect to the diameter of the cavity and distance between roadbed and the cavity

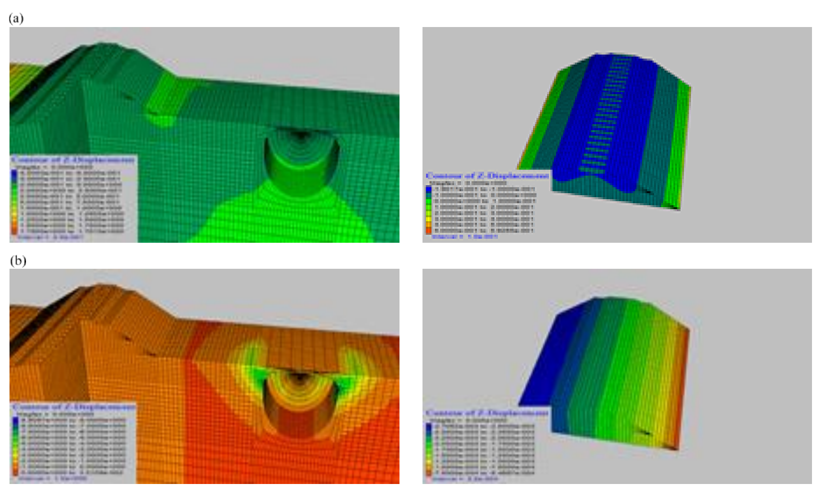


Figure 10. Vertical displacement contours of the roadbed for a cavity diameter 8 m, at the roadbed-to-cavity distance of 25 m with respect to GWL = ground surface **(a)**. GWL = (-)20 m **(b)**.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-412
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 14 December 2017

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

The roadbed settlement (Fig. 11) is highly influenced by groundwater. Ground settlement for 4-m and 6-m diameter cavities located at a distance of 20 m from the roadbed (Figs. 11a and 11b) satisfies the allowable value for GWL=(-) 4m and (-) 12m, respectively. The ground settlement for 8-m and 10-m diameter cavities located at a distance of 25 m from the center of the roadbed (Figs. 11c and 11d) has substantially decreased as groundwater level is 8 m and 15 m below the ground surface, respectively, and satisfies the allowable value as its level is 18m and 22m below the ground surface, respectively. Therefore, a roadbed settlement is highly influenced by groundwater levels to an extent greater than even the influence of the size of the cavity.

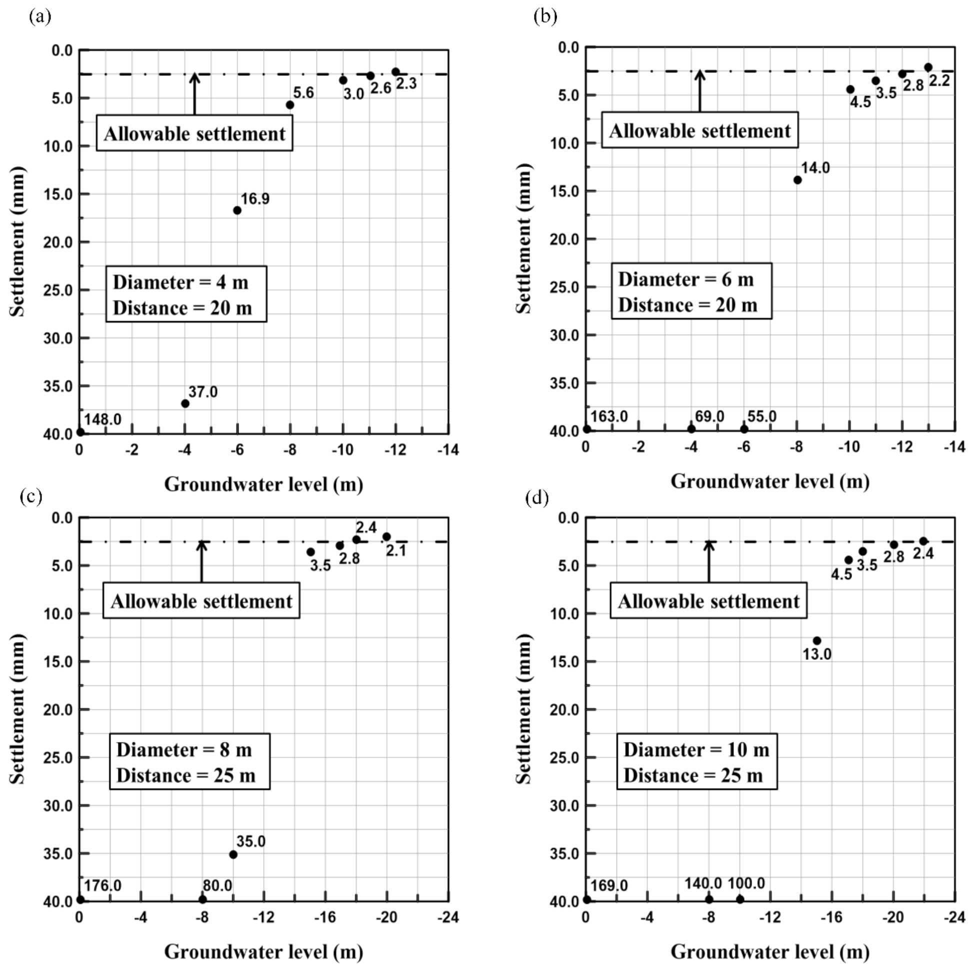


Figure 11. Roadbed settlement with respect to the groundwater level. Diameter of the cavity = 4 m and distance of roadbed from the center of the cavity = 20 m **(a)**. Diameter of the cavity = 6 m and distance of the roadbed from the center of cavity =20 m **(b)**. Diameter of the cavity = 8 m and distance of the roadbed from the center of cavity = 25 m **(c)**. Diameter of the cavity = 10 m and the distance of the roadbed from the center of the cavity = 25 m **(d)**.

4.3 Risk level assessment of roadbed

Roadbed settlements induced by the cavity near urban railways have been estimated with respect to the groundwater level, distance between the roadbed and cavity, and size of the cavity. The risk level has been estimated by the occurrence of roadbed settlements. Its risk level has been defined by the value of the roadbed

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-412
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 14 December 2017

Natural Hazards and Earth System Sciences
Open Access
Discussions

settlements relative to the allowable settlement. The risk level is defined as safe (not problematic for both ride quality and track repair), caution (not problematic for track repair), warning (between caution and danger), and danger (highly probable traffic accident) as a settlement is equal to or less than 2.5 mm, greater than 2.5 mm and equal to or less than 4 mm, greater than 4 mm and equal to or less than 9mm, and greater than 9 mm, respectively As listed in Table 5, the roadbed settlement increases as the size of the cavity increases and the cavity is located close to the roadbed. As listed in Tables 6 and 7, the roadbed settlement for the groundwater condition is less than the allowable value, whereas it is in extreme danger when groundwater is present. When it is in the status of danger, train operation should be stopped and the roadbed should be reinforced or repaired. A database of measurement sensors for urban railways should be established for real-time monitoring of the roadbed, structures and groundwater for disaster prevention.

Table 5. Risk level of the roadbed with respect to the diameter of the cavity and the distance between the roadbed to the cavity for the groundwater condition

		Distance (m)										
		25	24	23	22	21	20	19	18	17	16	15
Diameter (m)	10	Case B										
	8			Random Sampling						Danger		
	6			Safety			Case A					
	4											

※ Safety(Settlement≤2.5mm), Danger(9.0mm<Settlement)

Table 6. Risk level of the roadbed with respect to the diameter of the cavity and groundwater levels at a distance of 20-m between the roadbed and cavity for case A

		Groundwater Level (m)							
		-13	-12	-11	-10	-8	-6	-4	Ground surface
Diameter of cavity (m)	4	Safety		Caution		Warning		Danger	
	6								

※ Safety(Settlement≤2.5mm), Caution(2.5mm<Settlement≤4.0mm), Warning(4.0mm<Settlement≤9.0mm), Danger(9.0mm<Settlement)

Table 7. Risk level of the roadbed with respect to the groundwater levels at a distance of 25 m between the roadbed and cavity for case B

		Groundwater Level (m)							
		-22	-20	-18	-17	-15	-10	-8	Ground surface
Diameter of cavity (m)	8	Safety						Danger	
	10		Caution		Warning				

※ Safety(Settlement≤2.5mm), Caution(2.5mm<Settlement≤4.0mm), Warning(4.0mm<Settlement≤9.0mm), Danger(9.0mm<Settlement)

5 Conclusions

The number of occurrences of ground subsidence induced by a leakage of aged pipelines for water and sewage in urban areas resulting in various sizes of cavity near the urban railway in Seoul City has been found to increase and it may cause the roadbed settlement to exceed the allowable value. A large-scale cavity is rarely found, but if it is close to the roadbed, the roadbed is highly influenced by the cavity and may cause train derailment.

In this study, a three-dimensional numerical analysis is carried out to estimate roadbed stability and its risk level associated with various groundwater levels, sizes of cavities, in simulated ground conditions and tracks in Daejeon urban railways in South Korea.

Future work should focus on coupled hydro-mechanical analysis for groundwater flow and a real-time monitoring system of measurement sensors installed on the railway ground and structures with groundwater to prevent disasters in advance.

Acknowledgements. This work was supported by the 2017 INJE University research grant.

References

Choi, C. Y., Kim, D. S., Lee, J. W., and Shin, M. H.: Development of Database System for Management of Roadbed Settlement in High Speed Railway, Proceedings of Korean Society for Railway Fall Conference, 496-500, 2007

Chosunilbo: Excavations for 15-m diameter large-scale sinkhole Fukuoka in Japan, http://news.chosun.com/site/data/html dir/2016/11/08/2016110801318.html, last access: December 2016.

Itasca Consulting Group, Inc: FLAC3D Manual-Theory and Background, Minnesota, USA, 2002

Jeon, S.-S.: Roadbed behavior subjected to tilting-train loading at rail joint and continuous welded rail, Journal of Central South University, 21, 2962-2969, https://link.springer.com/article/10.1007/s11771-014-2263-2, 2014

Kyunghang times: Additional finings of ground subsidence in Seckchon subway in Seoul, http://news.khan.co.kr/kh_news/khan_art_view.html?artid=201408211343301&code=940100, last access: December 2016.

Kyunghang times: '6; sinkholes concurrence at the same time' nearby sanseongjungang of subway 9th line station, http://sports.khan.co.kr/culture/sk_index.html?cat=view&art_id=201504031002483&sec_id=562901&pt=nv, last access: December 2016.

Lee, H. J., Lee, Y. T., Choi, I. W., Lee, M. S., and Lee, T. G.: Investigation of Settlement of Concrete Track on High-Speed Railway Due to Groundwater Variation, Journal of the Korean Society for Railway, 20, 248-256, 2017

Lee, J. H., Lee, H. S., and Lee, I. H.: IoT-based Convergence Technology for Urban Underground Sinkhole Prediction, in: 2015 Summer metting of The institute of electronics and information engineering, The institute of electronics and information engineering, 1735-1737, 2015

Lee, K. Y. and Kang, S. J.: Causes and Countermeasures of Sinkhole Swallowed the City, Issue and Analysis, 156, 1-23, 2014.

Lee, S. J., Lee, J. W., Jung, Y. N., and Cho, H. J.: Sensitivity Analysis of the Deformations caused by Cavity Generation in Subway Trackbed Foundation using the FEA, Proceedings of Korean Society for Railway Fall Conference, Yeosu, 1480-1485, 2015

Ministry of Land, Infrastructure and Transport, Seoul, Korea, available at: http://www.molit.go.kr/portal.do, (last access: 15 june 2015), 2013

Ministry of Land, Infrastructure and Transport.: Seoul, Korea, available at: http://www.molit.go.kr/portal.do, (last access: 15 may 2017), 2017

Newshankuk: Asphalt road in swallowed by sinkhole brief moment, http://www.newshankuk.com/news/content.asp?fs=12&ss =57&news_idx=201202201707081291, last access: December 2016.

Oh, D. W., Kong, S. M., Lee, D. Y., Yoo, Y. S., and Lee, Y. J.: Effects of Reinforced Pseudo-Plastic Backfill on the Behavior of Ground around Cavity Developed due to Sewer Leakage, Journal of the Korean Geoenvironmental Society, 16, 13-22, 2015

Segye Ilbo: Half of sewage pipelines left for tohirty years without maintenance leads to disaster of sinkhole, http://www.segye.com/newsView/20150322002265, last access: 3 December 2016.

Shin, E. C. and Roh, J. M.: Estimation of RPS Method Using 3-Dimensional Numerical Analysis, Journal of the Korean Society for Railway, 9, 174-179, 2006

Sisa China: Three of buildings one subsidence at Guangzhou in China, http://sscn.kr/news/view.html?section=1& category=5&no=3561, last access: December 2016.

Wikitree: "Giant sinkhole" resulting in rushed car and depth of sheriff, http://www.wikitree.co.kr/main/news_view. php?id=284413, last access: December 2016.

Yonhap news: Large-scale at Ottawa in Canada sinkhole, http://www.yonhapnews.co.kr/bulletin/2016/06/09/0200000000 AKR20160609069000009.HTML, last access: December 2016.