MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 21. Year 2019 ISSN 1506-218X 1579-1588

Impact of Compression on Bed Porosity in Gravitational Filtration Process

Jacek Piekarski[*]
Koszalin University of Technology, Poland
[*]*corresponding author's e-mail: jacek.piekarski@wilsig.tu.koszalin.pl*

1. Introduction

Filtering layer makes the most important part of a filter and the device efficiency as well as filtrate parameters depend on its correct selection, therefore, it should well stop suspended solids and make little hydraulic resistance for filtrate stream. Permeability of such layers in the case of suspended matter liquid phase and its ability to stop the solid phase depends on the size and shape of grain comprising the filtering layer. Flow of the medium in the gravitational filtration process is a hydrodynamic phenomenon velocity of which is directly proportional to pressure difference occurring on both sides of the filtering layer and inversely proportional to the resistance that such medium meets during flow through, among other things, pores of the filtering layer. Filtration velocity rises more slowly than the pressure difference increase because in the case of increasing of the pressure difference, porosity of the filtering layer decreases and resistance increases (Ciborowski 1973, Piecuch 2007, Rup 2006). Process equations describe filtration in partly idealised conditions in which impact of the process distorting factors is eliminated. Also in practical considerations an assumption is being made that porous granular bed is not compressed during the filtration process accomplishment. However, thickness of the filtering layer decreases to a small degree under impact of various factors (e.g. flow, pressure difference), resulting in increase of compression coefficient and bed total resistance (Domski et al. 2017, Głodkowska et al. 2018). Bed porosity as well as filtration and permeability coefficients decrease. Therefore, the primary filtration equations cannot always be used without making proper corrections (Żużikow W. A. 1985, Piekarski 2009).

In this paper variation of values of selected parameters, i.e. bed porosity, filtration coefficient, total resistance and volumetric flow rate depending on the change of bed compression as a factor distorting the gravitational filtration process are presented in mathematical form.

2. Methodology of research

Quartz sand with a mass of 1000 g used in the tests was subjected to grain size analysis. The data from screening were entered into FILTRA software, which computed characteristic diameters and derived filtration bed grain size distribution graphs. The filtration bed was then put in a water-filled column of 5 cm diameter and subjected to backwashing. In the next stage bed height was corrected up to 30 cm. The initial difference between the water-table height in the filtration column and filtrate in overflow tank was 36 cm. The bed infiltration column was subjected to dynamic compacting, after each test series, obtaining various bed compression height values.

The independent variable parameter in the gravitational filtration process was the different bed height obtained in dynamic compaction, hence, the initial difference of water-table height in the filtration column and in the overflow tank as well as compression coefficient value. However, the main variable resulting parameter of the process was the average time of water-table lowering in the filtration column. The process parameters were entered into FILTRA software, which computed the filtration coefficient values based on the variable pressure method and through application of Hazen, Krüger, Seelheim and Slichter empirical formulas (Piekarski 2009). Numerical application based on the Krüger and Slichter formula provided bed porosity value. However, based on the values of filtration and dynamic viscosity coefficients as well as medium density, the software computed the filtration bed permeability coefficient value. Furthermore, the application derived the total bed resistance and volumetric flow rate values (Piekarski 2009).

3. Test results and interpretation

The grain size nonuniformity coefficient of the tested bed, computed from the grain size analysis (Figure 1), amounted to U=2.39. Grain reliable diameter d_M was 376 μm, modal diameter d_{MO} reflecting the maximum of mass share curve $f_N(d_i)$ was 250 μm. Medial diameter d_{ME} equal to 50% of mass share was 467 μm, whereas: d_{10}=220 μm, d_{20}=296 μm and d_{60}=525 μm.

The non-compressed bed filtration coefficient after intense backwashing (through the bottom of the bed) computed from laboratory tests through application of the variable pressure method was 3.53E-4 m/s. After taking into account of temperature value (T=22°C) density of water directed to the filtration process was 997.79 kg/m^3 and the dynamic viscosity coefficient value was 9.55E-004 Pa·s. Hence, the computed value of the permeability coefficient was 3.44E-011 m^2. Based on the grain size nonuniformity coefficient amounting to U=2.39, empirical coefficient value C_H=463 was adopted, so the filtration coefficient value based on Hazen formula was 3.53E-004 m/s. However, the filtration coefficient value based on Seelheim formula was 1.06E-004 m/s, and according to Krüger – 3.44E-004 m/s. Based on Slichter empirical formula, the computed filtration coefficient value was 3.59E-004 m/s.

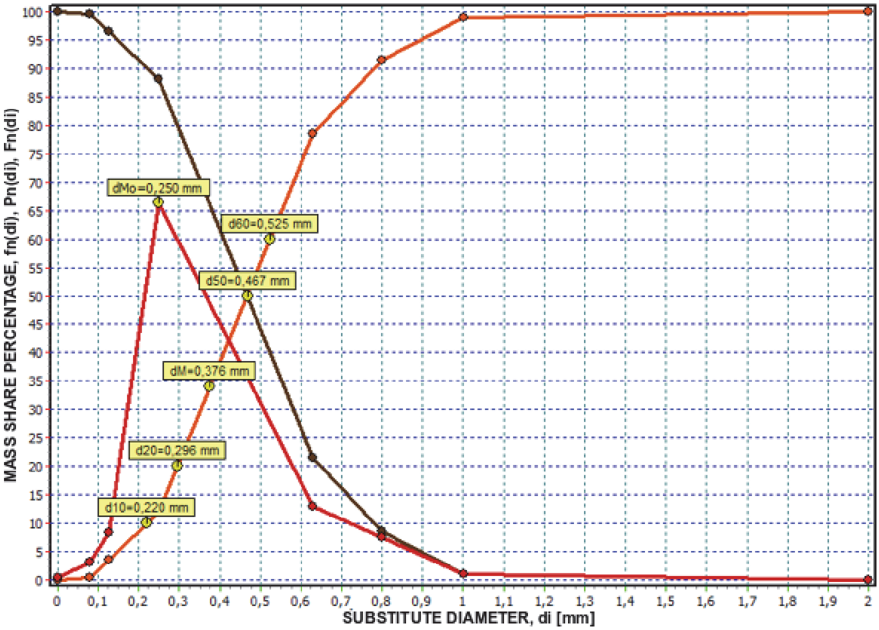

Fig. 1. Filtration bed granular composition analysis with indication of characteristic diameters

After transformation of Krüger and Slichter formulas the calculated value of bed porosity amounted to 0.44. The substitute diameter (taking into account bed porosity value 0.44 and equivalent diameter 288 μm) was 151 μm, hence, according to Kozeny-Carman empirical formula, the permeability coefficient value was 3.44E-11 m^2, being equivalent to the value computed through application of the variable pressure method amounting also to 3.44E-11 m^2. The filtration bed total resistance value was 4.24E9 $N \cdot s/m^5$, whereas the value of volumetric flow rate was 9.24E-7 m^3/s.

Table 1. Results of bed height H [mm] change impact on the values of average time of medium-table lowering t [s], porous filtration bed compression coefficient x [%], filtration coefficient K [m/s], permeability coefficient k [m/s], bed total resistance Rz [N·s/m^5], bed porosity ε [-] and volumetric flow rate qv [m^3/s] due to bed compression in gravitational filtration process

Parameter	Symbol	Unit	Bed height H [mm]				
			300	290	280	270	268
Surface lowering	L	[mm]	0	10	20	30	32
Bed compression	x	[%]	0.00	3.33	6.67	10.00	10.67
Average time of medium-table lowering	t	[s]	39	58	72	82	83
Bed porosity	ε	[-]	0.44	0.39	0.36	0.34	0.33
Filtration coefficient ($\cdot 10^{-4}$)	K	[m/s]	3.53	2.39	1.78	1.52	1.48
Permeability coefficient ($\cdot 10^{-11}$)	k	[m^2]	3.44	2.23	1.70	1.47	1.44
Bed total resistance ($\cdot 10^{9}$)	Rz	[N·s/m^5]	4.24	6.32	7.84	8.92	9.03
Volumetric flow rate ($\cdot 10^{-7}$)	qv	[m^3/s]	9.24	6.04	4.74	4.06	3.99

Due to dynamic compaction originating from 3.33% compression, bed surface height was decreased by 10 mm. This resulted in reduction of the filtration coefficient values by 1.14E-4 m/s and permeability coefficient by 1.21E-11 m^2. Porosity decreased by 5% (Figure 2). The total resistance value increased by 2.08E9 $N\cdot s/m^5$, which finally caused reduction of the volumetric flow rate value by 3.20E-7 m^3/s (Figure 3). Following further compaction bed surface height was reduced, with relation to its initial value, by 20 mm. In this particular case the bed was compressed by 6.67%. Decrease of the filtration coefficient value by 1.75E-4 m/s and permeability coefficient by 1.74E-11 m^2 was found. Porosity decreased by 8%. The total resistance increased by 3.60E9 $N\cdot s/m^5$, whereas the volumetric flow rate value decreased by 4.50E-7 m^3/s.

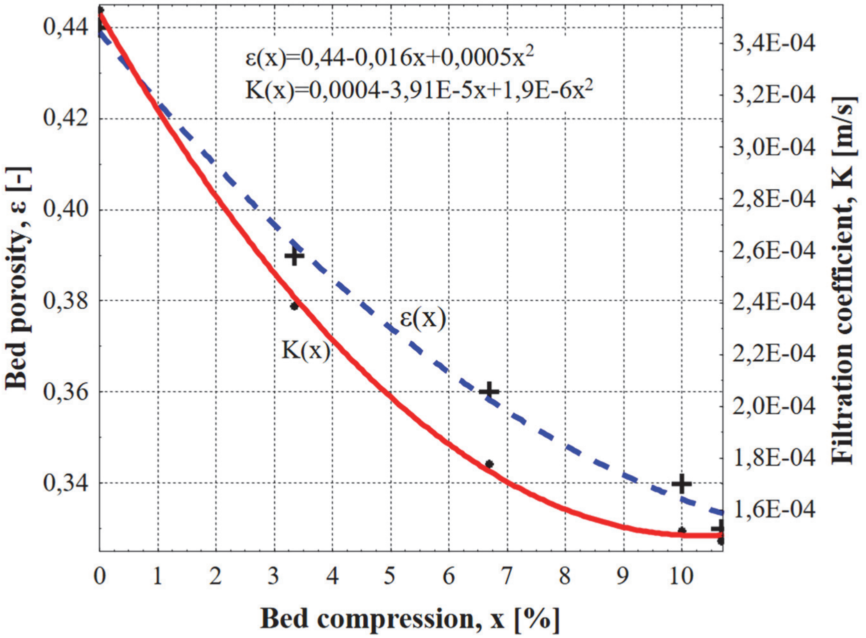

Fig. 2. Impact of bed compression value change x [%] on the change of filtration bed porosity value ε [-] and filtration coefficient K [m/s] in the gravitational filtration process

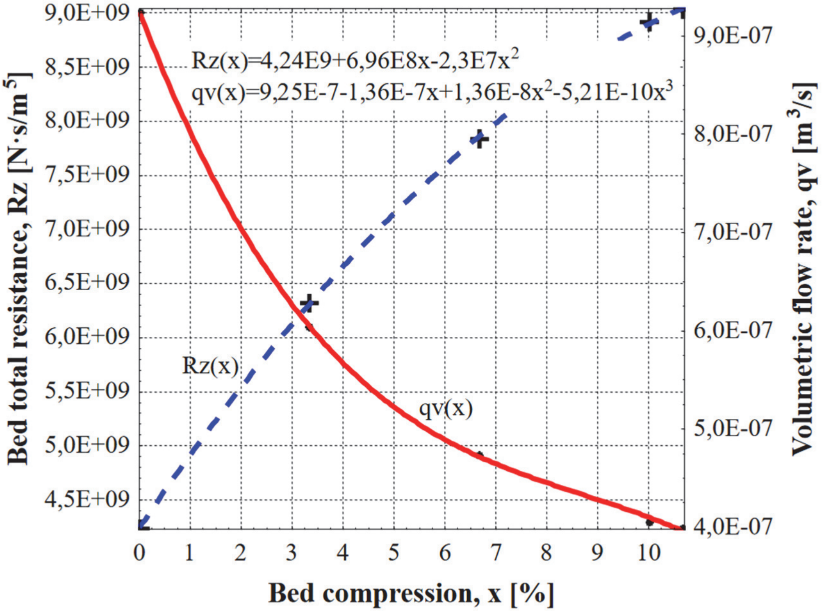

Fig. 3. Impact of bed compression value change x [%] on a) the change of bed total resistance value Rz [N·s/m^5] and volumetric flow rate qv [m^3/s] in the gravitational filtration process

In the subsequent stages of this research work, volume of free spaces in the filtering layer porous structure decreased due to further dynamic compaction (Table 1), which resulted in the bed surface lowering max. by 32 mm. This resulted, finally, in increase of compression by approximately 11% and total resistance by 4.79E9 N·s/m^5. Values of filtration coefficient decreased by 2.05E-4 m/s and permeability – by 2.00E-11 m^2. Porosity decreased by 11%. Finally, the volumetric flow rate decreased by 5.25E-7 m^3/s.

At the second stage of tests, empirical equations presented in Figures 2 and 3, were checked. To do that, the filtration bed was subjected again to intense backwashing (through the bottom of the bed) and tests for change of porosity and volumetric flow rate values, depending on the change of compression values in conditions different to those in the previous test part, were performed. FILTRA software computed bed porosity through Slichter formula transformation whereas the volumetric flow rate was computed based on Darcy equation. Bed total resistance occurring in the equation was computed by the application using the compression coefficient values variable. The test results are presented in Table 3.

Tab. 3. Test results for impact of bed compression change on bed porosity values change, total resistance and volumetric flow rate in the gravitational filtration process in model and real conditions

Bed compression	Bed porosity	Bed total resistance	Volumetric flow rate	
			Model conditions	Real conditions
x	ε	R_Z $(\cdot 10^9)$	q_v $(\cdot 10^{-7})$	
%	-	$N\cdot s/m^5$	m^3/s	
0.00	0.44	4.24E+09	9.25	9.19
1.67	0.41	5.34E+09	7.33	7.17
5.00	0.37	7.15E+09	5.20	5.30
8.33	0.34	8.44E+09	4.35	4.21

Based on the graph presented in Figure 4 it can be stated that as compression values increased from 0 to 8.33, the volumetric flow rate calculated from the model decreased from 9.25E-7 m^3/s to 4.35E-7 m^3/s, e.g. by 4.9E-7 m^3/s (approximately 47%), whereas in laboratory tests similar change was noted within the range from 9.19E-7 m^3/s to 4.21 m^3/s, i.e. by approximately 4,98E-7 m^3/s (approximately 46%).

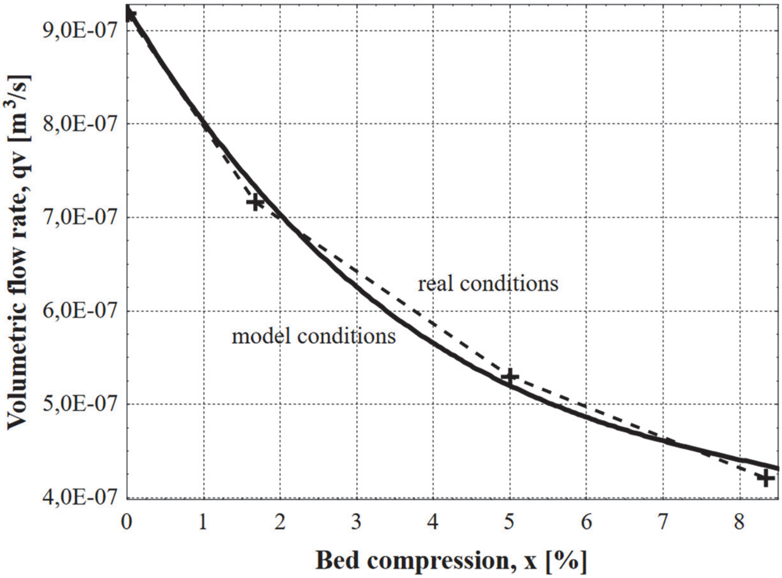

Fig. 4. Graph illustrating impact of bed compression values change x [%] on volumetric flow rate values change qv [m^3/s] in model and real conditions

4. Conclusions

Based on the research work performed it can be stated that:

1. Filtration bed gets, due to action of various factors, compressed to insignificant degree. Reduction of its thickness, causes, depending on the shape and size of grain making the filtering layer, decrease of porosity, therefore, decrease of filtration and permeability coefficients values and increase of bed resistance value.
2. Due to compression phenomenon within the range from 0% to approximately 11%, amount of free spaces in the filtering layer porous structure decreased, which is confirmed by decrease of porosity coefficient values within the range from 0.44 to 0.33. Consequently, decrease of values of filtration coefficient (from 3.53E-4 m/s to 1.48E-4 m/s) and permeability coefficient (from 3.44E-11 m^2 to 1.44E-11 m^2) and increase of total resistance values (from 4.24E9 $N \cdot s \cdot m^{-5}$ to 9.03E9 $N \cdot s \cdot m^{-5}$) was found.
3. It is well-founded to use in the equations pertaining to filtration bed porosity computation such parameter as bed compression. Furthermore, mathematical equations originating from polynomial regression describing change of resulting variable parameter values for porosity, filtration and permeability coefficients as well as total resistance depending on bed compression values change can be used with sufficient accuracy in description of the gravitational filtration phenomenon.
4. Analysis of bed porosity, depending on its compression in the gravitational filtration process, should be further developed to a broader extent, in particular, with relation to the impact of solid phase occurring in the medium directed to the process on bed compression because it has a significant impact on the filtration process type.

References

Ciborowski, J. (1973): *Inżynieria procesowa*, WNT, Warszawa.

Domski, J., Głodkowska, W. (2017): Selected Mechanical Properties Analysis of Fibrous Composites Made on the Basis of Fine Waste Aggregate. *Rocznik Ochrona Srodowiska, 19,* 81-85.

Głodkowska, W., Ziarkiewicz, M. (2018): Cracking behavior of steel fiber reinforced waste sand concrete beams in flexure – Experimental investigation and theoretical analysis. *Engineering Structures, 176*, 1-10.

Głodkowska, W. (2018): Waste Sand Fiber Composite – Models of Description of Properties and Application. *Rocznik Ochrona Srodowiska,* 20(3).

Piecuch, T. (2007): *Technika Wodno-Mułowa - Urządzenia i procesy*. Wydawnictwo Politechniki Koszalińskiej.

Piekarski, J. (2009): *Numeric modelling of filtration and sorption process*. Wydawnictwo Politechniki Koszalińskiej.

Piekarski, J. (2009): Analysis of Selected Parameters of Colmatation in the Process of Gravitational Filtration. *Rocznik Ochrona Srodowiska,, 11*, 421-437.

Piekarski, J. (2009): Colmatation blockage during gravitational filtration process of coal suspension on sand bed. *Mineral Resources Management, 25(3)*, 121-133.

Rup, K. (2006): *Procesy przenoszenia zanieczyszczeń w środowisku naturalnym*. WNT, Warszawa.

Żużikow, W. A. (1985): *Filtracja. Teoria i praktyka rozdzielania zawiesin*. WNT, Warszawa.

Abstract

Gravitational filtration process velocity is directly proportional to the pressure difference occurring on both sides of the filtrating layer and inversely proportional to the resistance that the medium meets during its flow through filtering layer pores. Velocity of filtration increases at a smaller rate than the pressure difference increase because in the case of the pressure difference increasing, filtrating layer porosity decreases and resistance increases. Therefore, correct selection of the porous layer has impact on the filtration device efficiency and filtrate parameters, so, it should stop suspended solids and generate insignificant hydraulic resistance to the filtrate stream. Often an assumption is made in practical analyses that granular porous beds do not get compressed during filtration process. However, due to action of various factors, thickness of the filtrating layer reduces resulting in increase of compression and bed total resistance. Bed porosity and filtration, as well as permeability coefficients values, decrease. Change of bed porosity value can be determined through mathematical approach depending on, among other things, bed compression change as gravitational filtration process distorting factor.

Keywords:
gravitational filtration, bed porosity, bed compression, mathematical modelling

Wpływ kompresji na porowatość złoża w procesie filtracji grawitacyjnej

Streszczenie

Szybkość procesu filtracji grawitacyjnej jest wprost proporcjonalna do różnicy ciśnień powstającej po obu stronach warstwy filtrującej i odwrotnie proporcjonalna do oporu jaki napotyka medium w trakcie przepływu przez pory warstwy filtrującej. Szybkość filtracji wzrasta wolniej niż zwiększa się różnica ciśnień, ponieważ w przypadku zwiększania różnicy ciśnień maleje porowatość warstwy filtrującej i wzrasta opór. Od prawidłowego doboru warstwy porowatej zależy wydajność urządzenia filtracyjnego oraz parametry filtratu, dlatego powinna ona zatrzymywać cząstki stałe z zawiesiny oraz generować nieznaczny opór hydrauliczny strumieniowi filtratu. Często w analizach praktycznych zakłada się, że ziarniste złoża porowate w trakcie procesu filtracji nie ulegają kompresji. Jednak na skutek działania różnych czynników zmniejsza się grubość warstwy filtrującej, czego efektem jest wzrost kompresji oraz oporu ogólnego złoża. Zmniejsza się porowatość złoża oraz wartości współczynników filtracji i przepuszczalności. W ujęciu matematycznym zmianę wartości porowatości złoża można wyrazić między innymi w zależności od zmiany kompresji złoża jako czynnika zniekształcającego proces filtracji grawitacyjnej.

Słowa kluczowe:
filtracja grawitacyjna, porowatość złoża, kompresja złoża, modelowanie matematyczne