Mini-Report #6

USE OF HYDRAULIC HEAD FOR EVALUATING GROUND WATER FLOW IN A VARIABLE DENSITY SYSTEM: SIMPLE ANALYTICAL EVALUATION

Basalt Waste Isolation Project
Subtask 2.5
Numerical Evaluation of Conceptual Models

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1.0 INTRODUCTION

Traditionally, hydrologists have relied on the concept of hydraulic head for defining ground water flow directions and flux rates in hydrogeologic systems. Hydraulic head is very convenient for practical application because it represents a scaler (nondirectional) quantity which is readily measurable in observation wells and piezometer installations. In using the head concept, hydrologists have generally assumed that ground water within the flow system has constant density; a reasonable assumption for most shallow flow systems. Where fluid density is known to vary, two methods for correcting heads have been developed. These include:

- Fresh Water Head

- Environmental Head

In addition, hydrologists commonly assume that the static water level in an observation well or piezometer represents a reliable measure of head, even in variable density systems.

The analysis presented herein is intended to evaluate the general applicability of hydraulic head for describing flow in variable density systems. More specifically, the use of fresh water head, environmental head, and static water levels are individually analyzed.

1.1 GENERAL STATEMENT OF THE PROBLEM

The purpose of this analysis is to address the following question:

> Does hydraulic head provide a useful indicator of ground water flow direction and flux rate in a variable density ground water flow system?

1.2 RELEVANCE TO NRC

As described in Section 10 CFR 60.122 (a) (1), qualitative siting criteria have been developed by the NRC which require the license application to provide information that can be used to assess "reasonable assurance" that performance objectives will be met. These siting criteria are based on pre-emplacement/post-emplacement conditions and are categorized in terms of "favorable" and "potentially adverse" conditions. The conditions relevant to BWIP which require a knowledge of hydraulic heads are listed below:

Favorable Conditions

122(b)(1) "The nature and rates of tectonic, hydrogeologic, geochemical, and geomorphic processes (or any other processes) operating within the geologic setting during the Quaternary Period, would not affect or would favorably affect the ability of the geologic repository to isolate waste."

122(b)(2)(ii) "Downward or dominantly downward hydraulic gradient in the host rock and immediately surrounding hydrogeologic units"

122(b)(2)(iii) "..... low hydraulic gradient between the host rock and surrounding hydrogeologic units."

122(b)(7) "Pre-emplacement groundwater travel time ... that substantially exceeds 1,000 years."

Potentially Adverse Conditions

122(c)(2) "Potential for foreseeable human activity to adversely affect the groundwater flow system, such as ground water withdrawals, extensive irrigation, subsurface injection of fluids, ..."

122(c)(3) "Potential for natural phenomena ... of such a magnitude that large-scale surface-water impoundments could be created ..."

122(c)(5) "Potential for changes in hydrologic conditions that would affect the migration of radionuclides ..."

122(c)(6) "Potential for changes in hydrologic conditions resulting from reasonably foreseeable climatic changes ..."

With regard to heads, "favorable conditions" are based on pre-emplacement conditions within the ground water flow system. "Potentially adverse conditions" generally require an evaluation of changes in hydraulic gradients resulting from natural and man-made phenomena.

In addition to the above qualitative siting criteria, the NRC has formulated performance objectives in Section 10 CFR 60.111 - 60.113. With regard to ground water flow, the EPA cumulative flux standard specifies the maximum amount of radionuclides which can reach the accessible environment over a period of 10,000 years. Since repository heat will be significant during this post-emplacement period, the effects of variable density ground water (due to temperature changes) on radionuclide transport will have to be addressed. As a consequence, the effect of heat and variable density water on hydraulic gradients will be an important concern in evaluating the EPA Criterion.

1.3 RELATIONSHIP TO OTHER SITE CHARACTERIZATION/REGULATORY TASKS

An important factor in assessing the suitability of the BWIP site is application of the GWTT criterion. To date, both DOE and NRC have placed a high degree of importance on this regulatory standard for evaluating high level waste sites. GWTT requires an estimate of the velocity of ground water flow along the "fastest" path between the repository and accessible environment. Both the fastest path and velocity along that path are determined, in part, from hydraulic heads (gradients). Thus, assessment of hydraulic head forms an integral part of the licensing process.

Evaluation of the EPA cumulative flux standard will require an understanding and quantification of the three dimensional ground water flow field under post-emplacement conditions. Since thermal affects may cause significant variations in ground water density, the effects of heat on hydraulic heads (gradients) will be an important consideration in applying this regulatory standard.

DOE is currently formulating its plans for future testing and analysis at the BWIP site. These activities will probably result in extension of the Baseline Monitoring Program, evaluation of data obtained from the monitoring installations, and application of this data (interpreted heads) to GWTT and the EPA standard. Evaluation of the suitability of hydraulic heads at the BWIP site can therefore provide important insights in developing and implementing future site characterization activities.

2.0 OBJECTIVE

The objective of this study is to determine, through the use of simple analytical solutions, the usefulness of hydraulic heads for determining ground water flow direction and flux rate in variable density systems.

3.0 EVALUATION

3.1 OPERATIONAL APPROACH

The general approach used in this evaluation is to consider a static, variable density flow system, and then determine if the various techniques for expressing hydraulic head would in fact predict no ground water flow. For the static system under consideration, an exact technique is one which would predict uniform heads throughout the flow system. If a technique can be shown to give different values of head at any two points, that method of expressing head is not exact for defining the flow system hydraulics.

3.2 CONCEPTUAL MODEL

The simplified flow system under consideration is represented in Figure 1 as a "U" tube manometer containing two fluids with different densities. Although the system is assumed to contain two distinct and separate fluids, conclusions drawn from this analysis are felt to be generally applicable to systems where gradual changes in fluid density occur. The differences in density could result from variations in temperature, salinity, and/or dissolved gas.

3.3 TECHNICAL APPROACH

Given a static, variable density flow system and the "U" tube analogue, equations are developed to compare fresh water heads, environmental heads and water levels at two different points within the flow system. Techniques which do not give equal values of head at the two points are not exact indicators of flow direction and flux rate within the static system.

4.0 ANALYSIS

4.1 FRESH WATER HEAD

Fresh water (or reference) head is defined as follows:

$$hr = \frac{p}{Do\ g} + E \tag{1}$$

where:

hr = fresh water head
p = fluid pressure
Do = arbitrary reference density
g = acceleration of gravity
E = elevation at the point of pressure measurement

To evaluate fresh water head, consider points "a" and "b" along the left vertical limb of the manometer (refer to Figure 1). In order for the volume of fluid between the points to be static, the following relation must hold:

$$Pb = Pa + D_2\ g\ L \tag{2}$$

where:

Pa = pressure at point a
Pb = pressure at point b
D_2 = actual fluid density (in this case, fluid number 2)
g = acceleration of gravity
L = distance between points a and b

Now define fresh water heads at points a and b using Equation (1):

$$hra = \frac{Pa}{Do\ g} + Ea \tag{3}$$

$$hrb = \frac{Pb}{Do\ g} + Eb \tag{4}$$

where:

hra = fresh water head at point a
hrb = fresh water head at point b
Ea = elevation at point a
Eb = elevation at point b

Since the flow system is static, fresh water head will be an exact indicator of ground water flow if the two heads are equal. We wish therefore to determine if:

$$hra \overset{?}{=} hrb \tag{5}$$

Substituting Equations (3), (4), and (2) into (5), and noting that L = Ea - Eb, one obtains:

$$1 \overset{?}{=} \frac{D_2}{Do} \tag{6}$$

Because the reference density (Do) is completely arbitrary, it is concluded that Equation (6) is generally an inequality. Therefore the fresh water heads at points a and b are generally not equal:

$$hra \neq hrb \tag{7}$$

For the case considered, fresh water heads would predict ground water flow, when in fact, the system is characterized by hydrostatic conditions. Thus, fresh water head is not an exact method for describing flow dynamics.

4.2 ENVIRONMENTAL HEAD

Environmental head is defined as:

$$he = \frac{p}{D\ g} + E \qquad (8)$$

where:

he = environmental head
D = fluid density at the point of pressure measurement

and other parameters were defined previously.

To evaluate environmental head, consider the volume of fluid between points "c" and "d" along the horizontal segment of the manometer (refer to Figure 1). In order for this volume to be static, the pressure at points c and d must be equal:

$$Pc = Pd \qquad (9)$$

The environmental heads at points c and d are given by:

$$hec = \frac{Pc}{D_1\ g} + Ec \qquad (10)$$

$$hed = \frac{Pd}{D_2\ g} + Ed \qquad (11)$$

As with the previous case, we wish to determine if:

$$hec \overset{?}{=} hed \qquad (12)$$

Substituting (9), (10), and (11) into (12) results in:

$$\frac{1}{D_1} \neq \frac{1}{D_2} \qquad (13)$$

Since Equation (13) is an inequality, it is concluded that:

$$hec \neq hed \qquad (14)$$

As with the previous case, environmental heads would erroneously indicate ground water flow in a system which is defined as being static. Thus, environmental heads are not an exact indicator of ground water motion for the variable density system considered.

4.3 WATER LEVEL

Water level in a piezometer or observation well is given by:

$$hw = \frac{P}{Dw\ g} + E \qquad (15)$$

where:

Dw = density of fluid in the borehole

A vertical limb of the manometer in Figure 1 can be considered analogous to a piezometer installation. Considering points c and d:

$$hwc = \frac{Pc}{D_1\ g} + Ec \qquad (16)$$

$$hwd = \frac{Pd}{D_2\ g} + Ed \qquad (17)$$

Equations (16) and (17) are identical to equations (10) and (11), respectively. It can therefore be shown by the mathematical development in Section 4.2 that:

$$hwc \neq hwd \qquad (18)$$

Thus, water levels are also not an exact indicator of ground water motion within the "U" tube.

5.0 CONCLUSIONS

For the variable density flow system considered, traditional methods used in hydrology to express hydraulic head would lead to erroneous conclusions regarding the system hydraulics. In each case, heads or water levels would have indicated fluid flow, when in fact the system was static. This conclusion raises serious questions regarding the general usefulness of hydraulic head for defining ground water flow in variable density hydrogeologic systems.

6.0 DISCUSSION

The "U tube" analogue considered in this study represents a gross simplification of real ground water flow systems. However, this simple illustration indicates the difficulty of using traditional measures of head in flow systems characterized by variations in fluid density (e.g., as a result of salinity and heat).

FIGURE 1. ASSUMED VARIABLE DENSITY FLOW SYSTEM: "U" TUBE ANALOGUE