Hydrogeological Numerical Modelling to Assess Active Dewatering Options at a Sand Quarry Site – A Case Study and Associated Methodology

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Abstract

In this paper, we describe an innovative numerical modelling approach used to rapidly assess the potential effectiveness of various dewatering options in reducing moisture content at the Holly Hill limestone quarry and cement manufacturing plant in South Carolina, United States. The numerous predictive scenarios output estimated moisture content of the quarried sands under varying assumptions of active dewatering options. The results were used to input into a wider cost-benefit assessment which is currently underway. However, the project additionally resulted in the development of a useful modelling and coding approach that can be applied to operational planning and scheduling decisions in the future.

Keywords: Carbon emission reduction, quarry, numerical modelling, dewatering, moisture content

Introduction

Reducing the in-situ moisture content of carbonatic sand used for cement production can significantly reduce the energy consumption associated with furnace-drying, as often used in the cement manufacturing process, which in turn can be of financial benefit as well as reducing carbon emissions. In this paper, we describe an innovative numerical modelling approach used to rapidly assess the potential effectiveness of various dewatering options in reducing moisture content at the Holly Hill limestone quarry and cement manufacturing plant in South Carolina, United States. We also discuss how this approach might be applied to future operational decisions.

Design Considerations and Conceptual Site Model

A highly flexible model with fast (< 10 minute) runtimes was required by the site as an operational tool not only to assess options for reducing in-situ moisture content but also to support operational planning decisions in the future. The model was therefore designed with simplicity and efficiency as essential. Importance was placed on capturing the main hydrogeological processes identified in the conceptual modelling. These key processes (see Figure 1) are:

- Large upgradient catchment area (extending c.18 km upgradient) and relatively constant hydraulic gradient (and groundwater flux) towards the site, even when taking into account seasonal variations. Thus, by calculating the minimum upgradient boundary that is outside the potential drawdown zone of the quarry, a ‘constant head’ (or ‘constant flux’) upgradient boundary condition could be placed well within the catchment area thereby reducing the area to be modelled.
- The overburden contains a shallow 3 – 6 m thick clay and sand layer which partially isolates the underlying carbonitic sand from vertical recharge from above i.e., greater than 90% of the precipitation at the site either runs-off or flows horizontally as shallow interflow. However, during overburden stripping,

which is undertaken between 6 months and a few years before quarrying, this clay layer is removed allowing direct recharge of a much higher percentage of precipitation to the 'target' carbonatic sand (Unit 1). This is confirmed by observed groundwater level response to rainfall once vegetation has been removed. Thus, the stripping schedule is considered a critical element in the model simulation.
- Downgradient, at the quarry boundary, there is a large swamp which flows perennially and can thus be considered a 'constant head' source/sink. However, groundwater-surface water interaction between the swamp and Unit 1 is minimised by the low permeability clay overburden.
- There is a diversion channel around the site which has exposed Unit 1 and which has been found to permit direct recharge to Unit 1. The diversion channel previously existed around both the northern and eastern property boundaries, however the eastern part has now been mined out.
- Previous trials were undertaken where c.1-2 m wide by c.16 m deep trenches were dug to intersect groundwater flow from the north, thus having the aim of reducing in-situ moisture content in the quarry. These were partially successful. However, the reductions in moisture content were very localised and the development and maintenance of the trench very costly and difficult. Groundwater level, trench discharge and in-situ moisture content data collected during this period is limited.
- Within Unit 1 (c.16 m thick), there is a low permeability hardpan layer that separates the upper half from the lower half.
- Below Unit 1 there is a hard and compact layer, with low fracture density, which thus creates a hydraulic separation between Unit 1 and an underlying aquifer which is under artesian pressures. For the purposes of modelling, it is assumed that there is no interaction with Unit 2 and thus the base of Unit 1 is a no flow boundary (bottom of the model). However, management considerations with regard to Unit 2 and ensuring it not be penetrated were included in the project recommendations.

Model Setup and Coding

The *Feflow* model represents both partially and fully saturated conditions. The vertical discretisation (layering) needed to be kept thin (2 m) within Unit 1 to sufficiently represent the variation in moisture content expected across the unsaturated zone. Local modelled and calibrated flow processes include:
- Representation of deep, high-sided historic trenches using seepage nodes along the edges of each layer at the base of the trench.
- Representation of the stripping of the overburden, by transiently de-activating the relevant elements using a callout to the *Python IFM FeflowDoc Class*, embedded to run with the Feflow model at the start of each time period. The progression of the stripping is calculated using mathematical

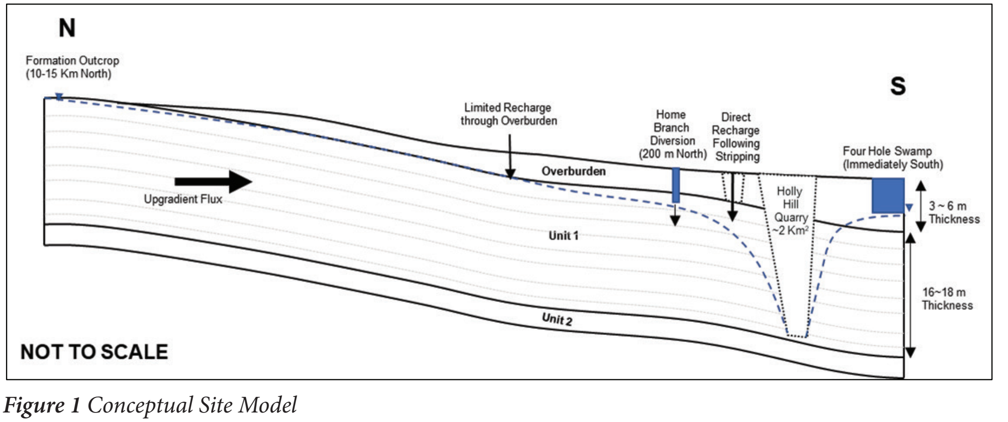

***Figure 1** Conceptual Site Model*

equations representing sequential spread across areas of 'block' format, and later change to a circular progression layout, as per the quarry stripping schedules. Once the upper overburden layer is deactivated, there is a significant natural increase in recharge to the next active layer (top of Unit 1) below.

- Mining of the sands is undertaken using a Bucket Wheel Excavator (BWE). There are two benches, each of c.8-10 m depth (see Figure 2). Sands are removed over the upper bench first, represented in the model using seepage nodes and inactive cells within Unit 1, and then the same area is later restarted as new depths as the bottom bench is mined out.

  In both cases, and as for the stripping, the progress of the benches is calculated using mathematical equations of sequencing over the mining area (see Figure 3) to represent a relatively well established and constant BWE quarrying pattern. Furthermore, the model representation using inactive elements and seepage nodes is coded using the *Python IFM FeflowDoc Class*, embedded to run with the *Feflow* model at the start of each time period.

  The advantages of using *Feflow Python Coding* of the mining activity include both the speed at which the mine plan can be implemented into the model, as well as the flexibility for change if there is an alteration to the mine schedule or area in the future.

- Additional boundary conditions used in the model include those representing interaction with local streams and stream diversions, as well as the swamp (see Figure 4).
- The hydrogeological units (representing variations in hydraulic conductivity, specific yield and unsaturated zone parameters) are varied vertically and include the Overburden, Upper Unit 1 (Marl), Middle Unit 1 (Hardpan) and Lower Unit 1 (Marl).
- The model was transiently calibrated to available water level measurements, with particular focus on response to high rainfall events, the implementation of historic trenches, and historical constant rate testing (Shafer *et al*., 2006).
- Sensitivity analysis scenarios were implemented to identify which parameters had the greatest influence on model results. These were found to be hydraulic conductivity in the Overburden (influencing seepage rates and the interaction with surface water), followed by the hydraulic conductivity of Unit 1 (influencing the drawdown zone).

Predictive Scenarios and Interpretation of Results

Predictive scenarios simulate future mine plans, as well as options for the stripping schedule and active dewatering solutions (including boreholes, wellpoints, horizontal drains and trenches). As previously described, these transient features are coded to automatically

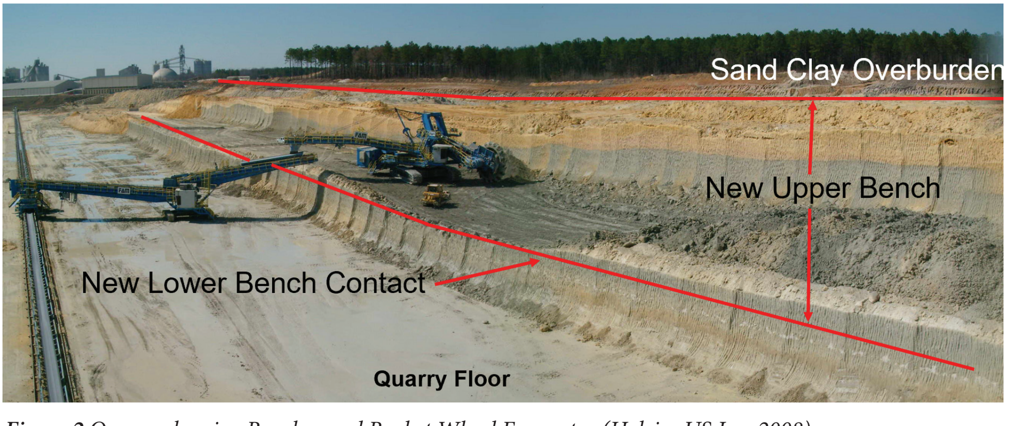

Figure 2 *Quarry showing Benches and Bucket Wheel Excavator (Holcim US Inc ,2008)*

Mining Plan

Example of mining timing calculations

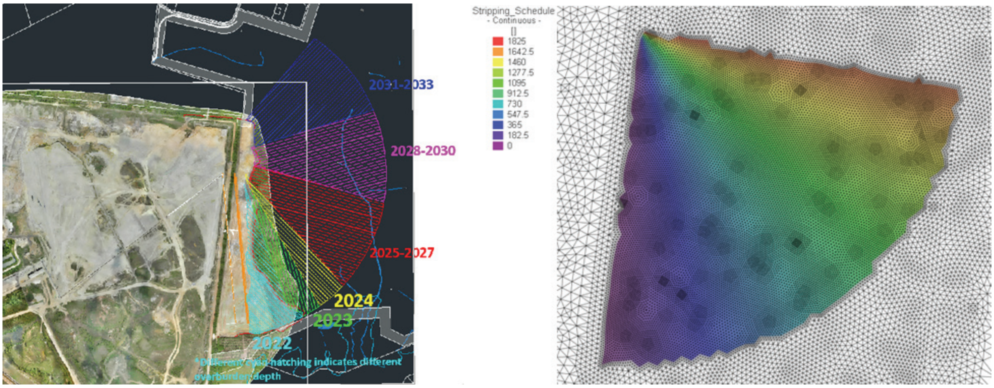

Figure 3 Example of Mine Sequencing in Feflow using User Defined Equations to form Nodal Distributions

update the associated boundary conditions and parameters using interactive Python scripts that read the data and assumptions from user-defined nodal distributions.

In addition, interactive Python scripts were used to extract and report the bulk moisture content within the wall of the 'next section to be mined' during the transient simulation, thus providing the model predictive outputs in a format relevant for immediate use in the cost-benefit analysis (Figure 5).

Various dewatering approaches were evaluated using the model, including horizontal drains, trenches and wellpoints (Figure 6).

Figure 7 shows the average modelled moisture content for nodes that will be mined out in next 30 days. The trench design shows diminishing reduction in moisture content with time from day 500. Wellpoints show more impact than drains at the same 100 m spacings. Implementing separate layers of drains in both the upper and lower

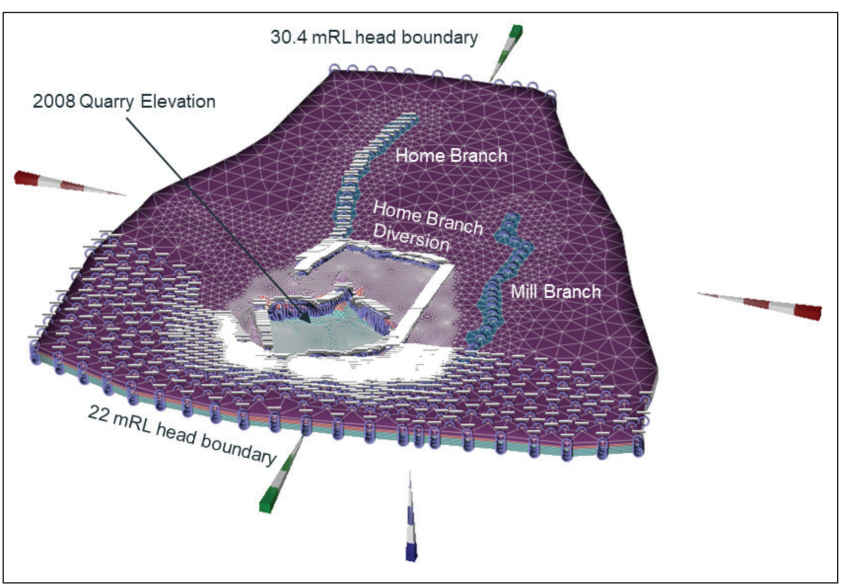

Figure 4 3D Numerical Model and Boundary Conditions

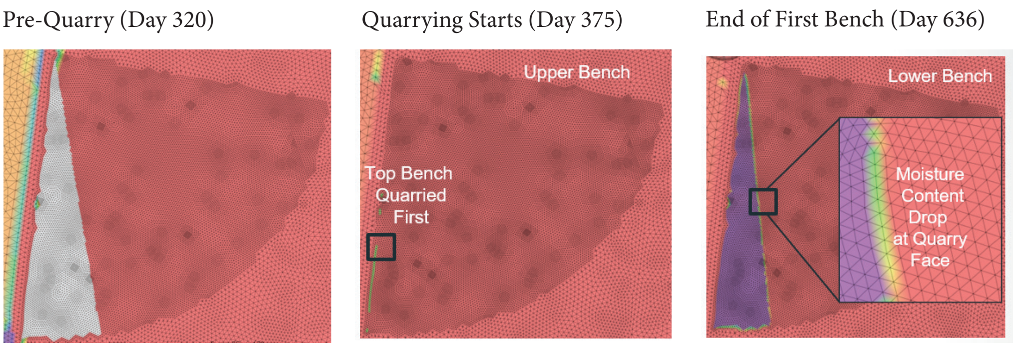

Figure 5 *Simulation Results Showing Moisture Content in Walls*

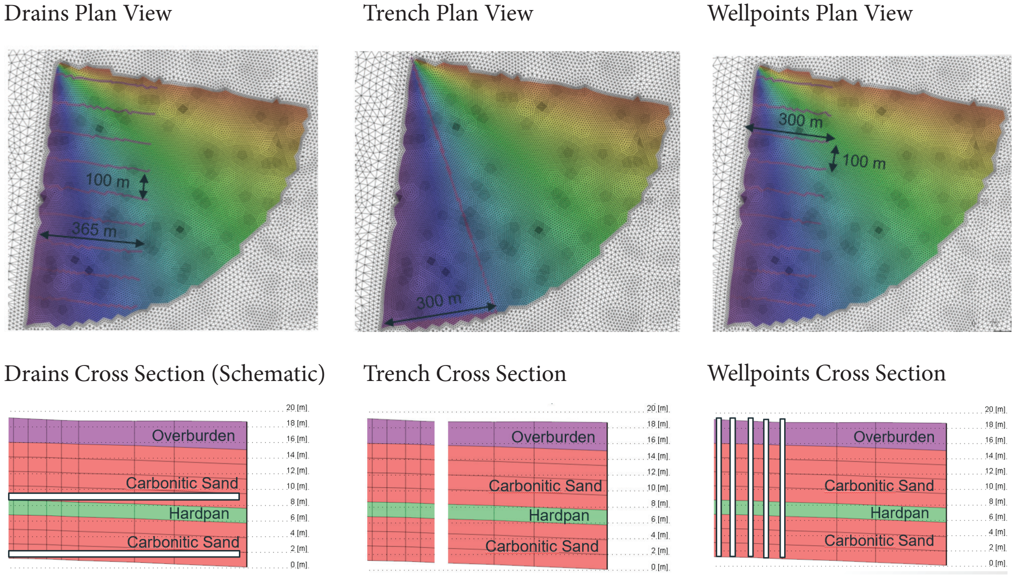

Figure 6 *Model Representation of some of the Dewatering Approaches*

benches appears to have little overall impact on moisture content reduction, suggesting that the low-K hardpans play a limited role in controlling drainage. The moisture content appears to drop semi-linearly with reduced drain spacing.

Next Steps

At the time of writing this paper, the following next steps are under discussion:

- Prototyping of the use of horizontal under-drainage.
- Regular monitoring, including flows from drains and moisture content at various agreed locations on site including in-situ in the walls (both benches and multiple heights and distances from the drains), as well as along the conveyor which takes the material form the quarry face and at the process plant.
- Cost-benefit analysis to decide on the future of a more permanent implementation of this solution or to test other potential options.
- Development of an interactive methodology and/or tool to regularly update and keep track of progress in decreasing moisture contents, and for ease of comparison between observed, predicted and 'updated predictive' results,

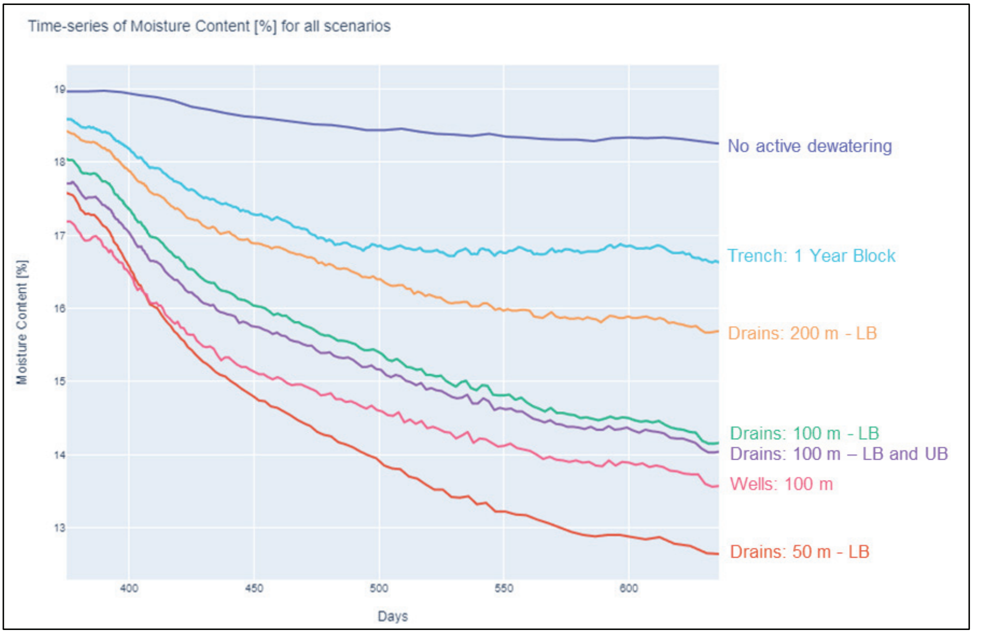

***Figure 7** Modelled Time-series of Moisture Content (%)*

thus forming an important tool for future management decision making.

Conclusions

This modelling approach has successfully simulated various dewatering options in terms of estimated bulk in-situ moisture content of quarried sands. The outputs provide a comparative assessment to input into a wider trade-off and cost-benefit assessment of various options (which is currently underway). The resulting simple and flexible model will be applicable to future operational planning and scheduling decisions. Additionally, the continued monitoring during implementation will assist in stream-lining the approach further.

Reducing the in-situ moisture content at the Holly Hill limestone quarry should result in financial benefit by significantly reducing the cost of processing and will additionally reduce the carbon emissions of the site. It is hoped it will also form an innovative prototype for use in the wider industry.

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