

裂隙岩体氡迁移三维分析软件：理论、模型及应用

Three-dimensional analysis software for radon migration in fractured rock: theory, modelling and applications

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摘要：裂隙岩体中氡迁移的数值模拟对环境中氡污染防治、氡示踪技术和煤铀资源联合开发具有重要意义。本文提出了一种基于分形离散裂隙网络（DFN）的模拟裂隙岩体中氡迁移的新模型，该模型能够更准确地反映裂隙的复杂结构，为氡迁移的研究提供了新的工具。在模拟过程中，提出了一种多级联乘过程，用于确定三维裂隙位置的详细方法。同时建立了氡在裂隙和岩石基质中的迁移控制方程，并用有限元方法进行数值求解。此研究开发了开源软件 DFNRn（氡迁移的离散裂隙网络模型），该软件模拟了裂隙岩体中氡在 100 m 范围内的迁移。结果表明，裂隙内流体对流对氡迁移的驱动作用大于扩散作用。通过与裂隙岩体实测数据的比较，验证了模型的准确性。在相同模型参数下的多次模拟结果表明，当模型运行 8 次以上时，计算结果趋于稳定。因此，为了保证准确性和可靠性，DFNRn 中的每次模拟需运行 8 次，计算结果取平均值。进一步研究双幂律模型参数和 von Mises Fisher 分布（ D_f , a , α , ω 和 κ ），以确定它们对裂隙密度渗透阈值（ P_{32} ）的影响。结果表明，在 $1.4 \leq D_f \leq 1.9$ 范围内，随着 D_f 的增大，渗流阈值呈线性降低， $D_f \leq 1.3$ 时不发生阈值渗流。在 $1.2 \leq a \leq 2.8$ 范围内， P_{32} 与 a 无关，且 $a \geq 2.9$ 的模型由于生成的裂缝小而分散，不发生阈值渗流。 P_{32} 在 $1 \leq \alpha \leq 1.8$ 范围内随 α 的增大而减小。当 $\alpha > 1.8$ 时， P_{32} 随 α 的变化最小。 P_{32} 随 ω 的增大而减小，与 κ 关。与氡扩散系数和渗透率相比，岩石基质的氡源项对裂隙岩体中氡迁移的影响最大。

关键词：氡迁移；裂隙岩体；离散裂隙网络；多级联乘过程；数值模拟

Abstract: Numerical simulation of radon migration in fractured rock bodies is of great significance for radon pollution prevention and control in the environment, radon tracer technology and joint development of coal and uranium resources. In this paper, a new model based on fractal discrete fracture network (DFN) for simulating radon migration in fractured rock bodies is proposed, which can more accurately reflect the complex structure of the fracture and provide a new tool for the study of radon migration. In the simulation process, a multilevel multiplication process is proposed for a detailed method of determining the location of a three-dimensional fissure. The equations controlling radon migration in the fissure and rock matrix were also established and numerically solved using the finite element method. This study developed the open-source software DFNRn (Discrete Fracture Network Model for Radon Migration), which simulates radon migration in the fractured rock matrix over a 100 m range. The results show that fluid convection within the fissure drives radon migration more than diffusion. The accuracy of the model was verified by comparing with the measured data of the fissured rock body. The results of multiple simulations under the same model parameters show that the calculation results tend to be stable when the model is run more than 8 times. Therefore, in order to ensure the accuracy and reliability, each simulation in DFNRn needs to be run 8 times and the calculated results are averaged. The double power law model parameters and von Mises Fisher distributions (D_f , a , α , ω and κ) were further investigated to determine

their effects on the crack density penetration threshold ($P_{32'}$). The results show that the percolation threshold decreases linearly with increasing D_f in the range $1.4 \leq D_f \leq 1.9$, and no threshold percolation occurs for $D_f \leq 1.3$. In the range of $1.2 \leq a \leq 2.8$, $P_{32'}$ is independent of a , and the model with $a \geq 2.9$ does not experience threshold seepage due to the small and dispersed cracks generated. $P_{32'}$ decreases with increasing α in the range of $1 \leq \alpha \leq 1.8$. When $\alpha > 1.8$, $P_{32'}$ varies minimally with α . $P_{32'}$ decreases with increasing ω with respect to κ . Compared with radon diffusion coefficient and permeability, the radon source term of the rock matrix has the greatest effect on radon migration in the fractured rock mass.

Keywords: radon migration; fractured rock; discrete fracture networks; multilevel multiplicative processes; numerical modelling