MDS and IDW transform for image processing of hydrogeological structure in rock mass

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ABSTRACT

A novel imaging method for the establishment of hydrogeological model of rock mass is proposed. The hydraulic data set of cross-hole test, which represents hydraulic property of in situ rock mass, is processed to evaluate a spatial distribution of hydraulic property by the multidimensional scaling (MDS) and the inverse distance weighted (IDW) interpolation. The reliability of this method is validated by numerical experiments using several continuum models with different hydraulic structures, and the applicability of the method is also examined by the field experiments.

Keywords: Preferential flow path, Multidimensional scaling, Inverse distance weighting, Cross-hole hydraulic test

1. INTRODUCTION

Cross-hole hydraulic test, which enables to evaluate the hydraulic property of in situ rock mass, was well investigated in the 1970’s to the 1980’s by Black (1978), Bouwer and Rice (1978), Houlsby (1976), Black & Kipp (1981), Heish (1987),, etc.

Several iteration-based inversion methods using cross-hole test data were proposed to estimate the spatial distribution of hydraulic property between the test holes. In most cases, the inversion result by each method is strongly influenced by its initial model, which is difficult to assume itself, especially in three-dimensional case. In addition, those methods often provide unrealistic flow paths, which are composed of the grid base elements.

Thus, this study proposes a new imaging method for hydrogeological structure using cross-hole test data in order to detect the heterogeneous flow paths in rock mass with high accuracy. This method involves space-warping by the multidimensional scaling (MDS) and the inverse distance weighted (IDW) interpolation. The method is validated by a series of numerical experiments and the applicability of the method is examined by field experiments.

2. METHODOLOGY

A vector based imasing method for hydrogeological structure is proposed in this section. This method is mainly composed of the following four processes.

2.1 Hydraulic distance matrix

A set of hydraulic diffusivity values, which shows the hydraulic property among several test intervals of cross-hole test in a real geographical space (where geographical distance is a measure), is determined from test results.

2.2 Projection of the points into the Hydraulic subspace

The hydraulic configuration of the points that represent the pumped and observation intervals of cross-hole test in an imaginary hydraulic subspace (where hydraulic distance that can be represented by reciprocal of hydraulic diffusivity is a measure), is determined from a matrix of hydraulic diffusivities between pairs of the test intervals by multidimensional scaling (MDS).

2.3 Reprojection of the points into the Geographical subspace

A set of equally spaced points, which is established in the hydraulic subspace, is relocated in the original geographical space by inverse distance weighted method (IDW) referring the relationship between the geographical and the hydraulic configurations of test intervals.

2.4 Imaging

The spatial density of the relocated points in the geographical space, which represents the hydraulic property, is measured in the final process. The spatial distribution of density creates an image of the heterogeneous flow path.
3. VERIFICATION OF THE METHODOLOGY

A series of numerical experiments is carried out to verify the availability of the proposed method and investigate its performance.

Two-dimensional and three-dimensional continuum models including several patterns of preferential flow path with a certain width are made for the numerical experiments. Hydraulic conductivity of $10^{-3}$ m/s is given for preferential flow path, while that of $10^{-2}$ m/s is given for the surrounding rocks. An identical specific storage of $10^{-1}$ m$^{-1}$ is assumed for any part in the model. The sides and the top of the region are head specified boundaries. The bottom of the region is specified impermeable boundary. The numerical cross-hole test with a constant injection pressure is carried out using seven test intervals.

The values of hydraulic diffusivity between pairs of the test intervals are determined from the computed temporal changes in hydraulic head, which are obtained from the finite element analysis of unsteady state groundwater flow. The hydraulic configuration of test intervals is determined by MDS using the values of hydraulic distance between all the pairs of test intervals. Sequentially, the configuration of obstacles is determined by IDW, and then the image of flow path is obtained by the raster base measurement and expression technique. The class of the obstacle density is log-normally defined. The availability of the proposed imaging method is examined by comparing the computed image of flow path to the original hydrogeological structure in the continuum model.

As the results of the comparisons between the several sets of the original hydrogeological structure and the computed image of flow path, in two- and three-dimensional cases, respectively, the appropriate images are obtained, and the availability of the proposed method is proved.

4. APPLICABILITY OF THE METHODOLOGY

The applicability of the proposed imaging method, which shows high performance in the numerical experiments, is also examined by the field experiments.

The cross-hole hydraulic test with constant injection pressure was carried out using the two boreholes, which were drilled in Tertiary alternation of mudstone, sandstone, and pumice tuff with homoclinal structure. The image of hydrogeological structure is composed of several layers with different hydraulic properties in the same direction as geological structure. Further, the layers, where the joints exist more densely, show higher permeability, while the layers, where the joints exist more sparsely, show lower permeability. This implies the proposed method provides an appropriate image for hydrogeological structure.

Also the cross-hole hydraulic test with sinusoidal injection pressure was carried out using the three boreholes, which were drilled in Cretaceous alternation of sandstone and mudstone. The presence of a steep fracture zone in the target polyhedron is confirmed by both of the adit wall observation and the borehole TV observation. This fracture zone is not directly appeared at any pumped and observation intervals. The computed image of flow path shows good agreement with the fracture zone, the only geological structure in the target polyhedron, which can be a preferential flow path. This implies the applicability of the proposed method to the three-dimensional field test.

5. CONCLUSION

Preferential flow paths are ubiquitous and always play an important role in the hydraulic behavior of a rock mass. The influence of these flow paths on the hydraulic behavior of a rock mass is difficult to characterize due to the inherent complexities in fracture network geometries, densities and connectivity. These factors often dominate the selection of the methodology used for the detection, characterization and visualization of flow paths.

In this study, a new method for visualizing the hydrogeological structure in rock masses that is simpler than computationally intensive inference or inversion was developed. The method was validated by numerical and in situ experiments. It does not require any kind of initial model and is able to determine the geometric and hydraulic properties of the flow paths, such as orientation, shape and hydraulic conductivity, in both two and three dimensions.

Although the method can be applied successfully, there are some differences in performance between the various situations presented in this study. The method appears to perform well for detecting the preferential flow path if there is a difference in hydraulic diffusivity between the point pairs involved in the cross-hole test. From the numerical analysis results, it was found that the degree of intersection determines whether the preferential path will have a large or a small impact on the measured diffusivity. The higher the degree of intersection (i.e., in the case of a horizontal flow path), the larger the impact on the measured hydraulic diffusivity will be. In case of such a high degree of intersection, the preferential flow path can be clearly visualized. However, if the degree of intersection is smaller (i.e., an oblique flow path) or similar for all point pairs, as in the vertical flow path cases, the calculated diffusivity for all pairs will be similar, and thus the preferential flow path cannot be visualized.

The possible orientation of the preferential flow path needs to be estimated before the methodology developed in this study can be applied. The identification of the preferential flow path orientation by means of geological mapping or geophysical techniques gives the information required to determine the orientation of the boreholes for the cross-hole test, so that the preferential flow path can be detected. In case of a dominant vertical flow path in the study area, inclined boreholes that can intercept the vertical flow path must be included in the cross-hole test.

REFERENCES


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