Referee #1

1. **Abstract: Too many background descriptions are presented and too few results are found in the abstract. Four sentences from lines 13 to 17 in page 1 may be merged in a sentence. However some valuable results and conclusions, e.g., the roadbed settlement and the effects of groundwater level, may be added.**

   P.1. Line 13-26: Background descriptions are briefly presented and four sentences from lines 13 to 17 in page 1 are merged in a sentence. The roadbed settlement and the effects of groundwater level are added in Abstract.

   In recent years, leakages in aged pipelines for water and sewage in urban areas have frequently induced ground loss resulting in cavities and ground subsidence causes the roadbed settlement greater than the allowable value. In this study, FLAC^{3D}, 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 roadbed settlement increases as the diameter (D) of the cavity increases and the distance (d) between the roadbed and the cavity decreases. The regression analyses results show that, as D/d is greater than 0.2 and less than 0.3, the roadbed is in the status of caution or warning. It requires a database of measurement sensors for real-time monitoring of the roadbed, structures and groundwater to prevent disasters in advance. As D/d exceeds 0.35, the roadbed settlement, which substantially increases and the roadbed is in the status of danger. Since it may result in highly probable traffic accident, train operation should be stopped and the roadbed should be reinforced or repaired. The effects of groundwater level on the roadbed settlement are examined and the analyses results indicate that a roadbed settlement is highly influenced by groundwater levels to an extent greater than even the influence of the size of the cavity.

2. **Discussion in the segment is not clear, and I think the segment is needed to be rewritten**

   P.11. Line 358-376: Discussion is rewritten in detail.

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, numerical analyses are carried out to estimate roadbed stability and its risk level associated with various groundwater levels, sizes of cavities. The analyses results show that roadbed settlement increases as the diameter (D) of the cavity increases and the distance (d) between the roadbed and the cavity decreases. The regression analyses results show that, as D/d is greater than 0.2 and less than 0.3, a database of measurement sensors should be established for real-time monitoring of the roadbed, structures and groundwater to prevent disasters in advance. As D/d exceeds 0.35, the roadbed settlement, which substantially increases and is in the status of danger, may result in highly probable traffic accident. Therefore, train operation should be stopped and the roadbed should be reinforced or repaired. The effects of groundwater level on the roadbed settlement are examined at the distance of 20 m for both 4 and 6 m diameter cavities and at 25 m for both 8 and 10 m diameter cavities. Ground settlement for 4 and 6 m diameter cavities located at a distance of 20 m from the roadbed satisfies the allowable value for GWL = (-) 4 and (-) 12m, respectively. The ground settlement for 8 and 10 m diameter cavities located at a distance of 25 m from the center of the roadbed has substantially decreased as GWL is 8 and 15 m below the ground surface, respectively, and satisfies the allowable value as its level is 18 and 22 m below the ground surface, respectively. It indicates that a roadbed settlement is highly influenced by groundwater levels to *an extent greater than even the influence of the size of the cavity.*

3. A brief review is anticipated for the development of the software assessing the road risks. Discussion in the 2nd and 3rd paragraphs are chaotic. Figure 1 may be erased.

P.1. Line 35-50: Literature review for risk assessment and numerical modeling is added.

Risk management associated with safety is a fundamental focus in railway operations. It has been integrated into global safety management system of railways (Berrado et al., 2010) and developed to allow a rapid risk assessment using a common risk score matrix (Braband, 2011). As roadbed settlements exceed the allowable limits, it may result in track irregularity and derailments of trains causing heavy loss of life. Therefore, risk management tools are developed to deal with track safety by controlling and reducing the risk of derailments (Zarembski et al., 2006). In this study, methods to secure the stability of roadbeds have been examined using numerical analysis.

Numerical analyses have been widely used for risk assessment. Numerical analyses using three-dimensional geotechnical codes were carried out to predict the subsidence area and its interaction with buildings (Castellanza et al., 2015) and a three-dimensional groundwater flow model for risk evaluation was developed to be an effective management strategy (Ashfaque et al., 2017). The coupling of numerical models and monitoring data contribute to undertake efficient risk reduction policies (Bozzano et al., 2013). Especially using FLAC, which is a finite-difference numerical code especially specialized in the area of geotechnical engineering, numerical computations to simulate the influence of rainfall (Pisani, 2010), both acoustic emission (AE) activities at AE sensor locations of the Kannagawa cavern (Cai et al., 2007), and a comprehensive pump test at Sellafield (Hakami, 2001) showed good agreement with field monitoring results. In this study, $FLAC^{3D}$, which is a three-dimensional finite-difference numerical code especially specialized in the area of geotechnical engineering, is adopted for numerical analysis.

P.11. Line 358-376: Discussion is rewritten in detail.

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In this study, numerical analyses are carried out to estimate roadbed stability and its risk level associated with various groundwater levels, sizes of cavities. The analyses results show that roadbed settlement increases as the diameter (D) of the cavity increases and the distance (d) between the roadbed and the cavity decreases. The regression analyses results show that, as D/d is greater than 0.2 and less than 0.3, a database of measurement sensors should be established for real-time monitoring of the roadbed, structures and groundwater to prevent disasters in advance. As D/d exceeds 0.35, the roadbed settlement, which substantially increases and is in the status of danger, may result in highly probable traffic accident. Therefore, train operation should be stopped and the roadbed should be reinforced or repaired. The effects of groundwater level on the roadbed settlement are examined at the distance of 20 m for both 4 and 6 m diameter cavities and at 25 m for both 8 and 10 m diameter cavities. Ground settlement for 4 and 6 m diameter cavities located at a distance of 20 m from the roadbed satisfies the allowable value for GWL = (-) 4 and (-) 12m, respectively. The ground settlement for 8 and 10 m diameter cavities located at a distance of 25 m from the center of the roadbed has substantially decreased as GWL is 8 and 15 m below the ground surface, respectively, and satisfies the allowable value as its level is 18 and 22 m below the ground surface, respectively. It indicates that a roadbed settlement is highly influenced by groundwater levels to an extent greater than even the influence of the size of the cavity.

P.1: Figure 1 is erased.

4. 2 Case studies of ground subsidence. I think this is only an introduction of ground subsidence instead of the case studies of risk assessments. Hence the segment may be simplified and merged into the first segment introduction.

P.1.Line 30-95: The segment is simplified and merged into the first segment introduction.

5. **Moreover, Figures 2 and 3 may be merged**

   P.2.: Figures 2 and 3 are merged to Figure 1.

6. **The principle of FLAC3D should be briefly and clearly described, or I cannot believe what you calculated are reliable**

   P.3. Line 97-189: The principle of FLAC3D is described.

2 Numerical analysis

In the following sections, the FLAC^{3D} given in this work are briefly described in the following sections by paraphrasing from those of Itasca Consulting Group (2002).

2.1 Theoretical background of FLAC^{3D}

FLAC^{3D} (Fast Lagrangian Analysis of Continua in three Dimensions) is numerical modeling software for advanced geotechnical analysis of soil, rock, groundwater, and ground support in three dimensions. FLAC is used for analysis, testing, and design by geotechnical, civil, and mining engineers (Itasca Consulting Group Inc., 2002). It is designed to accommodate any kind of geotechnical engineering project that requires continuum analysis.

The mechanics of the medium are derived from general principles (definition of strain, laws of motion), and the use of constitutive equations defining the idealized material. The resulting mathematical expression is a set of partial differential equations, relating mechanical (stress) and kinematic (strain rate, velocity) variables, which are to be solved for particular geometries and properties, given specific boundary and initial conditions.

An important aspect of the model is the inclusion of the equations of motion, although FLAC3D is primarily concerned with the state of stress and deformation of the medium near the state of equilibrium. It will be shown, in the numerical implementation section, that the inertial terms are used as means to reach, in a numerically stable manner, the equilibrium state.

2.1.1 Conventions

In the Lagrangian formulation adopted in FLAC^{3D}, a point in the medium is characterized by the vector components x_i, u_i, v_i and d_{vi}/d_t, i=1,3 of position, displacement, velocity and acceleration, respectively. As a notation convention, a bold letter designates a vector or tensor, depending on the context. The symbol a_i denotes component i of the vector $[a]$ in a Cartesian system of reference axes; A_{ij} is component (i, j) of tensor $[A]$. Also, a, i is the partial derivative of a with respect to x_i. (α can be a scalar variable, a vector or tensor component.) By definition, tension and extension are positive. The Einstein summation convention applies, but only on indices i, j and k, which take the values 1, 2, 3.

2.1.2 Stress

The state of stress at a given point of the medium is characterized by the symmetric stress tensor σ_{ij}. The traction vector $[t]$ on a face with unit normal $[n]$ is given by Cauchy's formulae (tension positive):

$$t_i = \sigma_{ij} \tag{1}$$

2.1.3 Rate of Strain and Rate of Rotation

Let the particles of the medium move with velocity $[v]$. In an infinitesimal time dt, the medium experiences an infinitesimal strain determined by the translations $v_i dt$, and the corresponding components of the strain-rate tensor may be written as

$$\xi_{ij} = 1/2(v_{i,j} + v_{j,i}) \tag{2}$$

where partial derivatives are taken with respect to components of the current position vector $[x]$. For later reference, the first invariant of the strain-rate tensor gives a measure of the rate of dilation of an elementary volume. Aside from the rate of deformation characterized by the tensor ξ_{ij}, a volume element experiences an instantaneous rigid-body displacement, determined by the translation velocity $[v]$, and a rotation with angular velocity,

$$\Omega_i = -1/2 e_{ijk}\omega_{jk} \tag{3}$$

where e_{ij} is the permutation symbol, and $[\omega]$ is the rate of rotation tensor whose components are defined as

$$\omega_{ij} = 1/2(v_{i,j} + v_{j,i}) \tag{4}$$

2.1.4 Equations of Motion and Equilibrium

Application of the continuum form of the momentum principle yields Cauchy's equations of motion:

$$\sigma_{ij,j} + \rho b_i = \rho(d_{vi}/d_t) \tag{5}$$

where ρ is the mass per unit volume of the medium, $[b]$ is the body force per unit mass, and $d[v]/dt$ is the material derivative of the velocity. These laws govern, in the mathematical model, the motion of an elementary volume of the medium from the forces applied to it. Note that in the case of static equilibrium of the medium, the acceleration $d[v]/dt$ is zero, and Eq. (5) reduces to the partial differential equations of equilibrium:

$$\sigma_{ij,j} + \rho b_i = 0 \tag{6}$$

2.1.5 Boundary and Initial Conditions

The boundary conditions consist of imposed boundary tractions (see Eq. (1)) and/or velocities (to induce given displacements). In addition, body forces may be present. Also, the initial stress state of the body needs to be specified.

2.1.6 Constitutive Equations

The equations of motion Eq. (5), together with the definitions Eq. (2) of the rates of strain, constitute nine equations for fifteen unknowns — the unknowns being the 6 + 6 components of the stress- and strain-rate tensors and the three components of the velocity vector. Six additional relations are provided by the constitutive equations that define the nature of the particular material under consideration. They are usually given in the form

$$[\dot{\sigma}]_{ij} = H_{ij}(\sigma_{ij}, \xi_{ij}, k) \tag{7}$$

in which $[\dot{\sigma}_{ij}]$ is the co-rotational stress-rate tensor, $[H]$ is a given function, and k is a parameter that takes into account the history of loading. The co-rotational stress rate $[\dot{\sigma}]$ is equal to the material derivative of the stress as it would appear to an observer in a frame of reference attached to the material point and rotating with it at an angular velocity equal to the instantaneous value of the angular velocity $[\Omega]$ of the material. Its components are defined as

$$[\dot{\sigma}]_{ij} = (d\sigma_{ij}/d_t) - \omega_{ik}\sigma_{kj} + \sigma_{ik}\omega_{kj} \tag{8}$$

in which $d[\sigma]/dt$ is the material time derivative of $[\sigma]$, and $[\omega]$ is the rate of rotation tensor.

7. **Figure 4 is not clear especially as it is printed.**

   P.5.: Figure 2 is magnified to be clearly presented.

8. **Figure 5 may be erased for a similar description has been given in Figure 7**

   P.5.: Figure 5 is erased.

9. **Might you try to simply tables 1-4 and merge them as a table?**

   P.6.: Tables 1-4 is merged to Table 1.

10. **We might pay more attentions on results and discussion**

    P.7. Line 280-287: Results are rewritten in detail.

    Roadbed settlement increases as the diameter (D) of the cavity increases and the distance (d) between the roadbed and the cavity decreases. Therefore, in this study, the roadbed settlement is examined with respect to D normalized by d (Fig. 7). The regression analyses results show medium to high correlations of $r^2=0.72$*. As D/d is greater than 0.2 and less than 0.3, the roadbed settlement is approximately 5 mm. It requires that a database of measurement sensors should be established for real-time monitoring of the roadbed, structures and groundwater to prevent disasters in advance. As D/d exceeds 0.35, the roadbed settlement substantially increases and is greater than 10 mm. Since it may result in highly probable traffic accident, train operation should be stopped and the roadbed should be reinforced or repaired.*

    P.11. Line 358-376: Discussion is rewritten in detail.

    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, numerical analyses are carried out to estimate roadbed stability and its risk level associated with various groundwater levels, sizes of cavities. The analyses results show that roadbed settlement increases as the diameter (D) of the cavity increases and the distance (d) between the roadbed and the cavity decreases. The regression analyses results show that, as D/d is greater than 0.2 and less than 0.3, a database of measurement sensors should be established for real-time monitoring of the roadbed, structures and groundwater to prevent disasters in advance. As D/d exceeds 0.35, the roadbed settlement, which substantially increases and is in the status of danger, may result in highly probable traffic accident. Therefore, train operation should be stopped and the roadbed should be reinforced or repaired. The effects of groundwater level on the roadbed settlement are examined at the distance of 20 m for both 4 and 6 m diameter cavities and at 25 m for both 8 and 10 m diameter cavities. Ground settlement for 4 and 6 m diameter cavities located at a distance of 20 m from the roadbed satisfies the allowable value for GWL = (-) 4 and (-) 12m, respectively. The ground settlement for 8 and 10 m diameter cavities located at a distance of 25 m from the center of the roadbed has substantially decreased as GWL is 8 and 15 m below the ground surface, respectively, and satisfies the allowable value as its level is 18 and 22 m below the ground surface, respectively. It indicates that a roadbed settlement is highly influenced by groundwater levels to an extent greater than even the influence of the size of the cavity.

11. **Texts in Figure 7 are too small and blur**

    P.7.: Texts in Figure 7 are magnified to be clearly presented.

12. **It's better that the number values of the vertical coordinates in Figures 8, 9, and 11 grow from the bottom up.**

P.8. & P.10.: In general, settlement starts from the top as shown in Figures 5 & 8.

P.9.: However, as shown in Figure 6, an origin of the vertical coordinates is positioned at the bottom for the purpose of regression analysis.

13. The unit of the horizontal ordinate may be added Figures 7-8.

P.8.: The unit is added in Figure 5.

14. Line width of Figure 9 is different to others

P.9.: Line width of Figure 7 is changed to be consistent with others.

15. What is the meaning of the horizontal ordinate caption in Figure 9

P.9.: In Figure 6, Caption in horizontal axis is added..

16. Lines 225-227 in page 9: Why could you define the risk level mentioned here?

P.7. Line 296-299: Definition of the risk level is moved to section 3.2.

17. Tables 8-10: Color blocks in the tables are not clear as they are printed in black and white

P.11.: Colors in Tables 8-10 are changed to black and white in Table 2.

18. From Segments 4.1 to 4.2, essential discussion on the problems related to the observed data may be added, and comparison of the results calculated in this study to other references may be replenished.

P.6-10.: Unfortunately, any observed data obtained from other references for roadbed settlement associated with cavity have not been found.

19. I could not find any quantitative conclusions here

P.11. Line 358-376: Conclusions are quantitatively described.

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.

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20. The manuscript is readable, but still many minor language errors exist. For examples: In line 180, page 7, the original sentences are: "Diameter = 4m (a). Diameter = 6 m (b). Diametr = 8 m (c). Diameter = 10 m (d)" I think to merge the sentences as follows is better: "(a) Diameter = 4m, (b) Diameter = 6 m, (c) Diamter = 8 m, and (d) Diameter = 10 m"

P.8. Line 301-302: Captions in Figure 6 are changed.

Figure 5. *Roadbed settlement with respect to distance between roadbed and cavity:* ***(a)*** *Diameter = 4 m,* ***(b)*** *Diameter = 6 m,* ***(c)*** *Diameter = 8 m, and* ***(d)*** *Diameter = 10 m.*

21. In line 207, page 8: "4-m and 6-m" may be revised as "4 and 6 m.

P.8. Line 304: "4-m and 6-m" is changed to "4 and 6 m. Errors similar to this are corrected.

22. The sentence in the lines 253-255, page 10, is too complicated to understand

P.11. Line 358-376: Conclusions are quantitatively described.

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.

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