FINITE ELEMENT SIMULATION OF CONSTRUCTION SITE DEWATERING

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Abstract. When a deep excavation reaches groundwater, that water must be extracted from under the development to provide a stable foundation during construction. The configuration of the extraction system depends largely on the soil properties and the volume of water that must be removed. Dewatering systems can range in complexity from a simple diaphragm pump removing water from the base of an excavation, to an elaborate array of wells surrounding the excavation. This paper presents the development and implementation of a construction dewatering analysis framework. It is well known that under certain natural conditions, the most efficient method for construction pit draining at low water yield of soils in the construction area, is the light well-point system, where the capacity and layout is determined by the potential inflow through the pit contour. One of the main problems associated with the use of well-point systems for construction dewatering is to define the best possible well configurations (i.e., well positions and pumping rates) that result in the least pumping effort and, hence, least dewatering costs. Numerous hydrological models exist for this type of analysis, however, at present, the application of this methodology to drainage of urban construction has been very limited. Among several available geo-mechanical software, we have chosen the FEFLOW 5.3 (WASY, GmbH) package because it can be adapted to most geometric and boundary conditions. In this context, to perform the dewatering model requires the following information: site coordinates, pump layouts, excavation area dimensions and depth, original water table level and aquifer properties (i.e. confined or unconfined, layers, permeability's). After running the simulation, the predicted water table level can be observed through user defined observation points, cross-sectional views or 3D graphs. In addition, the minimum pumping rates that satisfy given drawdown requirements throughout excavation area can be estimated. Without automated optimization, the user is forced to manually set the desired pumping rates, perform the analysis, and then examine the results to ensure that the predicted water table level lies below the required excavation level.

1 INTRODUCTION. Dewatering means the separation of water from the soil or perhaps taking the water out of the particular construction site completely. The purpose of construction dewatering is to control the surface and subsurface hydrologic environment in such a way as to permit the structure to be constructed in the dry. In many coastal regions, especially in lower elevations, groundwater is situated very close to the surface. Subsurface construction activities in these regions require some method of controlling ground water. Typical applications include sewer and water pipe installation and repair, roadway construction, foundations for power plants, buildings, water and wastewater treatment plants, retention ponds and gas line burial. Groundwater affects the design of the structure, the construction procedures, and the overall project cost. We have seen water problems of unexpected severity cause major delays, often requiring drastic re-designs of the original projects. The concurrent trends of population growth and population concentration have rent land values soaring, creating a demand for the development of sites that were previously considered unsuitable. At present, engineers and contractors confronted with groundwater problems can be much better equipped to solve them than were their predecessors of just a few years ago. However, as it has been claimed, even in the simplest aquifer situations, the mathematics of groundwater flow is far from simple. Some dewatering problems defined solution by analytical techniques until powerful personal computers and software appeared in the 1980´s. An accurate modelling of a construction process, involving dewatering, can help the development of better alternatives and optimization of the involved resources, Powers et al (1). Moreover the equipment and technology improved induce engineers and contractors to attempt bigger and deeper excavation, under increasingly difficult conditions. Definitively, construction dewatering helps to dry construction sites before excavation activity. However, construction dewatering in urban areas can be particularly problematic because induced settlements on surrounding buildings (structures) and roads (pavements) have been observed. To understand the potential impact, a geohydrological study was carried out on a project site located at Campus de Vera (UPV) in the City of Valencia, Spain. Results indicated that the potential impacts are strongly related to the phreatic surface change of the project site. The range of impact area, the depth of drawdown, the change in pore water pressure and the induced settlements are function of pumping discharge, soil type and composition, and varied with shoring type and dewatering device. Reducing the quality and duration of dewatering, minimizing drawdown and limiting influence area, are three important ways to mitigate the potential impacts of construction dewatering.

2 ACUIFER HYDROGEOLOGY. Subsurface structures in urban areas of Valencia City are often under flooded because of groundwater inflow; the major problem is the development of efficient methods for the assessment and interception of groundwater flow with the aim to drain construction pits and subsurface structures. In this study, the effect of existing subsurface structures and such structures under construction (pits) on the nearby urban territories is evaluated by mathematical modelling (nonlinear problem of water flow in a porous medium) and the possible application of a light well point system (LWS) as the main method for pit protection against groundwater inflow. Well points are most convenient in the case of compact planning, when the implementation of large-scale measures, which require large volumes of earthworks, is impossible. The general geological-hydro geological sections are depicted in Fig. 1, to investigate the response of a five-layer system to pumping.

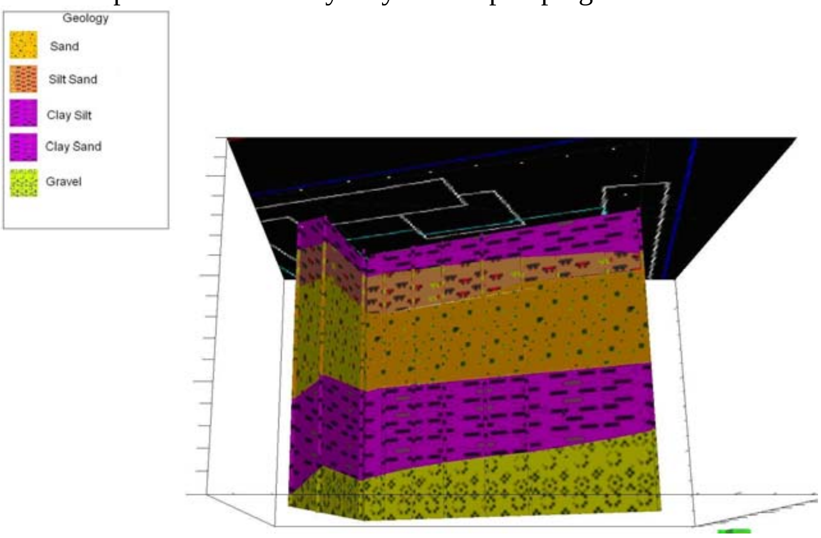

Figure 1. Hydro geological sections

The natural hydro geological conditions here feature the presence of two main aquifers in Quaternary deposits: subsoil waters in alluvial sands and clay above gravel-sands. The water-bearing alluvial deposits of the Upper Quaternary are represented by heterogeneous clays interblended by sands and silts, the hydraulic conductivity of which varies within wide limits (from 1.15 x 10^{-3} to 1.34 x 10^{-6} m/day). The thickness of the subsoil aquifer reaches 12 m. The underling aquifer in above-Jurassic sands occurs at depths down to 12 m. and often serves as the main water-bearing horizon, which is to be drained for the laying of a pit or operation of subsurface structures. The total thickness of this aquifer reaches 34 m and more, and its hydraulic conductivity rapidly increases downward from 1.24 × 10^{-1} to 2.1 m/s. and the groundwater flows are commonly directed toward natural drains of this aquifer. There is a third layer composite material lake of clay and gravel, where the range of values of hydraulic conductivity are from 1.31×10^{-3} to 2.0 in m/day having a thickness of about 22 m, and characterized by a great potential in terms of out-flow, The values of the conductivities are available in reference, Freeze and Cherry (2). In order to build our model, we have considered 5 layers that make up three layers described above, Li and Neuman (3) which were formed in reference to the litho-logical composition previously determined. The model is developed to simulate the behavior of the aquifer response respect the removal of the flow through of 20 wells with LSW technology, with the aim of controlling the water table.

3 SMALL-SCALE GROUNDWATER SYSTEM. Numerical models are increasingly used to simulate short-term and small-scale projects, such as construction dewatering, groundwater remediation, dumping-grounds, and urban hydrology. Basically, such models do not differ much from models for regional projects. However, it is the limited size of the area of interest, the distribution and quality of the available data, and the influence of local heterogeneities that may produce particular problems. The scale of the planed activity is often of the order of a few hundreds of metres. Since most planned activities are near ground (water) level and dewatering is usually a short-term activity, the radius of influence, R_0 , is often restricted. See for example the R_0 value reported here from Equation (4). On this very local scale, small hydrological objects such as trenches, and drains, and also foundations and leaky sewers, play their part in the flow system. Ground water flows in response to head gradients (e.g. ∂h/∂x) in accordance with Darcy´s law:

$$q_x = -K \frac{\partial h}{\partial x}$$

where q is the water flux and K is the hydraulic conductivity of the soil (LT^{-1}). Incorporating Darcy´s law into our flux balance equation, we have the following partial differential equation, representative of a three-dimensional groundwater flow in a porous media, Bear (4):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S\frac{\partial h}{\partial t} \qquad (1)$$

K_{xx}, K_{yy} and K_{zz} refers to the principal tensor components of the hydraulic conductivity. Double index denote flux and gradient directions respectively, which in the present case has been assumed coincident with the x, y, and z spatial coordinates. For simplicity, the z direction is assumed to be vertically orientated, being the units often used in m/day; *h* refers to the piezometric head in meters; S(m^{-1}) is the specific storativity and t(day) is time. The parameters S as well as K_{xx}, K_{yy} and K_{zz} are spatial-dependent of coordinates x, y, z , and Equation (1) is used to describe transient groundwater flows in a heterogeneous anisotropic porous medium, if the directions of coordinate axes and the principal axis of medium anisotropic agree.The solution *h (x, y z, t)* of Equation (1) gives a complete time-space characteristic of groundwater flow in the domain under consideration. In all cases, except for simplest model ones, equation (1) with appropriate boundary and initial conditions can be solved numerically. As can be seen in Figure 2, the flow domain was divided into model triangular cells, for which medium parameters, K_{xx}, K_{yy}, and K_{zz} are specific. Moreover, the calculation of a set of piezometric values *h(x, y, z, t)*, located in the centre of each cell, is generated solving Equation (1), where derivatives are replaced by the appropriate finite differences.

The boundary conditions for equation (1) are fitted to either the values of the piezometric head *h (x, y, z, t)* (Dirichlet condition) or to the fluid flux trough the boundary (Neumann condition). In some cases, it is practical to use Cauchy boundary condition, which specifies a linear relationship between the potential, *h*, and the flux, *q*.

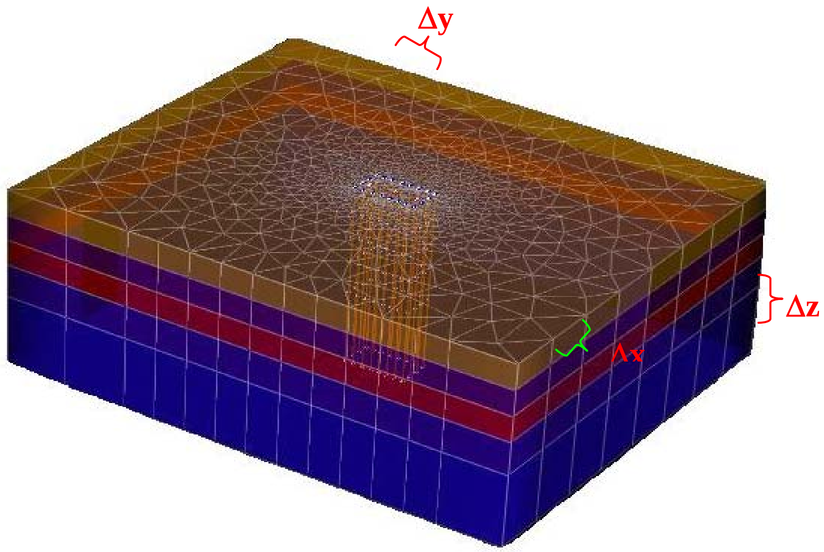

Figure 2. Model grid in the calculation domain

The upper boundary of the flow is the groundwater table *z* = H (x, y, t). Its shape is unknown in advance; therefore, a pair of boundary conditions should be specified on it. One of these is kinematics and has the form.

$$n\frac{\partial h}{\partial t} + K_{zz}\frac{\partial h}{\partial z} - K_{xx}\frac{\partial h}{\partial x}\frac{\partial H}{\partial x} - K_{yy}\frac{\partial h}{\partial y}\frac{\partial H}{\partial x}\ \Big|_{z=H} = R \qquad (2)$$

where function *z = H (x, y, t)* determines the shape of the free surface, *n* is active porosity, and *R* (m/day) accounts for the rate of groundwater recharge from above by atmospheric precipitation minus the evaporation. The second condition reflects the equality between the pressure of the water column and the atmospheric on the groundwater table, which can be expressed as follow:

$$p_{at} = \rho g(h - H)\ \Big|_{z=H'}$$

ρ is water density; *g* is acceleration due to gravity and p_{at} corresponds to atmospheric pressure. The model grid was chosen based on the assumption that the effect of engineering structures on the groundwater levels and flow does not extend further than the nearest water bodies with specified water levels. This assumption allowed the model domain to be approximated in the horizontal plane by a rectangular surface of 65 ha. A pit of 1 ha centred on the construction site, was drained by LWS method. The model domain is bounded from above by the level surface of the groundwater flow. Three main beds were identified for modelling: from upper to lower, represented by sands with hydraulic conductivities ranging from 3 to 15 m/day, respectively. The upper and lower beds are connected with another bed of low-permeability load with a hydraulic conductivity of 0.1 m/day. In the two modes of analytic calculations, these aquifers were assumed to be either absolutely isolated. The spatial discretization domain solution arises with a finite element mesh with triangular elements. The discretization of the model was determined by corresponding software with 998 elements. The vertical sizes of the cells, Δz, and the values of the hydraulic characteristics of the soil in them are variable, depending of the soil composition. Since the well points keep fixed head in wells, a constant head was specified in the upper layer along the boundary of the construction ground; the value of this head was chosen to ensure the specified drop in water table. In this report, the water level was fixed at 57 m elevation within the constructions site, with S = 1.10 m. The boundary conditions in the horizontal plane were specified in accordance with the positions of levels in surface watercourses. Equation (2) was solved using a standard software FEFLOW 5.3 package, because finite-element models allow for a more flexible spatial discretization based on e.g. topography, geology, and groundwater flow, since they often use irregularly shaped triangles. Currently, for the design of an irregularly shaped element grid it is advised to use a grid generator that builds a complete grid with a minimum amount of input data. The numerical calculations, as well as the analytical evaluation, were carried out for different schemes and boundary conditions.

4 DOMAIN OF THE SOLUTION. The geometrical shape of the excavation is rectangular, limited by concrete diaphragm slurry walls, with *a,b* dimensions. Permanent slurry walls are an ideal solution for structures requiring deep basements, particularly where a high groundwater table is present, as in the present case. We use here a representative parameter termed as equivalent well radius, r_e, which can be estimated by means of, Preene et al (5):

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$$re = \frac{a+b}{\pi} = \frac{27+42}{\pi} = 21.96\,m \qquad (3)$$

For the purposes of estimating flow rate to equivalent wells, we introduce R_0 as the radius of influence, which can be estimated from the empirical formula of Sichardt, Powers et al (1):

$$R_0 = C*(H-h_w)*\sqrt{k} = 3000*13*0.0137 = 537.38m \qquad (4)$$

Where C is an empirical calibration factor, usually taken as 3000 and $(H-h_w)$ is the drawdown of the water table in the equivalent well denoting the target drawdown in the excavation, and *k* refers to the soil permeability. The flow rate, Q, from aquifer can also be estimated using the Dupuit-Forcheimer equation.

$$Q = \frac{\pi * k\left(H^2 - h_w{}^2\right)}{\ln\left(\frac{Ro}{re}\right)} = \frac{\pi * 1.9x10^{-4}\left(96^2 - 83^2\right)}{\ln\left(\frac{537.38}{21.96}\right)} = 1563.67 m^3/h \qquad (5)$$

being H the initial piezometric or water table level in the aquifer and h_w is the piezometric level in the equivalent well. The domain model was built according to the topographic and morphological features, using the R_0 values calculated above, coupled into to the Jacob test pumping, extended over a 65 ha perimeter. The calibration of the model was performed in transient state for the efforts of six months, Hill and Tiedeman (6) and Kresic (7). The parameters mentioned for the calibration process are: K and S. The K values, ranging from 1.34 x 10^{-6} m / day to 2.5 m / day, were extracted from the available geological report. The S values, ranging from 0.08 to 0.12 m^{-1} was obtained from the following reference, Freeze and Cherry (2). Sets of the above specific data were used to run the FEFLOW code, according to the five-layer model. Moreover, the control of water table level variation, as consequence of the pumping extraction, was carried out with a set of Mini-Diver (D-1502). The Diver is a data-logger in a cylindrical housing with a suspension eye on the top. An rigorous control of the piezometric head with the above device for 20 wells tested were carried out during a period of six moths, Figure 3 shows a pictorial representation of the tested wells. As expected, it can be seen that piezometric heads and water flux exhibit a downward trend in the centric region.

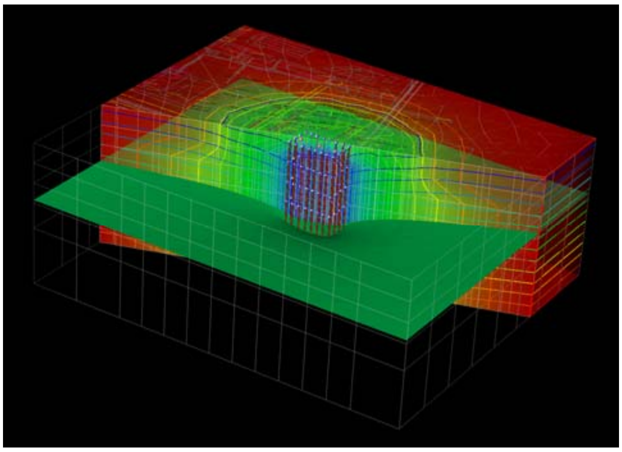

Figure 3. Advanced visualization with FEFLOW Explorer 2.0 showing contours for a simulated 3D head distribution

5 RESULTS AND DISCUSSION. Particular data collected for each well, do not show here for simplicity, with the aforementioned Divers, has served to establish a quantitative comparison between predicted, observed and simulated data for the five-layer model. Thus, the observed overall average flow rate was 1540 m^3 /day along the working period, whereas 1546 m^3 /day was the flux predicted with the model. Regarding the mass balance in Figure 4, we can also see that the second layer lead to the main contribution to drained flow, followed by the first layer, because the components and structure or both layer make easier the dewatering process. Another important aspect is the analysis of the results at light mass balances and piezometric configuration. A set of peaks located at the centre of the plane (in blue) represent the piezometric head of each well. Obviously position and intensity of these peaks are congruent with the actual outflow.

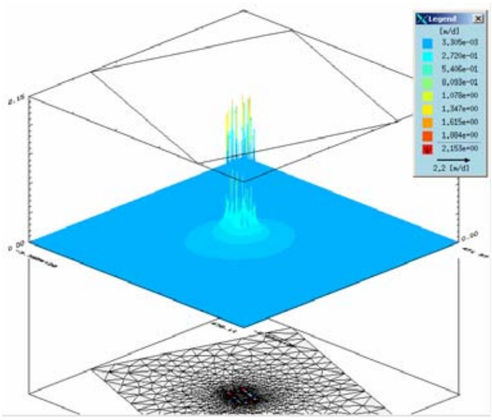

Figure 4. Velocity distribution in 3D

Figure 4 bottom plane also depict a set of flow velocity vectors representative of the correlation between dewatering and piezometric heads. A complementary visualization of this behavior is shown in Figure 5, where the central hole means the dry soil until a certain deep, according to the prevision done to facilitate the excavation works.

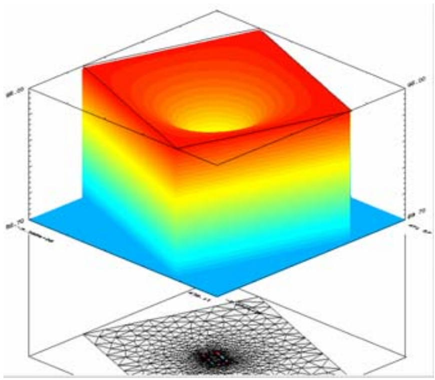

Figure 5. Head distribution in 3D

6 CONCLUSIONS. The fully-3D finite-element nature of FEFLOW is a significant advantage for complex groundwater modelling applications. Coupling the above code with the FEFLOW Explorer 2.0, an excellent graphic tool, allowing the user to construct complex ·3D animations, fly-troughs and the output is high presentation quality. The results assist us in determining the pumping flow rate, which is the objective of the modeling, thus determine the flow pump with LWS to control the water table level. We can conclude that the model reproduced accurately the actual results, for this reason we consider the prediction carried out with the model and code combination, for a next dewatering project under similar hydro-geological features. The calculation performed here show that LWSs technology can be an efficient and reliable engineering solution for drainage of relatively deep construction pits. The analytical solution and numerical groundwater models proposed for the evaluation of groundwater inflow-outflow as well as the drainage regime in subsurface structures and construction facilities can be implemented with different combinations of natural conditions and engineering requirements. Level drawdown values in specific wells placed along the pit edge could differ from the respective level values of wells located in the central part. This difference depends not only on the number of wells but also on the leakage from the lower layer and on the volume of atmospheric precipitation.

7 REFERENCES

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8 APPENDIX. Pictures below has been selected from the computer screen when running FEFLOW code, as an example of our simulation work, in order to confirm some assumptions and results handled and predicted.