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論文題目	Characterizing hydraulic properties of fractured rocks using DFN model and FEMDEM method for tunnelling applications（DFN モデルと FEMDEM 法を用いた亀裂性岩盤の水理的性質の特徴抽出とトンネル掘削への応用)		

（論文内容の要旨）

Fractures (e.g., faults and joints) provide pathways for fluid flow as hydraulic conductors or barriers that prevent flow across them. Characterization and detection of fractures in fractured rock mass have been of great interest in geotechnical, geological, geophysical, and hydraulic engineering practices. In particular, the relations between fractures and their physical properties (e.g., permeability, electrical resistivity, and seismic velocity) are fundamental to understanding fractured rock mass in tunnelling. Among several methods, the discrete fracture network (DFN) modeling approach has high capability of characterizing natural rock fractures. For stress-induced fractures (e.g., induced fractures around tunnel excavation), the hybrid finite-discrete element method (FEMDEM) is effective to model fracture initialization and propagation in rock mass. In this thesis, several methods were proposed to characterize fracture patters and their rock physical properties quantitively by the following six chapters.

Chapter 1 provides background information of fractures and their fractured rock physical properties (e.g., permeability, electrical resistivity, and seismic velocity). Also, DFN modeling approach as well as FEMDEM which characterize fractures in the rock mass are introduced briefly.

Chapter 2 presents a method for estimating effective permeability of fractured rock mass by using discrete fracture networks constrained by electrical resistivity data. Although the permeability of fractured rock mass is a fundamentally important property for the safe construction of civil and mining engineering structures such as tunnels, in-situ characterization of the permeability without resorting to hydraulic tests is difficult. For a quick estimate over a wide area, a method at a field-scale using geological and geophysical investigation data is proposed. The method is not based on the results of conventional hydraulic tests. Instead, it combines the stochastic generation of fracture networks with the crack tensor theory. The most important parameter for this method is the fracture length distribution. Although the distribution parameters in the DFN model are assigned through sampling, a bias is in general experienced, because of the limited sampling area. To improve the estimation of such parameter, in-situ electrical resistivity data and a symmetric self-consistent method are used as a constraint of the fracture length distribution. The proposed method is applied to the fractured crystalline rock mass of the Mizunami Underground Research Laboratory (URL) in the Tono area of central Japan. Its effectiveness and correctness are demonstrated by two case studies through good correspondence of the derived permeability with the in-situ measured permeability. For Case 1, an optimal DFN model with scaling exponent a = 3.0 was obtained with an in-situ measured resistivity of 2000 Ω·m. The corresponding average effective permeability is $\bar{k}$ = 5.30 × 10^{-16} m^2, which is about half of in-situ measured permeability 1.0 × 10^{-15} m^2. For Case 2, the calculated $\bar{k}$ was 1.18 ×10^{-14} m^2, which was about four times greater than the in-situ measured permeability of 2.67 × 10^{-15} m^2. Based on the results of these two case studies, we conclude that the constrained DFN modeling approach using in-situ resistivity data can avoid constructing unrealistic DFN models with too many short fractures.

Chapter 3 presents a conceptual model to interpret both increases in seismic velocity and electrical resistivity after a tunnel excavation in fractured rock mass. Excavation of a tunnel results in the formation of an excavation damaged zone (EDZ) in surrounding rock mass. Generally, seismic wave velocity and electrical resistivity decrease after a tunnel excavation, because fractures initiate and propagate in EDZ. However, a special phenomenon where seismic velocity and electrical resistivity increased after tunnel excavation in the Horonobe Underground Research Laboratory (URL) was observed. A possible conceptual model for the phenomenon is proposed in this chapter. The conceptual model assumes that a

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decrease in liquid saturation around tunnel excavation induces the increases in seismic velocity and electrical resistivity in EDZ. The main cause of liquid saturation change originates from relative humidity variation in the tunnel. In addition, liquid saturation does not have a great influence on stress redistribution after excavation based on a hydro-mechanical modeling of excavation in a fractured rock mass using FLAC3D and TOUGH2. The rock gas saturations around the tunnel excavation surfaces increased after the tunnel excavation with decreasing in their increase rates. The electrical resistivities and seismic velocities in the rock mass were also increased. The numerical simulation incorporating our proposed model succeeds in explaining the phenomenon observed in the Horonobe URL.

Chapter 4 presents a model that links a unified pipe network method and FEMDEM fracture model for estimating equivalent permeability of fractured rock mass. Based on fractures in a fractured rock mass captured by a FEMDEM fracture model, a unified pipe network model that includes matrix pipes and fracture pipes is used to estimate equivalent permeability. Four representative cases studies were carried out to validate its applicability in calculating equivalent permeability. In Case 1 where a single fracture was embedded in a rock, k_{xx} decreased whereas k_{yy} increased as the fracture orientation increased from 0° to 90°, where the *x* and *y* axes are in the horizonal and vertical directions, respectively, and the angle is defined counterclockwisely from the *x* axis. In Case 2 where DFN models with different fracture densities were prepared, their equivalent permeabilities increased with increasing the fracture density in general. In Case 3 for a uniaxial compression test of rock specimen, both k_{xx} and k_{yy} increased with increasing the time step. Case 4 for simulating a deep tunnel excavation, permeabilities in different locations around the tunnel also increased generally.

Chapter 5 presents a numerical method that calculates equivalent electrical resistivity of fractured rock mass using an approach, similar to that of Chapter 4. The fracture initiation and propagation in intact rock mas is modeled by FEMDEM model, and the electric potential through fractures is simulated by an adapted unified pipe network model. To validate our novel proposed model, four representative cases studies were carried out. The first case was to estimate equivalent resistivities of intact rock mass in which a single fracture was embedded. The change in resistivity was revealed with the change in fracture orientation, and its change pattern was different with the direction. In Case 2, resistivities of DFN models decreased as fracture densities increased. Another case presented a laboratory test for uniaxial compressive strength (UCS) with estimating resistivities of a rock specimen. The resistivities decreased with increasing the time step. The last case clarified resistivity changes at different locations around the tunnel excavation, and the resistivities increased common to all the locations with increasing the time step.

Chapter 6 summarizes the main results obtained by this dissertation and describes future, essential works.

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（論文審査の結果の要旨）

断層や節理を含む亀裂は岩盤に普遍的に存在し，連結してネットワークを形成することで，岩盤の水理的性質を支配する。岩盤中の亀裂ネットワークを予測するとともに，これと岩盤の浸透率，および浸透率と関連した物性で物理探査から得られる比抵抗や弾性波速度との関係を明らかにすることは，トンネル掘削の前方評価において重要である。加えて，トンネル掘削後の空洞周辺の亀裂進展と透水性の時間的変化の把握は，トンネルの保全管理に有用できる。しかしながら，亀裂ネットワークとこれらの岩盤物性との関連を明らかにできた研究は皆無に等しい。そこで本研究では，これらの関連の解明を目的とし，離散亀裂ネットワーク（discrete fracture network : DFN）モデルの応用によって亀裂ネットワークを正確に作成する手法を検討し，これから比抵抗と弾性波速度を推定する手法を開発した。それとともに，パイプネットワークと FEMDEM（Finite-element method and discrete-element method）の組合せによって，亀裂進展と浸透率の同時推定を初めて可能にした。主な成果は次の 3 点に纏められる。

1) DFN モデルによる亀裂ネットワークの構築において，亀裂長さ分布をべき乗則に当てはめ，その関数を原位置での比抵抗測定データと対称自己整合法から定義するという手法を提案し，得られた亀裂ネットワークモデルにクラックテンソル理論を適用することで浸透率を求めた。これらの手法を花崗岩から成る瑞浪超深地層研究所の坑道での亀裂と比抵抗データに適用したところ，浸透率の計算値と実測値が概ね整合し，手法の妥当性を実証できた。
2) DFN モデルをトンネル掘削で生成されるトンネル周囲の掘削損傷ゾーン（EDZ）の問題に適用し，EDZ での亀裂進展と，それに伴う比抵抗・弾性波速度の時間的変化の予測を試みた。ここにトンネル表面での毛細管圧とトンネル内の湿度の関係をケルビン式で与え，計算されたガス飽和率，およびアーチーの式と空隙弾性理論を用いて比抵抗と弾性波速度を計算した。泥岩で構成される幌延地下施設にこれらの手法を適用したところ，坑道掘削後に観測された EDZ における比抵抗と弾性波速度の増加を再現することができた。
3) トンネル掘削に伴う亀裂発生と進展を FEMDEM 法でシミュレートした後，亀裂内の流体圧をパイプモデルで表し，これによって浸透率と比抵抗を計算するという手法を提案した。この手法は一軸圧縮岩石試験での典型的な亀裂進展パターンを再現し，各進展段階での浸透率を妥当に算出できたとともに，亀裂方位に依存した浸透率の異方性も表現できた。またこれを応用して，幌延地下施設における深度 350 m 坑道での EDZ 生成・進展と比抵抗，浸透率の時間変化を予測できるようになった。

以上，本論文で開発された亀裂ネットワーク構築法と岩盤物性推定法の精度・有効性は高く，トンネルや坑道掘削が不可欠となる資源開発・土木分野に貢献できることが示された研究として，学術上，実際上寄与するところが少なくない。よって，本論文は博士（工学）の学位論文として価値あるものと認める。また，令和 3 年 8 月 10 日，論文内容とそれに関連した事項について試問を行い，申請者が博士後期課程学位取得基準を

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満たしていることを確認し，合格と認めた。

　なお，本論文は，京都大学学位規程第 14 条第 2 項に該当するものと判断し，公表に際しては，全文公表日までの間（令和 5 年 9 月 30 日），当該論文の全文に代えてその内容を要約したものとすることを認める。