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Design and modelling for groundwater engineering and control

Conception et modélisation pour l'ingénierie et le contrôle des eaux souterraines

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ABSTRACT: Groundwater engineering and control is regularly used to lower the water table and pore pressure beneath and surrounding deep excavations for the construction of shafts, tunnels and other deep structures. The construction methodology will greatly influence the type of groundwater control system most appropriate. There is a different groundwater control system required for an open-cut excavation, than that required for an impermeable steel sheet pile, secant or diaphragm wall. Similarly, the type of groundwater control system designed can greatly influence the type of construction required. A professionally designed dewatering system can result in a substantial reduction in cost and carbon emitted. If mathematical modelling is used during the design, the groundwater control system can be optimised. This paper presents recommended stages in the design, modelling and construction of a groundwater control dewatering system. Examples are presented of efficient design and modelling for both abstraction and recharge systems. Presented is a case study where a groundwater control system was designed to lower the water table below a deep detention shaft, an open-face pipe jack operation, and a smaller reception shaft in a mature garden. Modelling resulted in the final design only requiring boreholes around the deep shaft, eliminating unnecessary construction of boreholes and pipework around other structures.

RÉSUMÉ: L'ingénierie et le contrôle des eaux souterraines sont régulièrement utilisés pour abaisser la nappe phréatique et la pression interstitielle sous et autour des excavations profondes pour la construction de puits, de tunnels et d'autres structures profondes. La méthodologie de construction influencera grandement le type de système de contrôle des eaux souterraines le plus approprié. Il existe un système de contrôle des eaux souterraines différent de celui requis pour une palplanche en acier imperméable, un sécant ou un mur moulé. De même, le type de système de contrôle des eaux souterraines conçu peut grandement influencer le type de construction requis. Un système d'assèchement conçu par des professionnels peut entraîner une réduction substantielle des coûts et des émissions de carbone. Si la modélisation mathématique est utilisée lors de la conception, le système de contrôle des eaux souterraines peut être optimisé. Cet article présente les étapes recommandées pour la conception, la modélisation et la construction d'un système d'assèchement des eaux souterraines. Des exemples de conception et de modélisation efficaces pour les systèmes d'abstraction et de recharge sont présentés. Une étude de cas a été présentée dans laquelle un système de contrôle des eaux souterraines a été conçu pour abaisser la nappe phréatique sous un puits de rétention profond, une opération de vérin à tuyau à face ouverte et un puits de réception plus petit dans un jardin mature. La modélisation a abouti à la conception finale ne nécessitant que des trous de forage autour du puits profond, éliminant ainsi la construction inutile de trous de forage et de tuyauteries autour d'autres structures.

Keywords: Groundwater control; construction dewatering; deep excavations; tunnels; shafts.

1 INTRODUCTION

The control of groundwater during construction of deep excavations, shafts and tunnels, is critical to the safety of the project and the individuals working on the project. Groundwater control utilising the abstraction of groundwater (known as construction dewatering), is a complex operation requiring skill and knowledge of the disciplines of geology, hydrogeology, geotechnical and civil engineering. Examples of groundwater control systems implemented on-site across the world have been published previously (Bock and Markussen, 2007; Goodfellow and Thomas, 2018; Margat and van der Gun, 2013; Powrie and Roberts, 1995). The objective of a groundwater control operation is to achieve the aims of reducing the water table (phreatic surface) or the pore water pressure to acceptable levels to reduce the risks from groundwater (Figures 1, 2) Another requirement is to mitigate the impact of dewatering on the surrounding infrastructure and environment. This impact can involve the settlement of surrounding structures resulting from consolidation and reduction of groundwater resources caused by over-abstraction. Industry guidance is available outlining how to mitigate these risks (Powers, Schmall, 2007; Preene, Roberts, Powrie, 2016).

The safest and most cost-effective approach is to have a well-planned groundwater control operation, that is integral to both the temporary and permanent works design. This is best achieved by employing specialists with expertise and experience in this field.

Figure 1. A site without any groundwater control.

Controlling groundwater during a construction project, however, can have significant costs. It also takes up valuable project time and available space. For this reason, risks from groundwater are often ignored by a project team, with hazards and delays still emerging despite wishing otherwise.

Figure 2. A site with appropriate groundwater control.

A principal contractor who requires the control of groundwater for their deep excavation project, often chooses an expensive deep cut-off wall system instead of a more effective and efficient dewatering system, principally because of their familiarity. Construction dewatering is often seen as a complex art, in which the outcome, particularly the final cost, is uncertain. To remedy this uncertainty, the authors recommend the presentation of the dewatering process in colourful clear sequence drawings. This provides clarity and confidence to the contractor, who, as a result, is more likely to choose dewatering as a preferred option.

This paper does not aim to present to the reader all the expertise in this field, but instead serves to present understandable guidance in the form of key stages required to produce a safe and robust groundwater control system for a major construction project that requires excavation below groundwater levels.

2 GROUNDWATER CONTROL GUIDANCE

To provide a simple-to-understand guidance for the development of a safe and robust groundwater control system when constructing below the water table, or potentiometric surface, the following presents key stages in the process. Some of the stages can be undertaken by the principal contractor, some by the sub-contractor, and some by the consultant.

Whilst stages can be the responsibility of different parties, each stage must be managed by experienced and capable persons. All stages are to be integrated so that there are no gaps and shortfalls in the overall operation.

The following provides guidance that the authors have developed over decades of experience. The guidance is not to provide a strict specification, nor a construction standard, but is offered here as support to other guidance available within the industry.

2.1 Initial review of construction operation

A conceptual model of the ground and groundwater conditions is first required. An outline of the building structure can then be overlaid on the conceptual model to provide clarity of the risks during and after construction. It is then required to establish hydraulic boundary conditions to enable analysis and modelling.

Based on this information, an experienced and skilled groundwater engineer can then identify the critical risks to the construction process and provide an outline of groundwater control design. An example of a first-stage conceptual model is depicted in Figure 3.

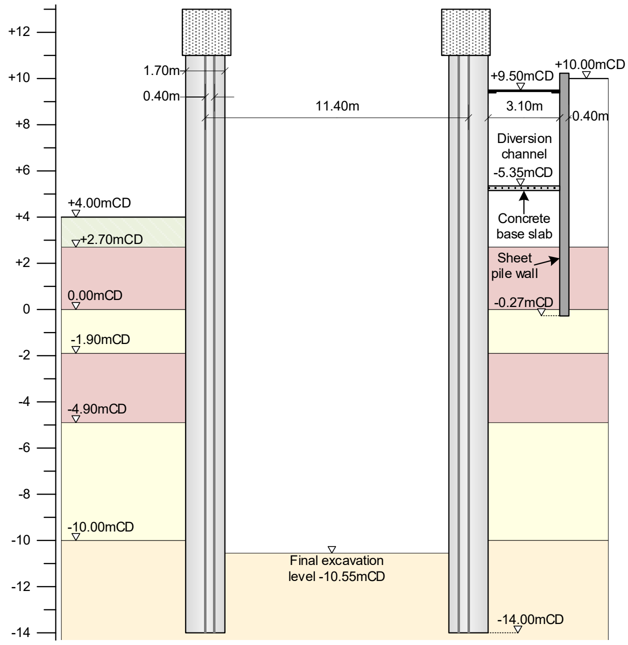

Figure 3. A conceptual model of the ground and structure.

2.2 Identification of critical success factors

With a first-stage conceptual model prepared, an initial dewatering design can be produced by an experienced designer. However, it is essential at this stage to further identify critical parameters that need to be quantified to enable a detailed design of a robust groundwater control system. Such parameters include: permeability, transmissivity, anisotropy, elevation of aquifer base, isolated artesian layers, and critical boundary conditions. Other factors can include (i) the ground compressibility if there are sensitive structures nearby, (ii) water supply wells or other water bodies that could be affected by the abstraction of groundwater, and (iii) factors that can affect the operation such as boulders, access, etc.

2.3 Preliminary groundwater control strategy

When developing a groundwater control design, it is good practice to produce a preliminary groundwater control strategy that includes an outline design based on a range of hydrogeological conditions established from the available groundwater information (Figure 4).

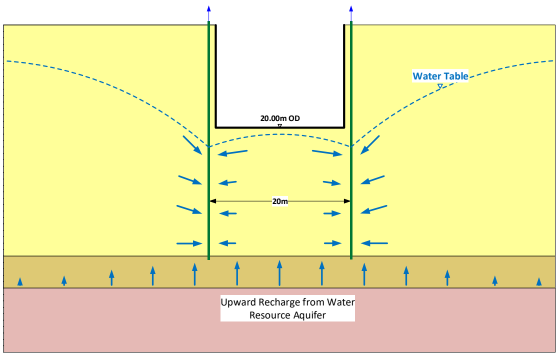

Figure 4. Preliminary groundwater control strategy.

In the authors' experience, information available from a standard site investigation is normally most inadequate as a basis for a final groundwater control design, especially in the case of the critical parameter of permeability. As a consequence, this preliminary strategy must emphasise that the design is based on a range of ground conditions, and that it is essential to undertake further specific pumping tests, together with additional groundwater-specific site investigation.

2.4 Design, implementation, analysis of project specific pumping test operation

Critical to the design of a groundwater control system, a pumping test and analysis is required, especially to establish the expected abstraction rate when applying for a permit from the UK environment agencies. Such tests normally require a minimum of constructing a groundwater pumping well, together with a series of piezometers to observe drawdown during pumping. It is good practice to undertake a series of tests, rotating the pumping from different wells and observation piezometers. Figure 5 provides an example plot of groundwater drawdown versus time, matched by a mathematical model, from which the required aquifer parameters can be back-calculated.

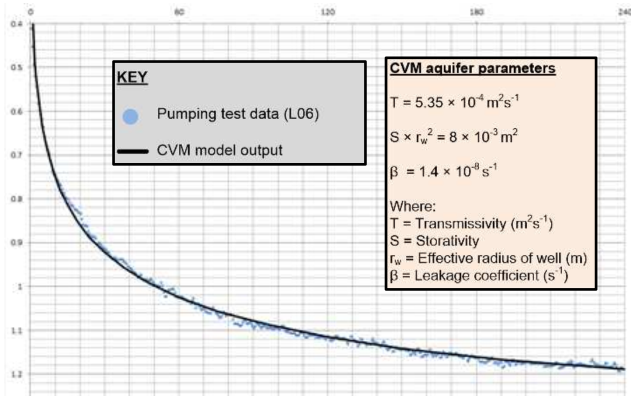

Figure 5. Pump test analysis to establish aquifer properties, where the x-axis is time, and the y-axis is drawdown.

With the site-based parameters calculated from a mathematical model, the same model can be used to calculate the range in expected abstraction rates based on the range of values obtained from the tests.

2.5 Development of mitigation strategies

Mitigation strategies are often required to mitigate the impacts that can result from groundwater abstraction. Strategies can include the deepening of cut-off walls to reduce groundwater inflow, or using recharge wells to provide a hydraulic barrier to reduce the radius of influence from the dewatering operation. Figure 6 depicts the proposed dewatering from boreholes inside a secant pile wall, with the abstracted groundwater pumped back to the ground to protect water resources.

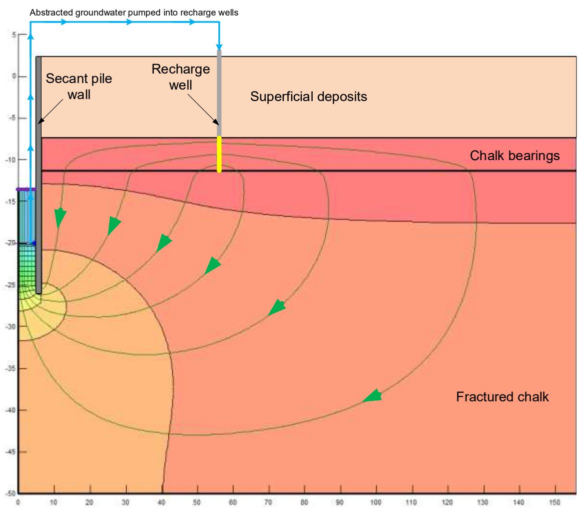

Figure 6. Groundwater pumping and recharge.

2.6 Detailed design and value engineering

Following the analysis of the pumping test results and any additional ground investigations, detailed design and value engineering are then undertaken. All parties then work together to value engineer the system in a collaborative manner. This value engineering takes into account constraints of working space, programme, geology, hydrogeology, and mitigation strategies. All play a part in the final detailed design (Figures 7 and 8).

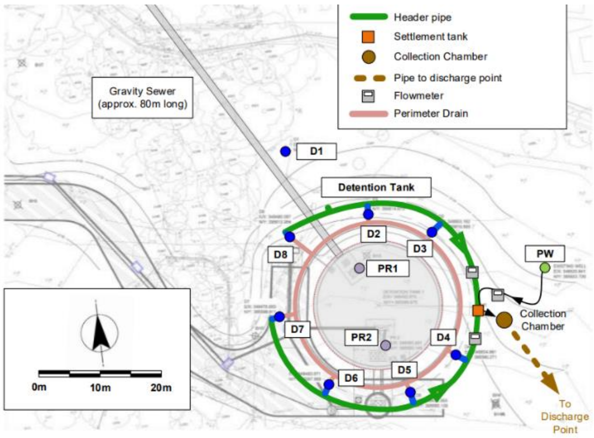

Figure 7. Location plan for dewatering boreholes.

After value engineering, the preliminary strategy document is updated to a strategy for construction. This document contains the detailed specifications for drilling and pumping, but always retains the flexibility to revise designs in light of the actual geology and hydrogeology encountered on site.

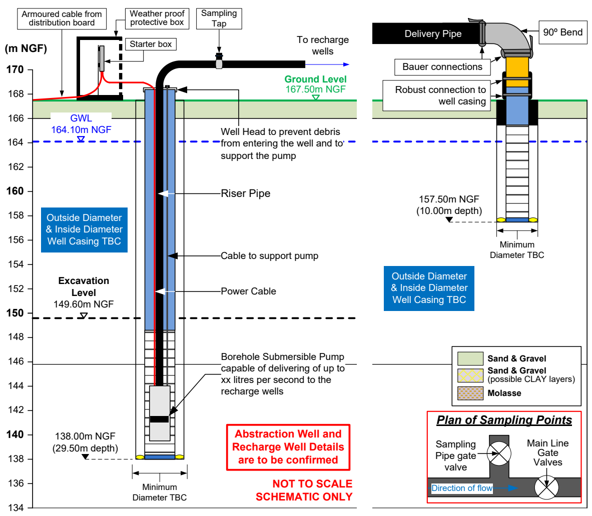

Figure 8. Drilling, pumping and recharge specifications.

2.7 Groundwater control system construction

Construction of a groundwater control system on site is required by an experienced, accomplished and specialist contractor (Figures 9 and 10). Drilling dewatering boreholes requires different skills to water supply boreholes, requiring experience in working on busy construction sites in close proximity to other trades.

Figure 9. Drilling of deep dewatering borehole.

Figure 10. Series of pressurised recharge boreholes.

2.8 Mathematical modelling of groundwater

Mathematical modelling uses computer software to solve the equations governing groundwater flow in a saturated or partially saturated porous material. The outputs are hydraulic heads, pore pressures and Darcy velocity. Modelling is highly valuable in predicting the groundwater behaviour of a dewatering operation.

Mathematical modelling of groundwater through soil or rock can be a major undertaking, with time and cost resources needed. It is recommended here to use a model only of sufficient complexity to solve a site situation. It is not recommended to use, for example, a fully three-dimensional model to apply to a simple pumping test operation from a single borehole.

For most applications, a multi-well analytical model is sufficient in a homogeneous aquifer, with most more complex transient and inhomogeneous aquifers being solved using a two-dimensional finite element model.

Figure 11 depicts the application of the finite element model SEEP/W to a shaft/tunnel project near Liverpool. Modelling was undertaken in advance of the dewatering operation and during the pumping test. This enabled the ground properties, and the model boundary conditions to be established. Modelling was also undertaken in "real-time" during the dewatering operation to refine the dewatering design. The benefits of this procedure included a prediction of a wide drawdown, which determined that after some time, no groundwater control was then required in the reception shaft in a mature garden, and so mitigating operations.

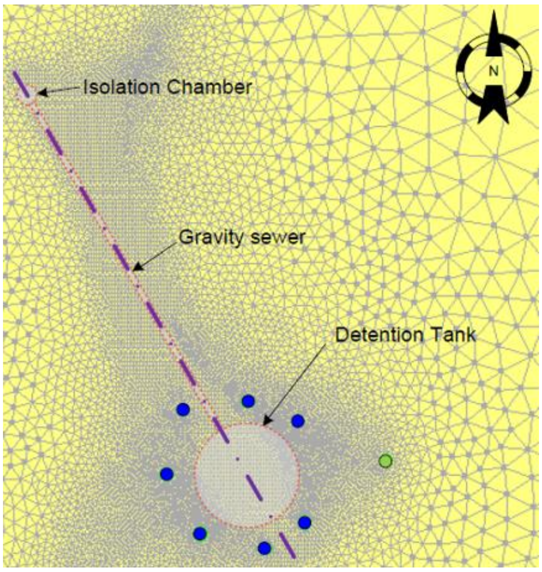

Figure 11. Finite Element modelling using Seep/W.

Another benefit to the project was the cost savings by predicting when additional pumps would be required. Only half the number of pumps was required for the dewatering operation, with pumping from boreholes only required for the deep shaft (Figure 12).

Using the groundwater model to enable the calculation of transmissivity, accurate predictions of the final groundwater abstraction could be made. This assisted with the application of licences and permits and enabled early appropriate pump selection.

2.9 Multi-well analytical modelling

To model a multi-borehole dewatering operation under steady-state conditions, OGI has developed efficient and effective models which use analytical solutions. These analytical models are extremely beneficial as they are simple to set up and fast to provide results.

Figure 13 depicts the conceptual model for an underground metro station, platform and tunnels, with Figure 14 depicting the simulated drawdown using a 2-D analytical groundwater model in plan.

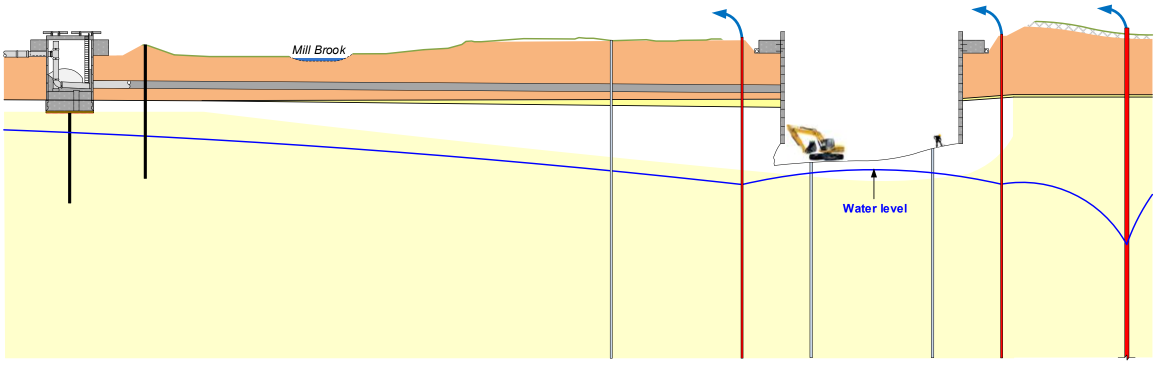

Figure 12. Simulation of dewatering from boreholes around a deep shaft, with drawdown reaching a smaller shaft.

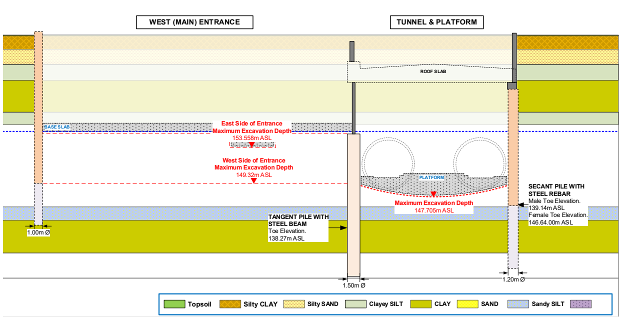

Figure 13. Conceptual model of metro platform and tunnel.

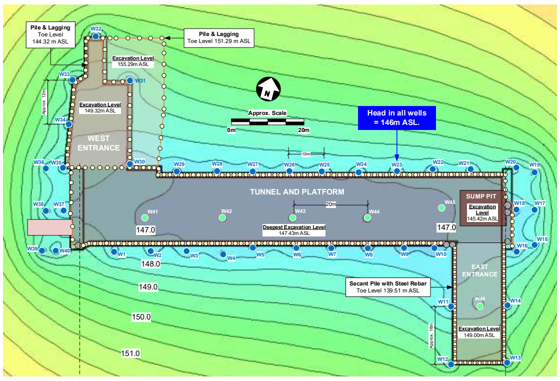

Figure 14. Simulated head using analytic modelling.

This analytical modelling enabled the simulation of abstraction wells and passive pressure relief wells in advance to the start of the dewatering operation. This capability greatly contributed to an efficient and effective groundwater control operation. At the start of pumping from only a few boreholes, drawdown was observed from non-pumping wells, after which aquifer properties were back-calculated using the analytical model to refine the design in real-time.

This enabled the additional pumping boreholes to be accurately positioned to provide the maximum impact. This was particularly valuable as the operation took place during the COVID-19 pandemic, where drilling crews were scarce, and optimisation was critical. Figure 15 demonstrates a successful outcome in challenging ground conditions.

Figure 15. Drawdown achieved beneath the metro station.

3 CONCLUSIONS

The principal stages in producing a groundwater control system are paramount within the Groundwater Engineering Industry. This paper outlines these stages and how their presence enhances a groundwater control system, and therefore, a project's success.

Conceptual models provide a visualisation of the subsurface and the proposed structures, which contribute to a preliminary groundwater control strategy. While useful, these strategies will always signify a requirement for further investigations to supplement the final design produced for a project.

Vital to these investigations are pumping tests and their subsequent analysis, which is inclusive of sensible mathematical modelling. The authors advocate that sensible modelling, encompassing only the required complexity, is needed to solve in advance the groundwater flow in the aquifer. The calculations using the aquifer properties feed into implementing mitigation strategies into the system design.

When these stages have been completed, they will augment the production of a detailed design that can be utilised to specify a robust groundwater control system to lower the water table to an acceptable level at a site, and so reduce the water risks accordingly.

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