Groundwater Resource Evaluation in Support of Dewatering a South Carolina Limestone Quarry

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Abstract. Holcim USA, Inc. operates a large cement manufacturing facility in South Carolina near Holly Hill. Here, limestone is quarried to supply the raw material for cement manufacturing. As the quarrying has progressed over the last several years the moisture content in the limestone has risen to levels that are now adversely affecting the production rate of cement. The Earth Sciences and Resources Institute at the University of South Carolina (ESRI-SC) has been working with Holcim at their Holly Hill quarry for three years devising groundwater management strategies to lower the moisture content of the limestone prior to it being quarried. The fundamental approach to moisture reduction is a system of deep trenches that facilitate the dewatering of the limestone by lowering the water table.

Prior to implementation of the trench system, ESRI-SC conducted a detailed study of the geologic, hydrogeologic, and hydrologic situation in and around the quarry. A borehole fluid displacement test with surface electrical resistivity tracking the NaCl as it was displaced from the well, and a well to well tracer test using NaCl were performed. The results of these tests are being used to improve the prediction of the effect of the trench system on moisture reduction in the limestone.

INTRODUCTION

Holcim USA Inc., operates a limestone quarry located in the upper coastal plain of South Carolina near Holly Hill. The quarry supports cement manufacturing at this same location (Figure 1). Reduction in the moisture content of the limestone before it is quarried can result in significant cost savings in the overall cement manufacturing process. The Earth Sciences and Resources Institute at the University of South Carolina (ESRI-SC) has been working with Holcim USA, Inc. for three years to understand the nature and behavior of the shallow groundwater resources at the Holly Hill quarry and, using this knowledge, evaluate alternative approaches to *in-situ* dewatering of the limestone prior to its extraction. A wide range of geologic and hydrogeologic studies and tests have been performed at the quarry including installation of groundwater observation wells and quasi-continuous monitoring of water levels, geochemical analyses, slug tests, and a multi-well aquifer pumping test.

Based on the results of these investigations it was decided that a slot trench dewatering system is the optimum approach to *in-situ* moisture reduction. The trenching system is designed to: 1) cut off regional shallow groundwater flow into the quarry; 2) eliminate the influence of a surface water diversion around the quarry on shallow groundwater levels; and 3) lower the water table in the limestone via gravity drainage. Much of our recent focus has been on evaluating and demonstrating the progress in dewatering resulting from the installed trenches (Figure 2). To this end we have recently conducted a borehole fluid displacement test using a brine slug, subsequently followed by electrical resistivity surveys and a natural gradient tracer test to better characterize the hydrogeologic properties of the limestone within the trench boundary. The borehole fluid displacement test and associated analyses are the focus of this presentation.

GEOLOGIC AND HYDROGEOLOGIC SETTING

Sedimentary textures and fossils indicate that the limestone quarried at the Holcim Holly Hill quarry is the Eocene Santee Formation, which was formed in a shallow marine and lagoonal depositional environment. The limestone at the quarry is overlain by approximately 10 ft to 20 ft of interbedded clay and sand that are removed before the limestone is quarried. The limestone is divided into three units below the overburden with Unit 1 being the high-grade limestone used in cement manufacturing. Unit 1 is roughly 55 ft thick lying immediately below the overburden. Due to its high phosphate content which is not conducive to cement production, limestone below Unit 1 (i.e., Unit 2 and Unit 3) is not quarried.

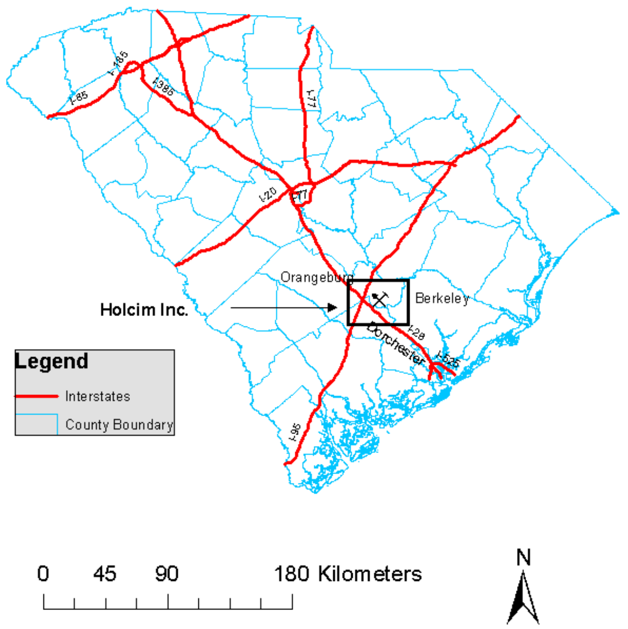

Figure 1. Map showing location of Holcim Holly Hill cement plant and quarry.

Shallow groundwater flow in the surficial units is predominately controlled by topographic relief. It is believed that in the vicinity of the Holcim quarry, shallow groundwater flows in a generally south/southwest direction discharging to Four Hole Swamp located just south of the quarry. At the quarry the undisturbed water table naturally occurs in the overburden just above the contact with Unit 1. While the water table fluctuates seasonally, the fluctuation has been somewhat damped over the years by the close proximity of Home Branch Diversion (HBD) to the quarry. HBD is a man-made shallow trench around the north and east perimeter of the quarry used to divert surface water around the quarry. However, along the course of HBD the overburden has been excavated to the top of the limestone. Consequently, HBD has become a line source of recharge to the water table. As noted above, one of the purposes of the dewatering trench system is to cut off HBD from continuing to recharge Unit 1 limestone.

METHODOLOGY

To date, 12 groundwater observation wells have been installed at the Holcim Holly Hill quarry by ESRI-SC (Figure 2). Many of the observation wells are located within the quarry block bounded by the trenches. Observation wells located outside the trench boundary provide background data that are compared to data from observation wells located inside the trench boundary. This comparison shows the effect of the trenches on lowering the water table in the quarry block inside the trench boundary.

To aid in the analysis of the efficacy of the trench dewatering system, ESRI-SC developed a fully three-dimensional groundwater flow simulation model of the quarry and immediately surrounding area including HBD. The model was used initially to investigate the feasibility of the trenching system but now is being modified to predict the extent of water table decline and hence moisture reduction in the quarry over time. In order to improve groundwater flow simulation model performance, additional studies have been performed to better characterize the hydrogeologic properties of the limestone for refinement of the model parameters. To this end we have conducted a borehole fluid displacement test followed by a surface electrical resistivity (ER) survey and natural gradient tracer test to directly measure groundwater flow properties (particularly hydraulic conductivity and specific yield) in Unit 1 limestone.

The borehole fluid displacement test was conducted in observation well H-10. H-10 is a typical 2” Schedule 40 PVC well with a slotted screen interval from 44 ft to 64 ft below land surface which places the bottom of the screen at the approximate bottom of Unit 1 limestone. The fluid displaced from H-10 was a pure NaCl brine that was injected into H-10 and circulated within the well to ensure a uniform vertical concentration distribution. The surface ER survey line is collinear with the direction of groundwater flow and passes through down gradient observation well H-9. The surface ER survey was designed to detect the migration of the salt slug away from H-10 over time. Groundwater observation well H-9 is located 111 ft directly down gradient from H-10. The design and construction of H-9 are identical to H-10. H-9 is being used in the tracer test to monitor breakthrough of the H-10 injected salt slug as evidenced by change in electrical conductivity over time.

The displacement of the NaCl brine injected in H-10 was monitored using a downhole electrical conductivity (EC) sensor that records µS/cm on a quasi-continuous basis. Background natural EC values in Unit 1 limestone average near 310 µS/cm. We determined that, given the volume of water in the H-10 casing and screen at the time of the test, 650 g of NaCl would result in an initial EC of approximately 46,000 µS/cm, more than two orders of magnitude above background. The H-10 fluid displacement test was conducted by logging the EC following brine circulation using a one minute time step until EC returned to background (hence the salt slug was displaced from the well). This curve is the basis for the analysis of groundwater flow properties in Unit 1 in the vicinity of H-10.

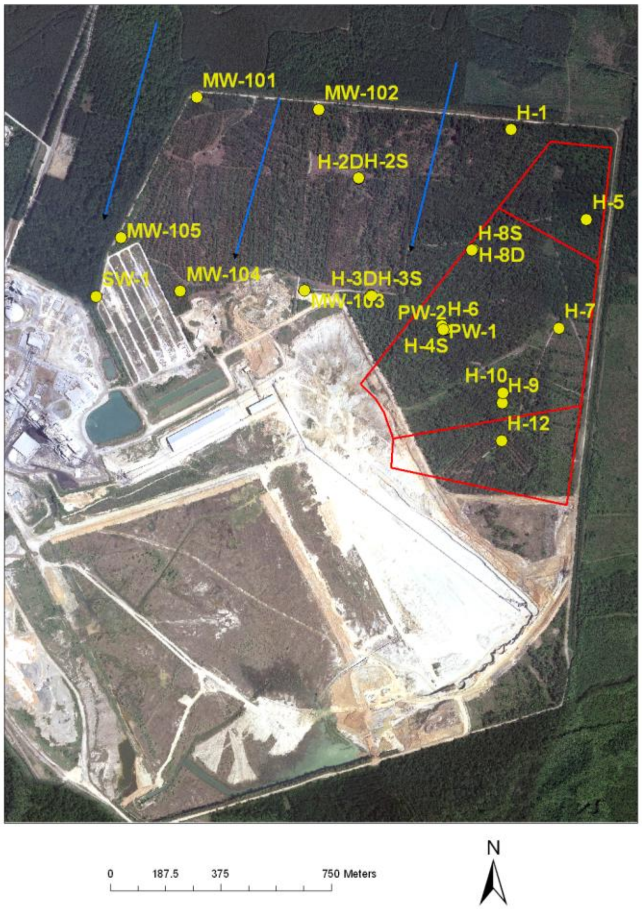

Figure 2. Holcim wells, trench (red line), and regional groundwater flow direction (blue arrows).

Three array patterns were tested for the surface electrical resistivity survey: Wenner; Schlumberger; and Dipole-Dipole. Through field tests we determined that a 365 ft Dipole-Dipole array with 56 electrodes spaced 6.56 ft (2 m) apart provided good coverage of depths below land surface up to 82 ft, well within the depth of interest. The objective of the ER surveys was to “see” the migration of the NaCl slug as it moved down gradient from H-10 over time. Our belief was that there would be enough of a resistivity contrast between the ultra-low resistivity of the brine and the natural rock/water resistivity to be evidenced by the ER survey. Therefore, multiple ER surveys were conducted over a two month period following the injection of the brine in H-10. The electrodes were dedicated to their locations so that each day of an ER survey the exact same survey configuration was established. A total of eight ER surveys were conducted during June and July 2008. Using the results from the fluid displacement test analysis, we determined that this time period should be adequate to image the migration of the brine slug. The surface ER data were processed and interpreted using EarthGather™ software.

Finally, the third component of this integrated study of limestone hydrogeologic properties is the detection of the brine slug breakthrough at H-9. The breakthrough of NaCl is being monitored by periodic profiling of the 1 ft vertical distribution of EC in H-9. At the same time, EC is being logged every 15 minutes by an EC sensor placed in H-9 near the bottom of the screen to account for density effects on the flow of the brine from H-10 to H-9. This phase of our study is still underway.

RESULTS AND CONCLUSIONS

There are a number of approaches to analyzing the results of a borehole fluid displacement test. Pitrak, et al. (2007), for example, describe a simple analytical approach based on the linear relationship between the natural log of the concentration and displacement time. The Pitrak, et al. (2007) approach results in an estimate of average groundwater pore velocity. While an estimate of the groundwater velocity is valuable information, hydraulic conductivity and effective porosity must be deduced from the velocity estimate. We took a more robust approach whereby we developed a density dependent, high resolution, three-dimension numerical flow and transport simulation model to analyze the displacement test results. Using this approach we were able to directly incorporate the effect of density differences caused by the brine in our analysis. We fit the Figure 3 raw test data (converting EC to concentration) to a simulated displacement curve by establishing the hydraulic gradient we measured between H-10 and H-9 and then adjusting the hydrogeologic parameters until the best fit between the observed fluid displacement curve and the simulated displacement curve was achieved. The results of this exercise are plotted in Figure 4. Note that for transport modeling purposes, EC

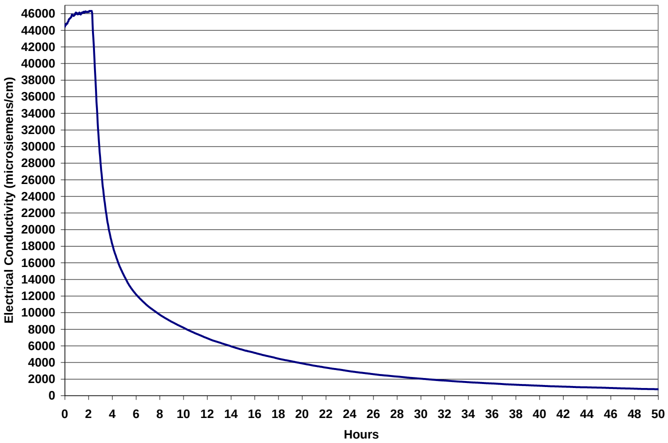

Figure 3. H-10 EC vs. time raw data.

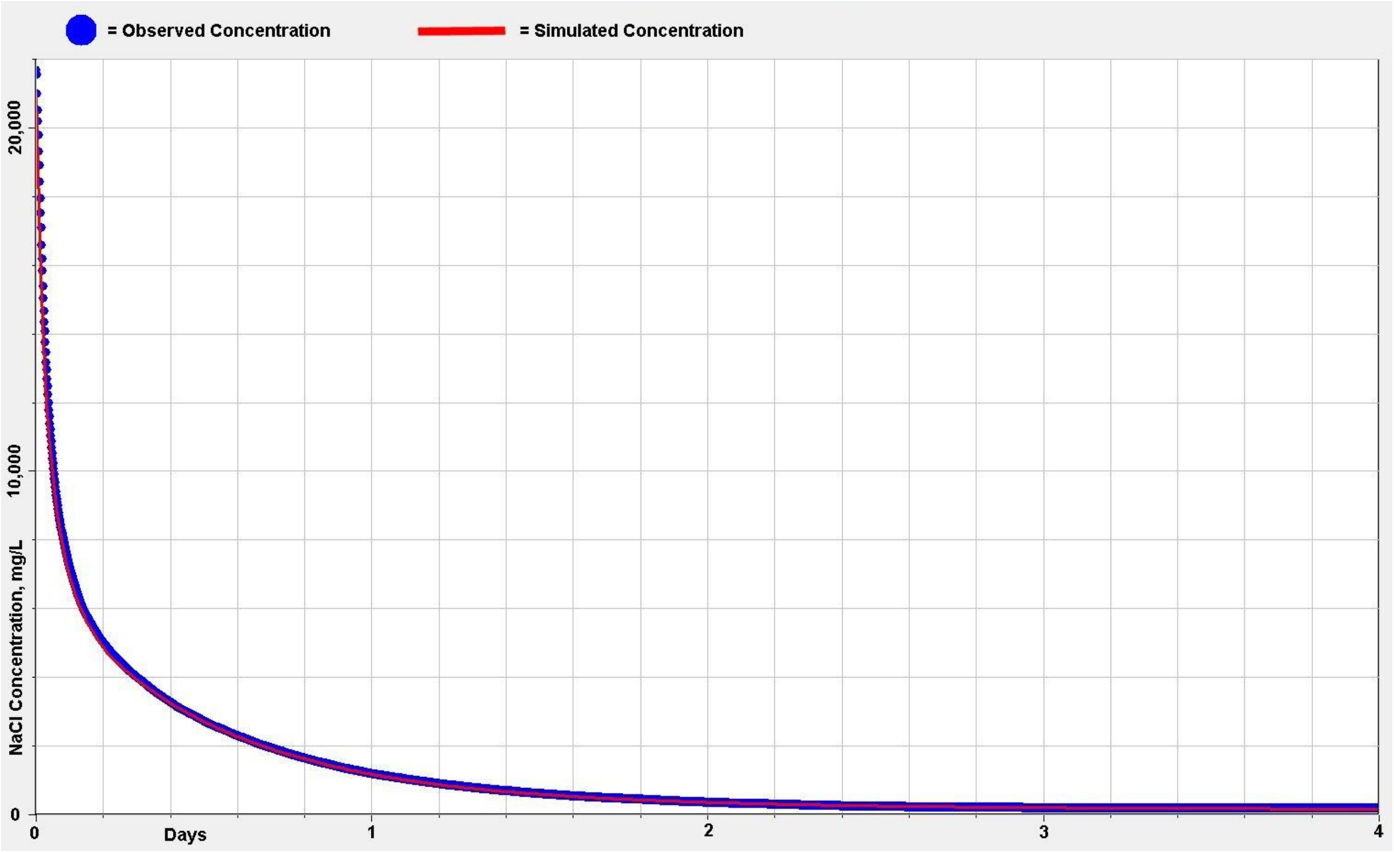

Figure 4. NaCl concentration as fluid displacement (observed vs. simulated).

has been converted to NaCl concentration in mg/L. Very close agreement between the observed fluid displacement data and the simulated data was achieved. The primary simulation model parameters that produced this close agreement are:

- Hydraulic conductivity = 1.2 ft/day (isotropic)
- Specific yield = 0.2

These values are in agreement with values reported in the literature for limestones and are consistent with estimates from previous studies conducted at the Holcim Holly Hill quarry.

To date, we have not confirmed that the surface electrical resistivity is an effective method of tracking the brine slug migration in this case. Initial results appear to identify the brine concentration in and immediately surrounding the well (Figure 5). Subsequent tests are inconclusive in showing the down gradient movement of this low resistance zone (Figure 6). Therefore, it cannot be confirmed that the low resistivity zone surrounding the well is indeed the NaCl slug. It is hypothesized that there are several reasons these tests are inconclusive. The two most likely reasons are: 1) the volume of brine added to the 2” well was too small to be detected with the resolution of the ER survey; and 2) the limestone/groundwater interface has such a low resistance that adding the NaCl only further lowered the electrical resistance an undetectable amount. The results will continue to be evaluated in light of other hydrogeologic data still being collected at the site.

The natural gradient tracer test tracking the migration of the NaCl slug from H-10 through H-9 is ongoing. Early results are inconclusive as to whether or not the early arrival of NaCl is being evidenced in H-9. Results from the H-10 displacement test simulation model suggest that the breakthrough of NaCl in H-9 may take as long as 200 days to detect with any certainty.

LITERATURE CITED

Pitrak, M., S. Mares, M. Kobr, 2007. A simple borehole dilution technique in measuring horizontal ground water flow. *Ground Water* 45:89-92.

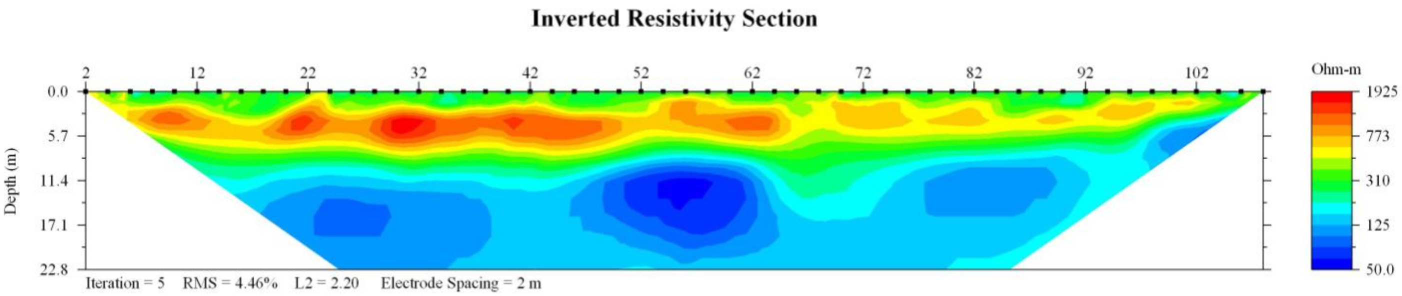

Figure 5. Inverted resistivity section from June 9, 2008.

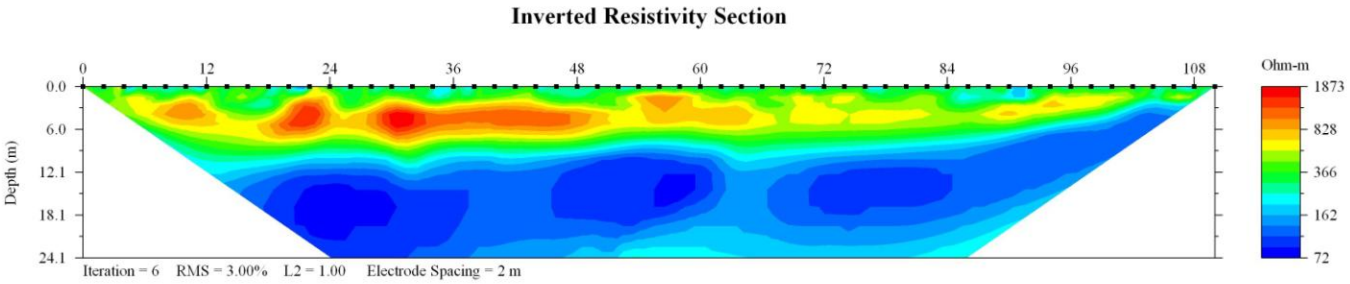

Figure 6. Inverted resistivity section from July 25, 2008.