Simulation of Flow in Porous Media Using Coupled Pressurized-free Surface Interconnected Conduit Network

1- Network Analysis

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Introduction

Simulation of fluid flow and transport phenomena in porous media has a wide range of applications in science and engineering including design of rockfill embankments and sand filters, design of gabion spillways, ground water utilization, and efficient management of oil reservoirs. In the past one hundred years, various efforts have been made to simulate such flow using both Darcy and non-Darcy laws. In recent years, research has been done on converting original porous media into a 2-D and/or 3-D pore network model to address the challenging and complex issues in these media (Acharya et al., 2004; Al-Raoush et al., 2003; Wang et al., 1999; Thauvin and Mohanty, 1998). Such a pore network can be conceptualized by a rectangular lattice having cylindrical pore throats connecting to pore bodies on all sides. The pore body can be spherical or simply the shape created by all connecting pore throats. The pore network is composed of the voids between grains and the pore throat. The pore throat represents the channel connecting two pore bodies. As the flow is exposed to the atmosphere on three sides, the existing methodology in pipe network analysis cannot be effectively used to analyze the fluid flow. This study proposed a modified methodology to analyze such a network for pressure and velocity field.

Objectives

This research fulfilled three main objectives. First, several methodologies were examined for analysis of a typical real pipe network (in vertical plane) exposed to atmosphere on three sides. Second, the assumptions were rigorously assessed and evaluated. Finally, by building and monitoring a real pipe network in the laboratory, experimental results were compared to the numerical results obtained through computer simulation for validation purposes.

Methodology

Previous works and related studies were reviewed to identify the gap in the existing literature. A theoretical background with due attention to the simulation of porous media using pore network model is provided. The nature of flow in porous media consists of a part which is under pressure and another part near the phreatic line which is exposed to atmosphere. Accordingly, a coupled pressurized-free surface flow model should be conceptualized using the network of pore body and pore throat. An effective modeling tool like an open source public domain software can then be used. In this study EPANET was modified to accommodate the nature of flow involved. For verification purposes, a physical model was built in the Hydraulic Lab at the School of Engineering in Shiraz University. Steady state water surface profile and outflow discharge were monitored for different upstream water levels. The collected database was used to calibrate and validate the developed computer model.

Results and Discussions

The conceptualized network was triggered for various upstream water levels. Water surface profile and resulting outflow discharge were digitally monitored in each case. Since the upstream water level was constant during each run, the fluid flow was considered to be steady. The conventional continuity and energy equations were therefore assumed to be applicable.
Typical flow resistance equations including Manning-Chezy, Hazen-Williams, and Darcy-Weisbach equations were used for friction modeling.

The developed computer model was also run for various upstream water levels and the resulting water surface profile and the outflow discharge were compared to the results from the physical model. Figure 1a compares the simulated and the observed water surface profile for one upstream water level based on three flow resistance equations. Figure 1b compares the simulated and the observed outflow discharge for various upstream water levels. While the resistance equation has little affect on the water surface profile, the outflow discharge increases more rapidly for the Darcy-Weisbach equation as the upstream head increases. This could be due to the fact that upon increase in the upstream water level, the streamlines curvature is more pronounced and such peculiarity violates the basic assumptions incorporated into the governing equations.

Conclusion

The current study considered the possibility to simulate fluid flow and transport phenomena in porous media via pore network model. The flow of water through a rectangular pipe network in the vertical plane was evaluated by two-dimensional flow analysis and compared to a laboratory experiment. A coupled pressurized-free surface flow model was developed to simulate fluid flow in a network bounded by atmospheric pressure on three sides. An open source public domain software, EPA NET, was modified for this purpose. This modified software analyzes the network in a recursive approach to delineate the phreatic line assuming that the tail water is not controlled by the downstream water level.
A laboratory rectangular pipe network was also built and triggered for various upstream water levels. The profile of the water surface and the resulting outflow discharge were digitally recorded and compared to results obtained by the numerical model. The model predictions had a satisfactory agreement with the experimental data implying the feasibility of the pore network model in simulating fluid flow through porous media.

**Keywords:** Non-Darcy flow, Flow through rockfill, Network model, EPANET, Porous media

**References**

