Using Fiber Optics and Vibrating Wire Piezometers to Characterize an Aquifer in Preparation for Ground and Aquifer Freezing

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Abstract The frozen ground shaft construction at the Leeville underground mine in northern Nevada provides a unique opportunity for aquifer characterization. Geotechnical borehole HGT-1 was located 15 m north of the shaft collar. The borehole was instrumented with seven vibrating wire piezometers (VWP's) and a fiber optic cable assembly. The instrumentation was mounted to a fiberglass resin epoxy (FRE) rod that minimizes heat transfer. The piezometer and fiber optics were grouted in place to a depth of 591 m. Pressure data from VWP's was used to confirm the fiber optic cable temperature measurements. Initial data shows temperature propagating preferentially along structures.

Keywords fiber optics, ground freezing, aquifer characterization, hydrogeology, temperature

Introduction

The underground Leeville mine is located 33 km northwest of Carlin, NV. The hydrogeology consists of a two-aquifer system, referred to as the Upper Plate (UP) and Lower Plate (LP) aquifers. These aquifers are separated by the regional Roberts Mountain Thrust Fault (RMTF) in Fig. 1. The mined ore body at Leeville is located in the depressurized LP aquifer that is currently being dewatered. The Leeville mine is expanding operations to the north and a ventilation shaft is being sunk through the entire thickness of the UP, near the current north operations boundary. A ground and water control management system must be implemented in order to sink the shaft through the UP Aquifer.

The UP consists of the Ordovician Vinini formation, which is made up of sandstone, siltstone, and chert. The Vinini was classified as gravel (GW) to clay (SC) in the initial boring drilled for a geotechnical and hydrological study (Call and Nicholas 2011). Ground freezing was chosen as the preferred engineering control because of the poor ground conditions. A frozen ground engineering project offers a unique opportunity to investigate geologic structure by monitoring temperature and pressure during the freeze process. The fiber optic cables were used to measure temperature and vibrating wire piezometers (VWP's) were used to monitor pressure. This case study reports the initial construction of the piezometer, ambient aquifer temperature data, and data collected during freeze well drilling.

Hydrogeologic Setting

At Leeville, as with most parts of Nevada, the majority of precipitation accumulates as snow on the mountain ranges, and spring snowmelt is the primary source of groundwater recharge. Precipitation in the area is approximately 25 cm per year (Plume 1996). Recharge occurs primarily along drainages at the valley margins, which feed directly into the alluvial groundwater system. Some recharge also occurs at higher elevations through direct infil-

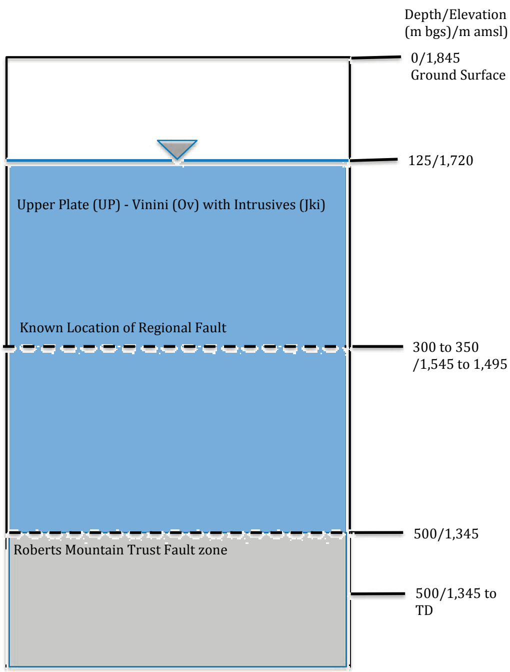

Figure 1 *Hydrogeologic and geologic features are given in both depth and elevation. The ground surface in the area of HGT-1 is 1,845m above mean sea level (amsl). Groundwater is measured in the area at 1,720m amsl. A know regional fault is located from 1,545 to 1,495 m amsl. The beginning of the RMTF is at approximately 1,345 m amsl This RMTF zone extends to a depth beneath the scope of this study. The Lower Plate carbonates are beneath the RMTF zone. The contact between the RMTF and the Lower Plate carbonates in the area of HGT-1 is located beneath the bottom of the fiber optic line and the VWP's.*

tration into fractures, eventually recharging the bedrock groundwater systems (Plume 1996). Groundwater flow in bedrock is controlled by fractures and fault boundaries, which compartmentalize the bedrock groundwater system.

The UP and LP groundwater systems are hydrologically distinct. The contact between the UP and LP occurs along the RMTF, as does the transition from the UP aquifer to the LP carbonate aquifer. Regional groundwater generally flows towards major drainages, such as the Humboldt River and Maggie Creek. Localized groundwater within the UP flows both horizontally and vertically towards lower heads within the LP carbonate aquifer. Flow is horizontal within the carbonates with localized vertical gradients caused by dewatering activities.

Groundwater modeling and aquifer testing in the Leeville area indicate that hydraulic conductivity (K) ranges from 3.3×10^{-7} to 2.3×10^{-2} cm/s in the UP aquifer and are 4.9×10^{-5} cm/s to 4.3×10^{-2} cm/s in the LP aquifer (Schlumberger 2011). The potentiometric surface is approximately 1,700 m elevation in the UP and approximately 1,150 m elevation in the LP. The current dewatering rate at Leeville is approximately 1,325 L/s. Dewatering occurs in the LP aquifer where groundwater flows radially towards the mine, with steeper hydraulic gradients at the dewatering well network. Site piezometric data indicate a prevalent downward hydraulic gradient in the UP aquifer.

Methods

Boring HGT-1 was converted to a piezometer by installing seven VWP's, one fiber optic cable, and two heating elements. The piezometer collar is located at 1,834 m elevation. The fiber optic cable assembly was constructed as follows:

- A fiber optic cable with four bend-tolerant, multi-mode fibers was packaged in a 3.8 mm steel-reinforced cable. The cable extended from the collar to the bottom of HGT-1 and back to the collar. Approximately 1,220 m of cable was used to reach a depth of about 590 m.
- Three copper direct-burial cables (6, 10, and 14 ga) were joined to the fiber optic cable so that with the application of 220 VAC two heating regimes could be obtained.
- Black electrical-tape binding was applied every 45 to 60 cm to hold the cable assembly together prior to installation.

- The near mid-point (655 m) of the fiber optic cable, at the location of the bottom of the assembly, the optical turn-around and electrical junctions were cast in polyurethane in a 5 cm diameter PVC protective housing.

The field installation occurred as follows:

- A reverse circulation drill rig reamed the boring to 20 cm in diameter and to a depth of 591 m below ground surface (bgs).
- VWP sensors with communication cables, fiber optic cable assembly, and heating elements were attached to the FRE rod using high strength adhesive tape.
- VWP sensors were installed at depths of 275 m, 320 m, 368 m, 417 m, 450 m, 501 m, and 569 m.
- Cement-bentonite grout was used to backfill the instrumentation borehole below 6 m from ground surface. The top 6 m was then sealed with neat cement.

Distributed Temperature Sensing (DTS) Machine

A DTS estimated the temperature along the fiber optic cable by measuring the spectrum of backscattered light (Selker *et al.* 2006). For the preliminary data shown in this paper, this device measured temperature every second at 12.5 cm intervals along the cable for 4.25 h. At each interval temperature was measure on each leg of the cable loop (down and back, thus two measurements per location). This temperature was averaged to obtain a single value. The temperature resolution was 0.01 °C between intervals.

A continuous calibration of the DTS was required to obtain consistent 0.02 °C absolute accuracy with 0.01 °C resolution along the cable. Two insulated baths were used for the temperature calibration; one filled with ice water and the other filled with continuously agitated salt water (allowed to come to ambient, sub-zero, temperature).

Implied Local Thermal Conductivity

Thermal conductivity was calculated from temperature data for comparison to identified geologic structures as well as aquifer characteristics. Saturated soil and rock typically have thermal conductivities between 0.5 and 4.0 W/m/K and sandstone, used to represent UP, typically has values from about 1.5 to 3 W/m/K (Alter 1969). The average observed temperature gradient in HGT-1 is about 0.020 K/m. Multiplying the observed temperature gradient by an average thermal conductivity of 2.25 W/m/K implies a vertical geothermal energy flux of 0.045 W/m^2. Using this value with the assumption that the geological system was at near steady state, the relative thermal conductivities of the vertical profile could be computed as the inverse of the observed thermal gradient (see Freifeld *et al.* 2008).

Freeze Well Drilling

Wells installed for ground freezing were drilled 15 m south of the piezometer during temperature and pressure data collection. Fluid lost during well drilling was expected based on past drilling experience in the Vinini formation. Drilling fluids lost to the formation during freeze well drilling acted as a tracer that could be detected by the fiber optic and VWP's.

Results

Temperature data obtained with the fiber optic cable were plotted against depth and compared to a visually fit straight line (Fig. 2). Four distinct variations from the visually fit straight line were detected: (1) the spike from 0 m to 25 m depth; (2) the temperature increase from 100 m to 150 m depth; (3) the spike from 300 m to 350 m depth; and (4) the increased slope at 500 m depth.

The first temperature spike from the 0 to 25 m depth represents ambient warming of the ground. The data expressed by the horizontal tail at 0 m is the portion of the fiber optic cable laying on the surface from the piezometer head to the DTS machine.

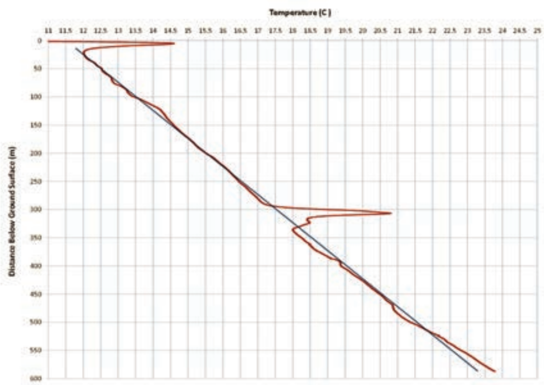

Figure 2 *Average temperature in HGT-1 from 19:47, 12 December 2012 to 00:02, 13 December 2013. The red line is measured average temperature. The blue line is a visually fit straight line, for comparison.*

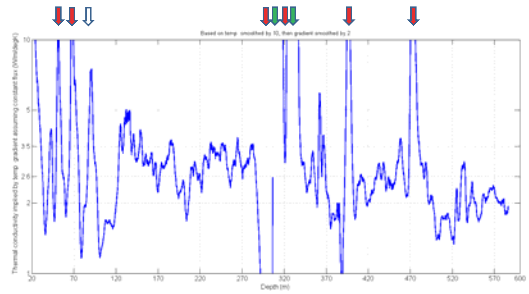

Figure 3 *Implied thermal conductivity of substrate in HGT-1 based on temperature profile of 12 December 2012 (W/m/K).*

The temperature profile from 25 m to 100 m represents the unsaturated zone. The temperature increase at 100 m is the first indication of the potentiometric surface. This elevation corresponds to historically observed UP heads.

The temperature spike from 300 m to 350 m reflects a transient source of heat. The shape of the anomalous temperature spike appears more consistent with a varied flow system than with thermal conduction, since a spreading thermal conduction signal would typically show a smooth Gaussian-shaped disturbance.

The 300 m to 350 m spike exhibits one major peak, with a large shoulder immediately below the peak. In the absence of cooling, the temperature in this area would gradually move to a value between the deep temperature and this elevated spike. Eventually, the temperature profile would “fill in” the cool valley between the anomalies, changing the anomaly from a spike to a change in slope of the profile. Since heat propagates slowly in the ground without moving fluids, it could take hundreds of years for this to occur. The fact that this thermal “valley” has not filled in indicates a recent injection of heat, such as adjacent drilling fluid loss from the freeze wells. The location of this spike corresponds to a known local structure.

The increased slope at 500 m depth indicates a long-term temperature change. This slope is interpreted as the location of the RMTF, which is expected to be at this approximate depth. The temperature data show the RMTF starting at 500 m and extending to a depth beyond the bottom of the boring. The LP, located beneath the RMTF, has not been instrumented with fiber optics, so the top elevation of the LP cannot be determined.

Fig. 3 shows thermal conductivity calculated from the temperature profile in Fig. 2. Heat flux is the vertical energy conducted through the formation from the earth’s core and is typically expressed in watts per square meter. Heat flux is equal to the coefficient of thermal conductivity, k, multiplied by the temperature gradient. In the absence of transient temperature changes, the heat flux is constant with depth. If flux is constant, the temperature gradient is inversely related to the conductivity. Thus, in the absence of heat sources or sinks, deviations from a uniform temperature gradient (blue line in Fig. 2) arise due to variations in thermal conductivity (Fig. 3). Steeper gradients reflect less conductive material and shallow gradients reflect more conductive material. Values outside the range expected for ground materials likely reflect water movement. Moving water can also transport heat, and where that is the case the gradient is not necessarily an indication of material conductivity.

Steady state conditions are assumed in Fig. 3 with no heat sources or sinks between the bottom of the piezometer and ground surface. Values outside of the range of 1 – 5 (indicated by red-filled arrows), and negative computed values (green-filled arrows) are interpreted to reflect conditions that are not controlled by steady state thermal conduction but rather heat advection from natural flowing water or injected drilling fluids. The white arrow indicates a location where the computed thermal properties could be conceivably explained by thermal conduction, but we believe this is better explained by local water movement.

The temperature profile in the top 100 m in Fig. 2 corresponds to the three peaks in the first 100 m of Fig. 3. This represents the area above the aquifer in HGT-1. The local water movement interpreted in Fig. 3 at the 100 m depth corresponds to the potentiometric surface observed in Fig. 2. The area from 300 m to 350 m of injected drilling fluids corresponds to the spike at the same depth in Figure2.

VWP Pressure Data Compared to Temperature Data

Pressure data from sensor "G" appear to be the most stabile and is the best representation of the potentiometric surface at 1,700 m elevation. This elevation corresponds to the observed temperature increase from 100 m to 150 m depth. The erratic pressure in sensors "F" through "B" can be attributed to fluid losses from adjacent freeze well drilling.

Drilling activity creates pulses of pressure that are strongest at 320 m, and affects all but the deepest sensor. Sensor "F" shows pressure fluctuations and pressure dampening effects corresponding to the depth of the sensor.

Observed pressure anomalies are attributed to the adjacent freeze well drilling and the subsequent drilling fluids transported along preferential flow zones intersecting both the freeze wells and HGT-1 (Fig. 4). These pressure anomalies are specifically prevalent in sensor F installed at 1,514 m (320 m bgs). This anomaly corresponds to the temperature spike from 300 m to 350 m. Pressure data were compared to fluid volume losses with depth from driller reports, but the fluid data from drilling reports are difficult to correlate.

There is a consistent reduction in pressure with depth, with the exception of sensor "A". The dramatic reduction of pressure at sensor "A" reflects depressurization and resulting transient conditions within the RMTF from mine dewatering. The pressures observed in

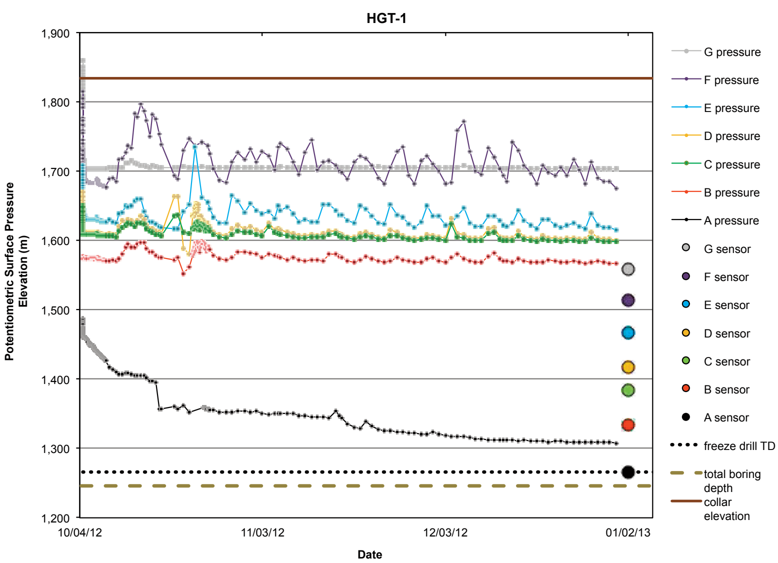

__Figure 4__ Potentiometric surface pressure represented as total elevation head in HGT-1. Symbols shown on the right side of the graph correspond with VWP sensor installation depths in HGT-1. The average total depth of the freeze wells drilled for construction of the shaft 15 m south of HGT-1 is indicated by "freeze drill TD." The final drilled depth of HGT-1 is indicated by "total boring depth".

sensors "G" through "B" show a prevalent downward hydraulic gradient in the UP. Water flow in the UP is not absolutely vertical, because there is a horizontal flow vector that cannot be established using a single piezometer. Pressure gradients show the direction of flow, but not the volume or existence of movement.

There is a distinction between propagation of pressure and propagation of temperature changes: pressure can propagate either with or without any flow. Any hydraulic connection can transmit pressure, even if low connecting permeability prevents significant flows. However, pressure propagation is attenuated with resistance to flow and distance. Changing temperatures, indicate significant flows that deliver fluids with different temperatures.

Conclusions

Fiber optics and VWP's were successfully installed in the UP adjacent to the planned frozen ground shaft construction collar. Temperature measurements from the fiber optic cable identified four major aquifer characteristics as well as geologic structures: (1) the unsaturated zone from 25 m to 100 m; (2) the potentiometric surface at 100m; (3) a major regional fault from 300 m to 350 m; (4) the RMTF at 500m. These locations were verified with the VWP pressure data. Both the fiber optic data and the VWP pressure data show the expression of lost drilling fluid in the formation. Lost drilling fluid movement through the aquifer was confirmed with implied hydraulic conductivity data. VWP data also confirmed the downward vertical hydraulic gradient in the UP aquifer.

Future studies will involve use of the heating wires. The correspondence between geologic structure and thermal conductivities implied by the temperature profile may be enhanced by the results of heat-pulse experiments. Pressure data will continue to be collected with VWP's, and will be used to correlate fiber optic temperature data. During ground freezing for shaft construction, the fiber optic cable will also be used to measure temperature as the temperature gradient propagates from the shaft location outward. Observation of these aquifer stresses will provide more accurate estimates of aquifer characteristics.

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