GROUNDWATER INFLOW ASSESSMENT FOR DEEP BASEMENT EXCAVATIONS: A CASE STUDY

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ABSTRACT

Approvals for proposed building developments in Sydney are granted by the consent authority with input on groundwater-related matters from NSW Office of Water. Developments with deep basements require approval for construction dewatering. NSW Office of Water input considers the requirements of the NSW Aquifer Interference Policy, including assessment of the excavation's "groundwater take" and potential impacts associated with dewatering.

In order to adequately assess the potential impacts associated with construction dewatering, and to design appropriate construction dewatering systems, it is important to accurately estimate groundwater inflow rates to deep basement excavations during construction.

This paper discusses and compares established methods to assess groundwater inflows to deep basement excavations, including analytical, analogue and numerical approaches. A case study for a proposed development in Sydney is used to demonstrate differences in estimated inflow based on these approaches, and highlight the benefits and disadvantages of each approach. Consideration is given to geological structures, basement design, and uncertainty in conceptual models and aquifer parameters that can complicate accurate assessment.

1 INTRODUCTION

Building developments with deep basements require approval for construction dewatering from the consent authority (typically local Council). The consent authority may seek input from NSW Office of Water, either directly or through the NSW Department of Primary Industries Integrated Development Process.

NSW Office of Water offers advice to consent authorities in the context of the NSW Aquifer Interference Policy. Their advice is based on assessment of the basement excavation's "groundwater take" and potential impacts associated with dewatering.

In order to adequately assess the potential impacts associated with construction dewatering, and to design appropriate construction dewatering systems, it is important to make accurate estimates of groundwater inflows to deep basement excavations during construction.

This paper discusses some well-established methods to assess groundwater inflows to deep basement excavations, including analytical, analogue and numerical approaches. The relative benefits and disadvantages of each method are examined. Consideration is given to geological structures, basement design, and uncertainty in conceptual models and aquifer parameters that can complicate accurate assessment.

2 GROUNDWATER INFLOW ASSESSMENT METHODS

The accurate assessment of groundwater inflows to deep basement excavations is contingent on adequate characterisation of the hydrogeological environment and the excavation retention structure's influence on groundwater flow.

In the Sydney region, retention of soil for deep basement excavations most commonly comprises piled walls that are retained as part of the basement wall structure. Typically, either a solider pile wall with shotcrete panels or a secant pile wall is constructed, but other methods such as sheetpile walls or soil cutter mix walls are sometimes adopted. As groundwater can flow through shotcrete panels, such a retention structure forms a drained excavation wall. Similarly, excavations in sandstone are typically near-vertical, with limited retention support required, resulting in a drained excavation face over the sandstone.

Secant pile walls provide increased groundwater cut-off, and inflows in such cases are partially controlled by the depth of the wall's penetration into the underlying ground (typically lower permeability rock). Groundwater flow through sheetpile walls is generally controlled by the flow through the interlocking joints, which is dependent on the dimensional proportions of the wall, the construction (e.g., driving) method, and sealants (if used). Groundwater cut-off may sometimes be partial; for example, walls may penetrate through sand to an underlying low-permeability clay layer (without penetrating rock).

These structures can have significant influence on groundwater inflows to excavations.

Estimation of groundwater inflows to an excavation assuming steady-state flow may yield reasonable estimates, provided aquifer storage is not significant. In hydrogeological settings where aquifer storage is significant (e.g., sandy soils), it is more appropriate to estimate groundwater inflows considering transient flow. In the absence of information on the groundwater flow regime within deep basement excavations in rock in Sydney, it is assumed that quasi-steady state groundwater flow occurs given the typically slow advancing rate of excavation.

Consideration must be given to geological structures, such as dykes, that intersect excavation walls. Such features can provide preferential pathways for groundwater to flow to the excavation.

Analysis of groundwater inflows to an excavation should also consider the potential for groundwater levels to rise due to seasonal variation and rainfall response.

3 CASE STUDY

Analytical, analogue and numerical modelling approaches were applied to a proposed deep basement excavation in Sydney.

The proposed development was located adjacent to harbour waters, and included multiple basement levels extending within sandstone bedrock. A thin layer of fill overlay the sandstone.

Within the sandstone rock mass, an approximately two metre-thick brecciated sandstone layer was present on the harbour-side of the development. Groundwater seepage was observed emanating from this unit during excavation of the adjacent building some years earlier, and is shown in Figure 1.

To illustrate comparative approaches, excavation inflows were assessed under steady state saturated flow conditions. Parameter values typical of Sydney geological conditions were adopted.

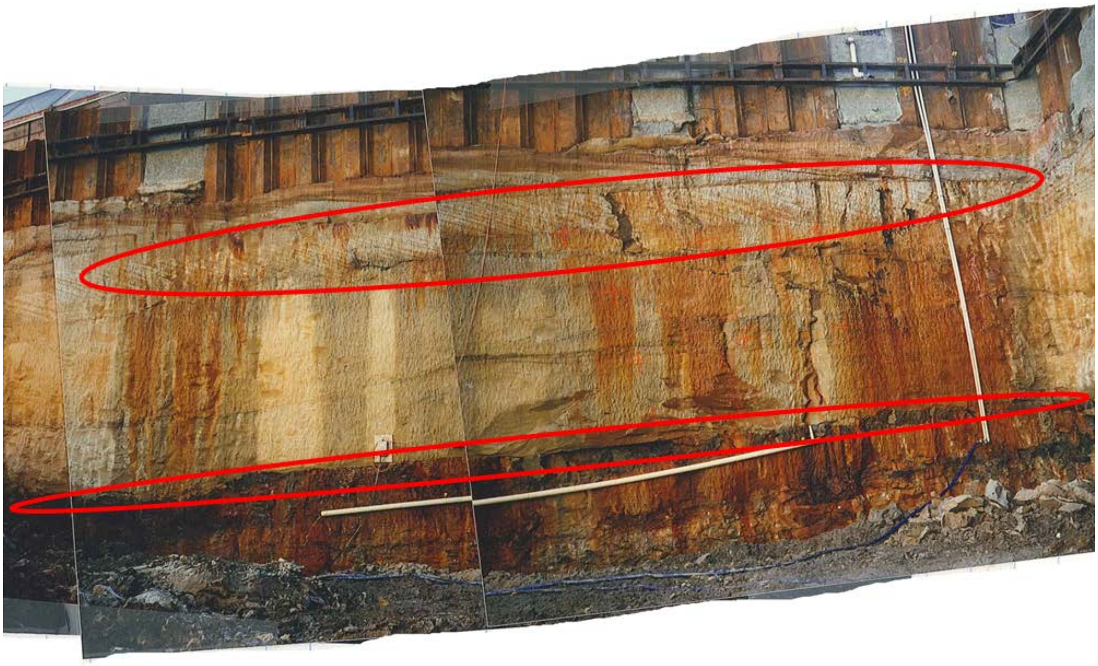

Figure 1: Zones of Significant Groundwater Seepage (Including From Lower Brecciated Sandstone Unit)

3.1 ANALYTICAL SOLUTIONS

Analytical models offer a simple and straight forward way to estimate groundwater inflows.

The simplest estimate of groundwater inflow to an excavation may be obtained by use of the Theim solution (Theim, 1906). The theory considers steady-state radial flow to a pumping well. In applying the theory to an excavation, an equivalent radius of the area of the excavation footprint is adopted as the well radius. The solution then requires knowledge of the extent of groundwater drawdown due to the excavation. This may be apparent if a constant head boundary (e.g., a water body) is present in the vicinity, but may otherwise be too arbitrary to define.

A significant improvement in estimation of inflows can be obtained by use of an analytical solution that instead adopts a boundary condition that is easier to identify and estimate, such as (rainfall) infiltration. An example is the theory presented by Edelman (1972) for steady-state radial flow from an extensive unconfined aquifer under uniform infiltration. Further improvement can be achieved by making use of the substitution $h^2/2$ for hH, as described by Verruijt (1982), where h is the saturated thickness at a particular location [L] and H is the full aquifer thickness [L]. This captures the change in aquifer thickness (i.e., the thickness of saturated media through which flow occurs) as drawdown decreases with distance from the excavation, and yields:

$$Q = \pi\eta(R^2 - r^2) \tag{1}$$

$$R_1 = \frac{2K}{\eta}\frac{h_R - h_r}{ln\left(\frac{R}{r}\right) - \frac{R_0^2 - r^2}{2R_0^2}} \tag{2}$$

where Q is the inflow to the excavation [L^3/T], η is the infiltration rate [L/T], R is the distance from the centre of the radial excavation to the point of zero drawdown (i.e., the extent of drawdown) [L], r is the radius of the excavation [L], K is the hydraulic conductivity [L/T], and h is the hydraulic head (saturated thickness) above the "aquifer base" [L]. R can be determined through an iterative approach using Equation (2). Figure 2 illustrates these parameters.

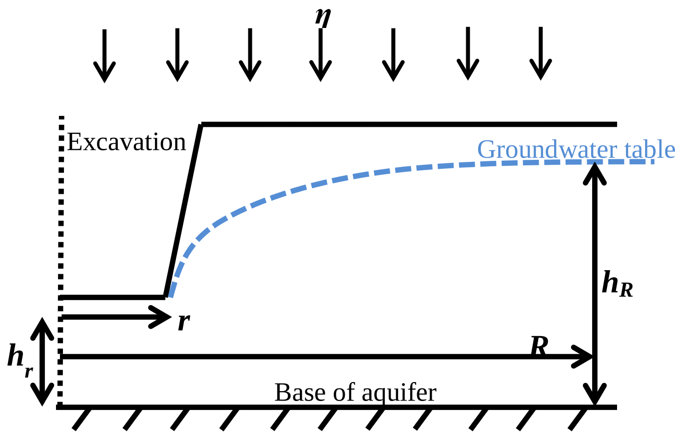

Figure 2: Parameters in Analytical Model Described Above

Analytical models may provide inaccurate estimates of groundwater inflow where ground conditions are significantly heterogeneous or non-uniform, or where excavation geometry or ground conditions dictate that the flow regime to the excavation would not be approximately radial. The analytical model discussed above would be inappropriate in settings where vertical flow is significant, since only horizontal flow is considered by the model.

Analytical assessment of long-term (steady state) inflow to the case study basement excavation (through the sandstone stratum) was undertaken based on theory presented above. The assessment considers the following conditions:

- Excavation footprint of 1,200 m^2 yielding an equivalent radius (r) of 19.5 m
- A hydraulic conductivity (K) of approximately 0.005 m/day for the sandstone. This hydraulic conductivity value is derived from hydraulic test results that were depth-averaged over the excavation depth
- The sandstone aquifer contributing to inflow is up to 30 m thick (h_R = 30 m)
- Lowest excavation level some 20 m below the groundwater table (h_R = 10 m)
- Infiltration (η) of 2% (typical of urban settings) of mean annual rainfall of approximately 1.2 m in Sydney.

Based on these assumptions, a radius of influence (*R*) of 185 m and an inflow to the excavation (through the sandstone only) of 2.6 ML/year were estimated.

The radius of influence is clearly an important parameter. In this instance, harbour waters are a minimum distance of 30 m from the excavation, suggesting that the above inflow rate is an over-estimate. However, as the harbour is only present on one side of the excavation, an *R* value greater than 30 m might be considered appropriate.

3.2 ANALOGUE SOLUTIONS

An alternative method of estimating groundwater inflow to a proposed excavation is to consider an existing basement as an analogue. Where groundwater inflows to an existing basement in a similar geological setting are known, those inflows can be scaled in accordance with the geometry of a proposed development. This method is particularly useful where aquifer property data are limited, or where the potential influence of geological features is uncertain.

The neighbouring building to the case study development possessed a basement. Water discharges from that basement's sump were recorded and are presented in Figure 3. Given the basement's proximity to the harbour, it is possible that groundwater seepage to the basement was influenced by harbour tides (particularly given a potential hydraulic connection through the brecciated sandstone). Further, many basement sumps receive additional flow from stormwater and it is clearly important to understand this contribution in order to accurately assess groundwater seepage to the basement.

Figure 3 therefore shows harbour tide level and daily rainfall (the 24 hours preceding 9 a.m.) to permit assessment of potential correlations between basement water collection and harbour water/stormwater.

Results indicate that tide level does not have a significant impact on inflow to the basement sump. Calculated inflows show significant correlation with rainfall and it is therefore likely that rainfall contributes to basement sump inflows by entering the basement drainage system. During periods without rain, the inflow was relatively consistent, at approximately 0.35 m^3/day (3.1 ML/year).

Sump water in the basement had an electrical conductivity (37,000 µS/cm) approaching values typical of seawater (40,000 µS/cm to 50,000 µS/cm), suggesting that harbour waters contributed significantly to the groundwater inflows to the basement. Based on this, and the orientation of the neighbouring building (longest dimension parallel with harbour) it was assumed that approximately 80% of groundwater inflow to the basement was drawn from the neighbouring harbour ("west" side) and the opposite ("east") side walls/floor combined (2.5 ML/year), while the remaining 20% was drawn from the neighbouring basement walls/floor perpendicular to the harbour (0.6 ML/year).

Groundwater inflow to the proposed excavation was estimated by scaling the measured inflow to the neighbouring basement in accordance with the relative basement/excavation dimensions. For example, the harbour-facing dimension of the neighbouring basement was approximately 50 m, while the proposed harbour-facing excavation dimension was approximately 40 m. Thus, the scaled portion of groundwater inflow to the excavation from the western and eastern side walls/floor combined was estimated as 2.0 ML/year (3.1×80%×40/50). Similar scaling was applied to the "northern" and "southern" basement walls/floor faces to the harbour to yield 0.2 ML/year drawn from the neighbouring basement northern and southern walls/floor (0.4 ML/year), except that half of this total flow would still enter the neighbouring basement, thus reducing this component contributing to the excavation to 0.2 ML/year.

The total scaled flow was then scaled in a similar way for the difference in basement/excavation depth between the proposed excavation and the neighbouring basement. The lowest basement floor level of the neighbouring basement lies some 16 m below the groundwater table, while the proposed development's lies some 19.5 m below the groundwater table. The total groundwater inflow to the proposed excavation was therefore estimated to be 2.7 ML/year ((2.0+0.2)×19.5/16).

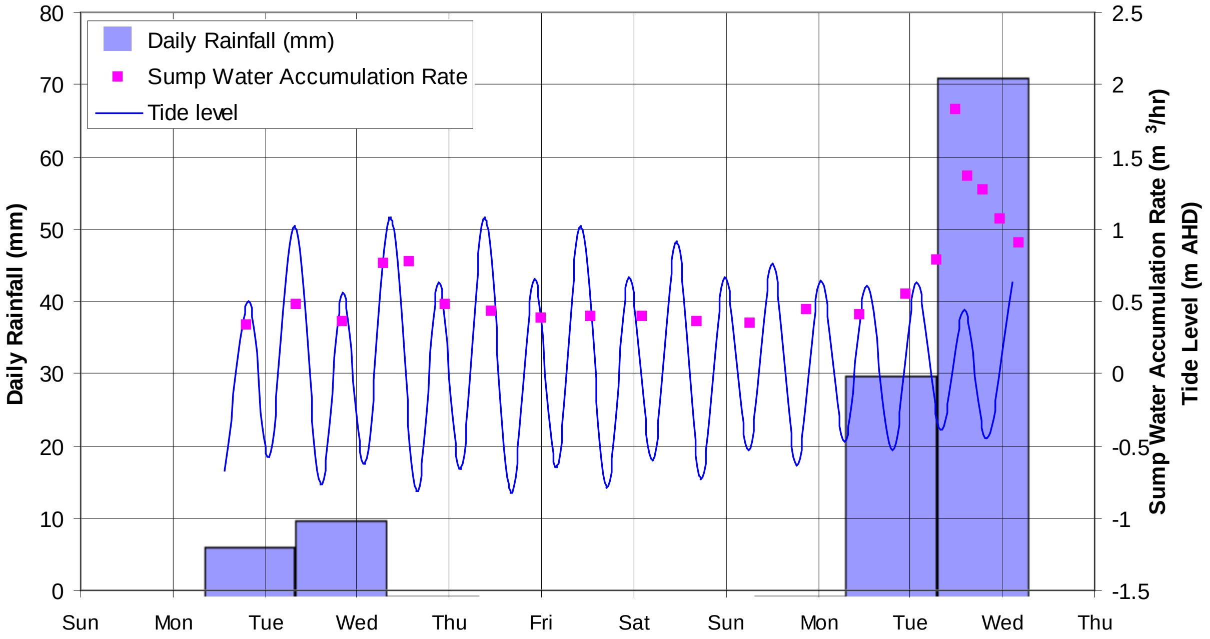

Figure 3: Measured Inflow to Basement Sump

3.3 NUMERICAL SOLUTIONS

Numerical models offer the potential to account for heterogenous and non-uniform ground conditions, and the influence of complex excavation geometry and retention structures on the groundwater flow regime.

A numerical model was developed in GEO-SLOPE International Ltd's numerical software package SEEP/W. The numerical model was used to consider the potential influence of geological conditions (such as the brecciated sandstone layer, and the presence of fill) and the proximity of the excavation to harbour waters.

A cross sectional model was adopted to consider geometry of the excavation (rock elevation varied with location), and the local groundwater setting (harbour waters and inland recharge processes). Boundary conditions comprised a seepage face along the basement walls and floor, a constant head associated with harbour waters and, in the opposite direction to the harbour, a constant head condition beneath a 100 m-distant ridgeline (equal to harbour water levels). Aquifer properties were consistent with those adopted for the analytical model: excavation within sandstone possessing a hydraulic conductivity of 0.005 m/day, and an aquifer thickness of 30 m. Figure 4 presents the modelled system.

The geometrical asymmetry of the excavation and local groundwater conditions induce different rates of inflow to each side of the excavation. Hydraulic head gradients also increase around the corners of the excavation where the floor and walls meet, leading to non-radial-type flow, and increasing inflow to the floor of the excavation.

The modelled inflow from the harbourside ("west side") and "eastern side" were 1.1 ML/year and 0.4 ML/year, respectively, along each of the 40 m-long excavation faces. Assuming consistent conditions to the north and south (and in the presence of adjacent existing basements), the inflow from the northern or southern side would be intermediate (0.8 ML/year to each side) between that from the eastern and western sides (note drawdown in Figure 4). Scaling these sides for their length (of 30 m as opposed to 40 m), the inflow to each of these sides is then 0.6 ML/year, and the total inflow to the excavation is 2.7 ML/year.

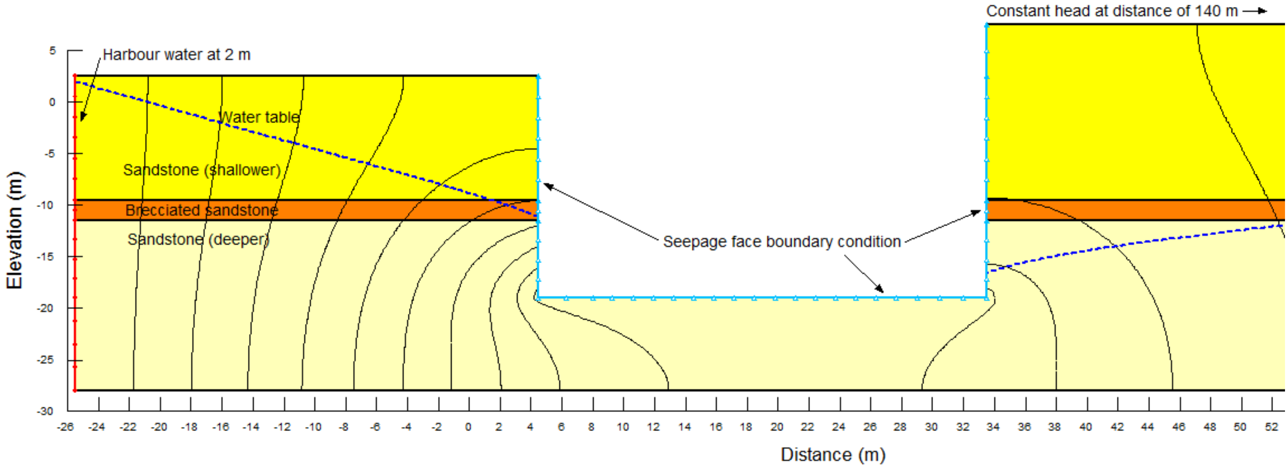

Figure 4: Modelled Uniform System and Hydraulic Head Contours (m)

The previous models assumed uniform ground conditions with only sandstone present. The potential influence of heterogeneous ground conditions, the brecciated sandstone layer, and the presence of overlying fill in hydraulic connection to harbour waters were also explored. The numerical model also takes into account vertical flow processes which are not addressed in the analytical approach discussed in Section 3.1.

The presence of the fill was modelled, with a hydraulic conductivity of 1 m/day, but groundwater within the fill was prevented from entering the excavation (appropriate excavation shoring would provide this).

The sandstone units, including the brecciated sandstone layer, were assigned hydraulic conductivity values approximately reflecting hydraulic test results over their respective depths. For illustrative purposes, a value of 10 for the ratio of horizontal to vertical hydraulic conductivity was adopted for all rock units.

Figure 5 shows model features.

The fill, charged with harbour water, provides an additional shallower source of groundwater to the excavation (in the saturated flow model). This model also replicates the likely increased inflow entering the excavation through the brecciated sandstone layer, as observed at the neighbouring site (Figure 1). The increased hydraulic conductivity of the geological units results in increased flow through the excavation walls. However, the reduced vertical hydraulic conductivity decreases inflow through the floor of the excavation. In this particular instance, these two influences compete, with the overall inflow reducing (relative to the previous case) to 2.2 ML/year.

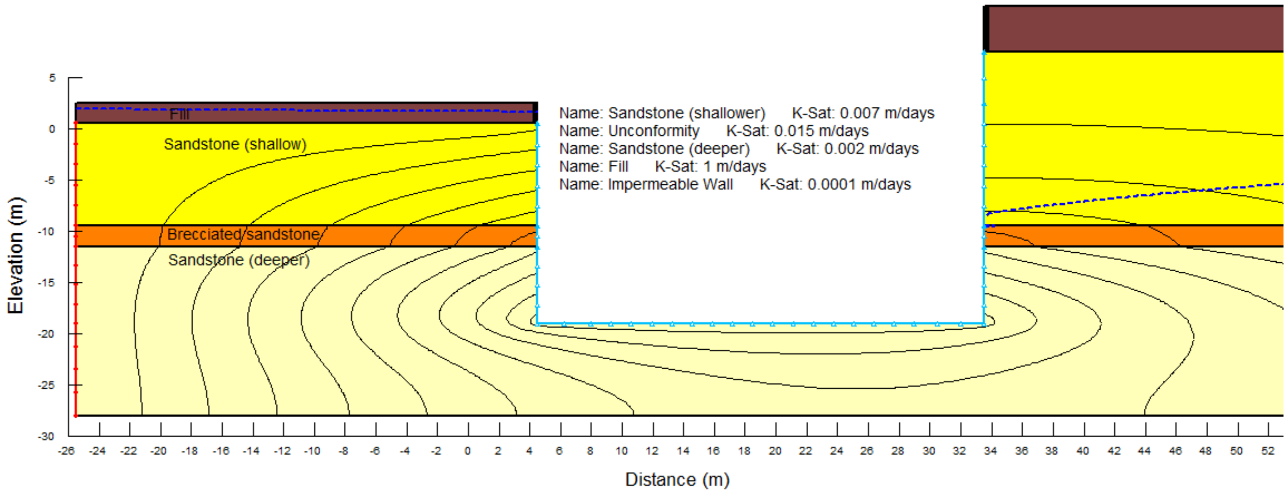

Figure 5: Modelled Heterogeneous System

The assessed inflow is significantly affected by the aquifer thickness (i.e., the thickness of saturated media) contributing to flow. As would be expected, the deeper the aquifer contributing to excavation inflow, the greater the inflow (all other conditions being equal). For greater aquifer thickness, the proportion of flow through the excavation floor increases and the proportion of flow through the excavation (rock) walls reduces, as illustrated in Table 1 for the model shown in Figure 4. The implication is that the drainage measures for construction dewatering and the basement drainage system (in the case that a drained basement is constructed) will need to accommodate this variability in seepage entering from the walls and floor.

Table 1: Variation in Wall and Floor Inflows with Aquifer Thickness

Aquifer Thickness Below Base of Excavation Floor (m)	**Proportion of Inflow Entering Excavation Through**	
	Walls	**Floor**
10	58%	42%
20	49%	51%
30	45%	55%
40	44%	56%

4 CONCLUSIONS

Assessment of excavation inflows using a variety of assessment methods can be useful to help understand the sensitivity of excavation inflows to particular conditions.

The estimates of inflow assessed by different modelling approaches were generally similar for this case study. Consistency in results between different analysis methods can provide confidence in inflow estimates, particularly where direct measurement is available and despite uncertainty in model parameter values. This may reflect the appropriate selection of assumptions and aquifer parameters, but may equally be the result of non-unique solutions (different model conceptualisation/parameter values yielding a similar result). Understanding the reasons for differences in results from different methods is therefore essential.

The case study discussed in this paper demonstrates that analysis using appropriate parameter values is more important than model complexity.

The adopted model(s) should reflect the hydrogeological setting of the excavation not only in terms of hydrogeological strata and expected groundwater flow regimes, but also in their representation of excavation retention structures, excavation geometry, geological features and conceptualised aquifer thickness.

Where the excavation and local groundwater conditions are geometrically suitable, an analytical radial flow model may be sufficient to estimate inflow with reasonable accuracy. Where ground conditions are non-uniform, numerical models can usefully assess inflows considering the influence of separate geological strata and features. This approach naturally requires additional hydrogeological parameter data to characterise the environment, and uncertainty in assessed inflow increases with use of questionable parameter values.

Where an analogue assessment is possible, this may prove useful in providing meaningful estimates of inflow, particularly when there is insufficient data to adequately characterise the hydrogeological environment. This method has the benefit of estimating inflows based on direct measurements, but may not be relevant in settings where long-term and short-term inflows are likely to be significantly different (measured basement inflow rates are then likely to be lower than short-term construction inflow rates), or where the geometry or geological setting of the excavation is significantly different to that of the basement at which inflows are measured.

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