The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 3.4
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.3.4

Numerical study on the appearance of mud spots due to clay-fouled ballast

F. Mitlmeier[1], F. Kotter[1], C. Moormann[1], N. Lillin[2] and S. Freudenstein[2]

[1]Institute of Geotechnical Engineering, University of Stuttgart, Germany
[2]Chair and Institute of Road, Railway and Airfield Construction, Technical University of Munich, Germany

Abstract

In the case of ballasted tracks and cohesive water-saturated subsoils mud spots may occur due to cyclic and dynamic loading by railway traffic. By means of mechanically-hydraulically-coupled dynamic 2D-FEM simulations in this paper evolving mud spots due to clay fouling are investigated. Dynamic loading is considered by model of Frýba, the mechanical behaviour of ballast and clay is represented by hypoplastic constitutive models. According to an ascending ballast contamination it can be shown that vertical deflection of the track is continuously increasing and different zones of suction and of excessive pore pressure in the subsoil are developing.

Keywords: mud spot, dynamic FEM, clay-fouled ballast, hypoplasticity

1 Introduction

Railway track stability essentially depends on the condition of the track, its ballast bed, the load from rail traffic [1] and the properties of its substructure and subsoil [2]. Mud spots can compromise the railway track's stability due to an accumulating deformation of the super- and substructure and can ultimately cause significant damage to the railway structure [3].

The cyclic and dynamic stresses caused by railway traffic can cause contamination of the ballast through internally or externally introduced fine components [4] classified by [5], [6] and [7]. Furthermore, fully saturated cohesive soils underlying the ballast bed can favour clay fouling: by reason of pumping effects [8] fine particles from cohesive layers enter into the ballast bed. Shear strength and stiffness [7, 9] deteriorate as a result and a loss of drainage function is observed [7, 10].

The objective of this paper is to analyse the effect of upcoming mud spots due to clay fouling by means of a mechanically-hydraulically-coupled dynamic 2D-FEM model. The low-frequency components of rail traffic are considered according to the model of Frýba [11]. Constitutive soil model following hypoplasticity [12] with intergranular strain concept [13] is used for the (contaminated) ballast material. Hypoplastic model with intergranular strains in accordance with [14, 15] is adopted for the clayey subgrade.

An evolving mud spot is numerically modelled based on the investigations by Tennakoon [7]. The influence on rail deflections as well as pore water development in ballast and subgrade while train crossing is evaluated.

2 Methods

Based on dynamic FEM, the simulation model considers a realistic vehicle-track-subgrade interaction according to [16]. For determining rail traffic loading, static axle loads were considered. The low-frequency components as a vertical-stress-time-curve were determined according to Frýba [11] (see Figure 1). In this study, a driving trailer type BR 928.4 and a railcar type BR 628.4 were chosen, as they were representative for the investigated track section. The resulting vertical stress-time curve for a crossing of these specific driving trailer and railcar is shown in Figure 2.

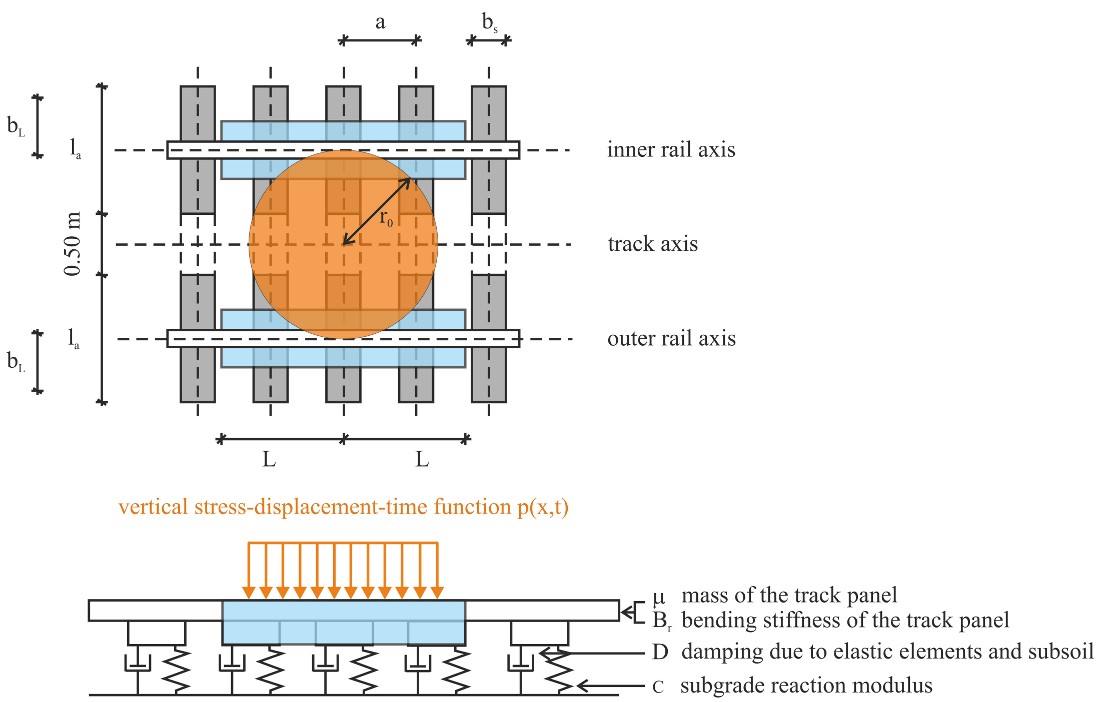

Figure 1: Frýba model [11] and load distribution according to Zimmermann (1888)

Using PLAXIS 2D 2018, a rotationally symmetrical 2D dynamic finite element model (Figure 3) with Rayleigh-damping, absorbing elements and a fully coupled analysis – referred to as *dynamic with consolidation*-analysis - was developed.

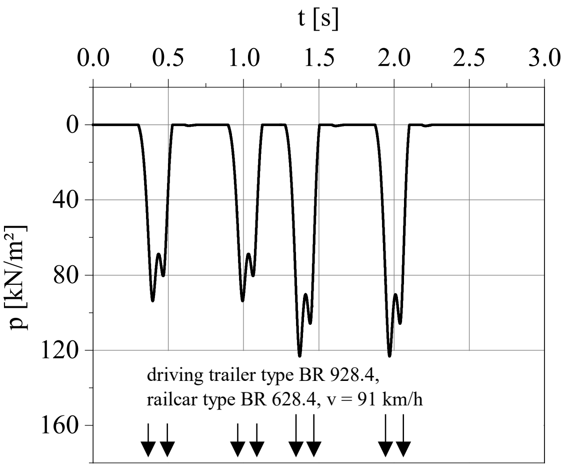

Figure 2: Vertical stress p at sleeper underside while crossing of driving trailer type BR 928.4 and railcar BR 628.4, v = 91 km/h

Hypoplasticity [12] with intergranular strain concept [13] was used to represent the complex soil behaviour of the (fouled) ballast. The hypoplastic parameters are determined mainly based on the monotonic and cyclical drained triaxial tests carried out by Tennakoon [7] and were correlated with empirical values from [15]. Subjacent soils in this track section are homogenized to one semi-solid clay layer in the numerical model, represented by the hypoplasticity law according to Mašín [14, 15]. Material parameters of the cohesive soil were determined on the basis of laboratory test results with the assistance of comparable clayey soils from the literature [15, 17]. Groundwater level is defined in the transition area between ballast bed and the clayey soil layer, cf. Fig. 6.

The simulation procedure starts with the calculation of the initial stress state, followed by the activation of the ballast bed. Subsequently, following Wegener's approach [16], the track renewal machine PM 1000 - URM crossing twice is simulated as a preload phase. Then the simulation of phenomenological mud spot development is started. Based on Tennakoon's definition of fouled ballast [7], for every Void Contaminant Index ($VCI = V_{f'} / V_{vb}$, where $V_{f'}$ is the actual volume of fouling material within the ballast voids and V_{vb} is the volume of voids within a total ballast) - beginning with clean ballast VCI 0 % and ending with highly fouled ballast VCI 100 % - ten train crossings are simulated. Rail deflection and pore water pressures are always evaluated in the last phase for each degree of gravel contamination at discrete nodes, as shown in Figure 3.

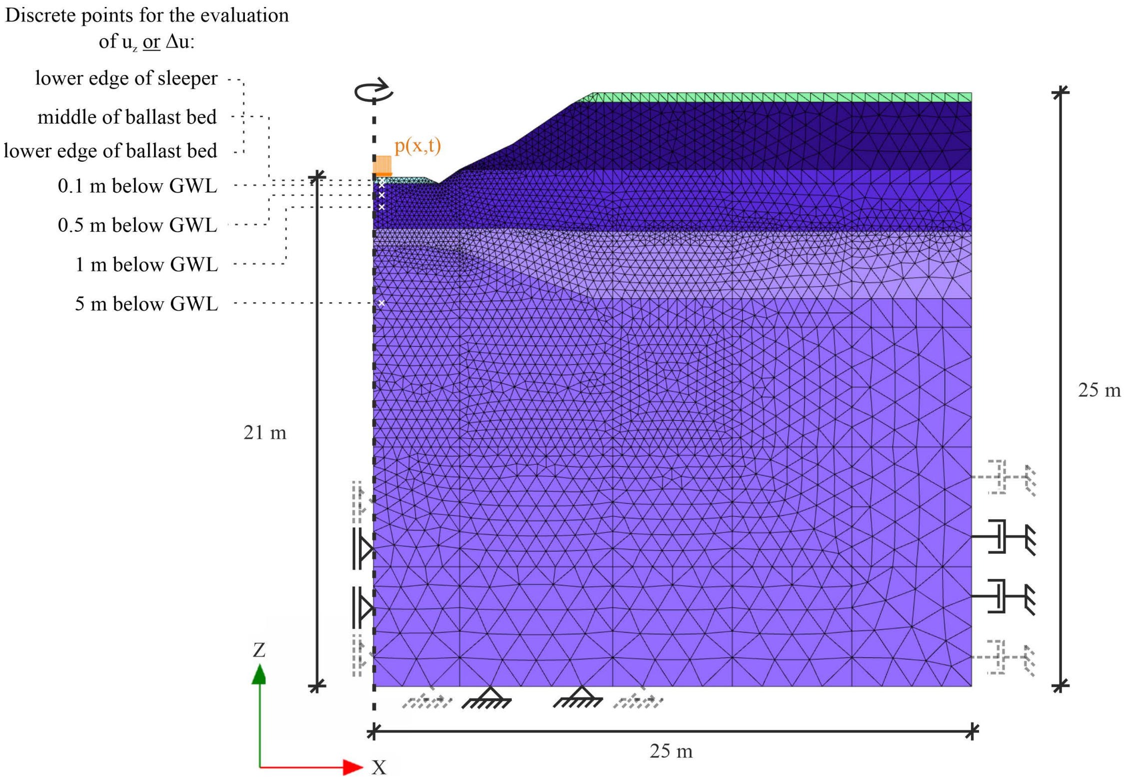

Figure 3: Rotationally symmetrical 2D-FEM model with boundary conditions

3 Results

Figure 4 shows the vertical deformation curves u_z at the lower edge of the sleeper while crossing of driving trailer type BR 928.4 and railcar BR 628.4.

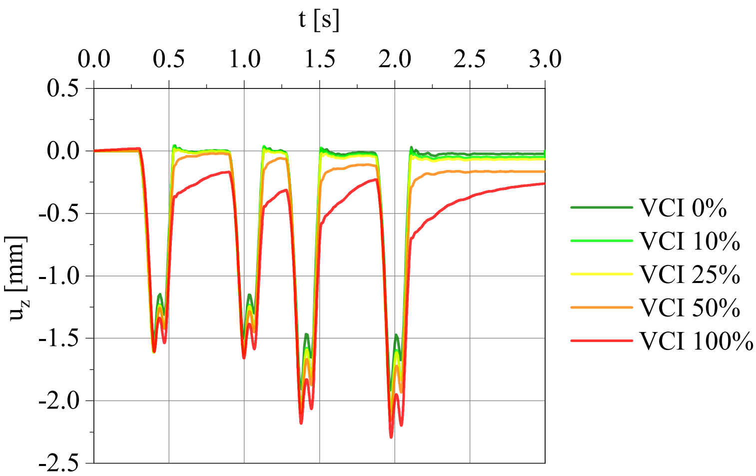

Figure 4: Vertical deformation u_z at the lower edge of the sleeper while crossing of driving trailer type BR 928.4 and railcar BR 628.4, v = 91 km/h

It is observed that with an ascending Void Contaminant Index, deflection of the track resulting from the axle loads is continuously increasing. Beginning with a

VCI of 0 %, the minimum deflection under the railcar axle is 1.9 mm, while with a highly fouled ballast bed (VCI 100 %) maximum deflection under the same axle is 2.3 mm.

Figure 5 presents the change of pore water pressures during and after the train crossing, at various depths. Here it is shown that the railway ballast behaves drained up to a VCI of 10 %. Starting with a VCI of 25 %, the ballast bed behaves increasingly undrained due to the declining hydraulic permeability. Consequently, the excess pore water pressures increase significantly during axle-crossing. In the short unloading-periods following axle-crossing, suction begins to develop in the gravel, starting with a VCI of 25 %. In the transition area between ballast and cohesive subsoil, i.e. 0.1 m below the groundwater level (GWL), excess pore water pressures decrease with an ascending VCI during axle-crossing. An accumulation effect of excess pore water pressures in the cohesive soil at a depth of 0.5 m below GWL is evident. At a depth of 1 m below the GWL the influence of ballast contamination on accumulating pore water pressures subsides.

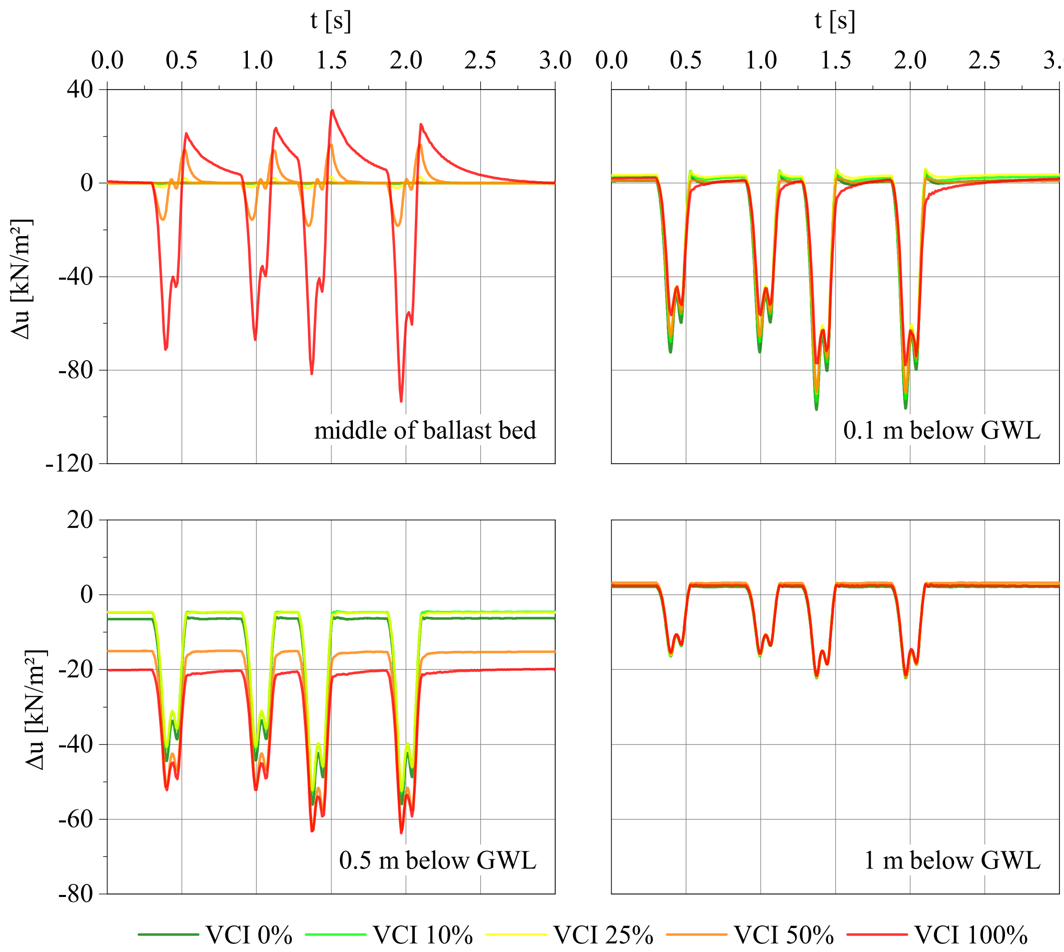

Figure 5: Change of pore water pressure development Δu at various depths while crossing of driving trailer type BR 928.4 and railcar BR 628.4, v = 91 km/h, and increasing VCI

These findings are validated by the results shown in Figure 6. It can be seen that an excess pore water pressure zone develops in the area between 0.2 m and 0.8 m below the GWL. Additionally, two suction zones are observed: one in the area between the ballast and cohesive subsoil, the other fully surrounding the excess pore water zone. The maximum and minimum porewater pressure values in these zones increase with a rising ballast contamination, up to a VCI of 50 %.

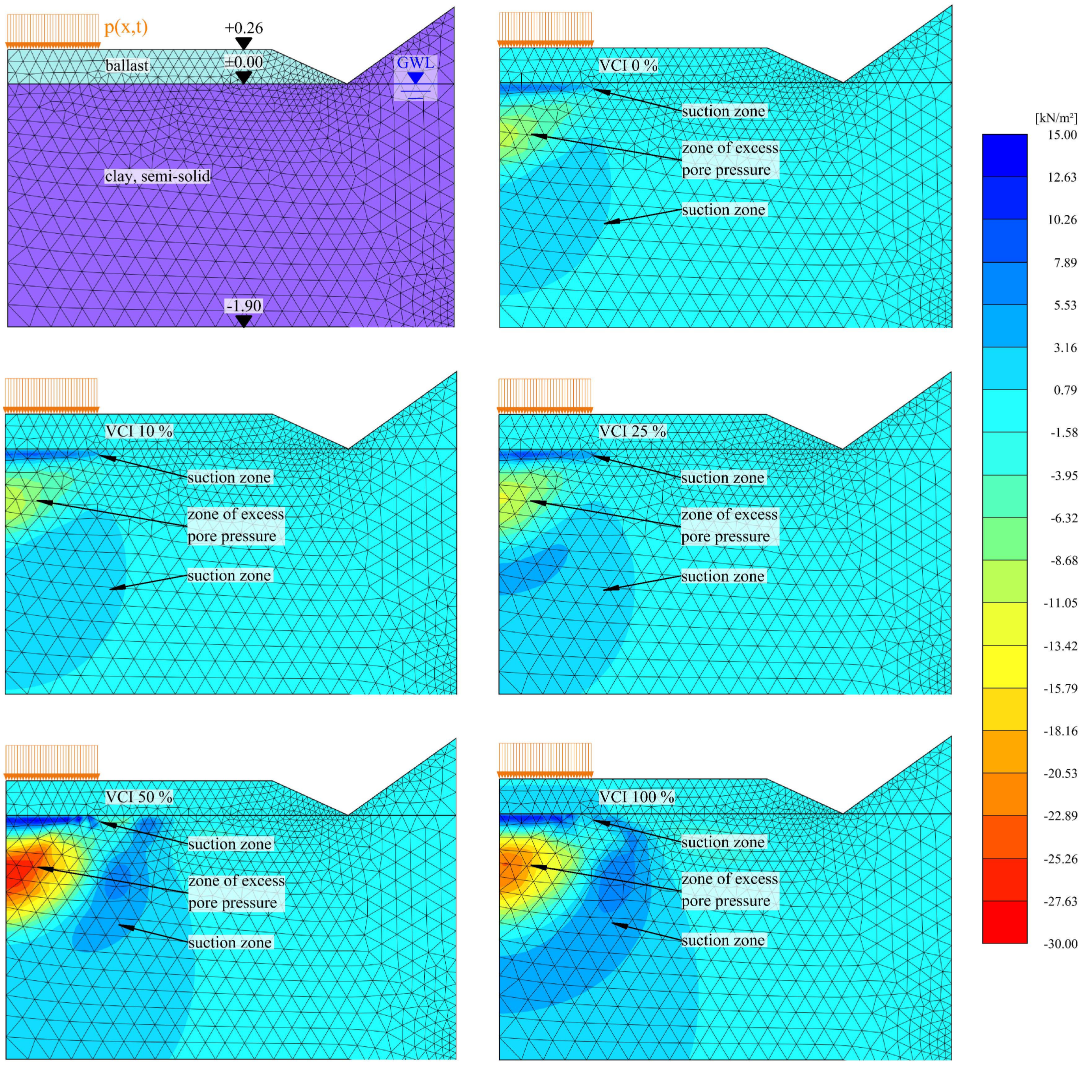

Figure 6: Change of pore water pressure Δu after ten crossings of driving trailer and railcar per VCI

4 Conclusions and Contributions

The progressive contamination of the ballast bed, one of the decisive processes for an evolving mud spot in conventional ballast railways, is numerically modelled by means of a mechanically-hydraulically-coupled dynamic 2D-FEM. Its influence on rail deflections as well as pore water development in the ballast and subgrade while train crossing was evaluated.

It could be shown that the continuous reduction in the shear strength and stiffness as well as the decrease in the hydraulic permeability of the railway ballast consequently lead to a progressive deterioration of the track position. Furthermore, an ascending Void Contaminant Index (VCI) leads to an increasingly undrained behaviour of the ballast bed due to the declining hydraulic permeability. With an increasing VCI, excess pore water pressure accumulation in the area between 0.2 m and 0.8 m below GWL was observed.

Further investigations will transfer the soil dynamics model into 3-dimension evaluations. Two new approaches of vehicle-track-subgrade-interaction will thus be proposed: Approach 1, where dynamic rail-wheel forces determined by a *quasi-rigid* multi body simulation model (MBS) are coupled with a soil dynamics model, and approach 2, where rail seat forces determined by a *flexible* MBS are coupled with a soil dynamics model.

Acknowledgements

The present work has been funded by the German Research Foundation (DFG) under grants MO 2246/3-1 („Simulation punktueller Instabilitäten infolge plastischer Verformungen im Unterbau/Untergrund unter dynamischer Belastung durch Eisenbahnverkehr - EPIB 1.2“) and FR 2910/2-1 („Detektieren von punktuellen Instabilitäten anhand typischer Rad-Schiene-Kräfte - EPIB 2“). The authors would like to acknowledge the support of the DFG.

References

[1] Duley, A., Pen, L. L., Thompson, D., Powrie, W., Watson, G., Musgrave, P., Cornish, A., “Critical train speeds and associated track movements - a case study“, XVI ECSMGE, ICE Publishing, pp. 253-258, 2015.

[2] Lieberenz, K., Müller-Boruttau, F. H., Weisemann, U., “Sicherung der dynamischen Stabilität von Unterbau/Untergrund“, Eisenbahningenieur (EI), Vol. 54(2), pp. 14-24, 2003.

[3] Martin, U., Rapp, S., Moormann, C., Aschrafi, J., “Früherkennung von Instabilitäten an Bahnkörpern in Schotterbauweise“, Eisenbahningenieur (EI), Vol. 66(1), pp. 31-36, 2015.

[4] Ebrahimi, A., Tinjum, J., Edil, T. B., “Deformational behavior of fouled railway ballast“, Canadian Geotechnical Journal, Vol. 52(3), pp. 344-355, 2015.

[5] Selig, E. T., Waters, J. M., Track Geotechnology and Substructure Management, Thomas Telford, 1994.

[6] Feldman, F., Nissen, D., “Alternative testing method for the measurement of ballast fouling: percentage void contamination“, Proceedings of the Conference on Railway Engineering, Wollongong, Australia, pp. 101-109, 2002.

[7] Tennakoon, N., Geotechnical study of engineering behaviour of fouled ballast, Department of Civil, Mining and Environmental Engineering, University of Wollongong, PhD thesis, 2012.

[8] Alobaidi, I., Hoare, D. J., “Factors Affecting the Pumping of Fines at the Subgrade Subbase Interface of Highway Pavements: A Laboratory Study“, Geosynthetics International, Vol. 1(2), pp. 221-259, 1994.

[9] Han, X., Selig, E. T., “Effects of Fouling on Ballast Settlement“, 6th International Heavy Haul Railway Conference, South Africa, pp. 257-268, 1997.

[10] Doung, T. V., Cui, Y.-J., Tang, A. M., Dupla, J.-C., Canou, J., Calon, N., Robinet, A., “Investigating the mud pumping and interlayer creation phenomena in railway sub-structure“, Engineering Geology 171, pp. 45-58, 2014.

[11] Frýba, L., Vibration of solids and structures under moving loads, 3rd Edition, Thomas Telford, 1999.

[12] von Wolffersdorff, P.-A., “A hypoplastic relation for granular materials with a predefined limit state surface“, Mechanics of Cohesive-Frictional Materials, Vol. 1, pp. 251-271, 1996.

[13] Niemunis, A., Herle, I., “Hypoplastic model for cohesionless soils with elastic strain range“, Mechanics of Cohesive-Frictional Materials, Vol. 2 , pp. 279-299, 1997.

[14] Mašín, D., “A hypoplastic constitutive model for clays“, International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 29(4), pp. 311-336, 2005.

[15] Mašín, D., Modelling of Soil Behaviour with Hypoplasticity, Springer Verlag, 2019.

[16] Wegener, D., Ermittlung bleibender Bodenverformungen infolge dynamischer Belastung mittels numerischer Verfahren, Technische Universität Dresden, Institut für Geotechnik, Mitteilungsheft 17, Dissertation, 2013.

[17] Fuentes, W., Mašín, D., Duque, J., “Constitutive model for monotonic and cyclic loading on anisotropic clays“, Géotechnique, Vol. 71(8), pp. 657-673, 2020