Environment and Natural Resources Trust Fund
2017 Request for Proposals (RFP)

Project Title: **ENRTF ID: 047-B**

Quantifying Depth-Dependent Permeability of Fractured Rock

Category: B. Water Resources

Total Project Budget: $ 296,739

Proposed Project Time Period for the Funding Requested: 3 years, July 2017 - June 2020

Summary:

Fracture permeability will be measured and related to depth below the surface, and this information is essential to protect groundwater from landfills, septic tanks, and other pollution sources.

Name: Bojan Guzina

Sponsoring Organization: U of MN

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Web Address

Location

Region: Metro, Southeast

County Name: Anoka, Dakota, Fillmore, Goodhue, Hennepin, Houston, Olmsted, Wabasha, Washington, Winona

City / Township:

Alternate Text for Visual:

Illustration shows water flowing in a rock mass, and techniques used to measure permeability and wave speed.

_____ Funding Priorities	_____ Multiple Benefits	_____ Outcomes	_____ Knowledge Base
_____ Extent of Impact	_____ Innovation	_____ Scientific/Tech Basis	_____ Urgency
_____ Capacity Readiness	_____ Leverage	_____ TOTAL	_____%

PROJECT TITLE: QUANTIFYING DEPTH-DEPENDENT PERMEABILITY OF FRACTURED ROCK

I. PROJECT STATEMENT

Fractures in a rock mass, rather than the intact rock itself, provide conduits for groundwater flow, and knowledge of fracture permeability is essential to protect groundwater from landfills, septic tanks, and other pollution sources. Traditional means of determining fracture permeability through field tests require drilling and possibly coring, which are highly expensive and time-consuming procedures. The situation is further complicated by the fact that the data are inherently depth-dependent, which can be attributed to changing stress conditions in the subsurface.

The overall goal of this project is to relate permeability to fracture characteristics by

- enabling the quantification of fracture opening and surface roughness indices of a fractured rock mass (affecting the speed of seismic waves) through seismic surveys, a powerful and relatively inexpensive geophysical method performed by state agencies and private consultants, and
- correlating the fracture indices to the permeability of fractured rock under varying stress levels, which represents changing depth within the rock mass, through well-controlled laboratory experiments.

It is well known that a strong coupling exists between permeability of a fractured rock mass and fracture opening, whereby specific features of the fracture surface dictate the success or failure to protect and remediate groundwater. Consider for instance the Magnolia member of the Platteville limestone, where the increased emphasis on subsurface hydrogeology is driven by pressing environmental concerns across southeastern Minnesota, especially the Twin Cities. The flow characteristics of subterranean fractures, described by permeability, must be known beforehand in order to predict and manage seepage quantities. What is equally important is the density of a fracture network, but this is for future study.

The results of this laboratory study will reveal if and how seismic surveys can be used to identify *in-situ* fracture permeability profiles and related flow quantities that are essential for managing groundwater. If our approach is successful, this would suggest that a non-invasive field technique can be developed for efficiently assessing seepage characteristics. If the data do not reveal the correlation, the study will provide critical information about information about fracture flow and permeability properties of actual fractured rock masses. These results will be valuable to State regulators and engineering consultants.

II. PROJECT ACTIVITIES AND OUTCOMES

Activity 1: Small-scale seismic testing of fractured rock **Budget: $95,000**

Ultrasonic experiments will be performed on naturally and artificially fractured rock specimens (20 specimens of local limestone, obtained from the Platteville formation), selected in conjunction with Minnesota Geological Survey (MGS), in the UMN's *Waves & Imaging Laboratory*. Representative specimens of limestone will be machined into dimensions 100 × 87 × 44 mm and pre-stressed in the direction perpendicular to the predominant fracture orientation. The fractured rock specimens will then be “illuminated” ultrasonically by a piezoelectric transducer, providing laboratory-scale seismic excitation, while computing the apparent wave speed in the specimen from the time-of-flight measurements. In this setting, ultrasonic testing will be used to individually characterize each fractured specimen by measuring the variation of its seismic wave speed with increasing normal stress. In essence, the presence of a fracture introduces a *time delay* to the propagation of seismic waves. This time delay diminishes with increasing normal stress on a fracture, which produces an increase in the seismic wave speed – and thus the means to quantify fracture indices, namely its specific (shear and normal) stiffness, by seismic waves under varying levels of normal stress. Each specimen will be tested under five different normal pressures (spanning depth-induced stress values present in the Platteville formation), resulting in a total of 20 x 5 = 100 ultrasonic experiments. On completing the ultrasonic experiment, each limestone specimen will be tested for permeability as described in Activity 2.

Outcome	Completion Date
1. Ultrasonic testing (UT) of fractured limestone specimens (100 experiments)	10/31/17
2. Estimating fracture specific stiffness vs. normal pressure from UT measurements	4/30/18

Activity 2: Measuring permeability of fractured rock **Budget: $115,000**

Permeability experiments will be conducted with the UMN plane-strain apparatus (US patent 5,063,785) in the UMN's *Rock Mechanics Laboratory*. This unique apparatus was specifically developed for testing fluid-saturated rock under various stress states. Fractured limestone specimens, tested ultrasonically in Activity 1, will be sealed with a polyurethane membrane and placed inside a pressure vessel to simulate subsurface conditions. A permeability test will be performed by maintaining a constant pressure head difference across the specimen; this condition will be applied and preserved by connecting the pore water lines to microprocessor-based hydraulic pumps that maintain water pressure to appropriate values. An application of Darcy's law provides the basis for determining the effective permeability of a fractured rock specimen. The stress conditions will be changed and the permeability again measured. As in Activity 1, this effort will entail 100 permeability tests.

Outcome	Completion Date
1. Determining mechanical properties of rock and fractured rock	12/31/18
2. Measuring permeability at various stress states	10/31/19

Activity 3: Correlate the fracture indices to permeability under varying stress levels **Budget: $86,739**

On completing Activity 1 and Activity 2, the fracture surface of each rock specimen will be exposed and probed by a white light scanner in order to extract quantitative information about surface roughness. From the available data, *nomograms* will be developed that establish a correlation between the fracture indexes, measured ultrasonically (seismically), and its permeability, measured directly, as a function of (i) normal stress on a fracture, and (ii) specific roughness of the fracture surface. This information will then be synthesized to enrich the data base for the ongoing *County Geologic Atlas* program, with the long-term goal of enabling seismic surveys to provide *in-situ* permeability profiles of fractured rock formations.

Outcome	Completion Date
1. Measuring fracture surface roughness	12/31/19
2. Correlating seismic data on fractures to permeability	5/31/20

III. PROJECT STRATEGY

A. Project Team/Partners : The project will be led by Professors Bojan Guzina and Joseph Labuz, Department of Civil, Environmental, and Geo- Engineering, UMN. The team will consist of one graduate and one undergraduate student. Guzina has extensive experience in seismic and ultrasonic imaging of fractured systems, and Labuz is an expert on fracture testing and behavior of fluid-saturated rock. The Minnesota Geological Survey (MGS) will be part of the project; they will be consulted on appropriate rock mass samples and testing procedures.

B. Project Impact and Long-Term Strategy: This project will provide an understanding of the permeability changes with depth, which will be reproduced by varying stress states in the laboratory. Additionally, this will be the first study in the State of Minnesota to investigate how seismic imaging can provide detailed information on *in-situ* permeability of a fractured rock formation. This information is critical to protecting and managing groundwater from various pollution sources, as well as for potential irrigation purposes. Further, this work will form the basis to evaluate flow characteristics of *fracture networks* for future funding requests. The results will be disseminated through scientific literature, professional conferences, and a publically available final report.

C. Timeline Requirements: The project will be completed in a three-year period. The imaging and permeability measurements are time consuming and require detailed quality assurance/quality control protocols.

2017 Detailed Project Budget

Project Title: Quantifying depth-dependent permeability of fractured rock

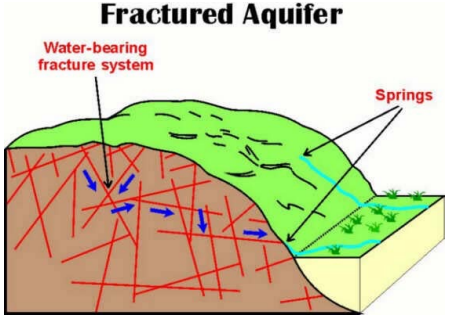
IV. TOTAL ENRTF REQUEST BUDGET 3 years

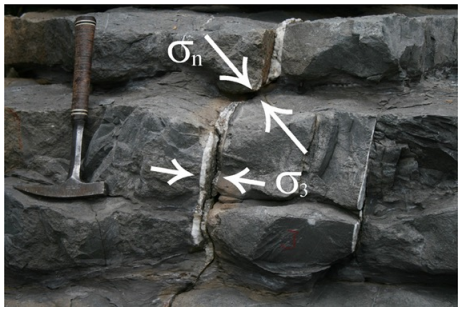
BUDGET ITEM	AMOUNT
Personnel: Guzina PI; 6% time per year for three years, salary 73.5% of cost, fringe benefits 26.5% of cost. Project supervision, provide guidance on seismic/ultrasonic imaging for the project, including transducer selection, transducer calibration, and data interpretation.	$ 56,827
Personnel: Labuz co-PI; 6% time per year for three years, salary 73.5% of cost, fringe benefits 26.5% of cost. Laboratory supervision, provide guidance on permeability measurements for the project, including specimen preparation, stress conditions, and fracture development.	$ 42,865
Personnel: Graduate student; 50% time per year for three years, 56% salary, 33% tuition, 11% fringe benefits. Conduct laboratory experiments and data analyses.	$ 139,047
Personnel: Undergraduate student; Approximately 350 hours per year, 100% salary. Assist with specimen preparation and experimental setup.	$ 15,000
Professional/Technical/Service Contracts: Minnesota Geological Survey. Sampling of rock at selected sites and review of testing procedures. Working with County Geologic Atlas program.	$ 15,000
Equipment/Tools/Supplies: Syringe pump for permeability measurements ($20,000). Laboratory supplies, including membranes, diamond saw blade, and grinding wheel ($3,000). Machining of platens to house ultrasonic transducers ($2,000). Replacement of transducers, including ultrasonic,	$ 27,000
Travel: Mileage charges to field sites for sample collection. Mileage will be reimbursed at University of Minnesota rates.	$ 1,000
TOTAL ENVIRONMENT AND NATURAL RESOURCES TRUST FUND $ REQUEST =	$ 296,739

V. OTHER FUNDS

SOURCE OF FUNDS	AMOUNT	Status
Other Non-State $ Being Applied to Project During Project Period: N/A	$ -	
Other State $ Being Applied to Project During Project Period: N/A	$ -	
In-kind Services During Project Period: Guzina and Labuz will provide unpaid time to the project, including 1% cost-share each. Because the project has no indirect costs, laboratory space, electricity, and other overhead expenses are provided at no charge to the project. The University of Minnesota indirect cost recovery rate is 52%.	$ 997	
Remaining $ from Current ENRTF Appropriation (if applicable): N/A	$ -	
Funding History: N/A	$ -	

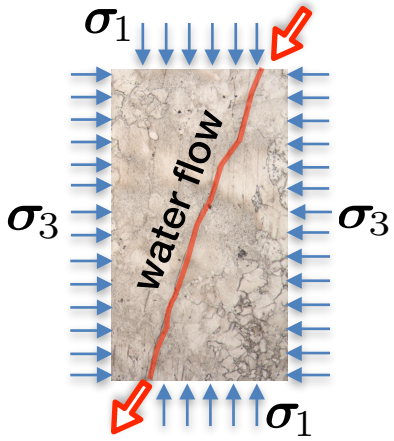
Quantifying depth-dependent permeability of fractured rock





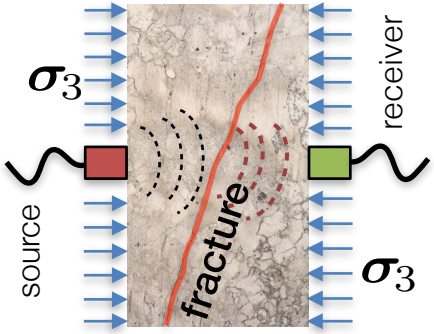
Importance: fractured limestone is a conduit for groundwater flow: fractures serve as major thoroughfares

Question: how does stress on a fracture, which increases w/depth, affect its permeability (**k**)?

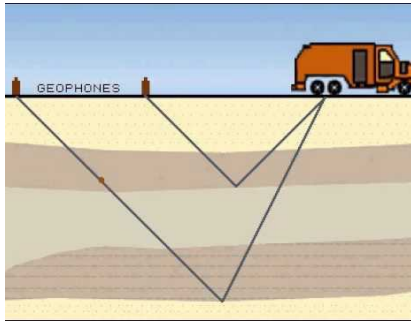


Laboratory tests can help us expose the variation of **k** in fractured rock w/stress

Problem: we need efficient tools to measure depth-dependent **k** in the field (no coring & lab testing)



Solution: seismic wave speed in fractured rock is stress-dependent: it can be measured in laboratory and correlated to **k**



Translation to field: using this study, seismic surveys can be used to provide site-specific **k**-profiles of fractured limestone

Summary: through laboratory testing, enable seismic surveys to provide in-situ **k** profiles of fractured limestone.
Applications: water supply, water pollution, irrigation (Platteville Formation, SE MN)

Project Manager Qualifications and Organization Description

Project title: Quantifying depth-dependent permeability of fractured rock

Project Manager Qualifications

Bojan G. Guzina
Shimizu Professor, Department of Civil, Environmental, and Geo- Engineering, University of Minnesota, Minneapolis, MN. Guzina has been at Minnesota since 1998, and he is leading expert in seismic and ultrasonic imaging of fractured rock.
1996 Ph.D., Geotechnical Engineering, University of Colorado, Boulder, CO
1992 M.S., Geotechnical Engineering, University of Colorado, Boulder, CO
1989 Dipl. Inz., Civil Engineering, University of Belgrade, Yugoslavia

Joseph F. Labuz
MSES/Miles Kersten Professor, Department of Civil, Environmental, and Geo- Engineering, University of Minnesota (UMN), Minneapolis, MN. Labuz has been at Minnesota since 1987, and he is a world leader in experimental investigation of fracture and damage of fluid-saturated rock.
1985 Ph.D. Civil Engineering, Northwestern University, Evanston, IL
1981 M.S. Civil Engineering, Northwestern University, Evanston, IL
1979 B.S. Civil Engineering (with honors), Illinois Institute of Technology, Chicago, IL

Organization Description

The University of Minnesota (UMN) has a world-class program in earth resources engineering, with over 50 years of initiating and promoting research and applications in fractured rock masses. Several significant contributions to the geomechanics field were devised or refined at UMN. These include the development of servo-controlled testing techniques for determining the post-peak behavior of rock, the displacement discontinuity method for predicting the stability of underground excavations, the distinct element method for modeling the behavior of blocky rock masses, and the constitutive response of fluid-saturated rock for determining solid-fluid coupling and flow characteristics of fracture rock.

The geomechanics laboratories at UMN are well equipped for determining hydro-mechanical properties of rock, including permeability and triaxial testing. Three closed-loop, servo-hydraulic load frames have been recently updated with the latest technology in digital control. Basic instrumentation associated with an experimental mechanics laboratory is also available. A rock specimen preparation room is fully equipped with circular saws, surface grinder, drill press, and lathe. Maintenance of hydraulic systems is performed annually by a certified technician. Supporting equipment to monitor fracture include acoustic emission and laser Doppler vibrometer.