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Multidimensional scaling and inverse distance weighting transform for image processing of hydrogeological structure in rock mass

Yoshitada Mito [a,*], Mohd Ashraf Mohamad Ismail [b], Takuji Yamamoto [c]

[a] Department of Urban Management, Graduate School of Engineering, Kyoto University, Nishikyo-ku, Kyoto 6158530, Japan
[b] School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Seberang Prai Selatan, Pulau Pinang, Malaysia
[c] Kajima Corporation, 19-1, Tobitakyu 2-Chome, Chofu-shi, Tokyo 182-0036, Japan

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SUMMARY

A new imaging method based on the multidimensional scaling (MDS) and inverse distance weighting (IDW) transform is proposed in this study. This method aims to identify, characterize and process an image of the preferential flow path in a rock mass, which strongly governs the hydraulic behavior of this rock mass. This methodology uses pair-wise hydraulic diffusivity data from cross-hole hydraulic testing as the input data. The input data are then processed by MDS and IDW to generate a spatial distribution map of the hydraulic properties, which can be used to infer the preferential flow path in the rock mass. The reliability of this novel method was validated through numerical experiments using several continuum models with different hydrogeological structures, and the applicability of the developed method to the actual field was verified through in situ experiments.

1. Introduction

The performance of underground facilities such as high-level waste repositories and underground storage caverns depends on the hydraulic behavior of the surrounding rock mass (Chung et al., 2003; Giramonti et al., 1978; Lindblom, 1989; Runchal and Maini, 1980; Tiren et al., 1999). The performance evaluation for such kinds of underground facilities normally focuses on the potential fluid transport from or to the surrounding hydrogeological environment, where the fluid flows are primarily governed by the hydraulic properties of the surrounding rock and the preferential flow paths embedded in the rock mass (Bonin et al., 2000; Kiyoyama, 1990; Kjorholt and Broch, 1992; Zimmerman and Bodvarsson, 1996).

In a rock mass, fluid flow is often concentrated or localized in certain flow paths, which heavily influence hydraulic behavior (Park et al., 2002; Wang and Kulatilake, 2008). Identifying these flow paths is therefore essential. However, knowledge of the presence and the connectivity of the flow paths, especially the super conductive fracture, is generally quite difficult to obtain due to the heterogeneity of the rock mass.

To grasp the heterogeneity of the hydraulic properties of rock masses, various hydraulic tests based on point-wise measurements have been developed, including the Lugeon test, pumping test, slug test and constant head injection test (Black, 1978; Bouwer and Rice, 1976; Butler and Zhan, 2004; Houlsby, 1976; Kipp, 1985; Pickens et al., 1987). These tests deliver point-wise data that require a spatial interpolation to estimate the properties at unsampled sites in the area surrounding the sampled points (Cassiani et al., 1998). However, the hydraulic behavior of a rock mass can vary by several orders of magnitude within the short distances between fractures and the matrix, thus increasing the uncertainty of the interpolation.

In general practice, the most conductive fractures at the borehole scale are identified based on the core logs and borehole television (BTV) observations. Subsequently, intensive packer testing is performed in multiple boreholes, and pressure variations in multiple intervals in the observation boreholes are monitored by the cross-hole hydraulic test (Martinez-Landa and Carrera, 2006). The sequential step is needed because the single borehole only provides information about the properties of the fracture segments surrounding the borehole, whereas the cross-hole hydraulic test provides information on the properties of the flow zones that connect borehole pairs. The pair-wise hydraulic measurements obtained by the cross-hole hydraulic test enable the evaluation of the hydraulic connectivity in rock masses (Le Borgne et al., 2007). In this context, hydraulic diffusivity is regarded as the key indicator of connectivity between two or more boreholes. Zones

* Corresponding author. Tel.: +81 75 383 3319; fax: +81 75 383 3318.
E-mail addresses: mito@kumst.kyoto-u.ac.jp (Y. Mito), ceashraf@eng.usm.my (M.A.M. Ismail), yamataku@kajima.com (T. Yamamoto).

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with a larger connectivity and diffusivity can act as a preferential flow path and have a substantial impact on the subsurface fluid flow and transport (Becker and Guiltinan, 2010; Black et al., 1986; Black and Kipp, 1981; Hsieh, 1987; Hsieh and Neuman, 1985; Hsieh et al., 1985).

In the past few years, the interpretation of such hydraulic features has been largely improved through advanced hydraulic tests, such as hydraulic tomography (Liu et al., 2002; Yeh and Liu, 2000; Zhu and Yeh, 2005). However, this method is time consuming and computationally intensive because of the inversion required to estimate the spatial distribution of hydraulic properties between the tested holes (Meier et al., 2001). In most cases, the inversion results are strongly influenced by the initial model, the accuracy of which is difficult to assume, especially in three-dimensional cases. In addition, the flow path, which is actually an assembly of several segments or vector-based objects, is often represented as an assembly of grid cells, causing unavoidable errors due to the size and geometry of the grid cells.

In this study, MDS and the IDW transform are implemented for the image processing of hydrogeological structures. These images are derived from the pair-wise hydraulic measurement data set from the cross-hole hydraulic tests. MDS is a set of related statistical techniques and is used here to gain insight in the relations between the pair-wise hydraulic measurement data, as MDS provides a geometrical representation of these relations (Kruskal and Wish, 1978). Meanwhile, IDW, a commonly used interpolation technique, is used to perform a spatial interpolation of the point-wise data generated with MDS (Shepard, 1964; Wackernagel, 1998).

The MDS and IDW transform is then used to identify, characterize and process an image of the preferential flow path in the rock mass. The reliability and applicability of the method were validated through a series of numerical experiments and verified through in situ experiments.

2. Methodology

The pair-wise hydraulic diffusivity data from cross-hole hydraulic tests are used as the input data. These input data are then processed by MDS and IDW to obtain an image of the preferential flow path. The following sub-sections provide details on the data acquisition and data processing procedures.

2.1. Data acquisition by cross-hole hydraulic testing

The cross-hole hydraulic test is a method to assess the hydraulic behavior between two or more boreholes (Hsieh, 1987; Hsieh et al., 1985; Martinez-Landa and Carrera, 2006). Each borehole is subdivided into several intervals using packers (multi-packer system). During the test, fluid is injected into an interval and the hydraulic head response is recorded at other monitoring intervals.

The injection and monitoring intervals are regarded as the points during data processing. The hydraulic diffusivities (hydraulic conductivity divided by specific storage) between an injection interval and monitoring intervals are determined from the hydraulic head at the injection interval, the temporal change in hydraulic heads at the monitoring intervals, and the distance between the injection interval and the monitoring intervals.

The cross-hole hydraulic test is often carried out using an injection borehole as an injection interval and the remaining boreholes as monitoring intervals. This configuration of data points is applied to geo-tomography in the geophysical field. However, this configuration is not essential for cross-hole hydraulic testing. Monitoring intervals can be set in the injection borehole as well because indirect fluid pressure propagation along the angular flow path is rather common, whereas elastic waves propagate in an almost straight line.

To perform a detailed analysis, it is desirable to obtain a matrix of hydraulic diffusivities between all pairs of test intervals by setting monitoring intervals in both the monitoring and the injection boreholes in the cross-hole hydraulic test. A matrix of the hydraulic diffusivities between all test intervals, which were based on the scheme of the cross-hole hydraulic test shown in Fig. 1, is illustrated in Table 1. The fluid injection pressure in the cross-hole hydraulic test is normally specified as a constant by the constant pressure injection test or sinusoidal by sinusoidal pressure test.

2.1.1. Constant pressure injection test

In the constant pressure injection test, the injection and monitoring intervals are treated as a pair of points. The head response in the monitoring intervals as a result of the constant pressure injection in the injection intervals can be obtained through graphical interpretation of the test results by conventional curve matching (Hsieh, 1987; Hsieh and Neuman, 1985; Hsieh et al., 1985).

Labeling the distance between the injection point and the monitoring point as R, the solution for the injection point and monitoring point can be written as (Hsieh and Neuman, 1985):

$$\Delta h = \frac{Q[K_d]^{1/2}}{4\pi R D^{1/2}} erfc\left[\left(\frac{R^2 S_s}{4K_d t}\right)^{1/2}\right] \tag{1}$$

$$D = \begin{vmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{vmatrix}, \tag{2}$$

where Δh is the head increase at the monitoring point, Q is the volumetric injection rate at the injection point, t is time elapsed, S_s is the specific storage of the rock mass, D is the determinant of K as expressed in (2) and K_d is the directional hydraulic conductivity between the injection and monitoring intervals.

The dimensionless form of (1) is expressed as:

$$\Delta h_{PD} = erfc[1/4(t_D)^{1/2}], \tag{3}$$

where Δh_{PD} is the change in the dimensionless hydraulic head and t_D is the dimensionless time, which are, respectively, defined as:

$$\Delta h_{PD} = (4\pi R\Delta h/Q)[D/K_d]^{1/2}, \tag{4}$$

and

$$t_D = K_d t/(R^2 S_s). \tag{5}$$

To analyze the constant pressure injection test results, a theoretical type curve of Δh_{PD} versus t_D was prepared on a log–log plot according to (4) and (5).

Then the following steps are performed for each monitoring interval j:

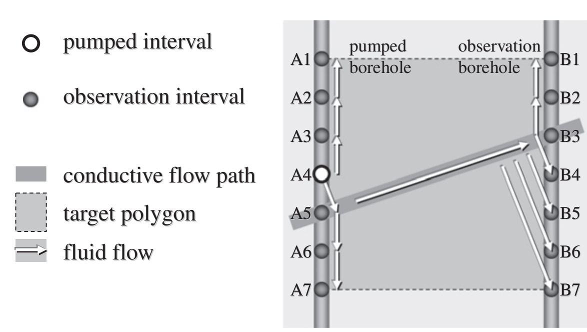

Fig. 1. Schematic of cross-hole hydraulic test with the superconductive flow path.