# Remediation in Rock Masses



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# **Remediation in Rock Masses**

EDITED BY

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*Abstract:* This book contains theoretical analyses, case studies, and recommendations by experts on aspects of remediation of contaminants in rock masses. Theoretical modeling of liquid movement and mixing in rock fractures is presented. Occurrence of contaminants in fractured rock systems at selected industrial sites, landfills, and hardrock or coal mining sites is reviewed. Contaminants include: gasoline, trichloroethylene (TCE), tetrahydrofuran and heavy metals. Site characterization techniques to determine interconnectivity between fractures are discussed. Evaluations of pneumatic and hydraulic fracturing to increase formation permeabilities are presented. Remediation technologies reviewed include pump-and-treat, soil vapor extraction (SVE), bioremediation, and alcohol flooding.

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## Foreword

In situ characterization of fissured/fractured geomedia at a scale that is adequate for the use of obtained data in contaminant migration modeling and evaluation of cleanup effectiveness is still a difficult problem. Often, the discontinuities that are significant with respect to contaminant fate and transport processes are not large enough to be discerned by geophysical and other in-situ techniques. Furthermore, the fissures and fractures that serve as contaminant holding conduits may not be continuous enough to allow externally imposed potentials such as hydraulics (in pump-and-treat systems), steam injection, and surfactant-enhanced flushing to be adequately effective. Relatively novel techniques such as pneumatic and hydraulic fracturing have been used to improve the effectiveness of remediation schemes in rock masses.

This publication contains theoretical analyses, case studies, and recommendations by recognized experts on various aspects of remediation in rock masses. For convenience, the papers have been presented in three categories: modeling, site characterization, and remediation. The papers included in this volume were peerreviewed in strict compliance with ASCE's general peer review policies for journal articles. Each of the papers published herein has received at least two positive peer reviews. Prior to final acceptance of some of these articles, revisions were recommended by the editors on the basis of comments made by the reviewers. The contents of the papers included in this volume are suitable for discussion in the ASCE Journal of Environmental Engineering. These papers are also eligible for ASCE awards.

The co-editors acknowledge the contributions of the authors, reviewers, and ASCE administrative personnel who made this publication possible. In particular, the tireless effort of Mr. John Daniels, who worked as the editorial assistant, is also acknowledged.

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#### Chapter 1

### The Fundamentals of Remediation in Rock Masses

Clifford J. Bruell and Hilary I. Inyang

#### Introduction

Remediation of contaminated rock masses is a complicated problem. Successful remediation requires knowledge of the types of contaminants present and an understanding of their properties and behavior within a fractured rock matrix. Contaminated rock masses exist at industrial sites, municipal or hazardous waste landfill sites, and hardrock or coal mining sites. Contaminants such as waste fuels and chlorinated organic solvents can occur as either dissolved contaminants, light non-aqueous phase liquids (LNAPLs) or dense non-aqueous phase liquids (DNAPLs). Heavy metals or radioactive wastes are also potential contaminants. Each type of site and contaminant combination presents unique technical challenges with respect to clean-up. The process of site characterization is used to determine the distribution of contaminants at a site and to identify possible pathways for contaminant movement within rock masses. Once a site has been adequately characterized, it is then possible to select the appropriate remediation technologies.

The technology or combinations of technologies utilized for remediation in fractured rock masses are often the same as those used for porous media clean-up. Pump-and-treat is often used to exert hydraulic control on an area to prevent further contaminant migration. In situ air sparging (IAS) can be used to either promote mass transfer of the contaminant into the vapor phase for subsequent removal or to stimulate aerobic biodegradation (Marley and Bruell 1995). Soil vapor extraction can be somewhat effective in unsaturated zones for the remediation of gasoline hydrocarbons using native organisms (McLinn and Rehm 1997; O'Cleirigh et al. 1997). However, under normal conditions, this process does not work well for the removal of most chlorinated species.

Clifford J. Bruell and Hilary I. Inyang, Center for Environmental Engineering, Science and Technology (CEEST) and Department of Civil and Environmental Engineering, University of Massachusetts Lowell, One University Avenue, Lowell, MA, 01854. When used alone, most of these technologies are highly inefficient for the removal of immiscible NAPL and DNAPLs because these materials are tightly held in rock fractures by capillary forces due to the relatively low permeability of the matrix. Therefore, additional companion technologies are often needed to favorably alter the fractured rock mass environment and allow the effective use of traditional subsurface remediation technologies.

#### **Behavior of DNAPLs in Fractured Rock Masses**

Chlorinated solvents are DNAPLs that are heavier than water. As a result of their relative density, DNAPLs discharged into groundwater systems will sink to the bottom of the aquifer and often penetrate fractured rock masses located there. If these chlorinated solvent DNAPLs are left in place they will slowly dissolve, leading to the formation of dissolved plumes containing contaminants that greatly exceed drinking water standards. However, with respect to mobilization and removal, the solubilities of most chlorinated organics are relatively low. Therefore, DNAPLs will remain in place and serve as a potential source of persistent contaminants of groundwaters for decades.

Fractured rock systems often have a complex system of fractures that exhibit extreme heterogeneity with respect to the number, density, size, and direction of fractures. When DNAPLs are introduced into fractured rock masses, they may enter very small ( $<20 \ \mu$ m) fractures and penetrate deeply into the fracture network (EPA 1992). Penetration of DNAPLs into a fracture network is depicted in Figure 1-1.

When two immiscible liquids come into direct contact, the force of interfacial tensions existing at the interface results in a pressure discontinuity. The pressure difference is know as capillary pressure,  $P_c$ , and is defined as follows (Bear 1972):

$$\mathbf{P}_{\mathrm{C}} = \mathbf{P}_{\mathrm{NW}} - \mathbf{P}_{\mathrm{W}} \tag{1}$$

where,  $P_{NW}$  is the pressure of the nonwetting phase (i.e., DNAPL) and  $P_W$  is the pressure of the wetting fluid (i.e., water). In all cases P represents pressure and has units of FL<sup>-2</sup>.

 $P_E$ , the entry pressure of the fracture, can be represented by (Kueper and McWhorter 1991):

$$P_{B} = \frac{2\sigma \cos \theta}{b}$$
(2)

where,  $\sigma$  is the interfacial tension between the nonwetting and wetting fluid (FL<sup>-1</sup>),  $\theta$  is the contact angle measured through the wetting plane (degrees), and b is the width of the flow aperture between two parallel plates (L).



# Figure 1-1. Typical scenario showing the migration of a DNAPL into a fractured rock mass (after Longino and Kueper 1995).

A theoretical examination and associated numerical simulations of entry and transport of DNAPL within water-saturated, rough-walled fractures in rock masses was conducted by Kueper and McWhorter (1991). Within this system, the capillary pressure  $(P_{c})$  of the DNAPL-water system must exceed the local entry pressure  $(P_{r})$  of the underlying fractures in order for DNAPL penetration to occur. This entry pressure is directly proportional to the interfacial tension between the liquids present, and increases as the fracture aperture sizes become smaller. Therefore, pooled DNAPL will enter a fracture network in areas containing larger fracture apertures and continue to migrate preferentially within the larger fractures. This may result in regions containing smaller apertures that do not ever become contaminated with DNAPLs. However, DNAPL has the potential of entering progressively smaller apertures with depth. This is because maximum capillary pressure increases as a function of depth of the advancing front. Numerical simulations reveal that the time required for a DNAPL to move through a fracture system increases as fracture size decreases. This theoretical examination reveals that to increase mobilization of DNAPLs during remediation efforts requires a decrease in fracture entry pressures. This can be accomplished either by decreasing interfacial tension (IFT) or increasing aperture size. This is the basis of two techniques used to aid in the remediation of rock masses: the addition of surfactants or alcohols to decrease IFTs, and pneumatic or hydraulic fracturing to increase aperture size and associated permeabilities.