LETTER REPORT

Title: Review and Evaluation of Field and Theoretical Investigations of Fractured Crystalline Rock Near Oracle, Arizona, NUREG/CR-3736 RW, August, 1985, by J. W. Jones, E. S. Simpson, S. P. Neuman, and W. S. Keys.

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REVIEW

This report describes research conducted to establish the structural, geophysical, and hydraulic characteristics of the Oracle "granite," a pluton located on the northwest end of the Santa Catalina Mountains, approximately five miles to the southeast of the town of Oracle, Arizona. The field data acquired in the investigation were obtained from a single "study site," a location where eight boreholes--250 to 350 ft deep and spaced 20 to 50 ft apart--were drilled to investigate the subsurface hydrology. These boreholes revealed that the regional water table at the site is located approximately 40 feet below land surface, and groundwater movement occurs predominantly by flow through local faults and joint sets.

The principal goal of the research was to identify the relationships, if any, among: (1) the locations, orientations, and physical properties of macroscopic fractures in the granite; (2) the geophysical properties of the rock, and (3) the characteristics of local groundwater flow. Most of the data gathered to elucidate these relationships were obtained from surface mapping, borehole geophysical logs, borehole cores, and thin sections. Borehole geophysical measurements consisted of neutron, gamma, acoustic-velocity, electrical-resistivity, and acoustic-televiewer logs. Additionally, more than 100 single-hole, straddle-packer injection tests were performed to identify the principal transmissive zones in the granite.

The discussion items below describe the most important results and conclusions presented in the report:

- Borehole geophysical data gathered during the investigation indicate that a variety of logging techniques can be successfully utilized to detect fractures and other lithologic variations in the Oracle "granite." For example, fractures were readily identifiable in single-point resistance, acoustic velocity, neutron, and natural gamma logs. However, acoustic-televiewer logs were particularly useful for fracture detection and characterization because they provided a visual record of the fractures which intersected the boreholes. (It was found that televiewer logging could detect fractures with apertures as small as 1 mm.) Moreover, when core recovery was impossible, acoustic-televiewer logs provided the majority of data acquired on the locations, orientations, and physical characteristics of individual fractures and major fracture zones. The only detrimental aspect of televiewer logging was that, in regions of high fracture density--e.g., fault zones--it was evident that some resolution was lost due to reduced acoustic reflection, and to irregularities in borehole diameter.

- Analysis of the borehole geophysical data for the Oracle site indicates a linear relationship between inverted-integral, neutron-log response and log-hydraulic conductivity. This result suggests that, among the various geophysical logging methods, neutron logs in particular are useful for identifying transmissive zones in fractured geologic media.

- The surface and subsurface fracture-orientation data for the Oracle site indicate that there are six identifiable fracture sets. Also, although there is an element of randomness in the spacing of fractures, several of the fracture sets tend to be evenly spaced or clustered into narrow zones. These characteristics of fractures at the study site explain the intricate pattern of local groundwater flow.

- The degree of interconnectivity among fractures in different boreholes was often difficult to determine on the basis of location and orientation data alone. [The only exceptions to this general rule were major fractures (mainly faults).] This difficulty is attributable to variable curvatures of fracture surfaces, spatial variations in the apertures of fractures, changes in the kinds and quantities of fracture-lining minerals, lack of fracture continuity between boreholes, and sampling errors. Owing to these complications, most of the reliable information on fracture continuity was obtained from cross-hole packer tests and tracer tests.

- A concerted effort was made to test the commonsense notion that hydraulic conductivity should increase with increasing fracture density. However, each time this hypothesis was tested, fracture density and log-hydraulic conductivity were found to be only weakly correlated. Furthermore, it was observed that log-hydraulic conductivity bears little relationship to fracture orientation.

These observations raise serious questions about the validity of existing conceptual models of fluid flow and contaminant transport through networks of discrete fractures when these models are applied to highly fractured rocks such as the Oracle "granite."

- Despite concerted efforts to ascertain the geometries and physical characteristics of fractures at the Oracle site, little was learned about the statistical distributions and correlations of such critical fracture parameters as shape, length, aperture, filling, roughness, and degree of interconnectivity. Furthermore, even if these fracture parameters had been successfully elucidated, it is uncertain how all of this information would be incorporated into a quantitative three-dimensional model of groundwater flow at the site.

- Some interesting results were obtained when a geostatistical interpolation procedure called "kriging" was used to estimate the three-dimensional distribution of log-hydraulic conductivity values between the boreholes at the study site. Kriging is a comparatively new geostatistical technique that has several important advantages over other, more conventional interpolation techniques. By considering the statistical-correlation structure of a set of log-hydraulic-conductivity data, kriging provides unbiased estimates of log-hydraulic conductivity between boreholes, provided that there is no bias in the measured values of this hydrologic parameter. The estimates of log-hydraulic conductivity obtained from kriging, which represent weighted averages of observed values, are superior to estimates obtained from other arithmetic averaging procedures because the estimation error has minimum variance. [However, values of "true" log-hydraulic conductivity are generally more variable (i.e., less smooth) than those estimated from kriging.] Furthermore, kriging provides information about the magnitude and structure of the error associated with the interpolation procedure. One of the more important applications of the log-hydraulic-conductivity estimates and the covariance matrix describing the structure of estimation errors is that this information can be used to generate random homologs of the "real" log-hydraulic-conductivity field. (Each of these homologs would have the same statistical validity.) With these homologs, it is possible to undertake stochastic modeling of fluid flow and contaminant transport in a fractured rock mass.

EVALUATION

This report describes a state-of-the-art investigation of the hydrologic properties of a highly fractured mass of "crystalline rock." The approach taken in the investigation and the results of the research suggest two major conclusions regarding the current ability of hydrologists to characterize the hydrologic behavior of highly fractured geologic media.

First, it is evident from the scientific strategy adopted in this investigation and similar investigations that there is a trend toward simultaneous application of a wide variety of techniques to elucidate groundwater flow in fractured rocks. The techniques employed by Jones et al. include surface mapping of fractures, core logging, several different types of downhole geophysical logging, packer and tracer tests, and geostatistical modeling. Another technique not used by Jones et al., but employed by other hydrologists, is theoretical modeling of discrete fractures. Therefore, it is apparent that hydrologic modeling of fractured geologic media is becoming increasingly multidisciplinary--involving not only the usual core logging and downhole packer and tracer tests, but also extensive downhole geophysical characterization, modeling of discrete fractures, and very sophisticated statistical modeling.

Second, it is also evident upon reading the Jones et al. report that, despite application of sophisticated modern methods of hydrologic characterization to the Oracle "granite," the results obtained to date are semi-quantitative at best and largely serve to emphasize the complexities and difficulties in attempting to quantify groundwater flow in highly fractured rocks. In particular, it is disconcerting that Jones et al. achieved only minimal success in accomplishing what certainly must be regarded as a necessary first step in characterizing fracture flow at the Oracle site: namely, identifying the spatial range and orientation of major conducting fractures in the rock. Thus, it appears that considerable additional work must be completed before it will be possible to devise a defensible quantitative model of groundwater flow at the Oracle site.