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Abstract

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Abstract

The groundwater inflow into a mine during its life and after ceasing operations is one of the most important concerns of the mining industry. This paper presents a hydrogeological assessment of the Irankuh Zn-Pb mine at 20 km south of Esfahan and 1 km north-east of Abnil in west-Central Iran. During mine excavation, the upper impervious bed of a confined aquifer was broken and water at high-pressure flowed into an open pit mine associated with the Kolahdarvazeh deposit. The inflow rates were 6.7 and 1.4 m^3/s at the maximum and minimum quantities respectively. Permeability, storage coefficient, thickness and initial head of the fully saturated confined aquifer were 3.5×10^{-4} m/s, 0.2, 30 m and 60 m, respectively. The hydraulic heads as a function of time were monitored at four observation wells in the vicinity of the pit over 19 weeks and at an observation well near a test well over 21 hours. In addition, by measuring the rate of pumping out from the pit sump, at a constant head (usually equal to height of the pit floor), the real inflow rates to the pit were monitored. The main innovation of this work was to make comparison between numerical modelling using a finite element software called SEEP/W and actual data related to inflow, and extend the applicability of the numerical model. This model was further used to estimate the hydraulic heads at the observation wells around the pit over nineteen weeks during mining operations. Data from a pump-out test and observation wells were used for model calibration and verification. In order to evaluate the model efficiency, the modelling results of inflow quantity and hydraulic heads were compared to those from analytical solutions as well as the field data. The mean percent error in relation to field data for the inflow quantity was 0.108. It varied between 1.16 and 1.46 for hydraulic heads predictions, which are much lower values than the mean percent errors resulted from the analytical solutions (from 1.8 to 5.3 for inflow and from 2.16 to 3.5 for hydraulic heads predictions). The analytical solutions underestimated the inflow compared to the numerical model for the time period of 2-19 weeks. The results presented in this paper can be used for developing an effective dewatering program.

Keywords: Irankuh Zn-Pb mine; SEEP/W; Finite element; Jacob-Lohman equation; McWhorter equation; Hydrogeology

1. Introduction

In mines where excavation is carried out below the water table, groundwater flows from the surrounding strata toward the mining works. In the case of a confined aquifer, as the overburden materials and the mineral deposit are extracted during the mining operation, the impervious bed(s) may break and water under high-pressure may flow into the mining excavation. Unexpected inflow in large quantities may impede production, delay the project and may cause many safety and environmental problems (Singh and Atkins 1985a). In addition, it may form a pit lake (sump). Undesirable effects of this may include loss of access to all or part of the mine working area, greater use of explosives, increased explosive failures resulting from wet blast holes, the need to use special explosives, increased wear on equipment and tires, inefficient loading and hauling, and unsafe working conditions (Morton and van Mekerk 1993). Furthermore, groundwater inflow can have a detrimental effect on pit slope stability. Hence, it is necessary to install an effective dewatering system to keep the mine workings dry. To achieve the goal, prediction of groundwater inflow into a mining excavation is a necessary task. In addition, dewatering can place considerable hydrological stress on the regional groundwater system, by creating an extensive and prolonged cone of depression, regional groundwater table lowering, overlapping cones of depression, land subsidence, and water quality deterioration, which can endanger mine productivity and human life (Keqiang et al. 2006). All of these problems are related to changes in hydraulic head (Morton and van Mekerk 1993) and therefore, modelling the hydraulic head during pit advance can provide valuable information for designing an appropriate dewatering scheme.

Many analytical solutions have been used to estimate the groundwater inflow into mining excavations (e.g. Hofedank 1979; McWhorter 1981; Singh and Atkins 1984, 1985 a, b; Singh et al. 1985; Singh and Reed 1987; Vandersluis et al. 1995; Lewis 1999 and Marinelli and Niccoli 2000). Analytical models are based on some assumptions and specific boundary conditions that limit their applicability in different mining situations. For example, most analytical solutions do not directly account for inflow through the pit bottom (Hanna et al. 1994) nor can they simulate water table and saturated-unsaturated flow conditions in an unconfined aquifer. Hence, analytical solutions are not appropriate for all hydrogeological situations.

Numerical models can simulate all aquifer conditions and provide a more realistic representation of the interaction between groundwater systems and mining excavations (Doulati Ardejani et al. 2003a). In recent decades several computer codes have been developed to model groundwater inflow. Some examples are:

- use of a finite element code to model complex mine water problems (Azrag et al. 1998);
- FEFLOW, a finite element subsurface flow and transport simulation model (Diersch 2006);
- optimization of mine drainage capacity using FEFLOW for the No. 14 coal seam of China's Linnancang coal mine (Dong et al. 2012).

However, many numerical codes are limited in their capability and cannot easily model a variety of aquifer conditions. In order to defeat some of these limitations, the authors have used a two-dimensional finite element model called SEEP/W (Geo-Slope International Ltd 2012) to simulate groundwater inflow to an open pit mine and the hydraulic heads at four observation wells. The software has already been used for similar purposes (Doulati Ardejani et al. 2003a; Aryafar et al. 2009 and Singh et al. 2012) but comparisons with actual data related to inflow have not been attempted in any of them.

Doulati Ardejani et al. (2003a) presented a two-dimensional numerical finite element model using SEEP/W code to predict groundwater inflow to surface mining excavations and to calculate the height of the seepage face in and around the pit. They simulated saturated-unsaturated flow conditions; taking into account the hydraulic conductivities and the water content as a function of pore water pressure. The simulation results were compared to those from analytical solutions and other existing numerical codes developed for pit inflow prediction. However, the application of the model in a real mine was not evaluated.

Aryafar et al. (2009) presented a model to simulate groundwater inflow from an infinite confined aquifer into the Sangan iron mine using SEEP/W software. The inflow simulation was first evaluated and verified by comparing the output from this model with results obtained from Theis, Cooper-Jacob and Jacob-Lohman analytical solutions. The model was then applied to predict groundwater inflow into the Sangan open pit mine during its advance. It was concluded that the analytical Jacob-Lohman solution and the numerical model present an approximately similar trend for inflow rate as a function of time. Although the model describes well the inflow problem related to a confined aquifer, a comparison between the predicted inflow and the real inflow was not considered.

Singh et al. (2012) investigated the hydrogeological issues relating to the Thar lignite field in Sindh, Pakistan. They described the proposed mine dewatering scheme to facilitate depressurising of the rock mass surrounding the mining excavations. Groundwater inflow to the surface mining excavation during its advance was predicted using SEEP/W finite element model. A sensitivity analysis of various factors affecting groundwater inflow was further conducted and it was found that the model is sensitive to permeability of the aquifer.

The main objectives of this research were to simulate groundwater inflow into an open pit mine and model the hydraulic heads in observation wells at different distances from the centre of the pit during a period of the mining process. To achieve these objectives, SEEP/W software was used. The accuracy and reliability of the model predictions are verified by field data and some of the well-known analytical solutions. The results of this paper can be effectively used for developing an efficient dewatering program.

2. Description of the Investigation Site

2.1. Geographical Situation and the Climate of the Study Area

The Irankuh district comprises several Zn-Pb deposits including the Goushfil pit (sulphide ore), the Kolahdarvazeh pit (non-sulphide ore) and the Tappeh-Sorkh pit. They are located in the Irankuh Mountain Range, 20 km south of Esfahan and 1 km north-east of Abnil in west-central Iran. The elevation of the mines is approximately 1700 m above the sea level. The minable ore reserve of these mines is estimated at approximately 10 million tones with 7.5% zinc and 2.4% lead. Mining operations in the Kolahdarvazeh mine started in 1962. The study area has a warm climate with an annual relative humidity of 30% (BAMA Mining Company 2003 and Esfahan Province Environmental Office 2013). The location of the study area and a schematic view of the Kolahdarvazeh open pit mine, pumping well and observation wells are shown in Fig.1. OW1, OW2, OW3 and OW4 (four observation wells in the vicinity of the pit) are located at 750, 1050, 1260 and 1440 m distance from centre of the pit respectively.

2.2. Geology

Detailed investigations on non-sulphide ore samples from the Kolahdarvazeh mine have been performed on boreholes DDH64 and DDH40, located within the area of the Kolahdarvazeh pit. Borehole DDH64 has a UTM position of 3598421.092N and 553313.532E with an elevation of 1670 m above the sea level. Its total depth is 129.2 m with an inclination of 80° and a dip-direction of 251°. Borehole DDH40 (3598484.102N and 553174.822E) is located 1620 m above the sea level and it's depth was 151.2 m with an inclination of 65° and a dip-direction of 70. Fig.2 shows the profiles of boreholes DDH 64 and DDH 40 (Reichert 2007). As illustrated in Fig. 2, the Pb and Zn mineralisation occurs in dolomite (which is of Barremian age) and it contains both sulphide and non-sulphide mineralisation types. Zn varies between 10 % and 20.1 % and between 3.5 % and 32 % in boreholes DDH40 and DDH64 respectively. The Pb grade ranges of 0.8-2.2 % and 1.5-4.4 % were determined for boreholes DDH40 and DDH64 respectively.

2.3. Hydrogeological Investigation and Precipitation

Based on a detailed exploration program (BAMA Mining Company 2003) and the study carried out by Reichert (2007) in the Irankuh district, an average thickness of 30 m was observed for a fully saturated confined aquifer in the dolomite rocks which extends toward the Kolahdarvazeh mine throughout the study area. It is an artesian aquifer type with a 60 m initial head and a porous medium flow domain is dominant. The average annual precipitation at the site is between 100 and 150 mm and the values of the hydraulic conductivity and storage coefficient of the confined aquifer were 3.5×10^{-4} m/s and 0.2 respectively.

2.4. Pit Geometry

Three-dimensional knowledge of the ore body, including thickness, dip, depth, lateral extension and the proposed mining boundaries, is generally required to define the pit geometry (Singh et al. 1985). Uppermost and lowermost benches of the study pit were 1670 m and 1565 m and the periphery extended about 1100 m NW-SE and 600 m NE-SW. The confined aquifer upper layer is located at 1593 m, above the sea level. The parameters considered in the open pit design were bench height of 10 m, individual bench slope about 70°, overall pit slope of 45°. In the final stage of mine development, the pit had penetrated 28 m into the confined aquifer (BAMA Mining Company 2003).

3. Materials and Methods

3.1. Measuring Field Data

Four data sets were prepared for this study. They include rate of groundwater inflow from the confined aquifer into the Kolahdarvazeh open pit mine, hydraulic heads at four observation wells around the pit during its advance over nineteen weeks and hydrodynamic coefficients and hydraulic heads at another observation well, 10 m from the pumping well, over a 21 hour period. All of the observation wells and the pump-test well fully penetrated the confined aquifer.

The water levels were monitored at the observation wells using a tape measure equipped with a device that is designed to make a noise when it touches the water surface. To quantify the aquifer hydrodynamic parameters comprising transmissivity and storage coefficient, a 0.6m diameter pumping well was drilled using a cable tool drilling method. The pit inflow rate from the confined aquifer was obtained by measuring the pump-out rate from the pit sump at a constant water level equal to the height of pit floor. In all wells, the aquifer thickness was approximately 30 m. The hydraulic conductivity and storativity of the aquifer obtained from the pump-test data were 3.5×10^{-4} m/s and 0.2, respectively.

The data obtained from the pump- test well (PW in Fig.1) and those from an observation well, 10 m from the pumping well, were used for model verification and the other data were utilised to check the modelling results for groundwater inflow and hydraulic head prediction.

Table 1 gives the minimum and maximum values of hydraulic head at the four observation wells, from the aquifer base.

3.2. Simulation Tool and Governing Equation

A commercial two-dimensional finite element software called SEEP/W, developed by Geo-Slope International Ltd. (2012) was used to predict groundwater inflow into the open pit and hydraulic heads at the observation wells. The software solves the governing flow equation (Eq. 1)

(Domenico and Schwartz 1990). The appropriate initial and boundary conditions are specified in order to constrain the problem and make the solution unique (Fig. 3).

$$\frac{\partial}{\partial x}\left(K_x(\varphi)\frac{\partial \varphi}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y(\varphi)\frac{\partial \varphi}{\partial y}\right)+Q=c(\varphi)\frac{\partial \varphi}{\partial t} \quad (1)$$

where, $K_x(\varphi)$ and $K_y(\varphi)$ = permeability values in x and y directions (m/s); φ = matrix potential (m); x and y= Cartesian coordinates (m); t= time (s); $c(\varphi)$= slope of the moisture characteristic curve (m^{-1}) and Q= boundary flux (s^{-1}).

Detailed theoretical aspects of SEEP/W software and solution method for the governing equation are well described elsewhere (Gray and Pinder 1974; Hofedank 1979; Doulati Ardejani et al. 2003a, b; Aryafar et al. 2009; Geo-Slope International Ltd. 2012).

3.3. Conceptual model

A real geo-water system and its behaviour are often complicated and much detail is needed to describe such environments. One of the major steps in the modelling process is the construction of a conceptual model of the problem and of the relevant domain. According to Bear and Cheng (2010), a conceptual model comprises a set of assumptions that reduce the real problem and the real domain to simplified versions that are satisfactory in view of the modelling objectives, the associated management problem, and the available data.

Fig.3 shows a conceptual model of the problem under investigation. This model identifies an open pit mine, a confined aquifer ruptured by the pit, initial hydraulic head, aquifer thickness and the pit depth at the aquifer. The flow vectors, aquifer boundaries and boundary conditions, drawdown curves, water level at the bottom of the pit and the pit advance are also illustrated.

Groundwater inflow to the pit takes place laterally from the pit walls and a vertical upward inflow also occurs from the pit floor (Esfahan Province Environmental Office 2013).

3.4. Evaluation of Aquifer Parameters

Using pump-out test data and values of water level monitored at an observation well 10 m from the pumping well, the transmissivity and storage coefficient of the aquifer can be calculated using the Cooper-Jacob equation (Cooper and Jacob 1946; Kruseman and De Ridder 1979) as follows:

$$T=\frac{2.3\times Q}{4\pi\Delta S} \quad (2)$$

where, Q = pumping rate (6.2×10^{-2} m^3/s) and ΔS = drawdown, in the logarithmic scale (1.081 m).

Thus, the average transmissivity of the aquifer is calculated as follows:

$$T=\frac{2.3\times 0.062}{4\pi\times 1.081}=0.0105\ m^2/s$$

The average hydraulic conductivity of the aquifer can be expressed as:

$$K = \frac{T}{m} \quad (3)$$

where, m = permeable thickness of the aquifer (30 m) and T = transmissivity (m^2/s)

Thus, the hydraulic conductivity (K) will be 3.5×10^{-4} m/s.

The storage coefficient can be calculated using the following equation:

$$S = \frac{2.25 \times T \times t_0}{r^2} \quad (4)$$

where, t_0 = intercept of drawdown line with the time axis (t_0 = 846.6 s) and r= radial distance from the pumping well (10m).
Thus, the storage coefficient of the aquifer will be:

$$S = \frac{2.25 \times 0.0105 \times 846.565}{10^2} = 0.2$$

3.5. Model Verification

One real problem is described related to the pumping test in a confined aquifer to verify the numerical modelling of the groundwater inflow process.

Fig. 4 shows a finite element grid incorporating 253 nodes and 50 elements in a single 30 m thick layer with a model length of 35 m. The rectangular mesh comprised eight-noded elements with an infinite element at the outer boundary of the aquifer in order to simulate an infinite, homogenous aquifer extending away from the pumping well. The grid spacing increases from the well to the outer boundary with a size ratio of 3. The size ratio is the ratio of the length of the last element to that of the first element along the side (Geo-Slope International Ltd. 2012). A steady-state simulation was first performed to establish an initial condition. The total head at the two ends of the aquifer was assigned a value of 60 m. Hence, a uniform total head distribution of 60 m was generated throughout the entire aquifer. An axisymmetric simulation was conducted by considering a radial flow towards the pumping well. 12 time steps were considered to simulate transient flow conditions. The following boundary conditions were assigned to the transient model:

- No-flow boundaries at the upper and lower layers of the confined aquifer.
- A constant head boundary at the right-hand side of the model.
- A flux boundary at the left-hand side of the model next to the pumping well.

The input parameters to the inflow model were:

- Hydraulic conductivity = 3.5×10^{-4} m/s,
- Storage coefficient = 0.2,
- The initial hydraulic head = 60 m,
- Thickness of the confined aquifer = 30 m,
- Pumping out rate = 0.62×10^{-1} m^3/s,
- The well radius = 0.3 m.

Fig. 5 compares the results of the numerical simulation and the field data for hydraulic head at an observation well, 10 m from the pump-out test well. The simulation results are in close agreement with the monitored field data, showing a relative error of 0.084%.

3.5 Sensitivity Analysis

In this paper, a sensitivity analysis was conducted in order to select the best values for parameters and to assess which parameters most affected the modelling results. The main parameters considered in this paper were hydraulic conductivity, aquifer storage coefficient, initial hydraulic head and aquifer thickness. According to Fig. 6, it is evident that modelling results are very sensitive to the hydraulic conductivity of the confined aquifer and initial head. The best values for hydraulic conductivity, storage coefficient, initial head and thickness of the confined aquifer were 3.5×10^{-4} m/s, 0.2, 60 m and 30 m, respectively.

3.6. Prediction of Groundwater Inflow to the Kolahdarvazeh Open Pit Mine

In order to predict groundwater inflow during mine advance, three successive simulations were carried out (Fig. 7). A number of special boundary conditions and important input parameters shared by all models include:

- No-flow boundary conditions at the upper and lower layers of the aquifer,
- An infinite element at the outer boundary, at the right-hand side of the confined aquifer,
- A constant head boundary at the right-hand side of the models = 60 m,
- Hydraulic conductivity = 3.5×10^{-4} m/s,
- Storage coefficient = 0.2,
- Aquifer thickness = 30 m,
- Model length = 1990 m.

An axisymmetric finite element simulation was carried out using a grid constructed with 66 elements and 134 nodes. The rectangular grid consisted of four-noded elements. Numbers of time steps were 6, 8 and 5 for phase 1, phase 2 and phase 3, respectively and the simulation time was 19 weeks. The axisymmetric analysis simulated a radial flow to the mine.

The advance of the pit was simulated by assigning a constant head at the radius of the pit corresponding to specified pit depths at various stages of the mining operation.

After constructing the finite element grid and giving the hydraulic conductivity, a steady-state simulation was performed to set up an initial condition for the aquifer before transient simulations. Constant heads of 60 m were assigned at the two ends of the aquifer and the model was then run. This simulation generated a uniform total head distribution of 60 m throughout the entire aquifer, representing the pre-mining situation (See Doulati Ardejani et al. 2003a for more details).

In the first phase of the transient simulation, a constant head of 20 m was assigned at the mine excavation. By calling the initial condition and by specifying a storage coefficient of 0.2, the inflow was modelled, in which 6 time steps were considered. During each time step, inflow to the pit was predicted.

Similarly, by assigning appropriate constant heads of 10 and 2 m at the mine excavation, the second and the third phases of transient simulations were performed, respectively. The predictions obtained for the last time step of each phase of the simulation were used to provide the initial conditions for predicting inflows during the following phase of the simulation.

One of the most important advantages of this simulation method is that it considers the effect of time and face advance on the predicted inflow quantity. In order to predict hydraulic heads at the observation wells (OW1, OW2, OW3 and OW4), the finite element mesh of each model (Fig. 7) was constructed wherein the observation wells are exactly located on the nodes at different distances from the pit axis.

4. Results and Discussion

Fig. 8 compares the field data with those from the SEEP/W model and analytical solutions (Jacob and Lohman 1952; McWhorter 1981; Singh et al. 1985) for groundwater inflow as a function of time into the Kolahdarvazeh pit during its advance. As Fig. 8 shows, unlike the results of analytical solutions, the numerical predictions indicate a close agreement with the field measured data with a relative error of 0.11%. The groundwater inflow quantities of three phases of simulations decreased with time at different rates. Phase 1 and phase 3 had the maximum and minimum decreasing rates respectively.

In the first phase of transient simulation, the inflow decreased sharply from 6.7 m^3/s to 3.04 m^3/s within two weeks of the beginning of the pit advance. From week 2 to week 6 (at the end of first phase simulation), it decreased linearly from 3.04 m^3/s to 2.1 m^3/s.

The inflow increased at a steady rate from 2.1 m^3/s to 2.6 m^3/s at the beginning of phase 2 (between weeks 6 and 7). It then decreased at almost same rate from 2.6 m^3/s to 2.3 m^3/s between times 7 and 8 weeks. At times between 8 and 14 weeks, the inflow decreased steadily at a lower rate from 2.3 m^3/s to 1.85 m^3/s. As time progressed (from week 14 to week 15), the inflow decreased linearly from 1.85 m^3/s to 1.55 m^3/s.

In the third phase, the inflow decreased very slightly from 1.55 m^3/s to 1.4 m^3/s with a gradual rate of decline (from week 15 to week 19).

Table 2 gives the mean percent error in predicting the groundwater inflow by the numerical model and analytical solutions over a 19-week time period.

At the end, hydraulic heads at four observation wells (OW1, OW2, OW3 and OW4) were predicted. Fig. 9 compares the field monitored data and those from the SEEP/W model and analytical solutions (Theis 1935; Kruseman and De Ridder 1979) for hydraulic heads as a function of time during pit advance. The hydraulic head decreased with time at four observation wells, with very similar trends.

As Fig. 9 shows, relatively slight differences can be seen between the field data, results of the numerical model and the analytical solutions. The closest agreement was achieved between the model simulated hydraulic heads and the field monitored data at the four observation wells, whereas the Theis analytical solution underestimated the hydraulic heads. This underestimation by the Theis equation is most obvious at the observation well OW2. The analytical solution of Kruseman and De Ridder (1979) slightly overestimated heads at the observation wells OW1 and OW4 and it underestimated heads at the observation wells OW2 and OW3.

In general, a slightly greater difference in hydraulic head can be seen between the model predictions and the observed data at the observation well OW1 (Fig. 9a) compared to that of the other observation wells (Fig. 9b to d). The correlation between the field data and the simulated results is very close for the time period of 1-9 weeks. For the period of 9-15 weeks, the model slightly overestimated the hydraulic heads. The overestimation by the numerical model related to the field data is more obvious for the rest of simulation time (between weeks 15 and 19).

Table 3 illustrates the mean percent error for predictions of the hydraulic heads by the numerical model and analytical solutions within nineteen weeks during three phases of the pit advance.

5. Conclusions

A numerical finite element model called SEEP/W has been used to predict groundwater inflow from a confined aquifer into the Kolahdarvazeh pit of the Irankuh Zn-Pb mine, Esfahan province, Iran. A pump-out test simulation was first performed. A sensitivity analysis was carried out in order to select the best values for parameters in the best quantities and to assess which parameters most affected the simulation results. The best values of hydraulic conductivity, storage coefficient, initial head and thickness of the study confined aquifer were 3.5×10^{-4} m/s, 0.2, 60 m and 30 m, respectively. It was found that the simulated results are highly sensitive to the hydraulic conductivity and initial head. The inflow simulation was verified by comparing the results from the present model with results obtained from the analytical solutions and the field monitored data. It was found that at the early stages of inflow simulations up to a time of 2 weeks, inflow values predicted by the model were quite similar to those calculated by the analytical models and the field data. Above 2 weeks time, the numerical predictions indicate a close agreement with the field measured data with a relative error of 0.108%. The analytical solutions underestimated the inflow for the time period of 2-19 weeks. The mean percent error for hydraulic head predictions by the numerical model varies from 1.16% to 1.46% at the observation wells. The results of this paper can be used for designing an effective groundwater management program to minimise the adverse effects of mine water during the life of the mine and after ceasing mining operation.

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Figure captions

Fig. 1. The location of the study area and a schematic view of the open pit, pumping well and observation wells.

Fig. 2. Profiles of boreholes DDH 64 and DDH 40 (Reichert 2007).

Fig. 3. Conceptual model of radial inflow from a confined aquifer to an open pit mine.

Fig. 4. Finite element grid of the pumping out test.

Fig. 5. Comparison of hydraulic head predicted by numerical model (solid line) and filed data (triangles) at an observation well, 10 m from the pumping test well.

Fig. 6. Sensitivity of the model to: a. hydraulic conductivity, b. storage coefficient, c. initial head and d. aquifer thickness.

Fig. 7. Finite element grids for modelling the groundwater inflow and hydraulic head during pit advance: a. phase 1, b. phase 2 and c. phase 3.

Fig. 8. Comparison of field data (triangles) with those from SEEP/W model (solid line) and analytical solutions (broken lines) for groundwater inflow into Kolahdarvazeh mine during pit advancement.

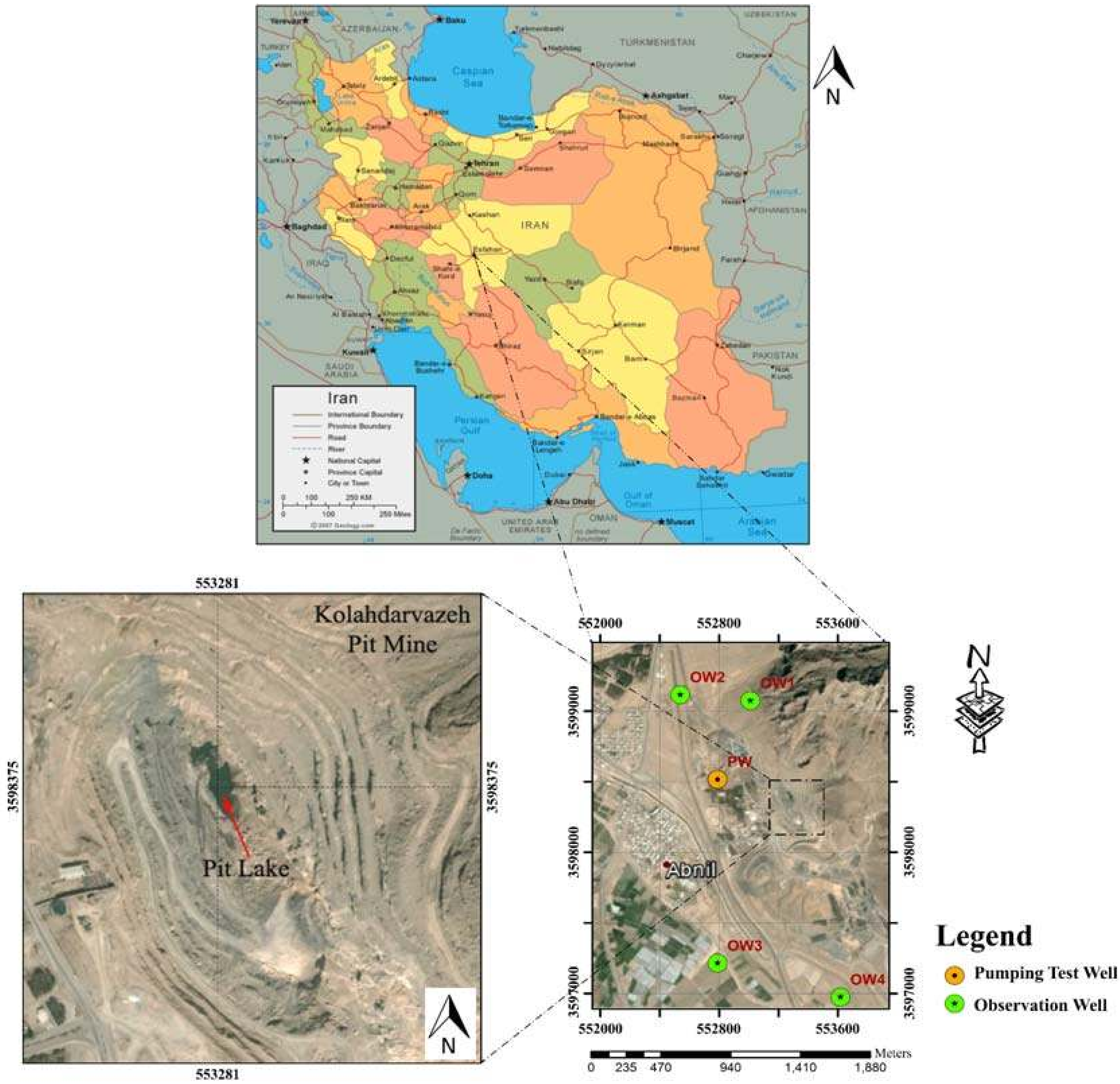
Fig. 9. Comparison of field data (triangles) with those from SEEP/W model (solid lines) and analytical solutions (broken lines) for hydraulic heads as a function of time at the observation wells: a. OW1, b. OW2, c. OW3 and d. OW4.

Table captions

Table 1. Minimum and maximum values of hydraulic head (H.H.) at observation wells, in metre.

Table 2. Calculated error (%) related to the measured values for groundwater inflow from the confined aquifer into the Kolahdarvazeh open pit mine.

Table 3. Calculated mean percent error related to the measured data for hydraulic head at the four observation wells (OW1, OW2, OW3 and OW4) during pit advancement.



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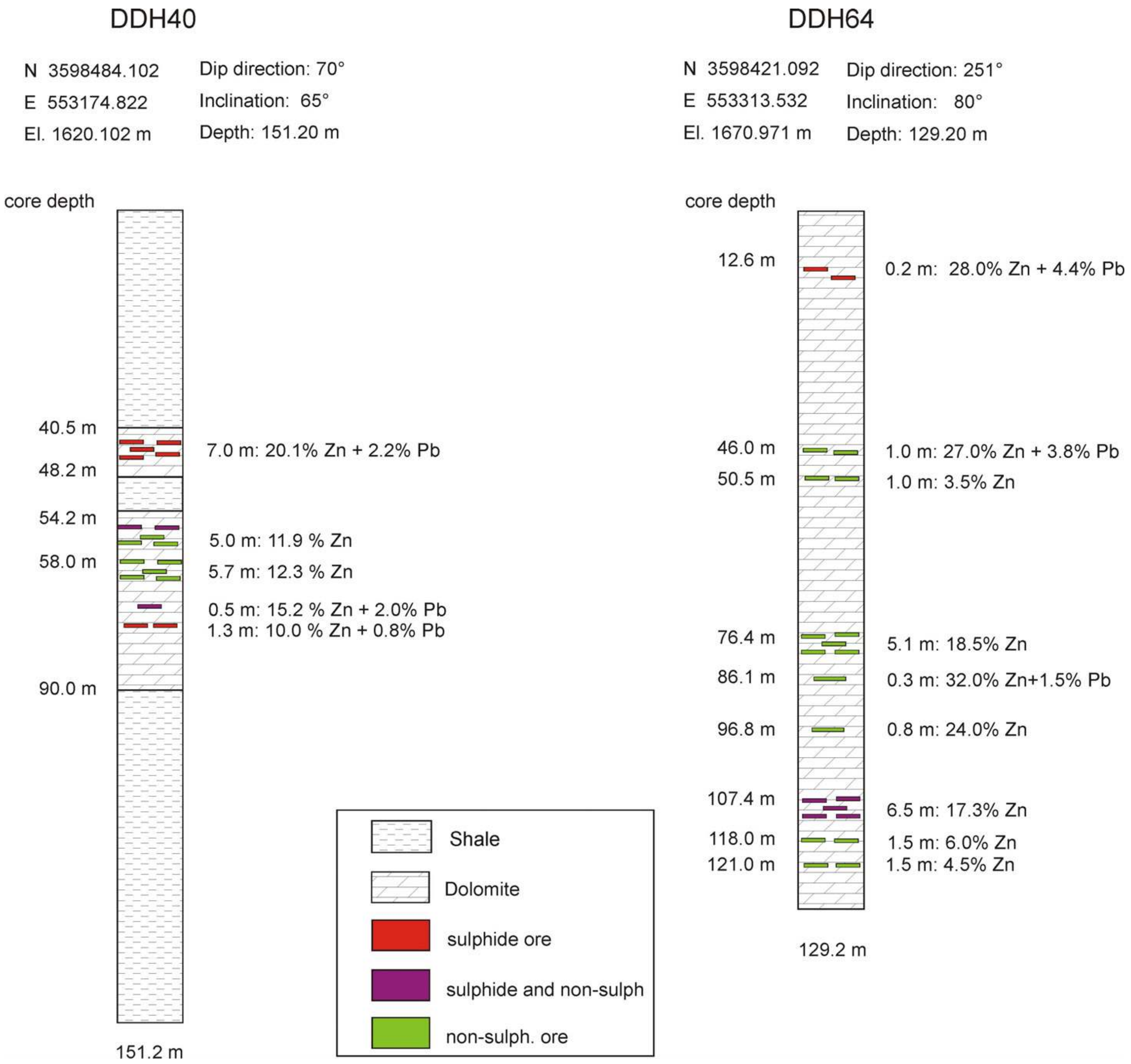

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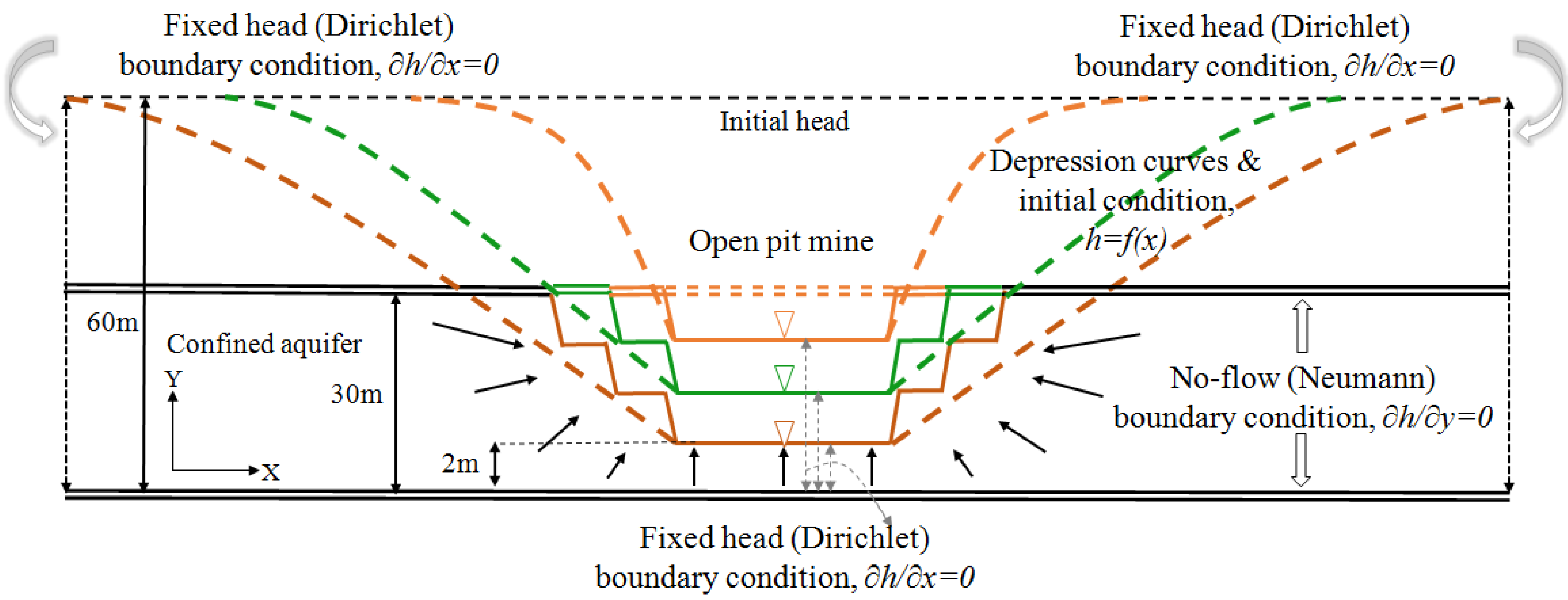

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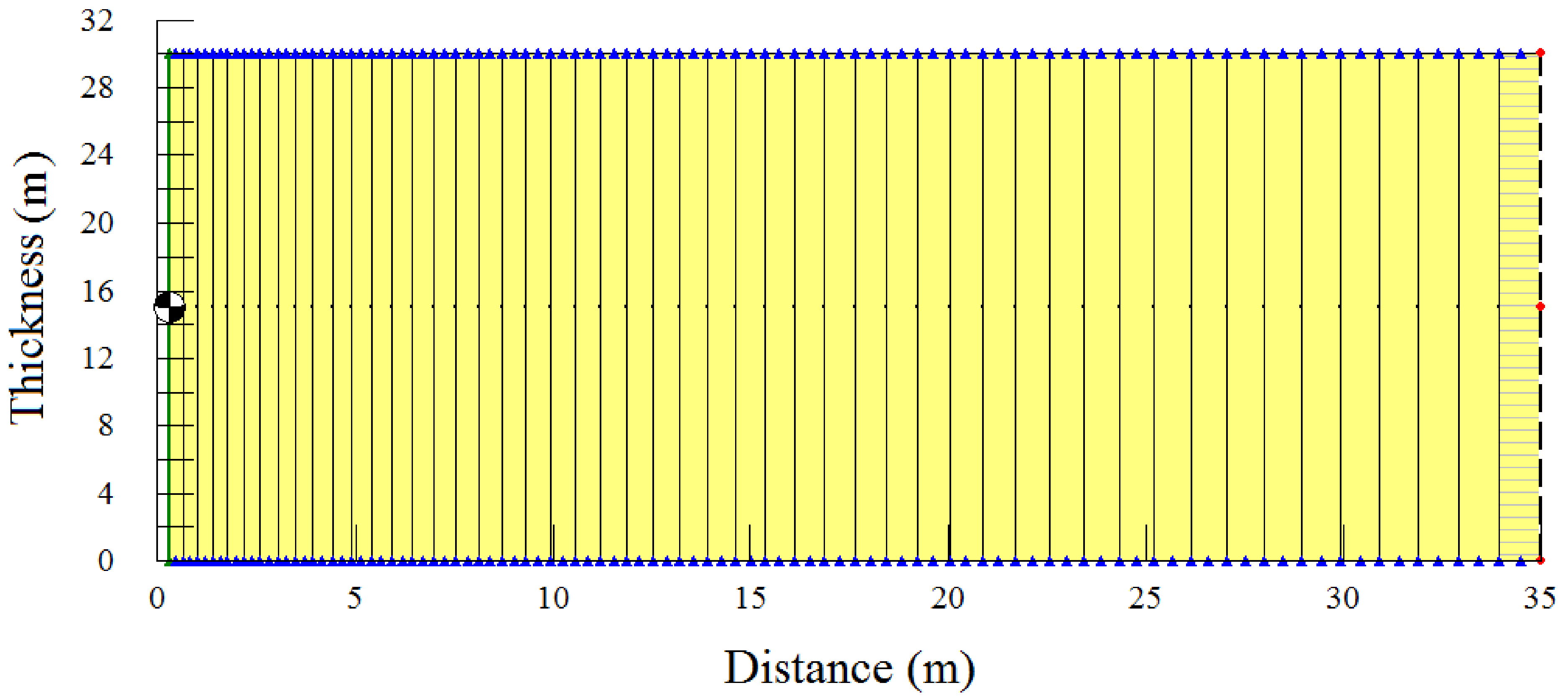

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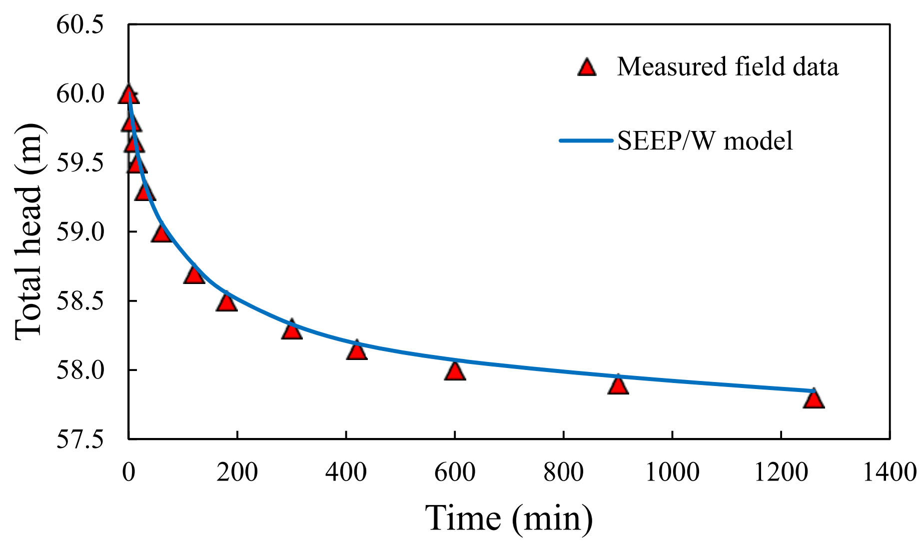

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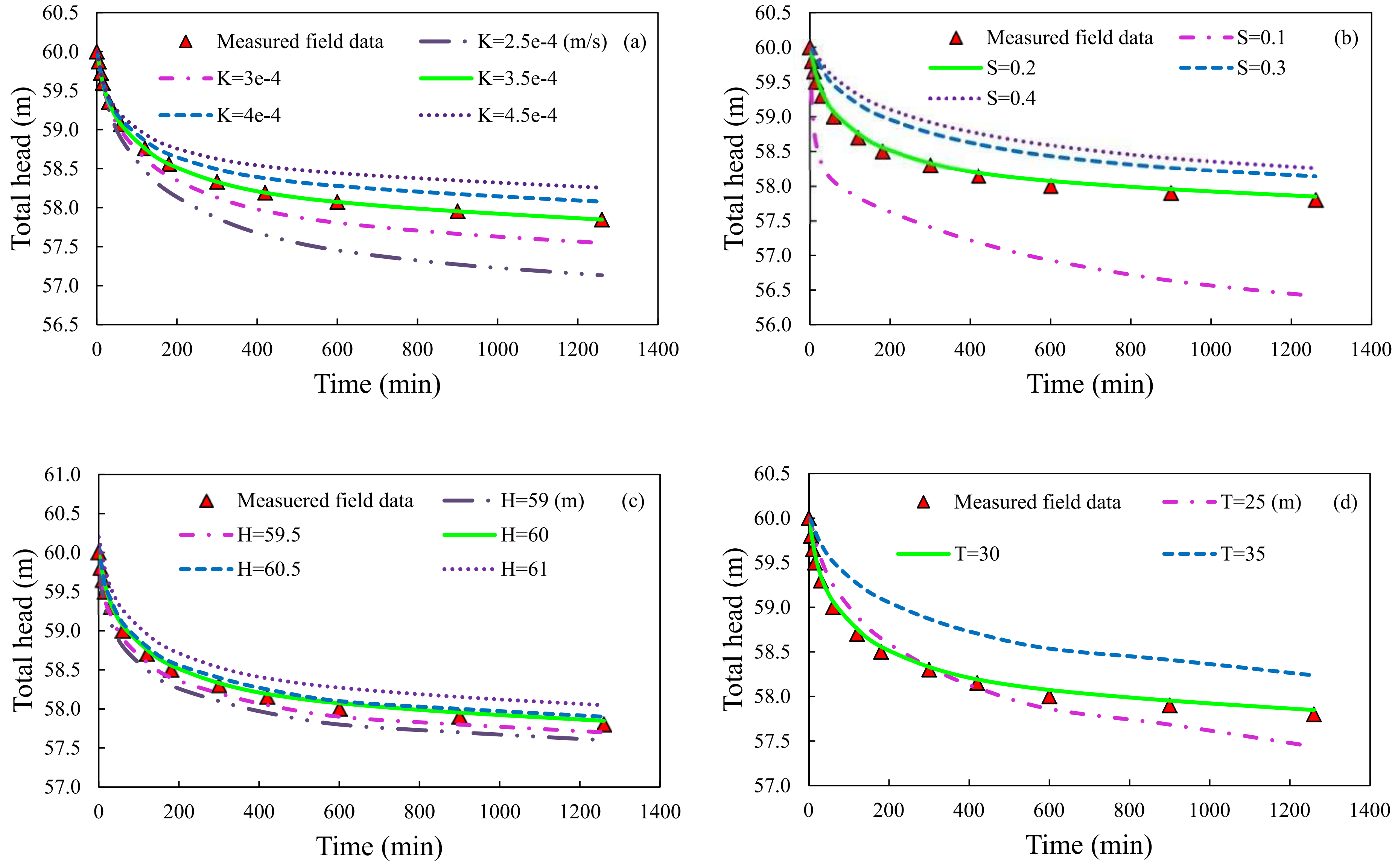

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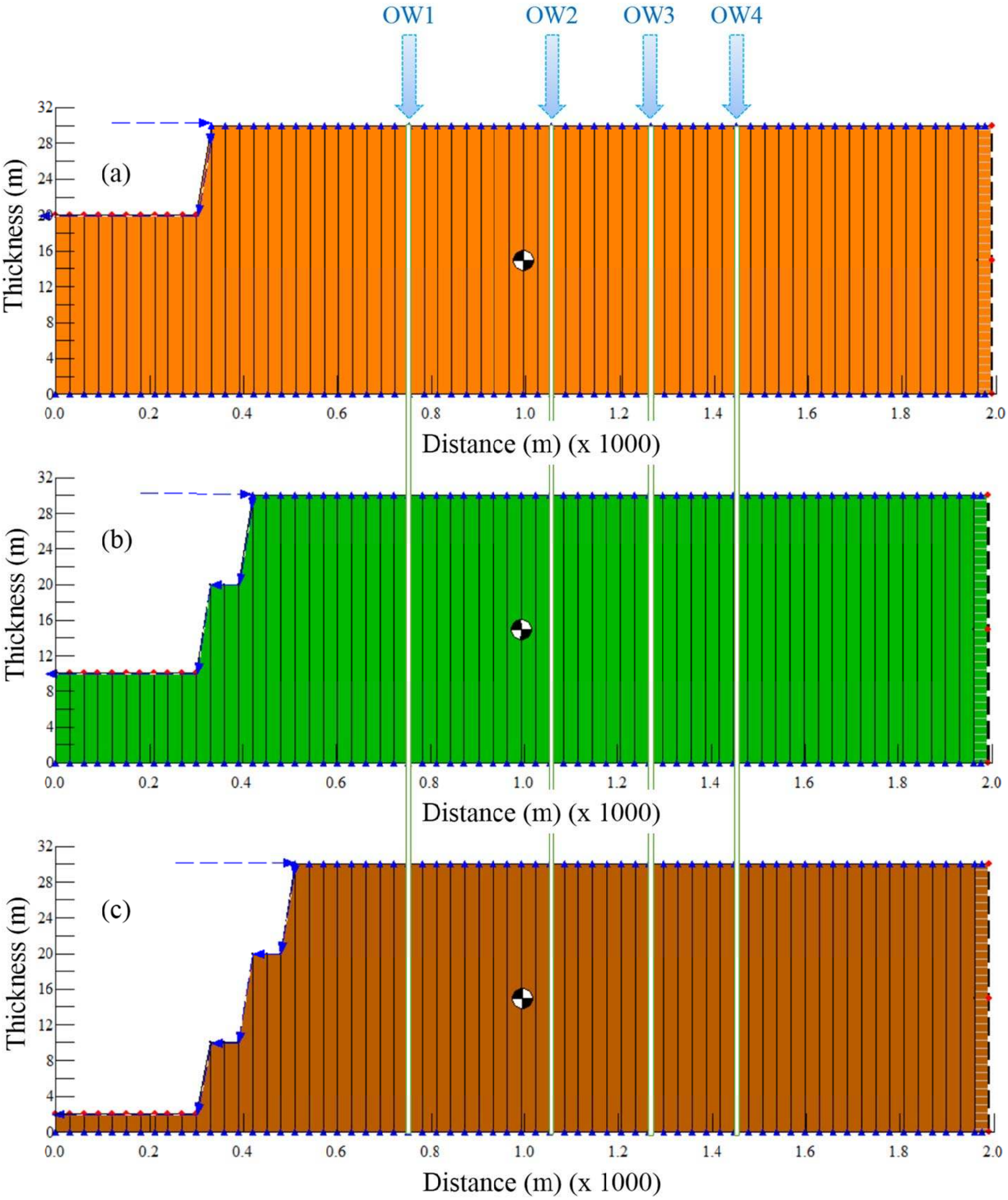

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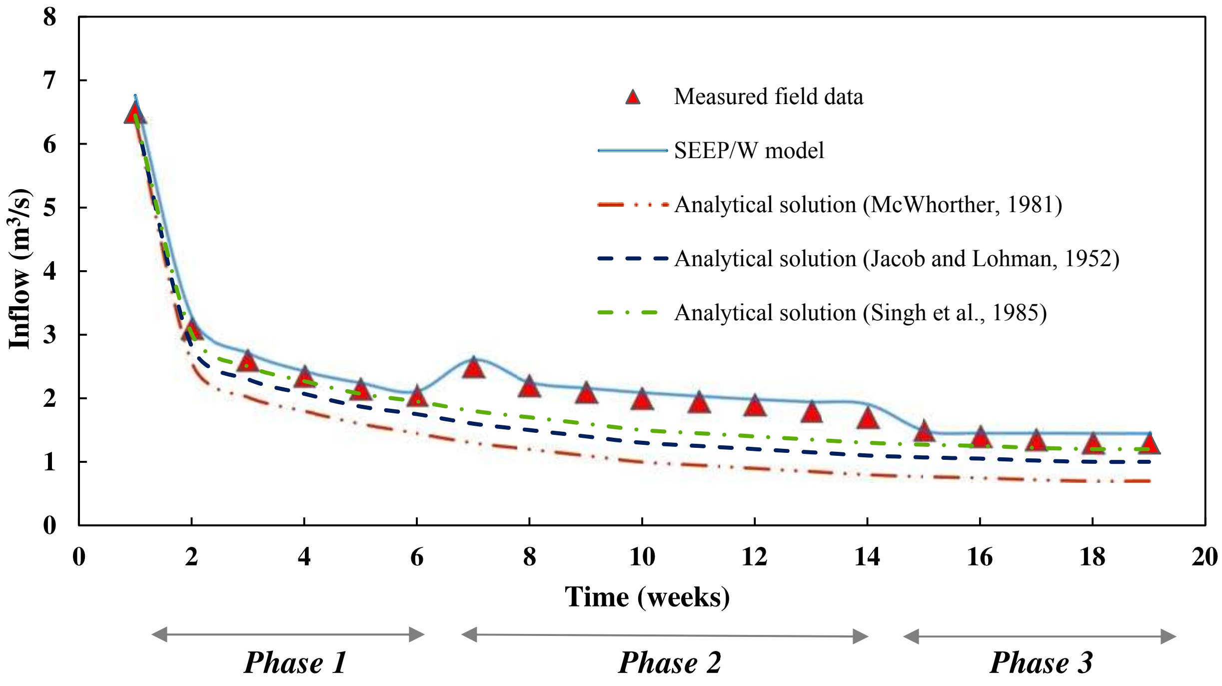

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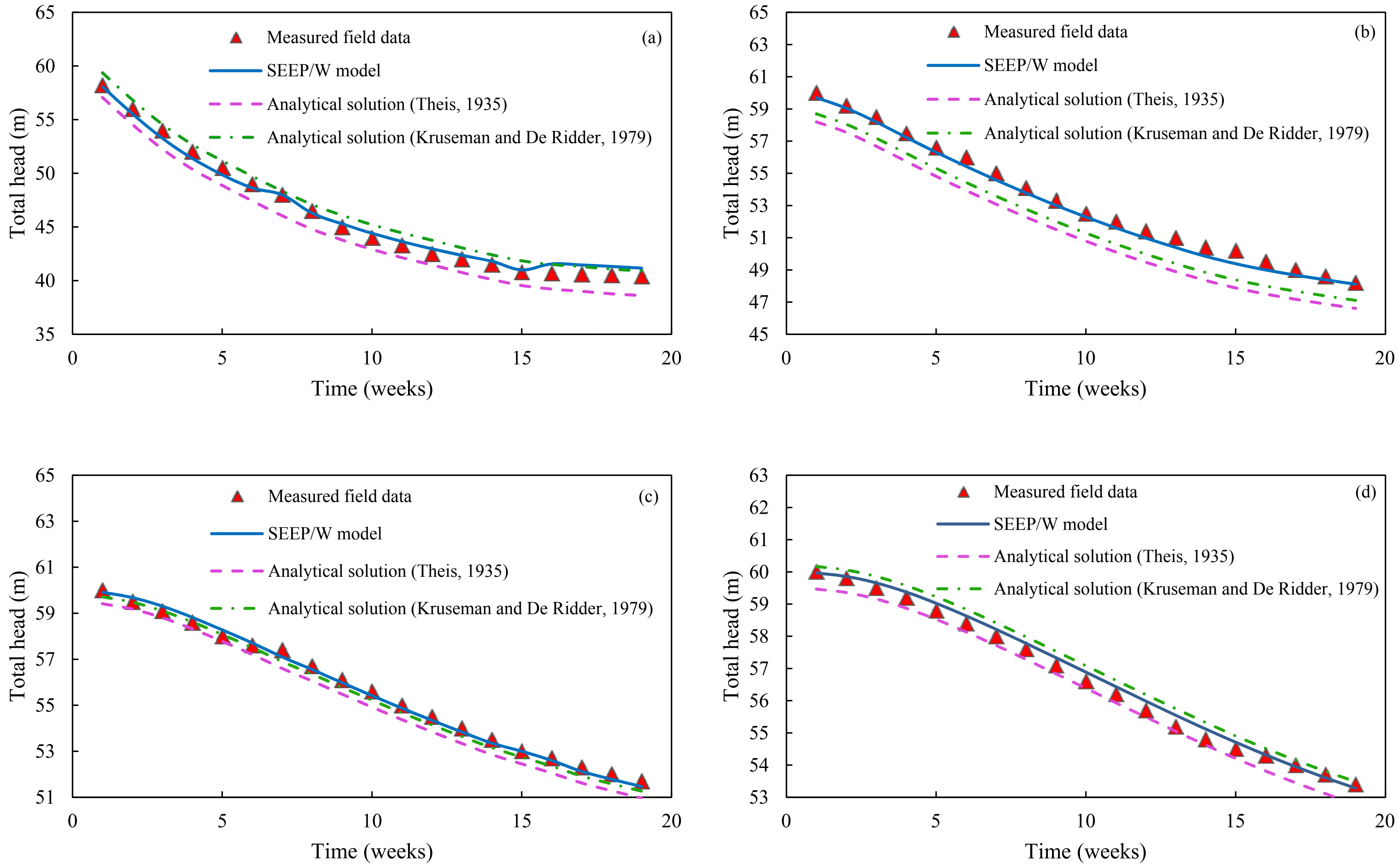

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Table 1. Minimum and maximum values of hydraulic head (H.H.) at observation wells, in metre.

	OW 1	OW 2	OW 3	OW 4
Minimum H.H.	40.4	48.2	51.7	53.4
Maximum H.H.	58.2	60.0	60.0	60.0

Table 2. Calculated error (%) related to the measured values for groundwater inflow from the confined aquifer into the Kolahdarvazeh open pit mine.

	SEEP/W model	Analytical solution		
		(Singh et al. 1985)	(Jacob and Lohman, 1952)	(McWhorther, 1981)
Mean percent error	0.108	1.8	3.1	5.3

Table 3. Calculated mean percent error related to the measured data for hydraulic head at the four observation wells (OW1, OW2, OW3 and OW4) during pit advancement.

Observation well	SEEP/W model	Analytical solution	
		(Theis, 1935)	(Kruseman and De Ridder, 1979)
OW1	1.46	3.50	2.30
OW2	1.37	3.43	2.23
OW3	1.16	3.32	2.16
OW4	1.18	3.20	2.18