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Modelling of groundwater flow in fractured rocks

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Abstract

Traditional groundwater flow modelling is based on the Darcy's law which is valid when the flow is laminar. However, the water flow in fractured aquifers can be non-laminar in discontinuities and in this case the Darcy's law is not valid. That is why a numerical solver is needed which is able to model both laminar and non-laminar flows. The MODFLOW-CFP by USGS is one of the programs that can be used for this issue.
Additionally to numerical experiments physical modelling can be also a useful and effective tool to explore the flow in fractured media in details. Besides some international published case studies exists a less-known Hungarian conduit model by Öllős & Németh (1960). In this study the Öllős-Németh's conduit model was rebuilt in the modified MODFLOW-CFP (CFPv2). The goal of this modelling study was to reach good agreement between the results of the numerical model and the measurements. After having studied many numerical cases and by means of sensibility analysis, the CFP model was verified. Based on the verification the model is applicable to simulate non-laminar flows in fractured rocks not only in laboratory-scale but even in real cases.
Following the international practice the MODFLOW-CFP is a usable tool to learn more about a well-developed karst aquifer in Hungary. Using the numerical model the flow in this karst area can be described in detail and more precisely.

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Keywords: fractured rock; non-laminar flow; physical model; conduit flow process; MODFLOW-CFPv2

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1. Introduction

There are several reasons why the investigation of fractured rock hydraulics is essential. Fractured aquifers are important fresh water sources, cannot be ignored by underground construction and they also have an important recreation role. Moreover, they are very sensitive to contamination caused by fast water flow occurring in fractured rock [1].
The traditional equations of groundwater flow are based on assumptions like laminar flow, homogeneous and isotropic media etc. which are not valid in fractured rocks, therefore their application in this case provides misleading or wrong results.
Laboratory investigation has many difficulties, and using the most common numerical programs is also unreliable because they are based on traditional equations. Although the investigation would be very necessary, the researchers have limited tools for this reason. There are several researchers who created applicable laboratory analogs [e.g. 1]; and some numerical modelling software [CAVE, TOUGH, MODFLOW-CFP, etc.] to analyse flow in fractured rock.

The major difficulty of all kind of investigation is that fractured rocks often have two flow regimes: fast flow in the fractures, and slow flow in rock matrix with long residence time. The flow in the matrix can be described by Darcy's law, but it is not valid in the fractures, conduits and caves where the flow may be turbulent. The two different flow regimes can be handled separately with exchange terms. This so called dual continuum approach is one of the idealisations used to describe flow in fractured rocks. First Barenblatt et al. [2] conceptualised this double porosity model and others developed it further [3, 4, 5, 6, 7, etc.]

In this study the fast flow regime was investigated with a laboratory and a numerical model. The main goal was to better understand the flow in fractures, conduits and caves. The flow in rock matrix and the exchange between the two flow regimes was neglected because the flow is dominated by conduits. This assumption is only valid in hard rock with low matrix porosity. The laboratory model was prepared by Öllős and Németh in 1960 [8]. This model was rebuilt in MODFLOW-CFPv2 [9, 10] and served as a benchmark.

2. Presenting the modelling methods

The laboratory model was conducted in 1960. It was well documented but has never been reproduced by numerical models. In this study the laboratory model was analysed with numerical software for the first time.

2.1. Öllős-Németh laboratory model and experiment procedure

The laboratory model was a vertical 2D model, built on a wood frame, as shown in Fig. 1. An orthogonal grid was built up by 60 cm length PVC-pipes with 420x240 cm overall size. The diameter of the conduits was 0.8 cm. A confined aquifer system was achieved with a high level tank. The constant water level was ensured by a weir crest which was above the highest conduit by 61.5 cm. The water from the high level tank flowed in a tube with a diameter of 15 cm. The tube divided the water among the five horizontal conduits. The flow could be stopped by faucets. At the end of the vertical and horizontal conduits were variable discharge points. Piezometer-outlets in the grid points were installed to detect hydraulic heads. These head data were used to draw equipotential lines in different model cases.

During the investigation different discharge points were opened; later the grid was refined and some conduits were connected to thicker ones. More than 30 model cases were modelled, tested and documented.

2.2. Numerical model design and calibration aspects

The experimental conduit system was rebuilt with MODFLOW-CFPv2 (CFP) which is a quite new module of the finite-difference ground water flow model, MODFLOW-2005. The CFP has the ability to simulate not only the Darcian laminar flow but the non-laminar flow as well. Mode 1 of the CFP was used, that describes the fractures as a discrete network of cylindrical pipes [9].

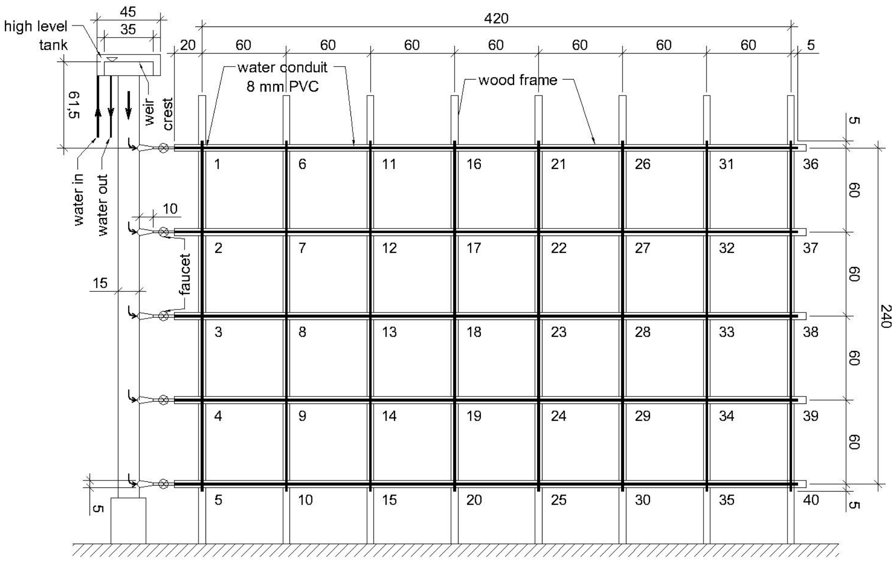

Fig 1. The original geometry of the laboratory model

77 pipes and 46 nodes were used in 6 layers, 9 columns and 1 row. The length unit was *cm* and the time unit was *min*, as these were in the laboratory model. The water temperature was 15°C. The high level tank was modelled by a fix head by the place of the weir crest. In the discharge points the well boundary conditions was used, the discharge rates were defined in Conduit Recharge Package of MODFLOW CFP. This package is able to route the diffuse areal recharge into nodes of conduit nodes and it is able to handle wells, discharge points [9, 10]

The Conduit Flow Process uses two Reynolds-numbers: an upper number needs to be assigned when the flow transitions from laminar to turbulent and a lower when turbulent flow transitions to laminar. For pipes the common critical Reynolds number is 2320. If the two Reynolds-numbers are too close to each other the model does not converge. Based on modelling experience the lower Reynolds-number is equal or less than the half of the upper Reynolds-number. For example, 2000 for lower and 2640 for upper value did not result convergence. The common value, 2320 was used as an upper Reynolds-number, because the flow over this number would be always turbulent. The lower Reynolds-number was selected 1000.

The calibrated parameter was the wall roughness of the conduits. At first 1.5E-4 cm was selected for conduits, which is an acceptable value for PVC-pipes; but this value did not give satisfactory results. For this reason was the roughness chosen as a calibration parameter. Furthermore, the diameter of the initial sections was also calibrated. In laboratory model confusors and faucets caused high hydraulic head losses between the tube with 15 cm diameter and the grid. Modelling of these losses required changes in the geometry of the initial section because the software cannot model confusors and faucets.

The basis of the calibration was a laboratory model case in which the discharge point was in the 38th node and the discharge rate was 5220 cm^3/min (A model case, see Table 1.). In this case hydraulic head data were available in every grid point, in the others only the figures of the equipotential lines were given.

3. Results of the numerical modelling

3.1. Calibration

Trial modelling cases demonstrated that the initial diameters and the roughness can be handled separately. First the roughness was calibrated, then the diameters. After several trials the difference between the numerical and laboratory models converged to a constant value. The calibration was stopped at 2.27E-2 cm roughness and 0.653 cm initial diameter. In this case the biggest difference between hydraulic heads of the two modelling methods was 4.31 cm (Fig 2.). The biggest difference appeared between 26-37 nodes, and at the discharge point the difference was zero. During validation the calibrated parameters resulted in more than 25 cm head difference and in some cases the convergation failed.

To improve the mode results, the calculation of the friction factor was analysed. The CFP uses Colebrook-White formula [9, 11] to calculate the friction factor by turbulent flow. The friction factor was calculated from the results of laboratory model of A model case and using this result the roughness was calculated with the Colebrook-White equation. The calculated roughness became 6.76E-4 cm which is an acceptable value for PVC-pipes. This roughness was not changed and the initial diameters were calibrated. The calibration and validation results showed that the new roughness is a bit low; therefore its previously unchanged value was increased step by step. The final parameters became 1E-2 cm roughness and 0.65 cm initial diameter. The difference between the hydraulic heads of the laboratory and the numerical model was under 1.5 cm except the discharge point (6 cm) and the nodes surrounding around the discharge point (1.5 and 3 cm), as shown in Fig 2. These differences could have been caused by two reasons: first, the error could occur during the measurement where the water left the overpressured zone. The second reason of the high differences between the laboratory and the numerical results could have been caused by the inaccuracy of measurement of the water discharge.

3.2. Validation

After the calibration by A model case, several other cases were used for validation. The parameters of these model cases and their difference from the results of the laboratory model are collected in Table 1.

As the Table 1. shows, there are some modified model cases according to the laboratory model cases. These modifications can see on Fig. 3. In G, H, I, J model cases the grid of the lower right corner was refined by pipes with 0.8 cm diameter. In H, I, J model cases thicker pipes were build in. In laboratory, pipes with 3.2 cm diameter were connected to the original pipes. These parallel pipes cannot be modelled therefore pipes with 3.3 cm diameter were used instead of the pipes with 0.8 cm and 3.2 cm diameters.

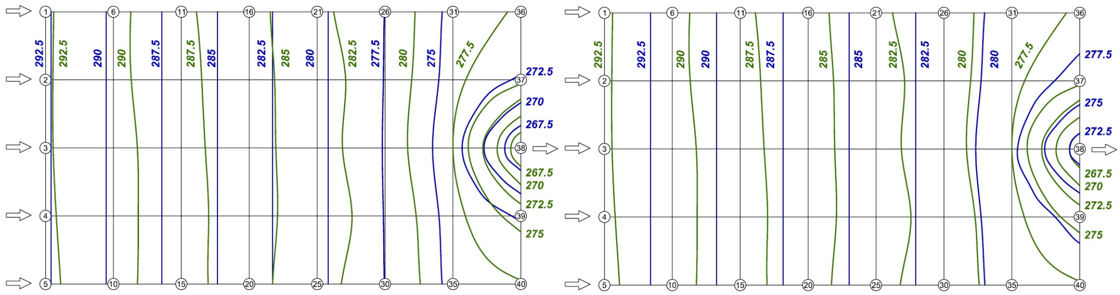

Fig 2. Calibration results: (a) roughness: 2.27E-2 cm, initial diameter 0.653 cm; (b) roughness: 1E-2 cm, initial diameter 0.65 cm. The green lines are the laboratory results, the blue lines are the numerical result.

Table 1. Model cases.

Mark of a model case	Discharge point	Discharge rate (cm^3/min)	Other Modifications	Hydraulic head differences *(cm)*
A	38	5220		1.5-6
B	38	8400		5-9
C	40	4500		3-9
D	30	9000		9-11
E	20	4570	recharge points: 1,2	10.5-17
F	20, 38	4000, 4300	2 discharge points	4-8
G	30	8460	finer grid	2-9
H	20	8760	finer grid+6 thicker pipes	2.5-8
I	38	10080	finer grid+11 thicker pipes	10-19
J	20	9000	finer grid+11 thicker pipes	2.5-14

The laboratory and numerical equipotential lines are parallel almost in every model cases (Fig 4., Fig 5.). In most of the cases the differences are around steady, the maximum is about 19 cm. In the C model case, which has a lower flow speed than the A, the numerical hydraulic head results are higher than the laboratory results. In the other model cases the numerical results are lower than the laboratory results. These model cases need initial diameter increase, but in this situation the difference would become higher in the C model case. Additional trials demonstrated that while the errors decrease in one model, in the other the errors would increase. The higher error appeared by I model case (Fig 5.). The 3.3 cm diameter instead of the two parallel pipes with 0.8 cm and 3.2 diameters might not be properly. When the discharge point is the 38th, the horizontal pipes deliver the largest volume of water (Fig 2.). The thicker pipes also become a main flow path: in I model case the horizontal pipes between 2nd and 27th node points deliver 50-70% of water (Fig 5.). The refinement of grid does not change the equipotential lines too much only if the discharge point is near to the refined area (G model case). The results of the modified model cases point out that the main area of the karst observation should be the environment of the discharge point and the thicker pipes, conduits and fractures between thinner ones because these circumstances were which modified the flow significantly. In laboratory models more than 10% of errors could occur, which is about 30 cm, compared to the fix hydraulic head value of 301.5 cm, and about 4-6 cm compared to the hydraulic losses measured in laboratory models.

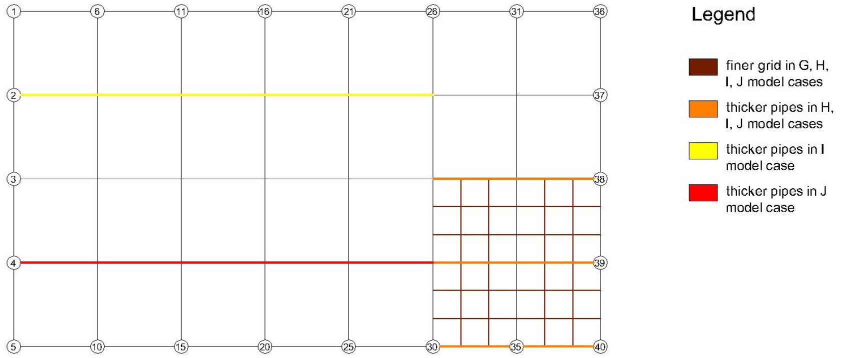

Fig 3. The modified geometry of the laboratory and numerical model

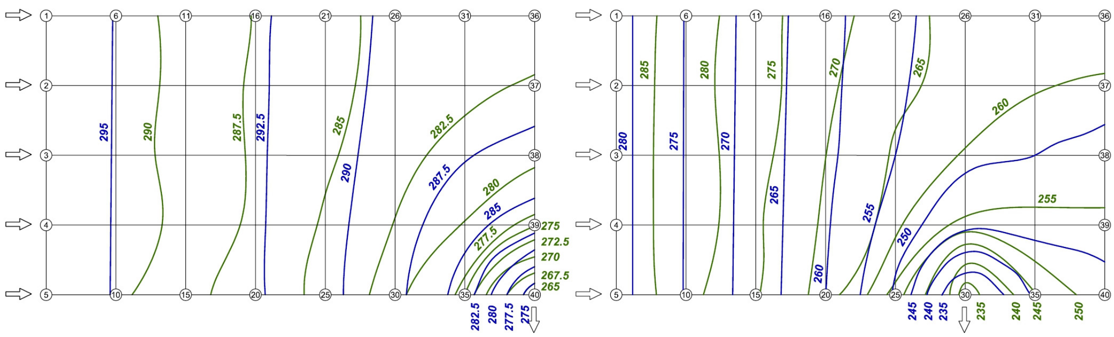

Fig 4. (a) C model case; (b) D model case. The green lines are the laboratory results, the blue lines are the numerical result.

This inaccuracy is clearly visible in Fig 2.: the boundary conditions are symmetrical for a horizontal line, but the equipotential lines of the laboratory measurement is not symmetrical. Knowing all of these the numerical model is acceptable.

3.3. Sensitivity analysis

The effects of water temperature, Reynolds-number, roughness of conduits and initial pipe diameter was analysed during the sensitivity analysis. Originally the water temperature was 15 °C, because in the laboratory tap water was used. Increasing the temperature to 20 °C the hydraulic losses became lower than the original case of about 0.5-1 cm. The Reynolds-number was also changed. The common critical Reynolds-number was defined by the lower Reynolds-number, the upper value was 4000. In many conduits the originally turbulent flow became laminar; in this case the friction factor is calculated from the inverse of the Reynolds-number. Roughness was changed first by 1E-3 cm. If the roughness was 9E-3 cm, in the A model case the differences between the laboratory and numerical models increased by about 0.1 cm.

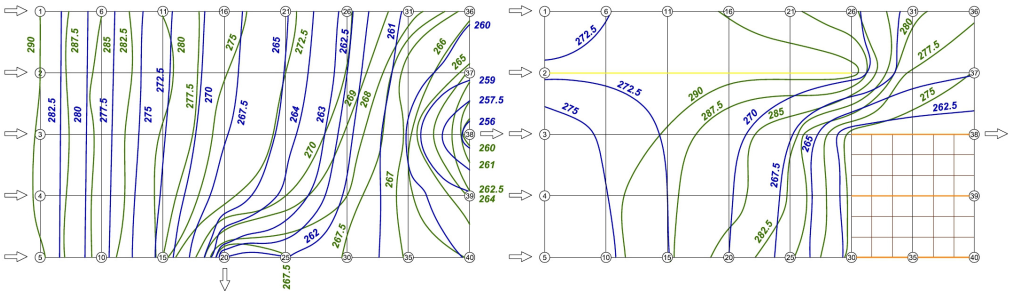

Fig 5. (a) F model case; (b) I model case. The green lines are the laboratory results, the blue lines are the numerical result.

If the roughness was 1.1E-2 cm, in the A model case the differences decreased by about 0.4 cm, but in the D model the differences increased by about 1 cm. After that other orders of magnitudes of roughness were tried. If the roughness was 1E-1 cm, the model did not converge, if it was 1E-3 or lower the hydraulic losses in numerical model became lower and lower than in the laboratory model. Although these values are closer to the roughness of a PVC-pipe, in this model higher values should be used. This might be due to the local head losses by conduit intersections which were not calculated by the software. The initial diameter was modified with 0.05 cm. The differences between laboratory and numerical hydraulic head results increased in A model case by 1-2 cm when 0.6 and 0.7 cm diameter were used. In the first case the errors in D model case increased over 20 cm, the thicker diameter caused higher errors in C model case (5-10 cm).

4. Additional use of results

The goals of both the laboratory model and numerical model are to analyse the water flow in conduit systems embedded in a hard rock mass. These are feasible tools to model a well developed Hungarian karst aquifer or a non-karstic fractured rock aquifer. Some good properties of these two modelling method are the ability of handling non-laminar flows and the possibility to use pipes with different order of magnitude. Proper geometry and enough precipitation and discharge data are rarely available, so the modelling needs data collection and assumptions [12]. The Molnár János Cave is a well developed conduit system under the Rózsadomb in Budapest (Fig. 6.). The system is confined; the conduits are filled with lukewarm thermal water. It is known in lengths of 8000 meters and in depth of 100 meters [13]. The cave system is diversified so it is slightly similar to the grid of the analysed laboratory and numerical model. Besides the well known geometry proper hydrological data are being collected.

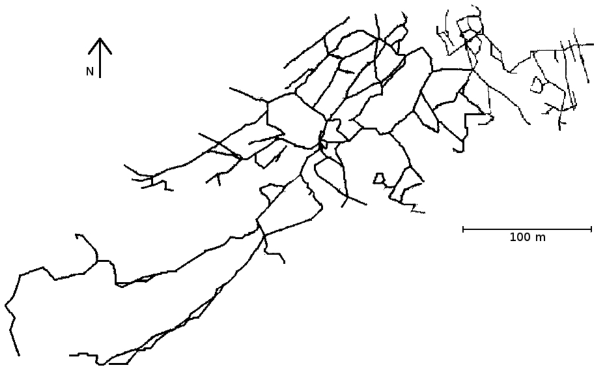

Fig 6. The conduit system of the Molnár János Cave (modified from [13])

Conclusions

A new numerical CFP model was prepared based on the Öllős &Németh's laboratory model. The two models show acceptable matching result. The CFP model was verified. This quite new software is able to help researchers to better understand flow in fractured rocks. The CFPv2 handle solute transport and has new boundary conditions, with this version the groundwater flow from infiltrated water to springs can be analysed. The study highlighted the feasibility of using laboratory models to analyse water flow in fractured rock. The laboratory model is also applicable to validate and verify numerical models. After verification, numerical models are available to model such cases which cannot be modelled in a laboratory. In this study only the fast flow regime was analysed. Another laboratory model and the numerical CFP software can handle solute transport and water exchange between fractures and rock matrix. Laboratory and numerical tools are applicable to model the complex system of groundwater flow in fractured rocks. With these tools the knowledge of fractured rock hydraulics will be expanded and these can help to better manage and preserve aquifers in hard rocks.

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References

[1] Faulkner J, Hu B, Kish S, Hua F. Laboratory analog and numerical study of groundwater flow and solutetransport in a karst aquifer with conduit and matrix domains. *J Contam Hydrol* 2009; **110** (1-2): 34–44.

[2] Barenblatt G, Zheltov Y, Kochina I. On basis concepts of theory of homogeneous fluid flow in fissurized rock. *Appl Math Mech* 1960; **24**: 852-64.

[3] Warren JE, Root PJ. The behavior of naturally fractured reservoirs. *Soc Petrol Eng J* 1963; Vol. **3**: 245-55.

[4] Streltsova TD. Hydrodynamics of Groundwater Flow in a Fractured Formation. *Water Resour Res* 1976; Vol. **12**, No. 3: 405-14.

[5] Moench AF. Double-porosity models for a fissued groundwater reservoir with fracture skin. *Water Resour Res* 1984; Vol. **20**: 831-46.

[6] Şen Z. Fractured Media type curves by double-porosity model of naturally fractured rock aquifers. *Bull Techn Univ Istanbul* 1988; **41**: 103-10.

[7] Şen Z. Applied Hydrogeology for Scientists and Engineers, Lewis Publishers, Boca Raton New York London Tokyo; 1995, 444 p.

[8] Öllős G, Németh E. Szakvélemény a repedezett kőzetekben lejátszódó folyamatok kisminta vizsgálatáról (Study of the physical modelling of the flow processes in fractured rock). Technical University Budapest; 1960.

[9] Shoemaker WB, Kuniansky EL, Birk S, Bauer S, Swain ED. Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005. Techniques and Methods 6 A-24. 2007. US Geological Survey, Reston, VA.

[10] Reimann T, Liedl R, Birk S, Bauer S. Documetation of changes to MODFLOW-2005 Conduit Flow Process Mode 1. Technische Universität Dresden, Institut für Grundwasserwirtschaft 2013.

[11] Colebrook CF, White CM. The reduction of carrying capacity of pipes with age. London, *J I Civil Eng* 1937; Vol. **7**: 99 p.

[12] Gallegos JJ, Hu BX, Davis H. Simulating flow in karst aquifers at laboratory and sub-regional scales using MODFLOW-CFP. *Hydrogeol J* 2013; **21**: 1749-60.

[13] Leél-Őssy Sz, Bergman Cs, Bognár Cs. A budapesti Molnár János barlang termálvizének veszélyeztetettsége (The contamination risk of thermal water of the Molnár János Cave in Budapest). *A Miskolci Egyetem Közleménye* 2011; A sorozat, Bányászat, Vol **81**.