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Strength and Numerical Analysis in the Design of Permeable Reactive Barriers

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Abstract. Permeable reactive barriers are one of the most important in situ technologies in groundwater remediation. Most of the installed PRBs have tended to use singular reactive media, but there is an increasing number of applications using combined or sequenced media to treat mixtures of contaminants within a groundwater plume. The concept of a multi-layered permeable reactive barrier (MPRB) to prevent and protect groundwater along traffic routes, especially in ecologically and naturally valuable areas, was developed following several field and laboratory investigations conducted in the Department of Geotechnical Engineering of the Warsaw University of Life Sciences. In accordance with the guidelines of the Interstate Technology & Regulatory Council for the selection of reactive materials, numerous laboratory and field investigations should be performed to determine the environmental conditions, type and concentrations of the contaminants, and the physical-chemical and permeability properties of the reactive materials. However, the deformation and strength properties of the reactive materials should be also considered in the design and evaluation of the safety conditions. In this paper, strength and deformation properties of silica spongolite, zeolite, and activated carbon were investigated using direct shear and oedometer tests. The laboratory test results were used in numerical calculations with the application of the finite element method. The aim of this study was to define the impact of the installation stages of a multi-layered permeable reactive barrier on the stability of a road embankment. Numerical analysis may prevent, reduce or eliminate the risk in the case of a breakdown during the construction or/and exploitation of a PRB.

1. Introduction

The Permeable Reactive Barrier (PRB) is an in situ permeable treatment zone designed to capture and remediate a contaminant plume. PRBs have become important components among the various technologies available to remediate groundwater contamination and are now a standard in the remediation industry [1]. The decontamination of groundwater, which usually occurs within and (or) down-gradient of the barrier, depending on the type of the applied reactive media, is accomplished via destructive and/or non-destructive processes [2], [3], [4], [5], [6]. Since the first implementation in the 1990s, the PRBs have remained an evolving technology with new reactive materials introduced to treat different contaminants, as well as innovative construction methods. “New” reactive materials include mulch, zeolites, sodium dithionite, oxides, “transformed red mud” (a waste material formed from bauxite ore), and other materials, such as carbon/zero-valent iron (ZVI) combinations are also being tested and used [7], [8], [9], [10]. Most of the installed PRBs have tended to use singular reactive media, but there is an increasing number of applications using combined or sequenced media to treat mixtures of contaminants within a groundwater plume [1], [11]. The concept of a multi-layered permeable reactive barrier (MPRB) to prevent and protect groundwater along traffic routes, especially in ecologically and naturally valuable areas, was developed following several field and laboratory investigations conducted in the Department of Geotechnical Engineering of the Warsaw University of Life Sciences [12], [13], [14], [15], [16], [17], [18]. Moreover, the application of sequenced PRB in the treatment of urban storm water runoff using calcite, zeolite, iron and sand fillings was presented by Reddy et al. [19]. The construction innovations include the use of single-pass trenchers, large-diameter boring installations, and injection methods [1].

In accordance with the guidelines of the Interstate Technology & Regulatory Council (ITRC) [1], the design of permeable reactive barriers should be preceded by field investigations and laboratory tests to determine the most favourable reactive material for the treatment of the contaminants, construction of a barrier, and methods of its installation in the field. Due to the possibility of failure construction during the installation of PBR in the ground, numerical modelling should be also performed in order to avoid delays in the investment process, as well as increased costs to cover potential damages [20]. Therefore, according to Park et al. [21] and Fronczyk et al. [12], for design purposes as well as for the removal efficiency of the barrier it is indispensable to estimate the barrier under the stress imposed by the overlying soil, and the strength of the barrier, composed of reactive material. The use of numerical modelling permits better management of these occurrence. The principles calculations of soil mechanics have been employed in the field of environmental science by several researcher [22], [23], [24], [25].

This paper presents an overview of the key design factors including the deformation and strength properties of silica spongolite, zeolite, and activated carbon for the development of multilayered PRBs against mixtures of contamination from road runoff. For this purpose, shear and oedometer tests were performed. Based on laboratory test results, numerical calculations with application of a finite element method (FEM) in plane strain conditions were carried out for the stability analysis of the MPRB.

2. Materials and methods

2.1. Materials

Granular clinoptilolite-rich Slovak zeolite tuff (Zeocem, Slovakia), granular activated carbon (Active Carbon Research and Production Company, Poland), and silica spongolite (Wrzosówka Mine, Poland) were used as the reactive materials in this study. A surface area and porosity analyzer (ASAP 2020M Micromeritics, USA), scanning electron microscope (SEM) images (FEG Quanta 250, USA), and X-ray diffraction (Philips X'Pert APD, Netherlands) spectra were used for the detailed characterization of the reactive materials (18). Characteristics of the particle size distribution, specific gravity and bulk density of the reactive materials are summarized in Table 1.

Table 1. Physical properties of the investigated reactive materials [18]

Material	Particle size [mm]	Specific gravity [-]	Bulk density [g /cm^3]
Zeolite	0.5 - 1.0	2.40	1.054
Activated carbon	0.5 - 2.0	1.96	0.450
Silica spongolite	0.5 - 2.0	2.71	1.820

2.2. Oedometer tests

The oedometer test method carried out during this investigation is a standard method of measuring consolidation properties [26], which involves the incremental loading of soil specimens. Incremental loading is the application of daily increments of vertical load on a submerged container in a rigid ring, with draining permitted through porous stones at the bottom and top. Oedometer samples were tested in 50 mm and 20 mm high rings. The relative density I_D of the samples was 0.6. The loadings were as follows 12.5, 50, 100, 200, and 300 kPa. In the beginning, the samples were loaded up to 300 kPa (the value of the in situ effective stress), and then unloaded to 12.5 kPa.

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2.3. Shear strength tests

The direct shear test was performed to determine the consolidated-drained shear strength of reactive materials according to the ASTM D3080 – 11 standards [27]. The test was performed by shearing a sample at a controlled strain rate. Dry samples were tested, each under a different normal load, to determine the effects on shear resistance and displacement. Each sample was placed in a 60 mm x 60 mm x 60 mm direct shear apparatus, which had two stacked rings to hold the sample; the contact between the two rings was at approximately the mid-height of the sample. A "confining stress" was applied vertically to the specimen, and the upper ring was pulled laterally until sample failure. Several specimens were tested at varying confining stresses to determine the shear strength parameters, the soil cohesion "c", and the angle of internal friction (commonly – friction angle "φ"). Soil failure is defined by the Mohr–Coulomb criterion [28]: $\tau = c + \sigma \tan\varphi$ where τ is the shear stress, c is the cohesion, σ is the effective stress, and φ is the angle of internal friction of the soil.

2.4. Numerical modelling

The impact of MPRB installation on a road embankment near National Road No. 50 in Poland was investigated in the numerical analysis. The parameters for the case study were obtained from a geological-engineering design for the Żyrardów bypass on National Road No. 50. The length of the planned investment is 15.1 km and it passes across farming land and forests.

The MPRB consists of the following layers of reactive materials: silica spongolite, zeolite, and activated carbon. The reactive materials and their order were selected according to the characteristic properties of removal of road runoff pollutants (amount and retention time, processes and removal products) and filter parameters constant in time (constant values of hydraulic conductivity k) [14], [15], [16], [17], [18].The sequence of the layers in the proposed barrier will allow for the pre-treatment of groundwater with chloride and heavy metals ions on silica spongolite using a pH adjustment processes and precipitation, followed by complete removal of the existing pre-treatment products and other heavy metals and petroleum substances on zeolite and activated carbon during sorption and ion exchange.

The assessment of upstream slope stability of the road embankment during WPBR installation was performed using the finite element method with interface elements in Plaxis 2D software (version 9.02) at plane strain conditions. The linear elastic-perfectly plastic model with the Mohr-Coulomb failure criterion was used for particular layers of soil and reactive materials. The geotechnical parameters for the layers of soil and reactive materials are listed in Table 2.

Table 2. Linear elastic-perfectly plastic model with the Mohr-Coulomb failure criterion parameters for particular layers

Layer	γ [kN/m³]	ν [–]	E [MPa]	M₀ (Eed) [MPa]	c [kPa]	φ [°]
Embankment	18	0.30	80	–	30	30
Underlay (IIa)	16	0.35	–	0.50	5	5
Sand +Gravel (Va)	18.5	0.30	–	20.00	30	30
Clay+ Gravel (VIIIa)	20	0.35	–	10.00	15	15
Sandy Clay+Gravel (XIIa)	20	0.35	–	36.00	20	20
Clay (XIIb)	22.5	0.35	–	60.00	23.4	23.4
Silica spongolite	20.6	0.30	–	23.45	0	20.6
Zeolite	19.6	0.30	–	16.48	0	19.6
Activated carbon	19.8	0.30	–	101.29	0	19.8

where: γ – unit weight, v – Poisson's ratio, E – Young's modulus, M_0 – oedometer modulus, c – cohesion, φ – friction angle.

According to ITRC [1], the barrier can be installed anywhere along the plume and designed to address different site-specific objectives. If the aim of the PRB is mass flux reduction and acting as a source-term management remedy, then the barrier should be installed near the source area. On the contrary, a PRB installed further down-gradient may be used to protect down-gradient receptors. Therefore, calculations were carried out for different variants of MPRB installation: in a roadside ditch (first and main receiver of the pollutants), and at a distance of 1 m and 5 m from the ditch. Moreover, numerical modelling was performed in three stages of the installation process (Fig. 1) using the technology of sheet pile walls [29], [30], [31], [32], [33], [34]. The first stage was in situ analysis, which was followed by load-deformation analysis. The second stage was sheet pile punching and excavation, while the third stage was reactive material filling and removing sheet piling. It was assumed that the analyzed section of the bypass road will be constructed on the embankment (road body) limited by the crown of the road and the slopes of the ditches.

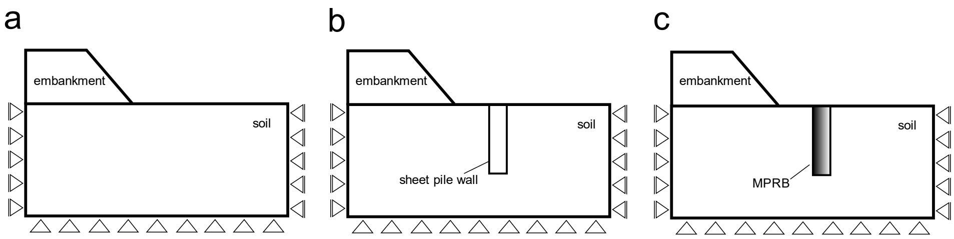

Figure 1. Numerical model (with the boundary conditions) of MPBR installation, where : a) in-situ state, b) sheet pile punching and excavation c) reactive material filling and removing sheet piles

In the calculations, 15-element nodes and a very fine mesh were used to increase the accuracy of the results. Moreover, according to Polish Law (Polish Journal of Laws 2000, 63, 735) [35] the traffic load of 15 kPa was used.

3. Results

The consolidation test results have shown that the largest values of the oedometer modulus (M) were obtained for activated carbon (M_0 – 101.29 kPa, M – 159.72 kPa). For zeolite and silica spongolite, these parameters were as follows: M_0 – 16.48 kPa, M – 61.04 kPa, and M_0 – 23.45 kPa, M – 72.90 kPa, respectively. The total volume changes for AC samples were in the range from 0.025% to 0.284%, for zeolite: from 0.049% to 1.771%, and for silica spongolite: from 0.443% to 1.354%, which indicates greater susceptibility of the two latter materials to deformation. The results of both unloading stages (with and without water) and swelling are presented in Figure 2.

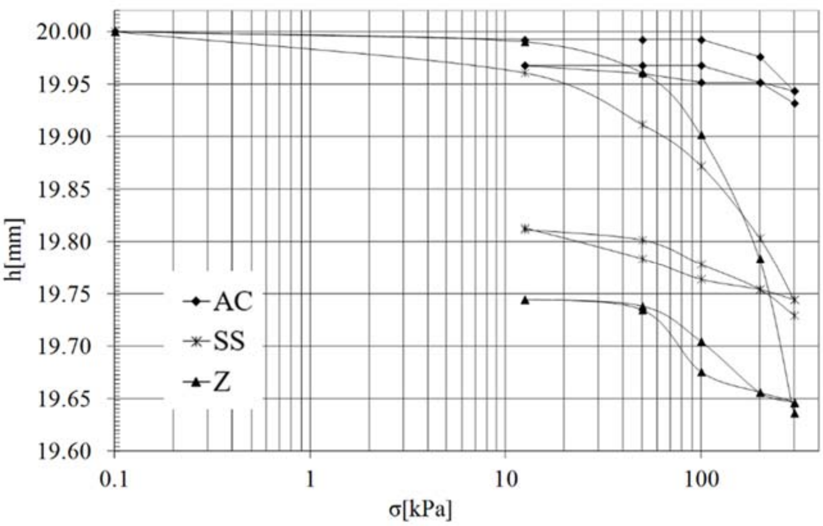

Figure 2. Compressibility curves from oedometer consolidation tests

The shear strength test of the reactive materials was undertaken as for granular soils. By plotting the vertical pressure σ versus shear stress τ at failure, the angle of friction φ was obtained. The values of φ for activated carbon, zeolite and silica spongolite were as follows: 19.8º, 19.6º, and 20.6º, respectively, and the values of c were 0 kPa. The results of the tests are presented in Figure 3.

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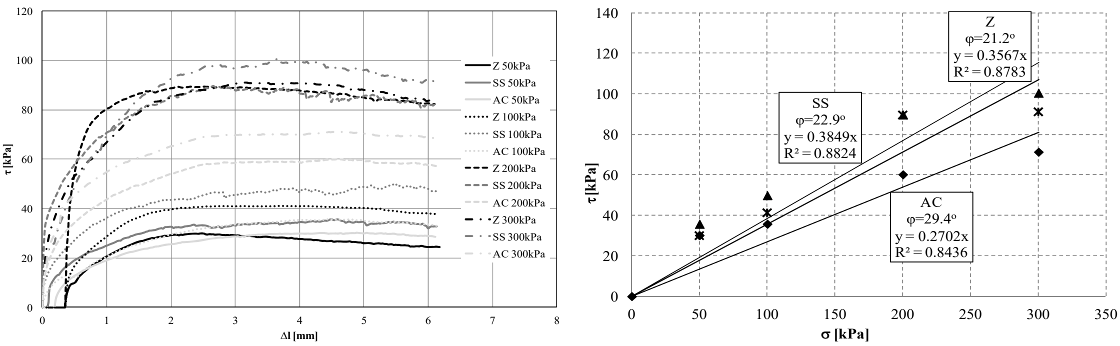

Figure 3. Displacement versus shear stress curves and normal stress relationship obtained from direct shear tests

The values of φ for the surveyed reactive materials were low and within the range of 21.2º to 29.4º. Lower values of φ for reactive materials were caused by cementation and/or abrasion of the material into smaller particles that formed an envelope around larger particles, facilitating slip during shear (lower friction). Results of the consolidation and friction tests were used in the assessment of the embankment stability to define parameters for the finite element method (FEM). The calculation results using the finite element method in Plaxis software presenting total displacements are shown in Figures 3–7 and Table 3.

Table 3. Total displacements and increase of total displacements

Stage	Total displacement [m]	Increase of total displacement [m]
In situ	0.004	$203.93 \cdot 10^{-6}$
1. Sheet pile wall	0.006	$341.51 \cdot 10^{-6}$
2.1. MPRB - road ditch	0.005	$603.28 \cdot 10^{-6}$
2.2. MPRB - 1 m from ditch	0.004	$395.29 \cdot 10^{-4}$
2.3. MPRB - 5 m from ditch	0.004	$105.58 \cdot 10^{-4}$

Stage 1. In–situ (road embankment – initial conditions)

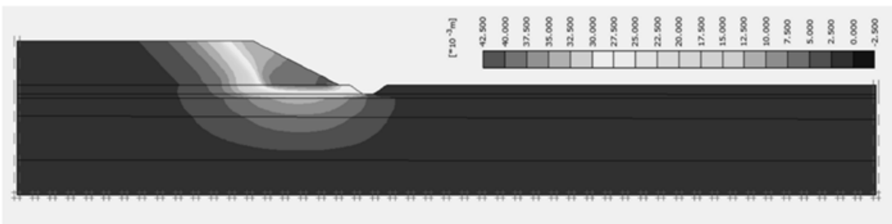

Figure 4. Isoplots of total displacements for in-situ conditions

Stage 2. The sheet pile punching and excavation (Variant 1. MPRB in road ditch)

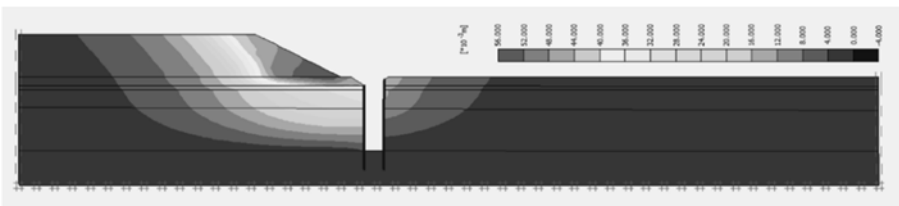

Figure 5. Isoplots of total displacements for stage 2

Stage 3. The reactive material filling and removing sheet piles (Variant 1. MPRB in road ditch)

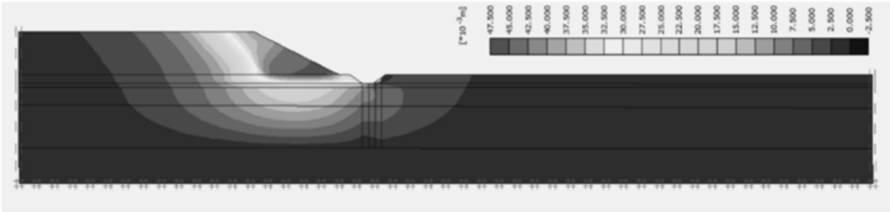

Figure 6. Isoplots of total displacements for stage 3

Stage 2. The reactive material filling and removing sheet piles
(Variant 2. MPRB in distance 1m from road ditch)

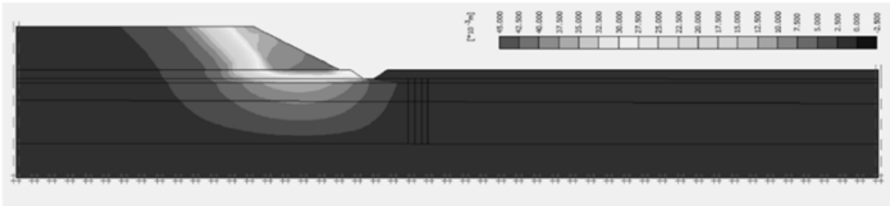

Figure 7. Isoplots of total displacements for stage 3

Stage 2. The reactive material filling and removing sheet piles
(Variant 3. MPRB in distance 5m from road ditch)

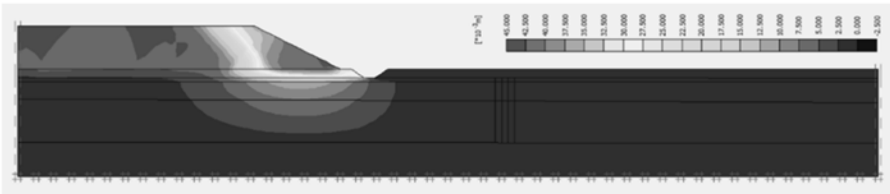

Figure 8. Isoplots of total displacements for stage 3

The performed stability analysis using the finite element method with interface elements has shown that the construction of the embankment slope is stable and the installation of MPRB at any step does not significantly affect the stability of the road embankment. Comparison of the results of the analyzes for the MPRB location variants shows that the safest for the proposed investment is the third variant – with the location of the barrier at a distance of 5 m from the road ditch. Barrier installation at a considerable distance had a minimal impact on the state of deformation on the surface and therefore did not affect the stability of the road embankment. Parameters characterizing the reactive materials had lower values than the surrounding ground. Therefore, the highest value of the friction angle was obtained for the construction of the barrier in the road ditch, which was characterized by the greatest influence on the deformation in the embankment at all stages of barrier installation.

4. Conclusions

The strength parameters of reactive materials may be used in the calculation of the limit states and installation technology in PRB design. The values of the oedometer modulus and friction angles obtained in laboratory tests were very useful in the numerical analysis performed in Plaxis. In direct shear tests, the construction of the apparatus had influence on the slip surface and also on the values of the strength parameters. In the case of triaxial tests, the stress state is controlled and the strength properties of the materials are determined more accurately. Moreover, during investigations in a triaxial apparatus, the principal stresses directions remained unchanged, while in the direct shear apparatus, the largest main tension changed in time. Based on the performed tests, it may be concluded that the strength tests should be conducted using a triaxial apparatus, which enables the realization of a number of different loading schemes and determination of the strength characteristics of reactive materials with greater accuracy. The design and construction of MPBR requires additional assessment using the finite element method to verify the influence on the existing infrastructure. Numerical analysis may be used to prevent the occurrence of a major accident and minimize its consequences - excessive costs and delays in the investment processes. In the case of MPBR construction along a bypass on National Road No. 50, the installation process did not significantly affect the stability (safety factor) of the road embankment. Properties of the reactive material had lower values than the surrounding soils. Therefore, a MPRB installed in the road ditch is the most critical variant, generating the largest impact on the deflection of the embankment during all stages of the installation process. Taking these circumstances into consideration, the MPBR should be located at least 1 m from the ditch.

References

[1] ITRC Interstate Technology & Regulatory Council, "Permeable Reactive Barrier: Technology Update". D.C: PRB: Technology Update Team, Washington, 2011.
[2] M. A. Carey, B. A. Fretwell, N. G. Mosley, J. W. N. Smith, "Guidance on the Use of Permeable Reactive Barriers for Remediating Contaminated Groundwater", National Groundwater and Contaminated Land Centre Report NC/01/51. Bristol: UK Environment Agency, 2002.
[3] R. T. Wilkin, R. W. Puls, "Capstone Report on the Application, Monitoring, and Performance of Permeable Reactive Barriers for Ground-Water Remediation": Volume 1 "Performance Evaluations at Two Sites". Report EPA/600/R-03/045a. Cincinnati, OH: U.S. Environmental Protection Agency, National Risk Management Research Laboratory, 2003.
[4] R. W. Puls, "Long-term performance of permeable reactive barriers: lessons learned on design, contaminant treatment, longevity, performance monitoring and cost – an overview". In I. Twardowska (Ed.), et al., Soil and Water Pollution Monitoring, Protection and Remediation. Dordrecht: Springer, pp 221-229, 2006.
[5] A. D. Henderson, A. H. Demond, "Long-term performance of zero-valent iron permeable reactive barriers: a critical review", Environmental Engineering Science 24(4): 401-423, 2007.
[6] Y. Chen, J. Li, C. Lei, H. Shim, "Interactions between BTEX, TPH, and TCE during their bio-removal from the artificially contaminated water". In Bionature 2011: The Second International Conference on Bioenvironment, Biodiversity and Renewable Energies. Venice: IARIA, pp 33-37, 2011.
[7] L. Banasiak, B. Indraratna, "Permeable reactive barrier (PRB) technology: An innovative solution for the remediation of acidic groundwater from acid sulphate soil (ASS) terrain". In R. Hryciw, A. Athanasopoulos-Zekkos, N. Yesiller (Eds.), GeoCongress 2012. Reston, VA: American Society of Civil Engineering, pp 3523-3432, 2012.
[8] Z. Guo, J. Han, X.-Y. Yang, K. Cao, K. He, G. Du et al., "Proteomic analysis of the copper resistance of Streptococcus pneumoniae", Metallomics 7: 448-454, 2015.
[9] F. Obiri-Nyarko, J. Grajales-Mesab, G. Malina, "An overview of permeable reactive barriers for in situ sustainable groundwater remediation", Chemosphere 111: 243-259, 2014.
[10] J. M. Abdul, S. Vigneswaran, J. Kandasamy, J. G. Mahinthakumar, "Fenton oxidation of metsulfuron-methyl with application to permeable reactive barriers", Environmental, Modelling & Assessment 21: 149-158, 2015.
[11] S. Fiorenza, C. L. Oubre, C. H. Ward, "Sequenced reactive barriers for groundwater remediation". Boca Raton, FL:CRC Press, 2000.
[12] J. Fronczyk, K. Garbulewski, "Selection of material suitable for permeable reactive barriers in vicinity of landfills", Annals of Warsaw University of Life Sciences - SGGW Land Reclamation 41: 3-9, 2009.
[13] J. Fronczyk, J. Bąkowski, K. Garbulewski, „Shear strength characteristic of zeolite and zeolite-sand mixtures in permeable reactive barriers", Scientific Review – Engineering and Environmental Sciences 47(1): 3-12, 2010.
[14] J. Fronczyk, K. Pawluk, K. Garbulewski, "Multilayers PRBs – Effective Technology for Protection of Groundwater Environment In Traffic Infrastructure", Chemical Engineering Transactions 28: 67-72, 2012.
[15] J. Fronczyk, K. Pawluk, "Hydraulic performance of zero-valent iron and nano-sized zero-valent

iron permeable reactive barriers – laboratory test", Annals of Warsaw University of Life Sciences - SGGW Land Reclamation 46(1): 33-42, 2014.
[16] K. Pawluk, J. Fronczyk, K. Garbulewski, "Removal of dissolved metals from road runoff using zeolite PRBs", Chemical Engineering Transactions 32: 331-336, 2013.
[17] K. Pawluk, J. Fronczyk, "Evaluation of single and multilayered reactive zones for heavy metals removal from stormwater", Environmental Technology 36(12): 1576-1583, 2015.
[18] K. Pawluk, J. Fronczyk, K. Garbulewski, "Reactivity of Nano Zero-Valent Iron in Permeable Reactive Barriers", Polish Journal of Chemical Technology 17(1): 7-10, 2015.
[19] K. R. Reddy, T. Xie, S. Dastgheibi, " Removal of heavy metals from urban stormwater runoff using different filter materials", Journal of Environmental Chemical Engineering, 2: 282-292, 2014.
[20] S. Liu, X. Li, H. Wang, "Hydraulics analysis for groundwater flow through permeable reactive barriers", Environmental, Modelling & Assessment 16: 591-598, 2011.
[21] J. B. Park, S. H. Lee, J. W. Lee, Ch. Y. Lee, "Lab scale experiments for permeable reactive barriers against contaminated groundwater with ammonium and heavy metals using clinoptilolite (01-29B)", Journal of Hazardous Materials B95: 65-79, 2002.
[22] A. Stokes, J. Ball, A. H. Fitter, P. Brain, M. P. Coutts, "An experimental investigation of the resistance of the model root systems to uprooting", Annals of Botany 78: 415-421, 1996.
[23] T. Fourcaud, J.-N. Ji, Z. Q. Zhang, A. Stokes, "Understanding the impact of root morphology on overturning mechanism: a modelling approach", Annals of Botany 101: 1267-1280, 2008.
[24] N. Tanaka, M. B. Samarakoon, J. Yagisawa, "Effects of root architecture, physical tree characteristics, and soil shear strength on maximum resistive bending moment for overturning Salix babylonica and Juglans ailanthifolia", Landscape Ecol. Eng. 8(1): 69-79, 2012.
[25] F. R. Harnas, H. Rahardjo, E. C. Leong, P. Y. Tan, L. F. Ow, "Stability of containerized urban street trees", Landscape Ecol. Eng. 12: 13-24, 2016.
[26] ASTM, "Standard test method for direct shear test of soils under consolidated drained condition (D3080-11)", West Conshohocken, PA: ASTM International, 2002.
[27] ASTM, "Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading (D2435/D2435M-11)", West Conshohocken, PA: ASTM International, 2011.
[28] K. Terzaghi, "The shear resistance of saturated soils and the angles between the planes of shear", In Proc. First Inst. Conf .Soil Mech. Foundation Eng., Cambridge, MA,USA, 22-26 June 1936, Cambrige: ISSMGE, pp 54-56, 1936.
[29] G. A. Boshoff, B. D. Bone, "Permeable Reactive Barriers", Oxfordshire: International Association of Hydrological Sciences IAHS, Wallingford, 2005.
[30] A. Gavaskar, N. Gupta, B. Sass, R. Janosy, J. Hicks, "Design guidance for application of permeable reactive barriers for groundwater remediation", OH: Battelle, Columbus, 2000.
[31] P. B. McMahon, K. F. Dennehy, M. W. Sandstrom, "Hydraulic and geochemical performance of a permeable reactive barrier containing zero–valent iron, Denver Federal Center", Ground Water 37(3): 396-404, 1999.
[32] D. L. Naftz, S. J. Morrison, C. C. Fuller, J. A. Davis, "Handbook of Groundwater Remediation Using Permeable Reactive Barriers: Applications to Radionuclides, Trace Metals, and Nutrients", Elsevier Science, Amsterdam, 2002.
[33] J. Nathanail, P. Bardos, C. P. Nathanail, "Contaminated Land Management: Ready Reference", EPP Publications, Nottingham, 2011.
[34] F. G. Simon, T. Meggyes, C. McDonald, "Advanced Groundwater Remediation: Active and Passive Technologies", ICE Publishing, London, 2002.
[35] Polish Law: The regulation of the Minister of Transport, Construction and the Maritime Economy of 30 May 2000 on the technical conditions which must be fulfilled by facilities for road and their location, Polish Journal of Laws 63, 735, 2000.