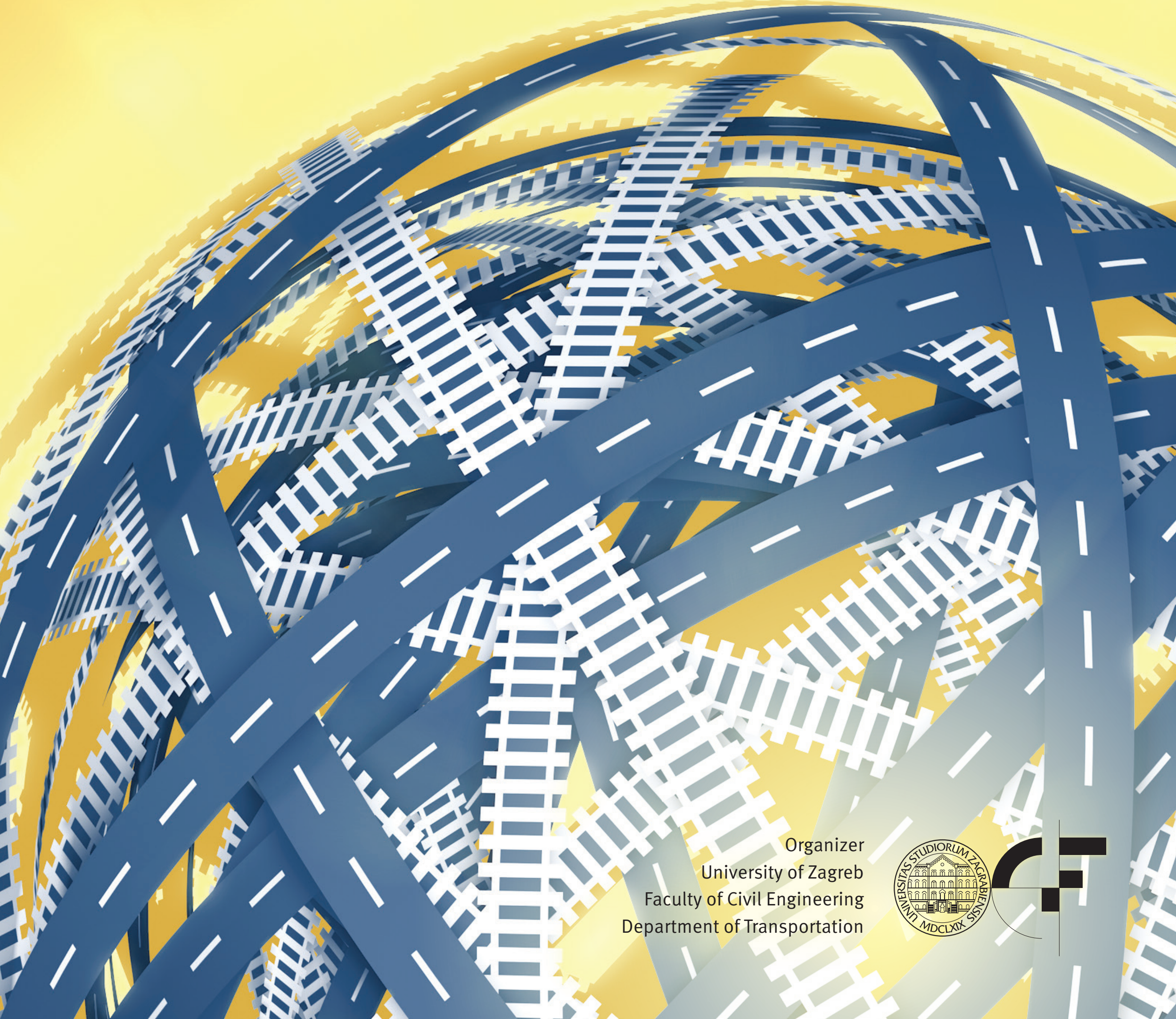
CETRA 2016

4th International Conference on Road and Rail Infrastructure
23–25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



Organizer
University of Zagreb
Faculty of Civil Engineering
Department of Transportation

CETRA[2016]
4th International Conference on Road and Rail Infrastructure
23–25 May 2016, Šibenik, Croatia

TITLE
Road and Rail Infrastructure IV, Proceedings of the Conference CETRA 2016

EDITED BY
Stjepan Lakušić

ISSN
1848-9850

PUBLISHED BY
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE
minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY
“Tiskara Zelina”, May 2016

COPIES
400

Zagreb, May 2016.

Proceedings of the
4th International Conference on Road and Rail Infrastructures – CETRA 2016
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Road and Rail Infrastructure IV

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STABILITY CHART FOR CAVITY EXISTENCE BELOW RAILWAY TRACK

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Abstract

Cavities are found many times recently in downtown of metropolitan cities due to old and damaged pipes installed in the ground. The cavities are generated by spilling out of water from pipes mostly. The cavities generated below subway track can make irregularities and instability of the track. In this study, a finite element program ABAQUS is used to analyze the structural behavior of the track in cases of existence of cavities in subway trackbed foundation. It is found from the FE analysis that there can be a lot of differences in displacement of the track, depending on soil modulus, depth and diameter of cavity. The most important influence factors on the structural stability of track can be provided from the analysis in case of cavity existence in the trackbed foundation. Influence index is proposed in this study for design purpose by investigating geometrical cavity location in the ground that is to be used for checking stability of railway track.

Keywords: cavity, FEA, subway, trackbed stability, influence factor

1 Introduction

Cavities and sink holes are found many times recently in downtown of metropolitan cities due to old and damaged pipes installed in the ground long time ago. It is well known that the cavities are generated by spilling out of water from old utility pipes mostly. The cavities generated below subway track can cause irregularities and instability of the railway track. However, design method for railway track that can be used for checking stability of the track structure in subway is not developed yet when cavities are generated below the railway track. In this study, a commercial finite element program ABAQUS [1] is used to analyze the structural behavior of the track in cases of existence of cavities in subway trackbed foundation. Purpose of study is to find out the most important influence factors on the structural stability of track that has a cavity below the track. Also, it is to develop a simple design method for railway track in case of cavity existence in the trackbed foundation. Influence index that can be used for checking stability of railway track with a cavity below the track is proposed for design purpose by checking cavity location in the ground geometrically.
Sensitivity analyses of the railway track using finite element analysis are performed for checking allowable deformation of the track that are generated by cavity existence.

2 Finite element analysis

2.1 Finite element modelling of track with cavity

In order to develop design chart for stability of trackbed foundation in case of cavity existence below railway track, three dimensional finite element analyses (FEA) are performed broadly. Computed settlements from the FEA are compared to critical allowable values defined by design code. A conceptual design for parametric study of FEA and the finite element mesh used for the analyses are explained in Fig. 1. Finite element mesh is modeled as axisymmetric and two independent axial loads are applied on top of the rails in order to simulate wheel load acting on the rail. The loads are computed by considering DAF (Dynamic Amplification Factor) with design velocity of subway rail cars. Infinite elements are used at the boundaries for reducing reflected energy waves that can affect FEA results such as displacements on top of rail flange. With change of diameter of the cavity, vertical deflections on the top of rails are computed from the FEA. The dimensions and the material characteristics of the elements used for the FEA are those requested by the Korean Railway Authority's (KR) design code [2] (Figure 1 and Table 1)

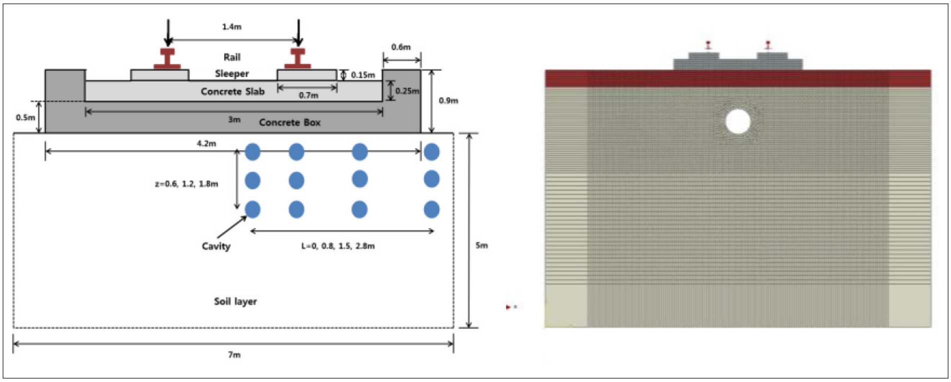

Figure 1 Conceptual design for parametric study of FEA and a typical finite element mesh used for the analysis

The cavities are assumed to be located at positions of L = 0, 0.8, 1.5, 2.8 m where L is horizontal distance from the center of railway track as shown in Figure 1. Diameters of the cavities are assumed as 0.3, 0.6, and 1.2 m. Geostatic stresses are generated by applying gravity forces based on unit weight of the soil. Thus, all computed stresses in the ground due to loading on the top of rail are represented by the following equation:

$$\sigma_v' = \sigma_{vo}' + \Delta\sigma_v \tag{1}$$

Table 1 Material input values used in numerical analysis.

Division	Modulus E [MN/m²]	Poison's ratio v	Density ρ [ton/m³]	Damping	
				α	β
Rail	210,000	0.167	7.85	30.81	5.00E-05
Sleeper	30,000	0.17	2.8	0.4	0.00073
Concrete Slab	30,000	0.17	2.8	0.4	0.00073
Concrete Box	23,000	0.15	2.4	0.4	0.00073
Soil	50, 80, 120	0.3	2	0.4	0.00073

Axial load (Q) of subway train used in Seoul Metro is 120 kN so that static wheel load (Q_w) is 60 kN. Design wheel loads ($Q_{w\text{-}dyn}$) are calculated by considering effective wheel load ($Q_{w\text{-}eff}$) and maximum design velocity (80 km/h) of subway train adapted in Seoul Metro so that pseudo-static wheel load with using DAF (Dynamic Amplification Factor) is computed as 86 kN and is applied on top of the rail. Usually, effective wheel load is 20% bigger than static wheel load. For calculation of DAF, the following well-known equation [1][3][4]is adapted:

$$DAF = 1 + t\phi(1.0 + 0.5\frac{V\text{-}60}{190}) \quad (2)$$

Where:
V – design train velocity;
t – the factor depending on confidence interval (=1);
φ – coefficient for track condition (=0.2).

When the wheel loads are applied on the track, vertical displacements on the top of rail are calculated by FEA. The all computed vertical displacements obtained from FEA are collected and analyzed in order to develop design charts for checking stability of the railway track in subway when a cavity is generated below the track.

2.2 Sensitivity analysis

KR(Korean Rail Authority) design code [1] for railway track describes total allowable vertical displacement(δ_{allow}) including residual displacement and elastic displacement to be less than 30mm after completion of construction of formation level. However, it is required in the code that elastic vertical displacement generated due to wheel load of railway train should be less than 5mm. This means that the vertical displacement of trackbed should be less than 25mm. In this study, the allowable elastic displacement due to wheel load is selected as 5mm in subway structure even though, in usual, more displacement can be allowed by using rail fastening device.
Sensitivity analysis is performed by changing different values of parameters such as elastic modulus of soil (E), diameter of cavity (D), depth of cavity (z). In case of cavity existence below trackbed foundation, all of the parameters E, D and z are regarded as important and critical parameters that can affect vertical displacement on the top of concrete slab used as trackbed as shown in the following figure. As shown in the figure, the concrete slab representing trackbed structure can be regarded as long strip foundation when two wheel loads are applied on top of rails. Therefore, vertical displacement computed at the centre of rails is assumed to be calculated by the following equation which is a modified form of existing equation for calculation of settlement of shallow foundation on elastic half space [5] :

$$\delta_{crtical} = \frac{qB \times (1-\nu^2)E}{qE} I_{cavity} \quad (3)$$

Where:
$\delta_{critical}$ – critical vertical displacement at the centre of rail (shown as red circle in the figure) when a cavity is located below trackbed structure (mm);
q – vertical distributed load at the bottom of concrete slab generated due to wheel load [kN/m²/m];
ν – Poisson's ratio of soil;
E – elastic modulus of soil;
I_{cavity} – influence index of vertical displacement when a cavity is located below trackbed structure.

The influence index (I_{cavity}) is assumed to be function of depth z, elastic modulus E, cavity diameter D and horizontal distance from the centre of loading to centre of the cavity h. In order to use the eqn (3), when a cavity exists below the trackbed, the influence index (I_{cavity}) should be known.

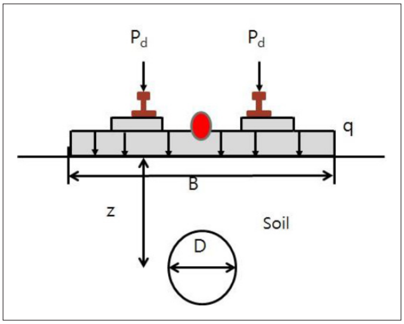

Figure 2 Conceptual diagram of loading on the track and position of vertical displacement computed in case of cavity existence below trackbed.

As defined by Schmertmann [6], settlement estimation of shallow foundation is based on simplified distribution of vertical strain under the centre of a shallow footing, and is expressed as the following equation with the form of strain influence factor (I_z):

$$\varepsilon_v = \frac{q}{E} \times I_z \tag{4}$$

Unlike the assumed distribution of vertical strain influence factor with depth proposed by Schmertmann[6], theinfluence index (I_{cavity}) used in this study is assumed as a function of Geometrical Function (GF) that is defined as the following equation:

$$I_{cavity} = f(GF) = f\{S(D/hz)^n\} = A^m S \cdot (D/hz)^n \tag{5}$$

where the geometrical function GF is assumed again to be dependent on cavity diameter D, depth of the cavity z and horizontal distance of the cavity from the center of track h as shown in eqn. (5).The geometrical function can be obtained from parametric study about track stability by FEA when a cavity exits below the track. In order to get GF, a statistical analysis is run using SPSS program by changing parameters D, h and z in FEA. Method to obtain a basic form of GF is to integrate vertical strain energy consumed in the area of interest with different paramters of D, h and z. Therefore, The factor A shown in eqn 5 is obtained from strain energy consumed due to loading to the track with a cavity. SPSS analysis with various parameters D, h and z can provide factors A and n, m in eqn (5).
If influence index (I_{cavity}) is known, it is possible to check stability of trackbed foundation structure based on the eqn (1) by computing vertical displacement. The first and easiest way to check stability of the track with a cavity is to get normalized vertical strain (ε_v) on the surface of the concrete slab (sleeper) when diameter D and depth z (location) of a cavity are known by GPR and elastic modulus E is measured by LFWD. As shown in Figure 3, the normalized vertical strain (ε_v) computed by using measured vertical displacement (δ) and assumed effective depth 4B where slab or sleeper width B (ex. B = 3 m) is represented and compared with different combination of depth z and diameter D of a cavity. Figure 3 represents a special case with a cavity in the ground located directly below the centre of the track. In order to provide the curves in Figure 3, computed vertical displacements from FEA based on modelling of loaded

track structure as shown in Figures 1 and 2 are used to get normalized vertical strain (ε_v). By selecting different combinations of values of the critical parameters E, D and z when a cavity is detected and is assumed to exist directly below the center of the track, evident trend lines between normalized vertical strains and depth/diameter (z/D) can be obtained as shown in Figure 3. For getting the curves in the figure, distributed load at the bottom of the slab q is assumed as 68 kPa, B = 3 m and Poisson's ration is 0.3. From the curves shown in Figure 3, the following meanings can be obtained:

1) The normalized vertical strains (ε_v) decreases with increase of elastic modulus of the soil (E).
2) The normalized vertical strains (ε_v) decreases with increase of depth of the cavity (z).
3) The normalized vertical strains (ε_v) increases with increases of diameter of the cavity (D).

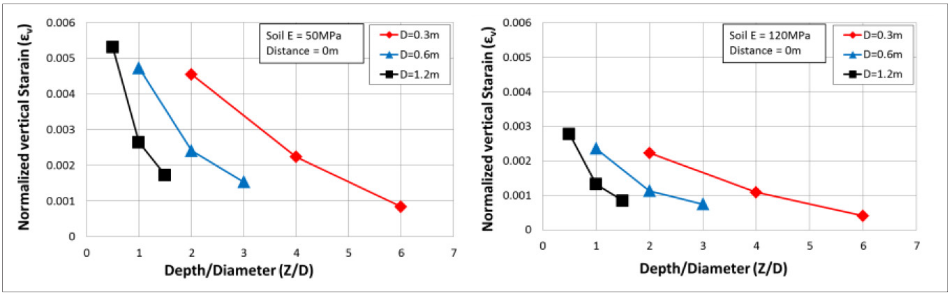

Figure 3 Normalized vertical strain(ε_v) ~ z/D curves

A regression is performed to get optimized graphs as shown in Figure 4 based on data represented in Figure 3. The obtained vertical strains (ε_v) in Figure 4 can be used to determine possibility of instability of the track with a cavity based the maximum vertical elastic displacement generated due to wheel load of railway train that should be less than 5 mm. With different combination of z/D, it is possible to check stability of track with a cavity when a cavity size and depth are known.

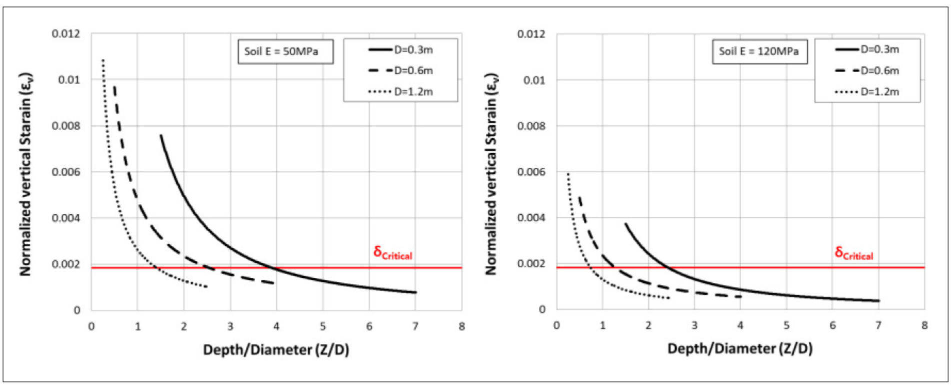

Figure 4 Normalized vertical strain(ε_v) ~ z/D curves

3 Conclusions

Cavities are found many times recently in downtown of metropolitan cities due to old and damaged pipes installed in the ground. The cavities are generated by spilling out of water from pipes mostly. The cavities generated below subway track can make irregularities and instability of the track. In this study, a finite element program ABAQUS is used to analyze the structural behavior of the track in cases of existence of cavities in subway trackbed foundation. It is found from the FE analysis that there can be a lot of differences in displacement of the track, depending on soil modulus, depth and diameter of cavity. The most important influence factors on the structural stability of track can be provided from the analysis in case of cavity existence in the trackbed foundation. Influence index is proposed in this study for design purpose by investigating geometrical cavity location in the ground that is to be used for checking stability of railway track. It is found from the FE analysis that there can be great differences in vertical displacement of the track with a cavity, depending on soil modulus E , depth z and diameter of cavity D.

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