CE En 545
Geotechnical Analysis of Earthquake Phenomena
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Section 1

Groundwater Flow in Fault Zones: The Hayward, California Fault Zone

Submitted to:
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by
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Abstract

Groundwater flow in fault zones is a complex and exciting topic. In this paper, I discuss how fault zones affect groundwater flow and temperature. I discuss three different case studies which show how groundwater flows in fault zones. In Marble Canyon along the Colorado River, fault zones transport water from underground aquifers and deposit the water in the Colorado River. In San Bernardino and Fremont, California, fault zones act as barriers to groundwater flow. On the up-gradient side of the fault, heads are high and recharge is swift. But on the down-gradient sides of the fault, heads and temperatures are low, drawdown is high, and recharge is very slow. As a part of this project, I conducted an in-depth study of the Hayward fault zone in Fremont, California. I constructed contour maps of the water table and groundwater temperature near the fault zone using the Department of Defense Groundwater Modeling System (GMS).

Introduction

Accurately representing groundwater flow in an area you ar e interested in can be a complex and challenging task. Groundwater flow can be affected in all of the following ways:

- Geologic conditions, including the location of bedrock, the hydraulic conductivity of the soil, and rock fractures,
- Recharge of the groundwater system through rainfall,
- Man-made pumping wells penetrating the aquifer,
- Rivers and lakes affecting the aquifer,
- Man-made drains in the aquifer,
- Evapotranspiration of the groundwater from the aquifer, and
- Other boundary conditions.

One of the other boundary conditions is a no-flow boundary. A no-flow boundary is when the flux across the boundary is zero. A no-flow boundary can represent impermeable bedrock, a groundwater divide, a streamline, or an impermeable fault zone. In this paper, I will discuss the impact of fault zones on groundwater flow and temperature.

First, I will use case studies and show how groundwater typically flows around fault zones. I will use case studies from the Colorado River area, the San Bernardino, California area, and the Fremont, California area to show how faults can either act as groundwater conduits or groundwater barriers.

Then, I will present the results of a groundwater study in the Fremont, California area. Using the results of this groundwater study of the Fremont, California area, I created contour maps of the groundwater table and temperatures near the Hayward fault zone. I created these contour maps using the Groundwater Modeling System (GMS). In this report, I will show how I created these contour maps in GMS. Also, I will use these maps to show how the Hayward fault zone effects the groundwater table and temperature in Fremont, California.

Finally, using the case studies and the results from the contour plot, I will make conclusions on how fault zones can affect groundwater flow in an area.

Purpose

The purpose of my research was to show how groundwater flows around fault zones using case studies and actual well data. After coming up with this data, I determined the impacts of fault zones on groundwater flow.

Objectives

I will accomplish the purpose of my paper by first explaining the concepts of groundwater flow around fault zones. Next, I will review some case studies which show how groundwater flows in certain fault zones. I will cover the following areas which contain faults:

- The Colorado River in Marble Canyon
- San Bernardino, California
- The Hayward fault zone in Fremont, California

Using data from Fremont, California, I created a contour map of the groundwater table around the Hayward fault zone. In addition, I created a contour map of temperatures around the Hayward fault zone to show the effect of the fault on the temperature of the aquifer. I created these contours using the Groundwater Modeling System (GMS), a computer program used to model aquifers which provides an interface to MODFLOW[1].

Finally, I will conclude by discussing some of the impacts of fault zones on groundwater flow.

Background

The Impact of Fault Zones on Groundwater Flow

C. W. Fetter explains that fault zones can af fect the flow of groundwater in two ways. Faults can either block groundwater flow or transmit groundwater flow. Fetter (1994) says,

"If the fault zone consists of finely ground rock and clay (gouge), the material may have a very low hydraulic conductivity. Significant differences in groundwater levels can occur across such faults.... Impounding faults can occur in unconsolidated materials with clay present, as well as in sedimentary rocks where interbedded shales, which normally would not hinder later al groundwater flow, can be smeared along the fault by drag folds." (p. 340).

Case Study: The Colorado River in Marble Canyon

Fault zones may work as barriers to groundwater, causing large changes in head across the fault zone. On the other hand, fault zones may transmit groundwater, as explained by C.W. Fetter (1994):

"If the fault zone has a high porosity and hydraulic conductivity, it can serve as a conduit for ground-water movement. Springs discharging into the Colorado River in Marble Canyon are c ontrolled by a vertical fault zone, the Fence Fault. The springs discharge where the faults intersect the river. The fault zones provide for vertical movement of recharging ground water from the land surface as well as lateral movement toward the river." (p. 340).

Thus, in Marble Canyon and in various other places, faults serve as conduits for groundwater flow. In Marble Canyon, springs discharge from faults into the Colorado River. These faults serve as conduits for groundwater flow from the regional flow system surrounding the Colorado River. These faults are a significant source of flow into the Colorado River.

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[1] MODFLOW stands for *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model* and is the most often used groundwater modeling program in the United States.

Case Study: Fault Zones in the San Bernardino Area

Groundwater flow in the San Bernardino area is described by C.W. Fetter. The San Bernardino area consists of highly permeable alluvial aquifers, but flow in these aquifers is affected by the San Jacinto Fault Zone. This fault zone works as a barrier to ground water movement in the San Bernardino area. Fetter (1994) says that the San Jacinto Fault Zone impedes groundwater movement in the San Bernardino area by:

- "Offsetting of gravel beds against clay layers,
- folding of impermeable beds upward along the fault,
- cementation by carbonate formation, and
- formation of clayey gouge." (p. 331).

Hydrogeology of the San Bernardino area

In Figure 1, you can see the location of the Bunker Hill ground-water basin in the San Bernardino area of southern California. This basin is bordered by the San Bernardino Mountains on the northeast and the San Jacinto Fault zone on the southeast. Groundwater recharge occurs from flood waters along the Santa Ana and other rivers which run through the Bunker Hill basin.

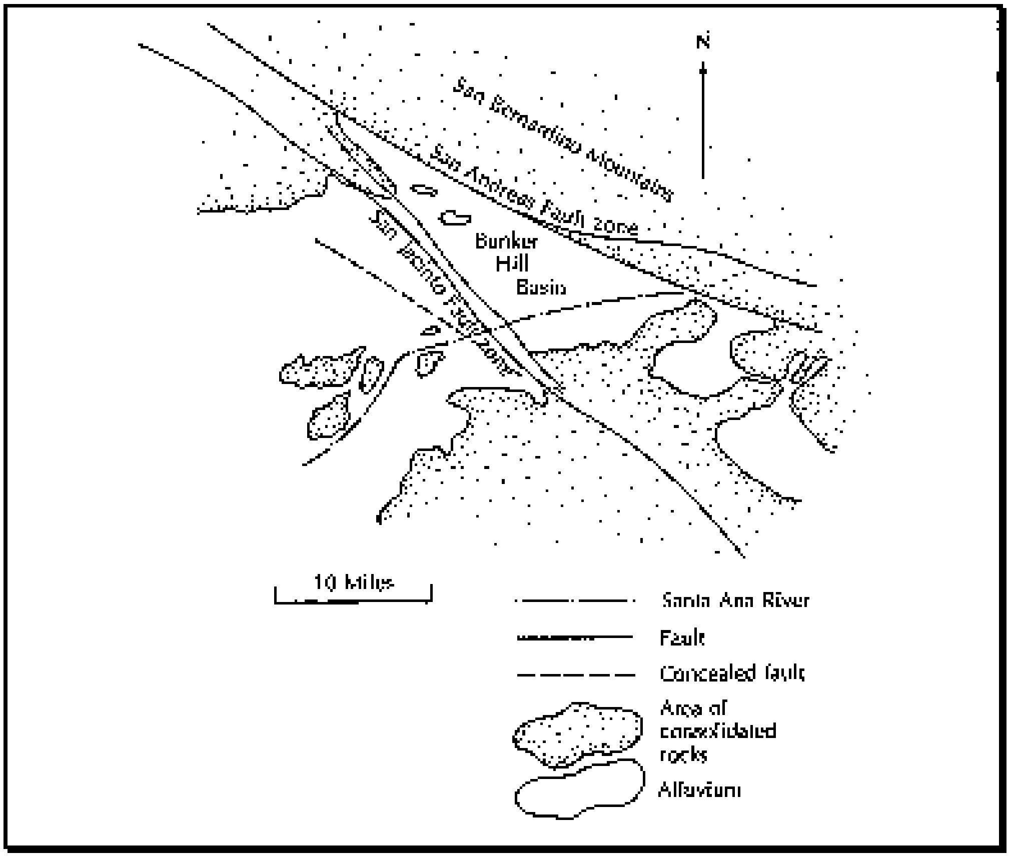

Figure 1: A map of the Bunker Hill ground-water basin in the San Bernardino area of southern California. From *Applied Hydrogeology*, by C.W. Fetter (p. 332).

A cross section of the deposits and the groundwater table in the Bunker Hill groundwater basin is located in Figure 2.

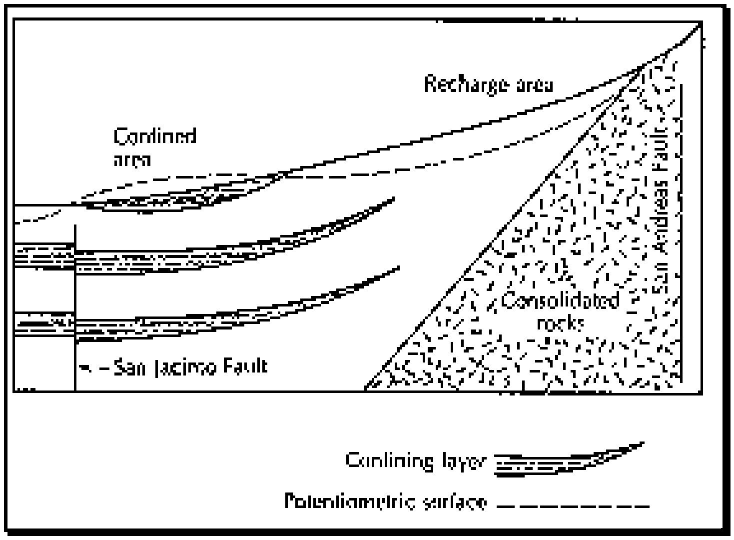

Figure 2: A cross section of the hydrogeology of the Bunker Hill ground-water basin. This section is along the course of the Santa Ana River, which provides recharge to the aquifers. From *Applied Hydrogeology*, by C.W. Fetter (p. 333).

In this figure, you can see that the San Jacinto Fault causes the potentiometric surface to rise above the surface elevation above the fault. Fetter (1994) describes the problems that have resulted be cause of the high aquifer head above the fault zone:

"By 1982 several years of above-average precipitation in the Bunker Hill Basin resulted in ground -water levels that were high enough to cause severe problems. Basements were flooded; abandoned wells began to flow (one beneath a building split the foundation); and springs at the land surface made a new water hazard in the fifth fairway of the San Bernardino Golf Club. An even greater fear was that the high ground-water levels might result in the failure of building foundations owing to soil liquefaction during an earthquake." (p. 333).

A study by the USGS showed that an earthquake of 7.0 or greater could cause liquefaction of the soil in many areas of San Bernardino. So the impermeable fault zone of the Bunker Hill basin has many problems in the San Bernardino area.

Case Study: The Hayward Fault Zone in the Fremont, California

The hydrogeology of the area surrounding the Hayward fault zone is described by Lockwood-Singh and Associates in a report prep ared for the office of the state architect of the state of California in 1984. Lockwood-Singh and Associates studied the Hayward fault zone and the possibilities of liquefaction near the California school for the blind in Fremont, California.

Hydrogeology of the Fremont area

Fremont, California is surrounded on the east by a mountainous recharge area. West of the Hayward fault zone, the aquifer has large depressions and a widely fluctuating water table. For my project, I created contour maps of the water table and temperature near the Hayward fault zone. I have included a contour map of the water table in the Hayward fault zone in Figure 3.

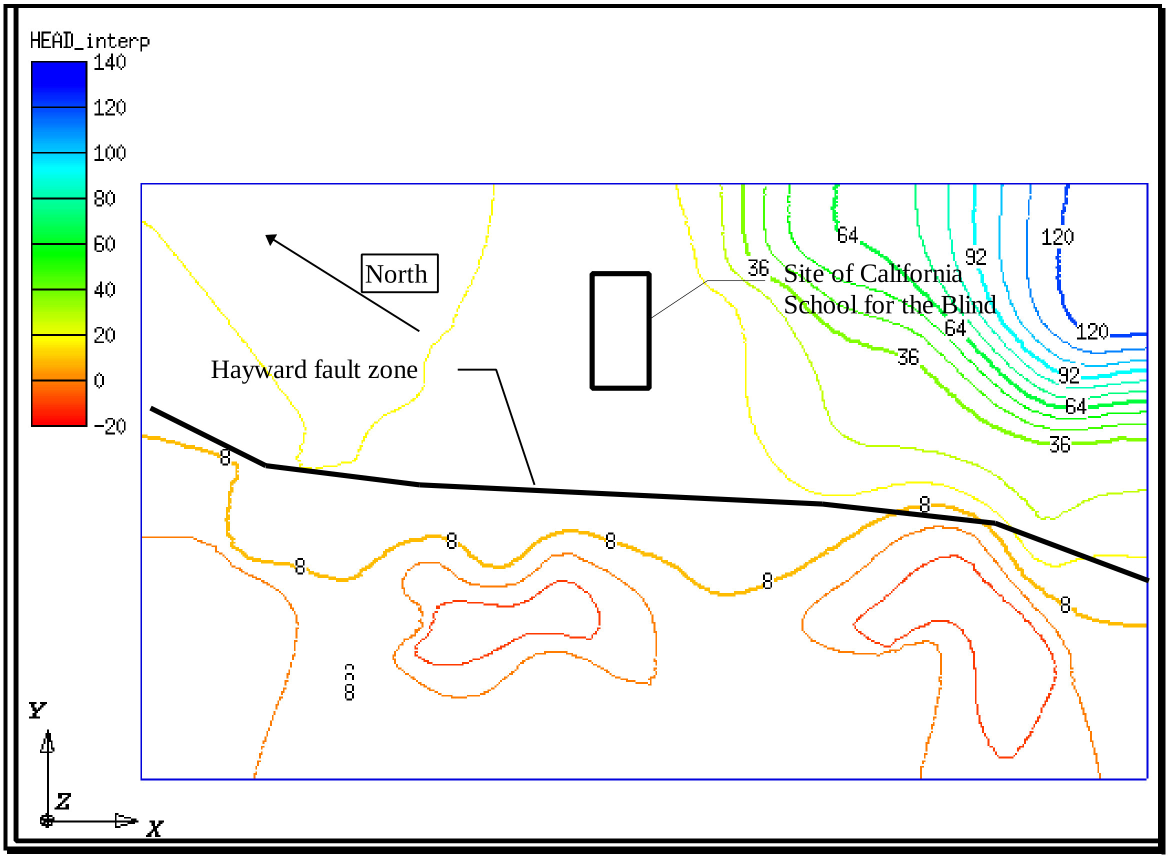

Figure 3: A contour map of heads around the Hayward fault zone in Fremont, California. The data is from *Lockwood-Singh & Associates*, 1984.

In Figure 4, you can see a contour map of the temperatures in the Hayward fault zone.

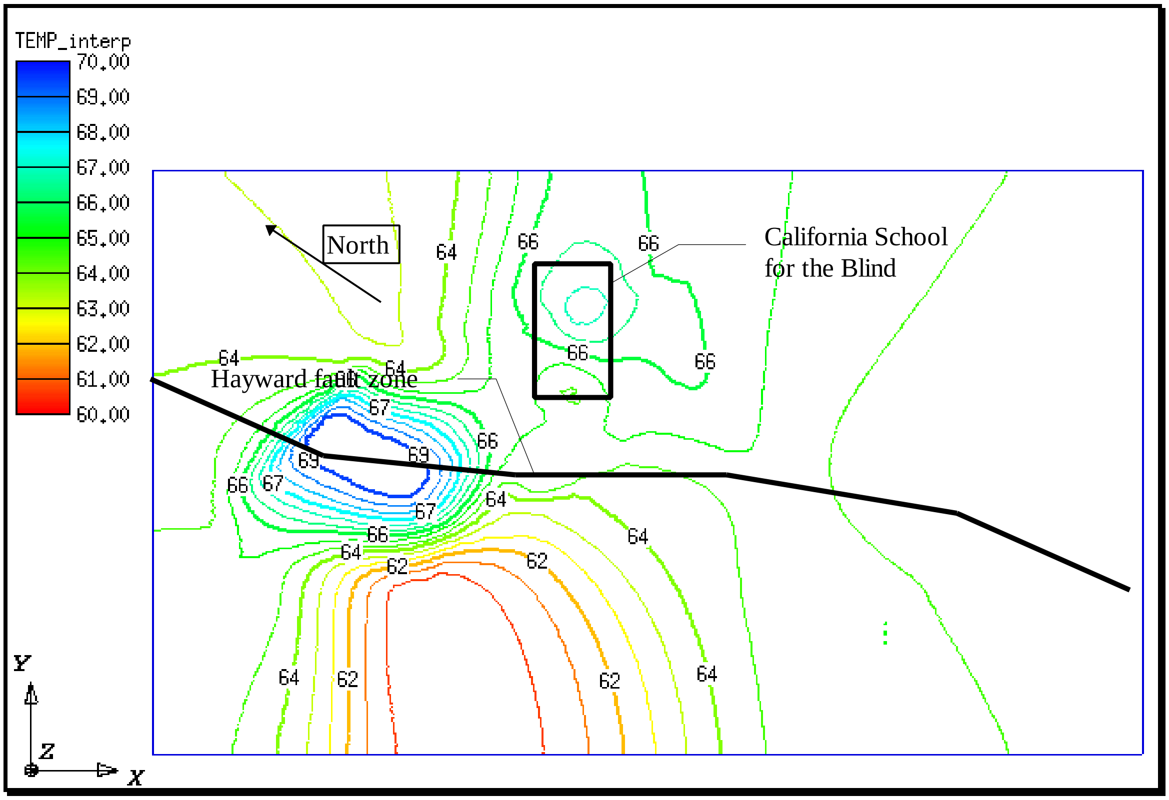

Figure 4: A contour map of temperatures around the Hayward fault zone in Fremont, California. The temperature data is from *Lockwood-Singh & Associates*, 1984.

Lockwood-Singh and Associates (1984) come up with the following conclusions, which are supported by Figures 3 and 4:

1. "The Hayward fault forms a partial barrier to ground water movement that results in widely different water table configurations on opposite sides of the fault. In the vicinity of the school the water table is uniform in character and unaffected by any impediments to moveme nt of the ground water.
2. "The Hayward fault poses a partial barrier to movement of water from the northeast side of the fault to the southwest side. Periodically, ground water withdrawals west of the fault are locally at a greater rate than can be replaced by flow from recharge areas east of the fault. Local cones of depression result. Similar conditions do not exist at the school site, or other nearby areas east of the fault. These areas east of the fault are characterized by rapid recoveries following periods of drawdown by well pumping. Water withdrawals result in an almost simultaneous uniform lowering of the water table over a widespread area, thus indicating the absence of any condition that would serve to inhibit uniform ground water movement through the area.
3. "Water temperature data indicate a general uniformity throughout the study area, and minor variations appear to be readily explainable on the basis of reasonable geologic criteria. Thus ground water in the area of highest recharge in the vic inity of the mouth of Niles canyon is characterized by temperatures 4 degrees or 5 degrees above those measured elsewhere in the study area. Other areas adjacent to the Diablo range, and also probably characterized by a higher recharge rate than valleyward areas, exhibit slightly higher temperatures than the areas away from the range front. However, the results of the temperature survey appear to be significant only in that they demonstrate the absence of any structures, or other conditions, in the study area that might allow anomalously warm (or cold) water access to the area." (pp. C21-C22).

In other words, the Hayward fault zone provides a partial barrier to the movement of ground water. By looking at the temperature contour map (figure 4), you can see that there is little change in temperature in the study area (a variation of about 10 degrees over the area). In the recharge area and in one portion of the fault zone, the temperature is slightly warmer. Sometimes high temperature readings are recorded along fault zones due to the upwelling of water from regional aquifers. This upwelling often occurs along fractures and joints associated with the fault structure. In the Hayward fault zone, there appeared to be only a slight variation in temperature along the fault zone. Lockwood-Singh and Associates (1984) attributes these slight temperature variations to the "proximity of the recharge areas" instead of upwelling from regional aquifers along the fault structure.

Methods of Study

To create the contour map in GMS, I performed the following steps:

1. First, I created an input file containing the coordinates of the observation wells with the temperature data and the water table data. This was the hardest part since I had to determine the coordinates of each well and enter the well data into an input file. I have included these input files in the appendix for reference.
2. Second, I read these input files into GMS.
3. Third, I created a two-dimensional grid that covered the entire area I desired to contour.
4. Forth, I interpolated the well data (both the temperature and the water table data) to the two-dimensional grid. I used a "natural neighbor" interpolation scheme with a constant nodal function and other default parameters.
5. Finally, I displayed the water table and temperature contours automatically using the contouring algorithm included in GMS. The 3-D results are displayed in figures 5 and 6.

Presentation of Data

In the appendix, I have included the text from the head and temperature data files I read into GMS. I have also included a map of the Hayward fault zone showing the location of the fault zone, the sites of the observation wells, and groundwater contours prepared by Lockwood-Singh and Associates. In figure 5, you can see an oblique view of the contoured heads around the Hayward fault zone.

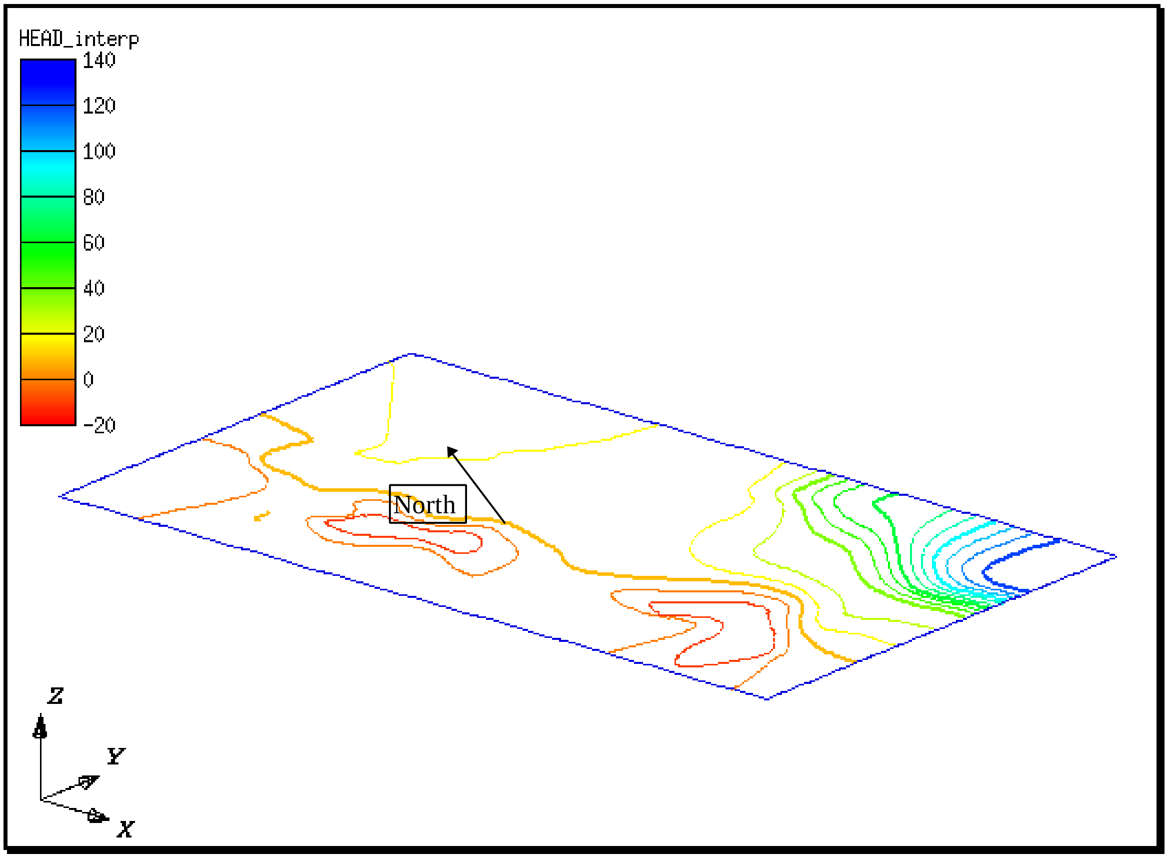

Figure 5: A oblique view of the water table contours in the Hayward fault zone, Fremont, California.

In figure 6, you can see an oblique view of the contoured temperatures around the Hayward fault zone.

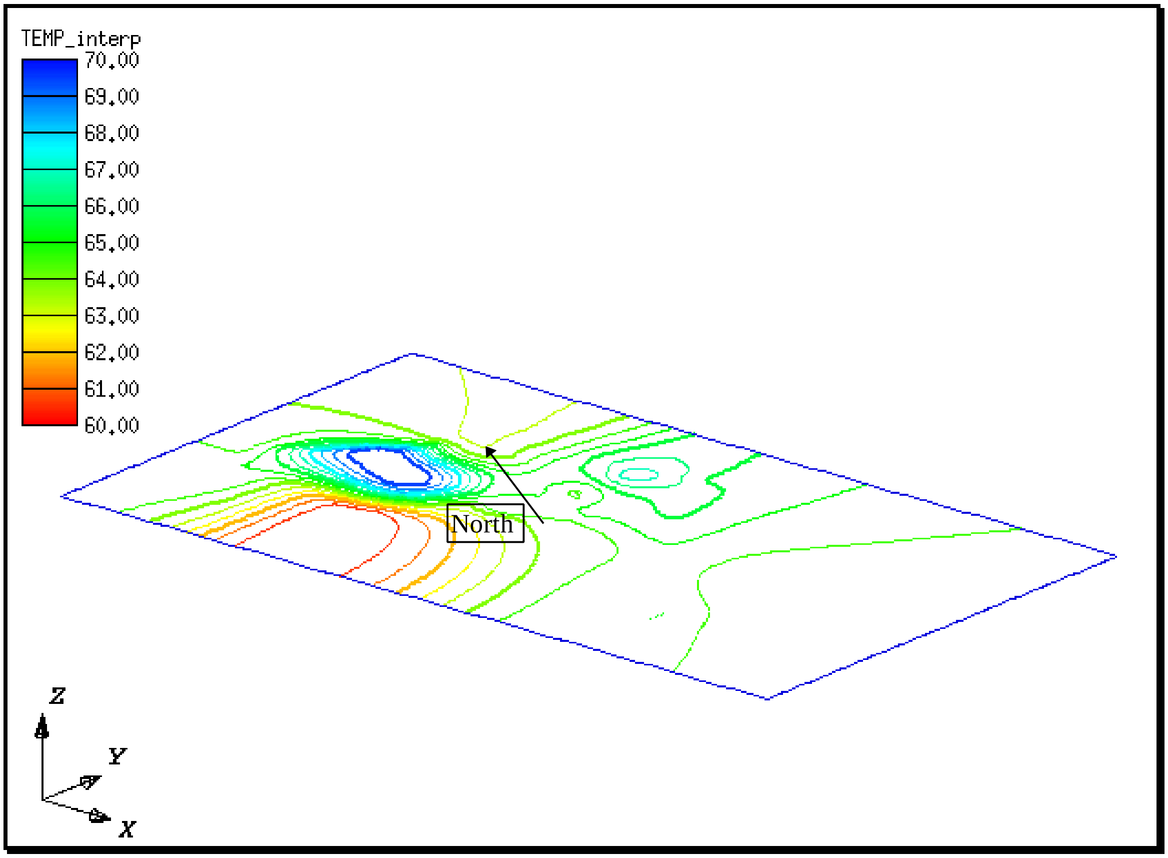

Figure 6: An oblique view of the groundwater temperature contours in the Hayward fault zone, Fremont, California.

Analysis of Results

What are the results from my temperature and head contouring project around the Hayward fault zone?

The contour maps of head and temperature in the Hayward fault zone are located in figures 5 and 6. On the eastern side of the fault zone is the recharge area associated with higher heads and temperatures. The western side of the fault zone is slow to recharge. This side of the fault zone has low heads and lower temperatures.

What do the results say about groundwater flow in fault zones?

Many faults serve as a groundwater barrier to inhibit the flow of groundwater from one side of the fault to the other. In figures 3 and 5, you can see that this is the case for the Hayward fault zone. On the eastern side of the fault zone, the recharge area provides quick recharge to all wells an d high heads in the aquifer. On the western side of the fault zone, the Hayward fault blocks flow from the other side of the fault. Recharge in this portion of the aquifer is slow and well drawdowns are more permanent.

Sometimes in fault zones, warmer water upwells from regional aquifer systems and enters the aquifer closer to the surface. According to the original researchers of the Hayward fault zone (Lockwood-Singh & Associates) the warm temperature spot in the fault zone is not due to this kind of upwelling, but is due to the warmer recharge water in this area (Figure 4). In general, you can see that the temperatures on the eastern side of the fault zone are higher than the temperatures on the western side of the fault zone. This is probably due to the warmer recharge water on the eastern side of the fault zone. The water on the western side of the fault zone has been in the ground longer, causing it to be cooler.

Conclusion

How does groundwater flow around fault zones?

- Some fault zones serve as groundwater barriers. These fault zones are comprised of low-permeability materials such as clayey gouge, carbonate formations, impermeable folded beds, or offset gravel beds along the fault. On one side of the fault, high heads and rapid recharge predominate. But on the other side of the fault, low heads, quick pumping well drawdown, and slow recharge predominate.
- Some fault zones serve as groundwater conduits. These faults have high porosity and hydraulic conductivity and are conduits for ground-water movement. An example of these types of faults are the faults emerging into the Colorado River in Marble Canyon.

What are the impacts of fault zones on groundwater flow and temperature?

- If fault zones serve as a barrier to groundwater flow, there may be little or no accessible groundwater down-gradient from the fault zone.
- Fault zones may serve as natural underground dams, causing groundwater to back up behind the fault. This may make a high recharge rate on the up-gradient side of the fault. But it may also cause liquefaction on that side of the fault. Liquefaction and/or flooding is a possibility if the groundwater rises too high and there is an earthquake to the East of the Hayward or the San Jacinto fault zones in California.

Appendix A: Selected and Cited References

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Appendix B: GMS Input Files and Groundwater Contour Map of the Hayward Fault Zone-Fremont, California