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An Improved Resistance Coefficient Method for Calculating Water Inflow into Foundation Pits with Suspended Cut-Off Walls in Confined Aquifers

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Abstract

With the accelerating development of urban underground space, accurate prediction of water inflow has become increasingly important for foundation-pit dewatering design. This study systematically extends the improved resistance coefficient method to foundation pits with suspended cut-off walls in confined aquifers. Based on Dupuit radial-flow theory, the seepage field is divided into four zones: a radial-flow segment represented by a partially penetrating well, a horizontal-flow zone beneath the cut-off wall, an internal exit zone, and a vertical seepage zone beneath the excavation base. An analytical expression for square foundation pits is derived, and an area correction coefficient is introduced to improve accuracy for large excavations. Validation against nearly 200 three-dimensional finite-element models shows that the maximum relative error was 10.60%, indicating generally good agreement between the proposed method and the finite-element results. Parametric analyses clarify the effects of cut-off wall penetration ratio, excavation area, permeability ratio between high- and low-permeability layers, and excavation aspect ratio, thereby defining the applicable range of the proposed method. The proposed method provides a computationally efficient approach for preliminary dewatering design of foundation pits within the identified applicability ranges.

Keywords: improved resistance coefficient method; suspended cut-off wall; foundation-pit dewatering; water inflow; confined aquifer

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1. Introduction

In recent years, rapid development of deep urban underground space in China has led to progressively deeper excavations, particularly in coastal soft-soil cities such as Shanghai, Hangzhou, and Nanjing. Consequently, an increasing number of deep foundation pits encounter confined groundwater and environmental-protection challenges during dewatering [1]. These projects exhibit complex three-dimensional seepage during pumping. Suspended cut-off walls lengthen groundwater flow paths and redirect flow from the surrounding ground toward the excavation, thereby reducing the environmental effects of dewatering [2,3].

In engineering practice, analytical and numerical approaches are the two main methods used to evaluate foundation-pit dewatering. Analytical methods are generally based on the Dupuit assumption, the Theis equation, and related idealizations; they simplify boundary

conditions and seepage patterns to derive convenient expressions for estimating groundwater responses during excavation dewatering [4–8]. However, dewatering with a suspended cut-off wall exhibits a marked scale effect [9]. Its performance is influenced differently by wall depth, excavation area, aquifer thickness, excavation depth, and other geometric parameters [10]. Including all of these variables yields a highly complex model that is difficult to solve, so many previous studies have neglected selected factors and consequently have a limited range of applicability. Numerical methods can accurately represent complex geological and boundary conditions, but they require specialist expertise and substantial computational resources and are therefore less suitable for preliminary scheme comparison and rapid on-site assessment.

Previous studies have quantitatively evaluated the influence of cut-off walls on groundwater seepage fields from different perspectives. Pujades et al. [11] identified the embedment depth of underground structures and the hydraulic properties of aquifers as important factors affecting groundwater drawdown distribution. Vilarrasa et al. [12] proposed a pumping-test-based method for evaluating the hydraulic effectiveness of annular low-permeability barriers. Shen et al. [10] investigated the hydraulic head difference across cut-off walls during excavation dewatering, providing a basis for evaluating the hydraulic barrier effectiveness of cut-off walls and their influence on the surrounding groundwater seepage field.

The improved resistance coefficient method originated from seepage calculations for sheet-pile structures in navigation-lock projects. Through subsequent systematic summarization and development, it evolved into a practical method for calculating seepage by dividing the hydraulic head loss into several segments [13]. Specifically, the seepage domain is divided into entrance and exit sections, an internal vertical section, and a horizontal section. The total hydraulic head loss is calculated using the resistance coefficients of each section. This method offers clear physical significance and high computational efficiency. Its underlying principle is consistent with that of the flow net method, which analyzes seepage behavior based on seepage paths and hydraulic head losses, providing an effective approach for simplifying the calculation of complex seepage problems [14]. In recent years, this method has gradually been applied to seepage analysis in foundation pit engineering. Zhu et al. [15] developed an axisymmetric local resistance-coefficient model for circular excavations. They showed that the ratio of excavation radius to foundation thickness strongly affects the resistance coefficient; the entrance/exit coefficient approaches the plane-seepage value only when the radius exceeds approximately ten times the foundation thickness, so direct application of a two-dimensional formulation to a circular excavation can produce substantial error. Huang [16] systematically investigated seepage-field models under complex boundary conditions, distinguished confined from unconfined seepage, and proposed methods for representing pumping wells and seepage barriers.

Building on these developments, the improved resistance coefficient method has been further applied to seepage calculations for foundation pits with suspended cut-off walls. Zhong et al. [5] and Peng et al. [6] introduced this method into the analysis of foundation pits with suspended cut-off walls and established corresponding seepage calculation approaches. Li et al. [7] proposed a simplified calculation method for depressurization dewatering in deep foundation pits with suspended cut-off walls. Wang et al. [4] and Zhu et al. [2] investigated the influence of cut-off wall penetration depth on foundation-pit water inflow through numerical analyses. Regarding international studies, Liu et al. [3] investigated the dewatering characteristics and water inflow prediction of deep foundation pits with partially penetrating cut-off walls in sand and gravel strata. Chu et al. [8] examined the dewatering characteristics and groundwater drawdown prediction of foundation pits with suspended

cut-off walls in soft-soil areas. Shen et al. [17] derived analytical solutions for water inflow into circular, strip-shaped, and rectangular foundation pits in confined aquifers.

These studies have investigated the seepage characteristics and water inflow calculations of foundation pits with suspended cut-off walls from different perspectives, providing a theoretical and methodological basis for the present study. However, the influence of three-dimensional flow convergence associated with variations in excavation plan dimensions has not been fully addressed. In particular, the effects of excavation plan dimensions on seepage resistance and water inflow under different cut-off wall penetration ratios require further investigation. Moreover, existing simplified calculation methods still have certain limitations in their applicability across different ranges of cut-off wall penetration ratios. Therefore, further improvements to simplified water inflow calculation methods for foundation pits with suspended cut-off walls are necessary.

To address these limitations, this study systematically extends and refines the improved resistance coefficient method. Based on Dupuit radial-flow theory, the seepage field is divided into a radial partially penetrating-well segment, a horizontal segment beneath the cut-off wall, an internal exit segment, and a vertical seepage segment beneath the excavation base. A water-inflow equation applicable to square foundation pits is then derived. This formulation overcomes the limitations of conventional two-dimensional analyses and represents the three-dimensional flow characteristics of foundation-pit dewatering more realistically. The resulting method broadens the use of the improved resistance coefficient approach in foundation-pit engineering and provides a rapid, reliable design tool. It retains the simplicity of an analytical formulation while achieving good agreement with numerical results and is particularly suitable for preliminary scheme comparison and parameter optimization.

2. Materials and Methods

2.1. Segmentation of the Seepage Domain

The improved resistance coefficient method was originally developed for sheet-pile seepage calculations in Chinese navigation-lock engineering [13] and provides a convenient means of determining hydraulic head at different locations beneath a structure. Equipotential lines passing through corners and tips of the underground contour are used to divide the aquifer into vertical and horizontal segments. Head loss in each segment is represented by a resistance coefficient that depends only on the segment geometry. As shown in Figure 1, the aquifer is divided into three basic segment types: (I) entrance/exit segments, (II) internal vertical segments, and (III) horizontal segments. Their resistance coefficients are calculated as follows:

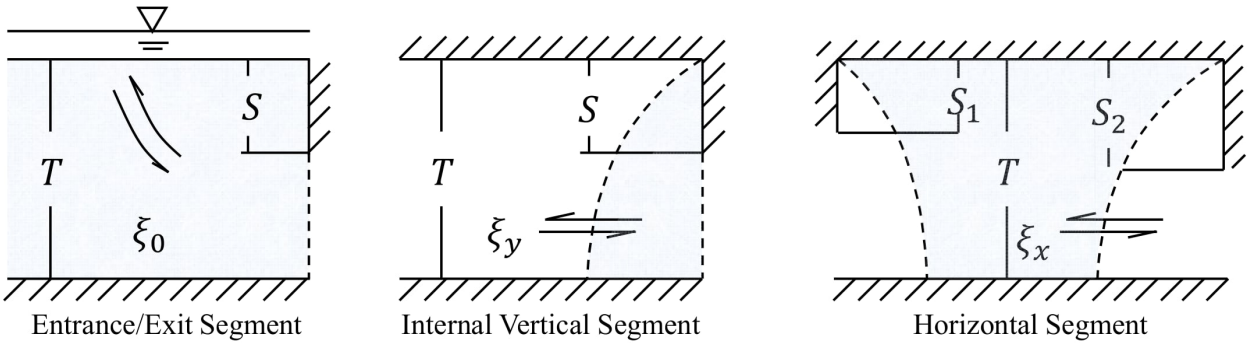


Figure 1. Cross-sectional forms of the basic seepage segments. From left to right: entrance/exit segment, internal vertical segment, and horizontal segment.

(I) Entrance/exit segment:

$$\xi_0 = 1.5\left(\frac{d}{M}\right)^{\frac{3}{2}} + 0.441 \quad (1)$$

(II) Internal vertical segment:

$$\xi_y = \frac{2}{\pi}\ln\cot\left(\frac{\pi}{4}\left(1 - \frac{d}{M}\right)\right) \quad (2)$$

(III) Horizontal segment:

$$\xi_x = \frac{l - 0.7(S_1 + S_2)}{T} \quad (3)$$

where ξ_0, ξ_y, and ξ_x are the resistance coefficients of the entrance/exit, internal vertical, and horizontal segments, respectively; S, S_1, and S_2 are the penetration depths of the sheet piles or cut-off teeth (m); T is the thickness of the permeable foundation layer (m); and l is the length of the horizontal segment (m).

For a foundation pit with a suspended cut-off wall under confined groundwater conditions, the wall alters groundwater flow paths within a finite zone and induces both vertical and horizontal flow. This influence gradually decreases with distance from the outer face of the wall and eventually becomes negligible.

Based on the equipotential lines on both sides of the wall in the sectional flow field, the seepage domain is divided into four zones, as illustrated in Figure 2. Zone ① extends from the radius of influence to the outside of the wall, where confined groundwater enters the base of the excavation through three-dimensional flow. Zone ② lies beneath the wall and is dominated by horizontal flow. Zone ③ is the confined aquifer inside the excavation, where horizontal and vertical flows are coupled. Zone ④ is the relatively low-permeability layer beneath the excavation, where groundwater flows mainly upward.

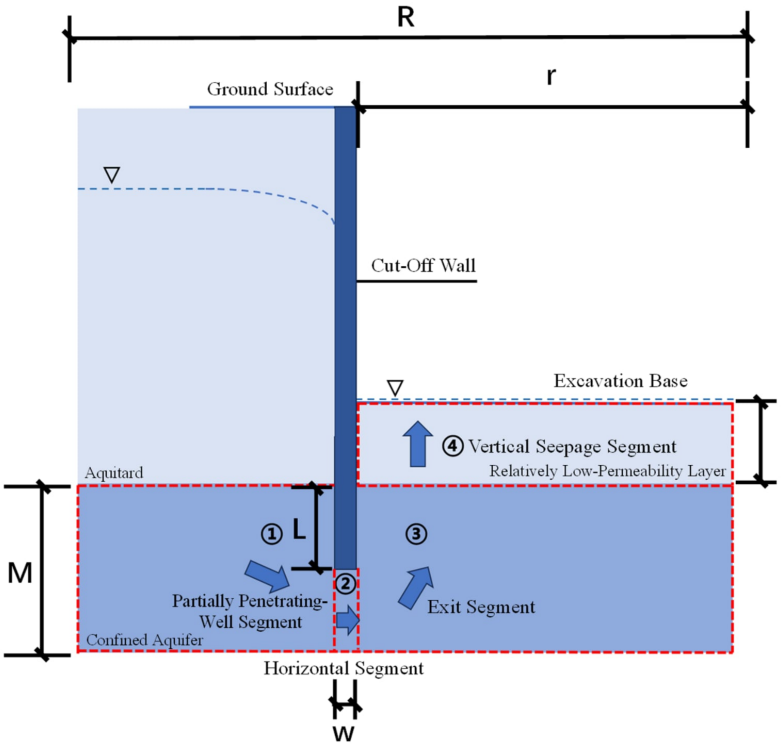


Figure 2. Segmentation of a foundation-pit seepage domain underlain by a confined aquifer. Labels identify the ground surface, cut-off wall, excavation base, aquitard, relatively low-permeability layer, confined aquifer, partially penetrating-well segment, horizontal segment, exit segment, and vertical seepage segment.

2.2. Calculation of Resistance Coefficients

The improved resistance coefficient method was originally formulated for two-dimensional sectional flow and assumes a constant seepage-section width L beneath a hydraulic structure. Foundation-pit dewatering is a more complex three-dimensional problem: groundwater converges toward the excavation center in plan, and the effective flow-section width decreases toward the center [6]. The applicability of the original expressions must therefore be evaluated separately for each segment of the foundation-pit seepage field.

2.2.1. Segmental Resistance Coefficients for a Confined Aquifer Beneath the Excavation

In Zone ①, horizontal and vertical groundwater flows are coupled. The square excavation is converted to an equivalent circular excavation of radius r_0 and treated as a partially penetrating well in a confined aquifer with inflow through the well wall. The discharge Q_1 is calculated using the equation proposed by Sha Jinxuan [18] for this configuration:

$$Q_1 = \frac{2\pi KM(H_R - H_w)}{\ln \frac{R}{r} + f_0} \tag{4}$$

$$f_0 = \frac{B}{L}\ln\left(1 + \frac{LB}{Mr}\right) \tag{5}$$

where K is the hydraulic conductivity (m/d); H_0 is the initial confined-aquifer head (m); Hw is the minimum piezometric head outside the excavation after depressurization pumping (m); M is the confined-aquifer thickness (m); B is the height of the flow section (m); R is the distance from the center of the excavation pit to the outer boundary of the dewatering influence zone (m); L is the penetration depth of the cut-off wall into the confined aquifer (m); and r is the equivalent excavation radius (m), the solution is obtained from Equation (14). The basic assumptions of Equation (4) are consistent with those of the classical solution derived by Hantush [19] for the same problem, with R = r + Rw. The influence radius Rw represents the distance over which dewatering influences the ground beyond the pit boundary; it is an empirical parameter and is commonly estimated in engineering practice using Sichardt's empirical formula, $Rw = 10\Delta H\sqrt{K}$ [20], where ΔH is the drawdown of the water level inside the pit (m).

Rearranging Equations (4) and (5) gives the resistance coefficient for Zone ①:

$$\xi_1 = \frac{r}{M}\left(\ln\frac{R}{r} + f_0\right) \tag{6}$$

Zone ② is a horizontal-flow segment. Its resistance coefficient is obtained from Darcy's law:

$$\xi_2 = \frac{w}{M - L} \tag{7}$$

where L is the penetration depth of the cut-off wall into the confined aquifer (m); M is the confined-aquifer thickness (m); and w is the cut-off wall thickness (m).

Zone ③ is an exit segment. Its resistance coefficient is calculated using the exit-segment expression of the resistance coefficient method:

$$\xi_3 = 1.5\left(\frac{\mathrm{L}}{\mathrm{M}}\right)^{\frac{3}{2}} + 0.441 \tag{8}$$

where L is the penetration depth of the cut-off wall into the confined aquifer (m), and M is the confined-aquifer thickness (m).

Zone ④ is a vertical seepage segment. Its resistance coefficient is obtained from Darcy's law:

$$\xi_4 = \frac{2\pi K_1 rl}{K_2 A} \tag{9}$$

where K_1 is the hydraulic conductivity of the confined aquifer (m/d); K_2 is the hydraulic conductivity of the relatively low-permeability layer (m/d); r is the equivalent excavation radius (m); d is the thickness of the relatively low-permeability layer beneath the excavation base (m); and A is the excavation area (m^2).

Substituting the segmental resistance coefficients from Equations (6)–(9) into the inflow equation gives the water inflow for a foundation pit underlain by a confined aquifer:

$$Q = \frac{2\pi K_1 r \Delta H}{\xi_1 + \xi_2 + \xi_3 + \xi_4} \tag{10}$$

where K is the hydraulic conductivity (m/d); r is the equivalent excavation radius (m); and ΔH is the difference between the initial confined-aquifer head and the head inside the excavation (m).

Equation (10) permits a preliminary estimate of water inflow into a foundation pit underlain by a confined aquifer using a small set of basic parameters.

2.2.2. Correction for the Effect of Excavation Area

As excavation size increases, the equivalent-area radius approach produces increasing deviation. In a large square excavation, the actual seepage path from a corner to the center is considerably longer than the path represented by the theoretical equivalent circular radius, and this difference increases approximately linearly with excavation size. Furthermore, the model simplifies the three-dimensional seepage field into an idealized radial-flow field, neglecting differences in flow paths between the corner regions and the middle portions of the excavation sides. These factors collectively lead to an underestimation of the overall seepage resistance, which may result in relatively large errors when calculating water inflow into foundation pits with large excavation areas.

To extend the applicable range of the method, the inflow equation was corrected by comparison with finite-element results as follows:

$$Q = \frac{2\pi K_1 r \Delta H}{\xi_1 + \xi_2 + \xi_3 + \xi_4/\alpha} \tag{11}$$

where α is a correction coefficient defined by:

$$\alpha = -0.5ln(r/M) + 1.2 \tag{12}$$

$$1 \geq \alpha \geq 0.2 \tag{13}$$

Equation (11) is used to estimate steady-state water inflow under prescribed hydraulic head boundary conditions and can be applied to preliminary dewatering scheme comparisons after groundwater flow has approached steady-state conditions. During the initial pumping stage, groundwater release from the aquifer and time-dependent variations in hydraulic head affect the pumping discharge and drawdown process. Therefore, the time required to achieve the target drawdown, the pumping discharge during the initial stage, and staged pumping arrangements should be determined based on pumping tests or transient seepage analyses.

The expression for α is an empirical best-fit relationship obtained from comparisons with a large number of finite-element results. The corrected equation retains the concise form of the original expression and introduces only one additional coefficient, making it straightforward for engineering application. Site engineers can rapidly determine α from project-specific excavation conditions. The corrected formulation also retains clear physical parameters and can be calibrated against field-test data when necessary.

3. Validation

3.1. Numerical Model Establishment and Verification

The three-dimensional finite-element model shown in Figure 3 was established to validate the proposed equation. The calculations were performed with IFSolver (v0.1-2022-08-09), and the soil-layer properties and cut-off wall parameters are listed in Table 1. The excavation is square. To minimize the influence of the pumping radius in the confined aquifer, the model dimensions were set to 2000 m × 2000 m × 100 m. A seepage face was specified at the excavation base, and a confined hydraulic head was prescribed at the outer boundaries. Continuous seepage interfaces were assumed between adjacent soil layers, ensuring continuity of hydraulic head and normal seepage flux across the interfaces. Impermeable layers were placed at the top and bottom of the confined aquifer to eliminate leakage recharge from the phreatic aquifer. The ground was discretized using an unstructured tetrahedral mesh.

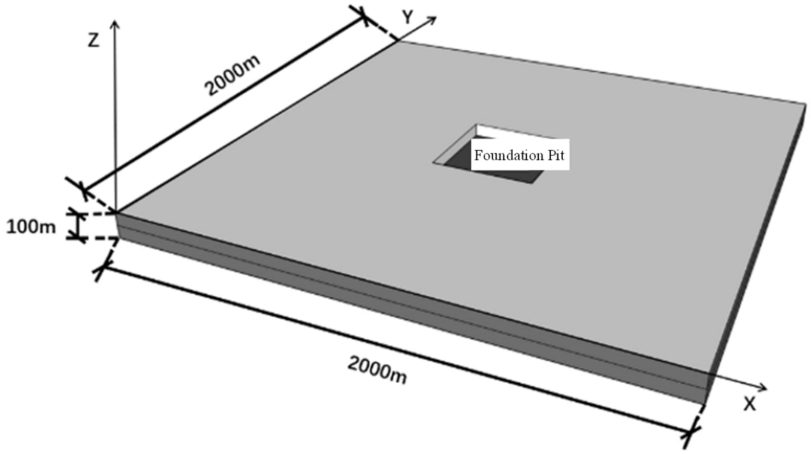


Figure 3. Three-dimensional finite-element model of the foundation pit; the center label denotes the excavation.

Table 1. Soil-layer and cut-off wall parameters.

Parameter	Value	Unit
Hydraulic conductivity K	0.1–10	m/d
Aquifer thickness M	10–50	m
Cut-off wall penetration ratio L/M	0.1–0.9	–
Excavation area	400–90,000	m^2
Head difference ΔH	5–20	m
Number of mesh elements	14,942–93,872	–

3.1.1. Mesh Independence Verification

To investigate the influence of mesh discretization on the calculated total water inflow, a square foundation pit with plan dimensions of 60 m × 60 m was selected as a representative case. The computational domain dimensions, soil-layer properties, cut-off wall geometry, and hydraulic boundary conditions were kept constant, while only the mesh size parameter was adjusted to generate four tetrahedral meshes with different element densities. The numbers of tetrahedral elements and the corresponding steady-state water inflow rates are presented in Figure 4.

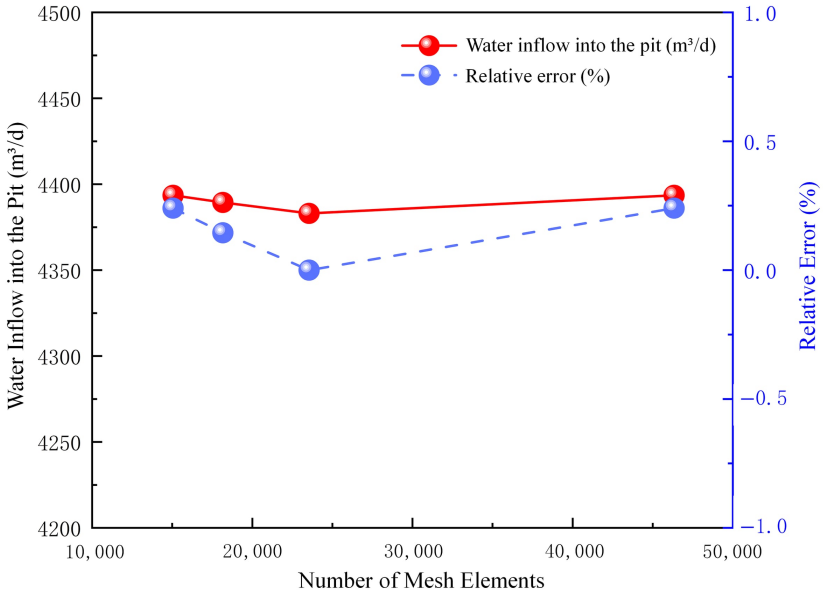


Figure 4. Effect of mesh element number on foundation-pit water inflow.

As the number of tetrahedral elements increased from 15,050 to 46,333, the total water inflow initially decreased from 4393.53 m^3/d to 4383.00 m^3/d and subsequently increased to 4393.53 m^3/d. The maximum difference among the four results was 10.53 m^3/d, corresponding to approximately 0.24% of the result obtained using the finest mesh. In particular, increasing the number of elements from 23,546 to 46,333 resulted in a change of approximately 0.24% in the total water inflow. These results indicate that further mesh refinement has only a minor influence on the calculated water inflow within the investigated range of mesh densities.

3.1.2. Sensitivity Analysis of the Computational Domain Size

To evaluate the influence of the horizontal dimensions of the computational domain on the calculated total water inflow, a square foundation pit with plan dimensions of 60 m × 60 m was selected as a representative case. Four three-dimensional seepage models were established with horizontal domain dimensions of 1000 m × 1000 m, 1500 m × 1500 m, 2000 m × 2000 m, and 2500 m × 2500 m, respectively. The height of each computational domain was maintained at 100 m, with the foundation pit located at the center of the domain. The soil-layer properties, cut-off wall geometry, and hydraulic boundary conditions were kept identical across all models. The tetrahedral mesh was regenerated for each computational domain, and the calculated results are presented in Figure 5.

Taking the results obtained for the 2000 m × 2000 m computational domain as the reference, the relative differences in total water inflow among the four models were all less than 0.5%. When the domain side length increased from 2000 m to 2500 m, the total water inflow decreased from 4383.00 m^3/d to 4380.96 m^3/d, representing a reduction of 2.04 m^3/d, or approximately 0.047% relative to the result before domain enlargement. These results indicate that further enlargement or reduction in the computational domain has only a minor influence on the calculated total water inflow for this representative case. Considering both numerical accuracy and computational efficiency, a computational domain of 2000 m × 2000 m × 100 m was adopted for the steady-state seepage analysis of this case.

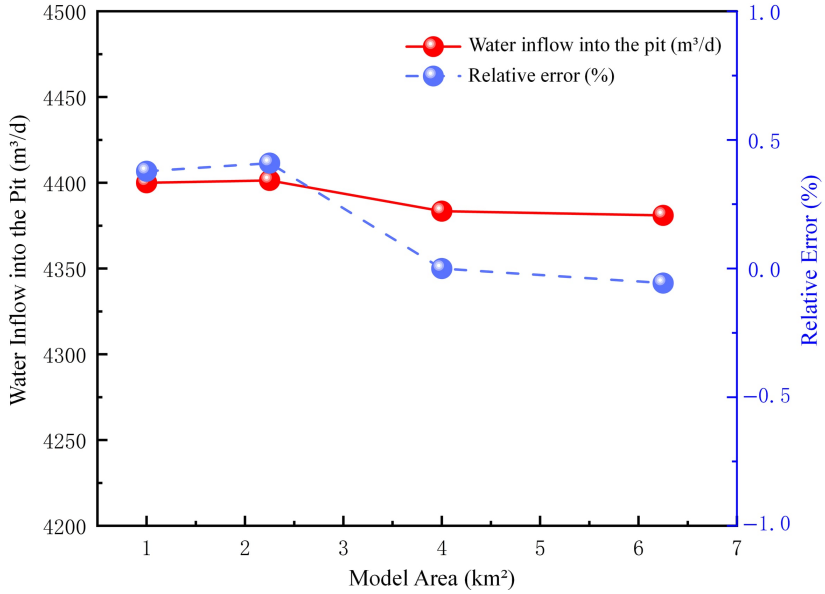


Figure 5. Effect of computational domain size on total foundation-pit water inflow.

3.2. Comparison of Water-Inflow Calculations

To assess the accuracy and applicability of the proposed equation, nearly 200 foundation-pit cases were analyzed by the finite-element method. The numerical results were compared with predictions from the proposed equation, as shown in Figure 6.

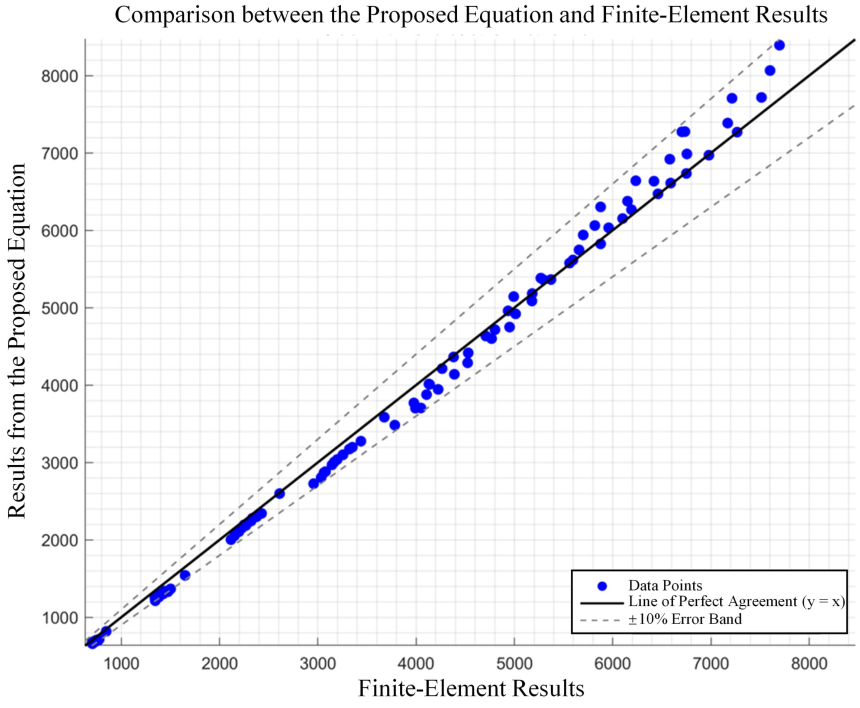


Figure 6. Comparison between the proposed equation and finite-element results. The axes show the two calculated results; the legend identifies the data points, the line y = x, and the ±10% error band.

The proposed method produced inflow values close to the finite-element results. The maximum and minimum relative errors were 10.60% and 0.004%, respectively, while the results generally showed good agreement with the finite-element solutions.

The finite-element flow net for a confined aquifer beneath the excavation is shown in Figure 7. The hydraulic head decreases from outside the pit toward the inside of the pit.

Far from the excavation, confined groundwater flows approximately horizontally; near the excavation, horizontal and vertical components are coupled. The overall flow pattern is consistent with that assumed for Zone ① in Figure 2.

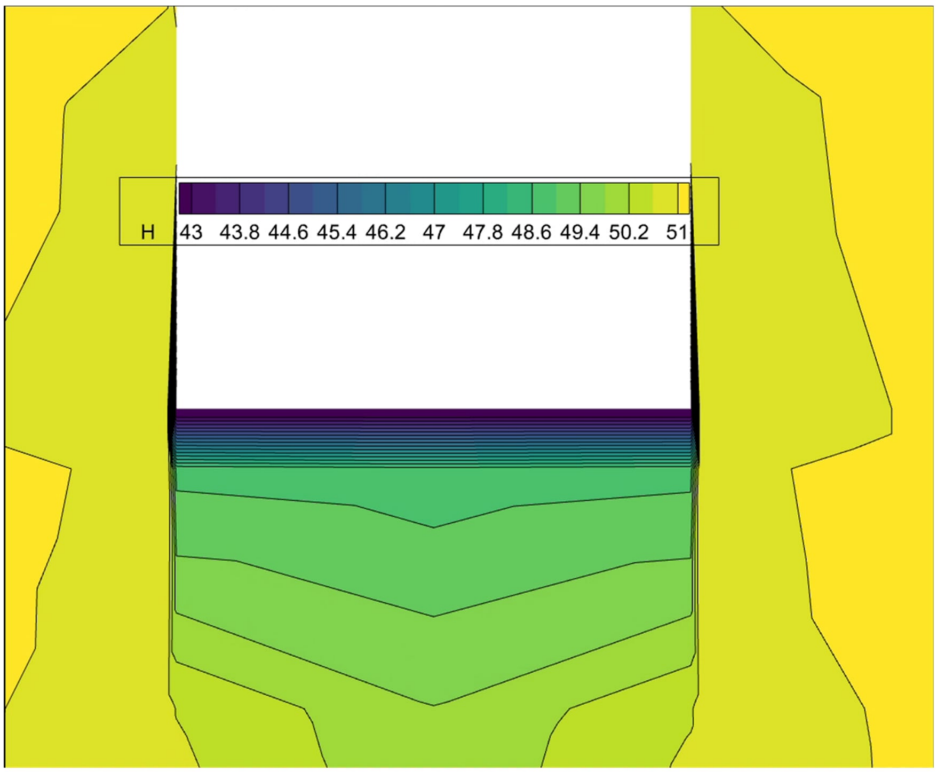


Figure 7. Finite-element flow net for a foundation pit underlain by a confined aquifer.

Figure 8 demonstrates the performance of the proposed method in estimating foundation-pit inflow. The calculated values exhibit both small relative errors and trends consistent with the finite-element results. Although the governing parameters directly affect water inflow, the simplified analytical equation rapidly captures their combined influence and keeps deviations from the finite-element solution within a reasonable range. The assumed confined-groundwater flow pattern also agrees with the numerical flow field, supporting the reliability of the proposed equation.

3.3. Parametric Sensitivity Analysis

3.3.1. Sensitivity to Cut-Off Wall Penetration Ratio

Excavations A and B were selected to evaluate the sensitivity of the equation to cut-off wall penetration ratio. The effects of wall penetration into the confined aquifer on pumping discharge are shown in Figures 9 and 10.

For Excavation A, both the improved resistance coefficient method and the finite-element model show the same overall trend as L/M increases from 0.1 to 0.9. Water inflow decreases relatively slowly for $0.2 < L/M < 0.6$ and more rapidly for $L/M \leq 0.2$ and $L/M \geq 0.6$. The deviation of the proposed method remains within ±10%, indicating good overall agreement and supporting the reliability of the model.

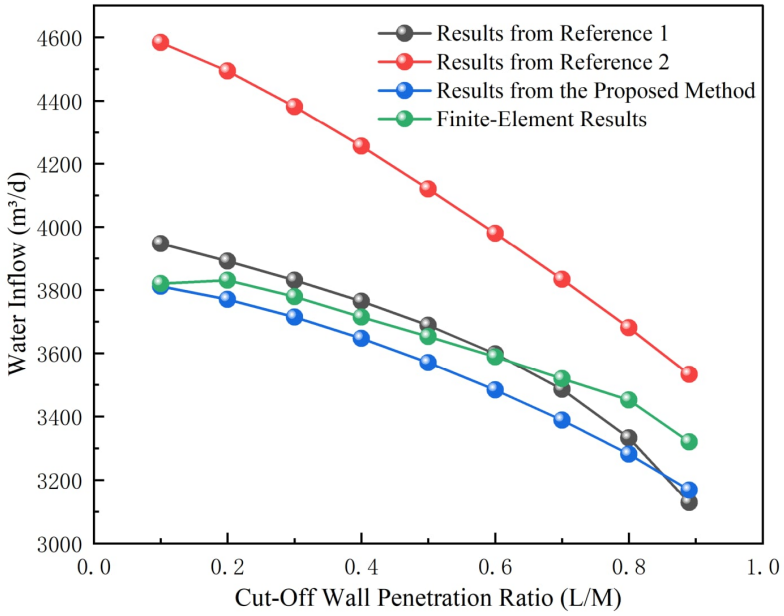


Figure 8. Comparison of the proposed method with results from other published methods. The axes represent L/M and water inflow (m^3/d); the series represent the proposed method, the finite-element model, and two published solutions.

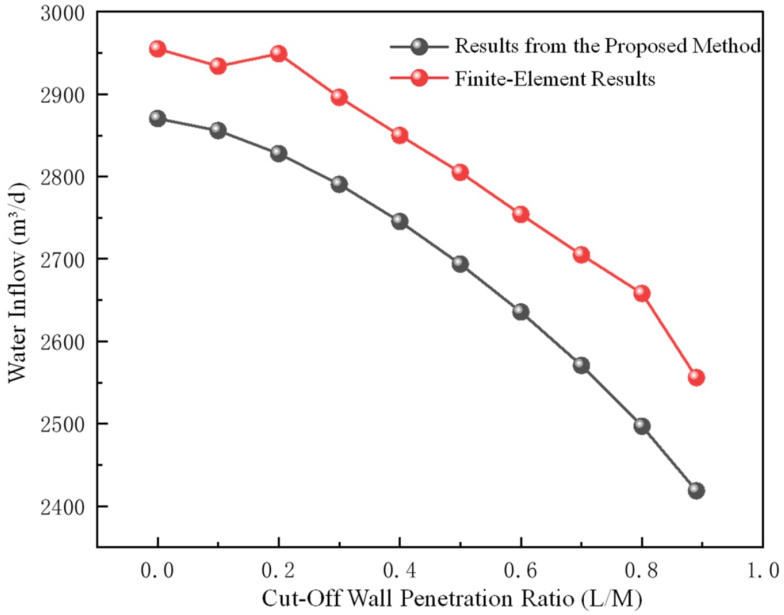


Figure 9. Effect of cut-off wall penetration ratio on water inflow for Excavation A. The gray and red series denote the proposed method and finite-element results, respectively; the axes represent L/M and water inflow (m^3/d).

For Excavation B, water inflow decreases continuously as L/M increases from 0.1 to 0.9. Within the critical range 0.1–0.9, the difference between the improved resistance coefficient method and the finite-element method remains approximately ±5%, indicating close agreement. At small penetration ratios ($L/M < 0.2$), horizontal bypass flow beneath the cut-off wall becomes more pronounced, and the proposed method may slightly overestimate the hydraulic effectiveness of the wall; a modest safety margin is therefore advisable in this range.

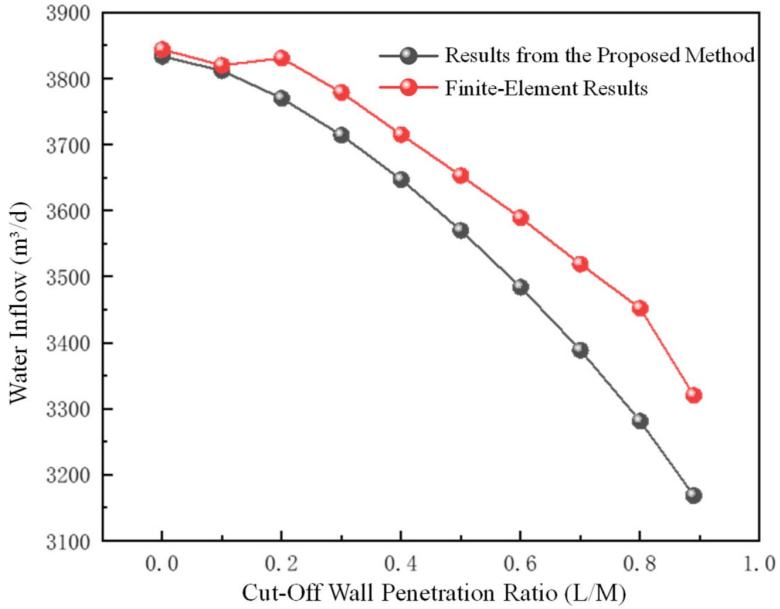


Figure 10. Effect of cut-off wall penetration ratio on water inflow for Excavation B. The gray and red series denote the proposed method and finite-element results, respectively; the axes represent L/M and water inflow (m^3/d).

3.3.2. Sensitivity to Excavation Area

The equivalent radius is calculated from the excavation area as follows:

$$r = \sqrt{\frac{S}{\pi}} \tag{14}$$

where S is the excavation area (m^2).

With the cut-off wall penetration ratio and hydraulic conductivity held constant, a sensitivity analysis was performed to examine the effect of excavation area on pumping discharge. The results are shown in Figure 11.

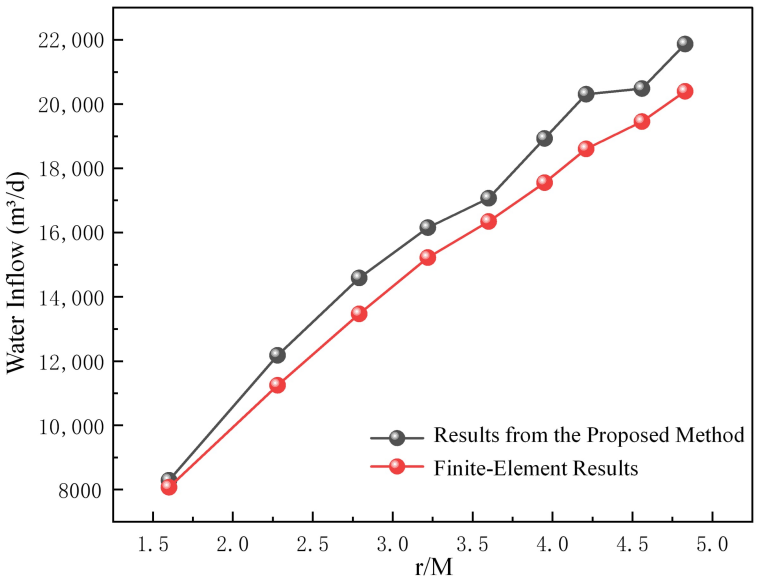


Figure 11. Effect of the equivalent excavation radius-to-aquifer thickness ratio (r/M) on water inflow. The gray and red series denote the proposed method and finite-element results, respectively; the axes represent r/M and water inflow (m^3/d).

As shown in Figure 11, inflow increases markedly with excavation area, represented by increasing r/M. At small r/M, the relative difference between the two methods is approximately 2.70%. As r/M increases, the difference rises to approximately 7.21%, indicating that the proposed equation may slightly overestimate inflow for large excavations. Overall, the method is reliable within its engineering range and provides a theoretical basis for dewatering design; for very large excavations, combined evaluation with numerical modeling is recommended.

3.3.3. Sensitivity to the Hydraulic-Conductivity Ratio

The model assigns different hydraulic conductivities to the high- and low-permeability layers. Figure 12 shows the influence of their conductivity ratio on foundation-pit inflow.

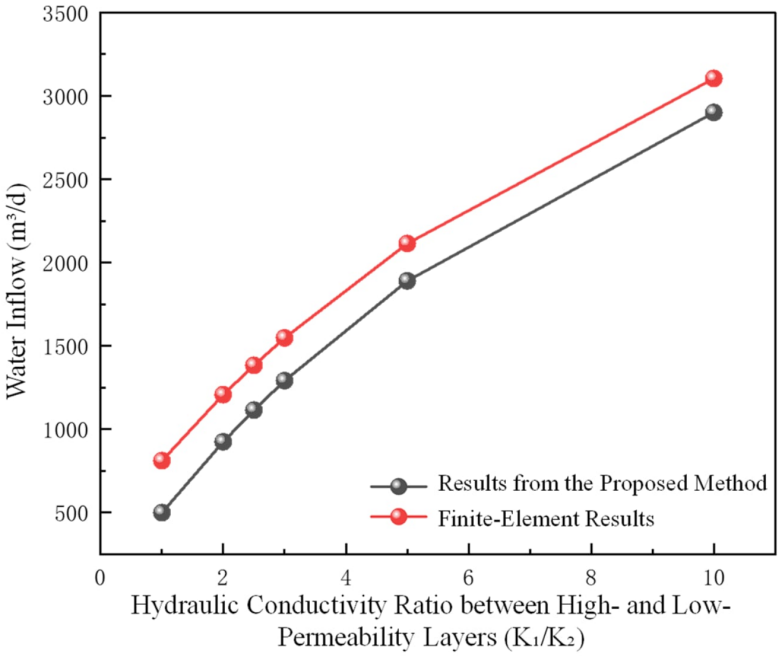


Figure 12. Effect of the hydraulic-conductivity ratio between high- and low-permeability layers on water inflow. The gray and red series denote the proposed method and finite-element results, respectively; the axes represent K_1/K_2 and water inflow (m^3/d).

Figure 12 presents the effect of the hydraulic-conductivity ratio K_1/K_2 between the confined aquifer and the relatively low-permeability layer. The proposed method is applicable when $K_1/K_2 \geq 5$. In this range, the contrast in permeability is sufficiently pronounced for the model assumptions to represent the actual seepage characteristics. When $K_1/K_2 < 5$, the two layers have similar permeabilities, the flow field becomes more complex, and the assumptions of the model are no longer valid, causing a substantial increase in calculation error.

3.3.4. Sensitivity to Excavation Aspect Ratio

The derivation considers a square excavation, for which conversion to an equivalent circular excavation using the equal-area method is most appropriate. Figure 13 evaluates the applicability of the proposed equation to rectangular excavations.

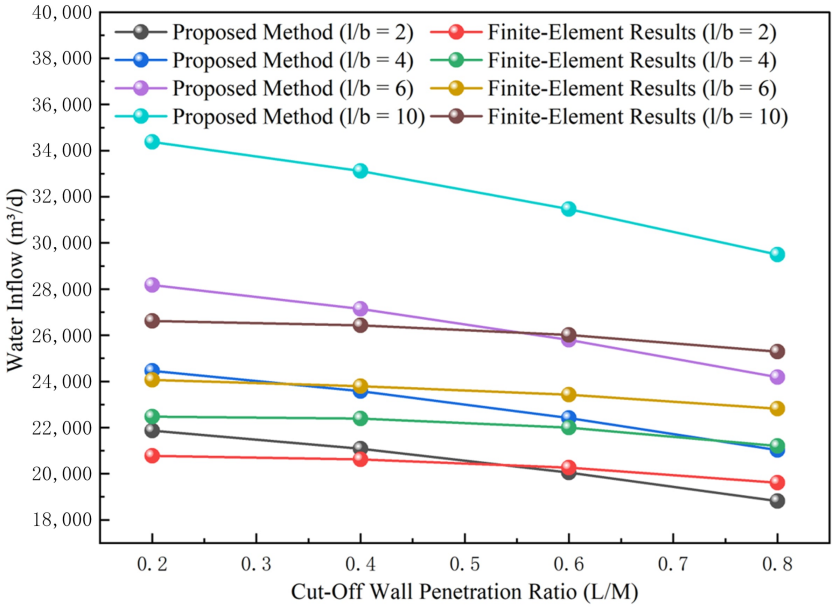


Figure 13. Applicability of the proposed equation to rectangular foundation pits. The axes represent cut-off wall penetration ratio L/M and water inflow (m^3/d); paired series compare the proposed method with finite-element results for aspect ratios l/b = 2, 4, 6, and 10.

As shown in Figure 13, the proposed equation is applicable to rectangular excavations with aspect ratios l/b from 1 to 4. When l/b > 4, radial convergence weakens and the inflow pattern changes from perimeter-controlled flow to flow dominated by the long sides. This behavior is inconsistent with the assumed radial convergence, and the calculation error increases substantially; the equation is therefore not recommended beyond this range.

4. Conclusions

This study systematically extends the improved resistance coefficient method, originally developed for navigation-lock seepage analysis, to the calculation of water inflow into foundation pits with suspended cut-off walls under confined groundwater conditions. By adapting the conventional method, refining the seepage segmentation, and combining case validation with parametric sensitivity analysis, a rapid prediction approach with both theoretical basis and engineering practicality is established.

Nearly 200 representative foundation pits were modeled in three dimensions for validation. For all cases, the maximum relative error was 10.60%, demonstrating good agreement with the finite-element results. The method also remained stable under different wall penetration ratios, supporting the rationality and effectiveness of the four-segment resistance formulation.

The sensitivity analysis focused on the cut-off wall penetration ratio. Results for Excavations A and B revealed a nonlinear relationship between inflow and L/M. Increasing wall depth produces a relatively modest reduction in inflow for $0.2 < L/M < 0.6$, whereas inflow is considerably more sensitive to penetration ratio when $L/M < 0.2$ or $L/M > 0.6$. This finding provides direct guidance for optimizing wall depth: indiscriminately increasing depth may not control inflow economically, and design should account for the critical sensitivity ranges. At very small penetration ratios, horizontal bypass flow dominates, and the method may systematically overestimate the hydraulic effectiveness of the wall, producing a positive bias of approximately 10% relative to finite-element results. This boundary condition should be considered in application.

To facilitate engineering application, the applicability conditions and limitations of the method proposed in this paper are summarized as follows.

(1) Applicable conditions. The proposed method is applicable under the following conditions: ① The aquifer is a homogeneous, layered confined aquifer, with a relatively low-permeability layer beneath the excavation base, and the hydraulic conductivity ratio satisfies $K_1/K_2 \geq 5$. ② A vertical suspended (partially penetrating) cut-off wall is employed without fully penetrating the confined aquifer, and the penetration ratio L/M ranges from 0.1 to 0.9. ③ The method is primarily developed for square foundation pits and can be extended to rectangular excavations with aspect ratios $l/b \leq 4$. ④ Dewatering has reached a stable stage and can be treated as steady-state seepage, while additional recharge or discharge pathways, such as artificial recharge and leakage through cut-off wall joints, are neglected. ⑤ The radius of influence R is determined according to site-specific hydrogeological conditions or pumping tests, and the correction coefficient α is calculated using the empirical fitting equation proposed in this study, with all input parameters remaining within the validated ranges.

(2) Non-applicable conditions and limitations. The proposed method has the following limitations: ① It does not account for transient seepage during the initial pumping stage, elastic groundwater release from the aquifer, or time-dependent boundary conditions. ② It is not recommended for rectangular foundation pits with aspect ratios $l/b > 4$ or irregularly shaped excavations, where three-dimensional flow convergence near the corners becomes more complex. ③ When $K_1/K_2 < 5$, the hydraulic conductivity contrast between the high- and low-permeability layers becomes less pronounced, causing the actual seepage field to deviate from the model assumptions and resulting in increased calculation errors. ④ When $L/M < 0.2$, horizontal bypass flow beneath the cut-off wall becomes dominant. Under such conditions, the proposed method may systematically overestimate the hydraulic effectiveness of the cut-off wall and consequently underestimate water inflow. An appropriate safety margin should therefore be considered, and three-dimensional numerical simulations are recommended for verification in critical engineering projects. ⑤ The method is not applicable to unconfined aquifers or conditions involving leakage recharge or defects in the cut-off wall. ⑥ For large foundation pits with relatively high r/M values, the calculation error may reach approximately 7%. Therefore, supplementary evaluation using numerical simulations is recommended.

The proposed method has several limitations that warrant further study. The derivation and validation primarily address square excavations. For rectangular excavations with large aspect ratios and for irregular excavations, three-dimensional convergence near the corners is more complex, and shape correction factors may be required. The method also assumes steady seepage and is intended to predict inflow after dewatering has stabilized. It does not explicitly represent transient flow during the initial pumping stage, elastic release from the aquifer, or time-dependent boundary conditions.

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