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Full Length Research Paper

Groundwater recovery simulation for determination of post-mining lake formation at the Sangan iron mine, Mashhad, Iran

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A two-dimensional axisymetric finite element software SEEP/W was used to simulate the groundwater recovery process in wells entirely confined in an aquifer at Sangan iron mine in Iran. The simulation model predicted very well with the results obtained from both analytical method and field data for well recovery process. It was inferred from the results that the rate of groundwater recovery process is highest immediately after mine closure with no dewatering program. The paper presents a methodology for predicting how the natural groundwater regime can be established to its equilibrium conditions after mining operation has ceased.

Key words: Numerical model, finite element, Sangan iron mine, groundwater recovery, pumping well, SEEP/W, post-mining lake.

INTRODUCTION

In many active mines where mining is carried out under large bodies of water in aquifers, water inflow occurs from the surrounding layer towards the mining excavation (Doulati Ardejani et al., 2003, 2005, 2007; Doulati Ardejani and Singh, 2004; Aryafar et al., 2007). With the development of mining, groundwater invasion and impacts of groundwater drainage, such as regional groundwater table lowering, overlapping cones of depression, subsidence, and water quality deterioration are environmental problems which endanger mining production and human life (Keqiang et al., 2006). In the case of a confined aquifer with an impervious layer, the layer could break during the mining operation and water with high pressure can easily flow into the mining excavation. During the mine life, water is normally pumped reduce its inflow into mines although this action impacts on groundwater drainage, such as regional piezometric surface lowering, overlapping cones of depression, groundwater rebound after cessation of dewatering and the associated soil settlement and land subsidence. At the end of mine life pumping activities cease and the natural groundwater regime is re-established to its pre-mining equilibrium position. This process is normally called as ‘water table rebound or water table recovery’ (Doulati Ardejani and Singh, 2004). Comprehensive studies into groundwater recovery have been reported by others including Norton (1983) and Reed and Singh (1986). These studies mainly focussed on groundwater recovery problems associated with open cut mines and showed that the groundwater recovery takes place at a faster rate immediately after cessation of dewatering operation and continues indefinitely at a relatively slower rate.

Many attempts have been made to understand how groundwater recovers in surface mines using both analytical and mathematical models (Naugle and Atkinson 1993, Vandersluis et al., 1995; Lewis 1999; Shevenell 2000). These approaches have been mostly limited to the unconfined aquifer to simulate the rates at which the pit lakes are filled. Other models have been developed for groundwater recovery and associated spoil mass settlement for open cut mines (Davis and Zabolotney 1996).

This article presents a two-dimensional axisymetric finite element model using SEEP/W (Geo-Slope International Ltd.

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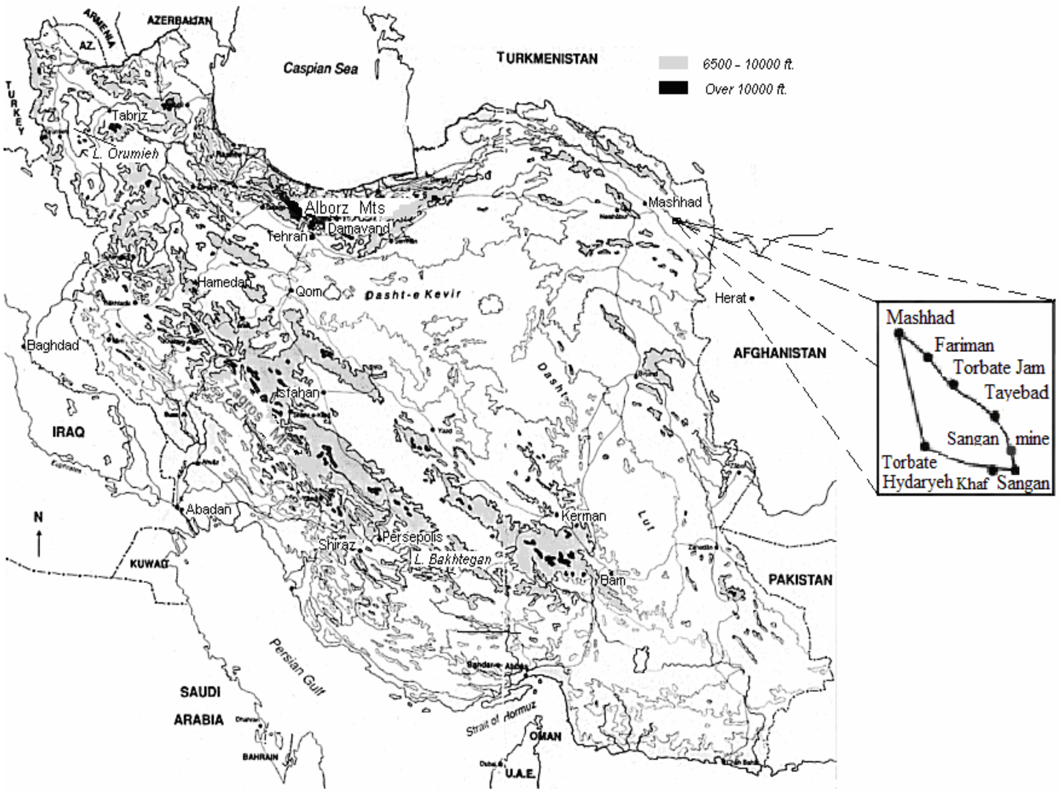

Figure1. Geographical location of Sangan iron mine.

2008) software to simulate the groundwater recovery process in wells entirely intersecting a confined aquifer. Unlike other models, this approach seeps into a confined aquifer using Sangan iron mine in Iran as a case study. Such an approach is useful in environmental management plan during the design stage of surface mining operation.

SITE DESCRIPTION

Climate and geography

Sangan Iron Mine (SIM) is located about 280 km southeast of Mashhad and about 16 km north of Sangan, Iran. SIM is the second largest iron mine in Iran, with about 1200 Mt ore reserve (Madan Kav Company, final report of detailed exploration of Sangan iron mine, 2002).The mine is located at latitude of 34° 24' N and a longitude of 60° 16' E at an average elevation of the mine is 1650 m above sea level.The site is characterised by an arid warm climatic condition. The average annual precipitation at the site varies from 140 - 200 mm. The annual relative humidity is 40%. Figure 1 shows the geo-graphical position of the mine.

Geological settings

Sangan ore deposit is recognised as skarn iron type which is elongated from east to west of Taleb mountain. Various rock types which can be recognised in the Sangan mine consist of Sarnosar granite, siltstone, sandstone and quartzite complex, north skarn unit, shale and siltstone, south skarn unit, volcanic complex. The iron ores in the Sangan area are mined as either high grade massive iron or low grade iron or oxidised zone and sulphide. Sangan iron deposit comprises three minable zones namely western, central and eastern zones. The western part is almost ready to extract. The detailed exploration works are mainly concentrated on two other parts. The western part covers an area about 6 km^2 and includes five anomalies as A, A', B, south C and north C.

Hydrogeological studies

A geophysical resistivity survey was performed in order to investigate the hydrogeology of the study area. The geophysical results indicate an average thickness of 80 m of fully saturated confined aquifer throughout the mine area by clay and marl layers. Sixteen pumping wells were drilled and tested in order to determine the hydrodynamic parameters of the aquifer. During the pumping tests the variations of the hydraulic head were monitored in the observation wells (Mahvi, 2004). Theis and Cooper-Jacob analytical equations (Freeze and Cherry, 1979) were used to determine the hydraulic parameters of the confined aquifer. The average values of 0.001, 8.755 m/day and 700 m^2/day

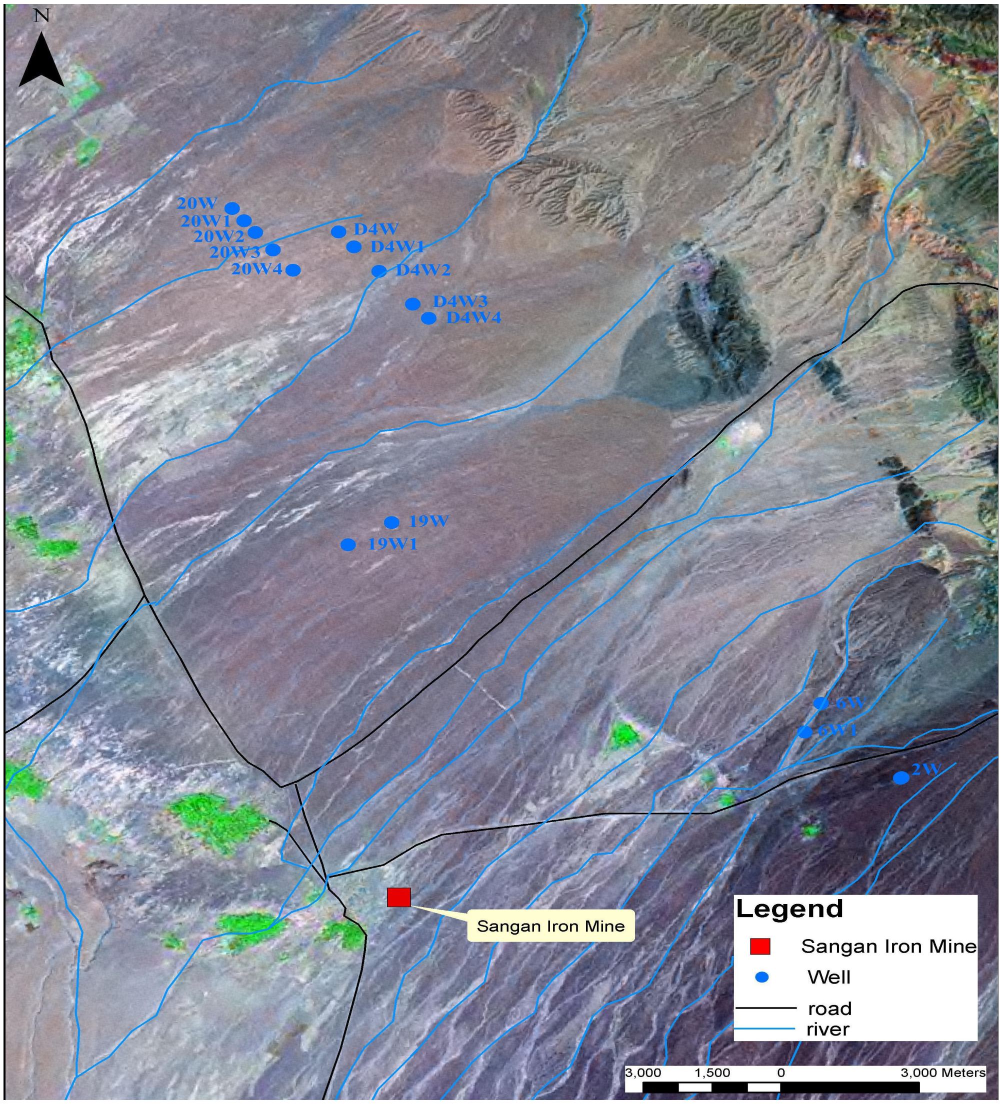

Figure 2. The ASTER image of the study area showing pumping wells position, access roads, water courses and Sangan Iron Mine.

were calculated for storativity, hydraulic conductivity and transmissivity of the aquifer respectively. Figure 2 shows the ASTER image of the study area, in which the pumping wells, access roads, water courses and the Sangan iron mine.

MODELLING TOOL

A two-dimensional finite element groundwater modelling software SEEP/W (Geo-Slope International Ltd., 2008) was used to simulate groundwater recovery process in wells entirely penetrated into a confined aquifer in Sangan iron mine. Compared to similar softwares, SEEP/W has the capability to model both saturated and unsaturated flow.

In porous medium, the hydraulic conductivity and the quantity of water (amount of water stored) may change as a function of pore-water pressure. SEEP/W may be used to model the relationships as continuous functions (International Geoslope Ltd., 2008). Furthermore, the SEEP/W can simulate heterogeneous hydraulic properties such as hydraulic conductivity and storage coefficient in an isotropic and heterogeneous flow system (Doulati Ardejani and Singh, 2004).

MODEL GOVERNING EQUATION

The SEEP/W model solves the following governing partial differential equation for given initial and boundary conditions are specified for the problem under simulation (Freeze and Cherry, 1979):

$$\frac{\partial}{\partial x}(K_X \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) - C\frac{\partial}{\partial t}(h) + Q = 0 \quad (1)$$

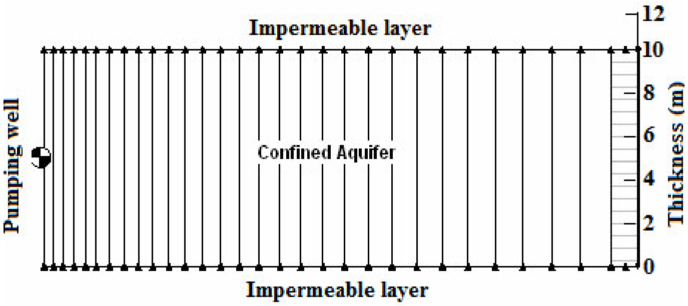

Figure 3. Finite element representation of the problem.

Where,

K_x, K_y = hydraulic conductivities in the x and y directions respectively $(\frac{m}{s})$

Q = recharge or discharge per unit volume $(\frac{m^3}{s})$

h = hydraulic head (m)
t = time (s)
C = slope of the water storage curve (dimensionless) (Geo-Slope International Ltd., 2008).

The Galerkin technique (Pinder and Frind, 1972) was used by SEEP/W model to solve Equation 1 for the given boundary conditions.

ANALYTICAL EQUATION FOR PREDICTION OF RESIDUAL DRAWDOWN

The following analytical solution presented by Theis (Kruseman and De Ridder 1979) was used to calculate the residual drawdown after dewatering has ceased.

$$\Delta h' = \frac{Q}{4\pi km}\left\{\ln(\frac{4kmt}{r^2 s}) - \ln(\frac{4kmt'}{r^2 s'})\right\} \qquad (2)$$

Where,

t' = time of rebound commences (s)
s' = storativity in rebound stage
m = aquifer thickness (m)
s = storativity in dewatering stage
r = well radius (m)
t = pumping time (s)
Q = pumping rate (m^3/s)
K = hydraulic conductivity (m/s)
$\Delta h'$ = residual drawdown (m)

MODEL VERIFICATION

Three case study examples were modelled using the above numerical techniques to study of the groundwater rebound mechanism after mining:

Case study 1- Simulation of well recovery in an artificial confined infinite aquifer

This example compares the results of a dewatering test in a confined infinite aquifer under transient conditions using an analytical solution incorporating the Theis equation (Equation 2) with those results obtained by the SEEP/W numerical model. The recovery period after stopping pumping test was taken into consideration in this example. The total hydraulic head in the confined aquifer was 20 m. The hydraulic conductivity of the aquifer was 0.005 m/s. The storage coefficient of the aquifer was 0.0001. Thickness of the aquifer, well radius, pumping rate and transmissivity of the aquifer were 10 m, 0.2 m, 0.15 m^3/s and 0.0005 m^2/s respectively.

A finite element mesh consisting of 62 nodes and 30 elements was constructed in a single layer 10 m thick (Figure 3). An axisymmetric analysis was used to simulate radial flow to a well. The rectangular grid contained four-nodded elements with an infinite element at the right end of the model. 10 time steps were considered for the transient simulation of well recovery. The final prediction of the hydraulic head calculated during the well dewatering simulation was used as an initial condition for the modelling of the recovery process. No flow boundary conditions were assigned at the top and bottom boundaries of the model to describe impermeable layers in the aquifer. A fixed-head boundary value equal to 20 m was specified at the right side of the grid. Figure 4 compares the residual draw-downs versus time predicted by the numerical model and those drawdowns calculated using the Theis analytical solution. As Figure 4 shows, a close agreement was achieved between the analytical results and the numerical predictions of the residual drawdown. The average error is about 1%.

Case Study 2 - Modelling of the groundwater rebound process in the well No.D4W1 at Sangan iron mine

In the second example, results from the numerical model are compared to those from an analytical Theis equation, and field data. The data were obtained from a dewatering test performed in a fully penetrating well (No.D4W1) in a confined aquifer at Sangan iron mine. This simulation considers both pumping and recovery periods.

The thickness of the aquifer, hydraulic conductivity, storage coefficient, transmissivity and initial hydraulic head were 66 m, 0.000271 m/s, 0.00007849, 0.0179 m^2/s and 928.19 m respectively. The well radius was 0.3048 m and the dewatering rate was 0.0358 m^3/s. To perform the simulation numerically, a finite element grid was constructed in a single layer 66 m thick. The grid had a rectangular shape with 64 nodes and 32 elements. An axisymmetric sim-

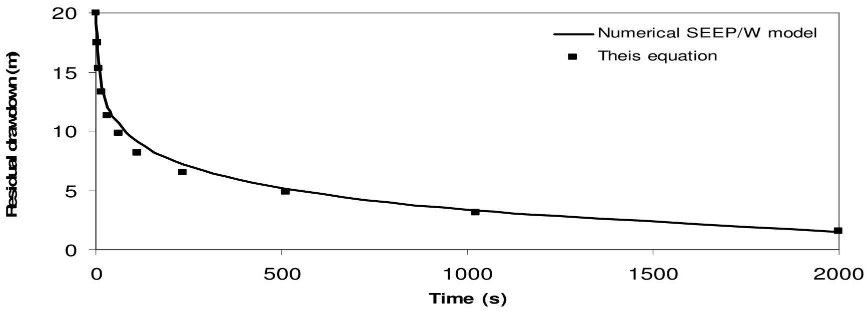

Figure 4. Comparison of residual drawdown versus time predicted by the numerical SEEP/W model and those calculated by the Theis solution at the pumping well axis.

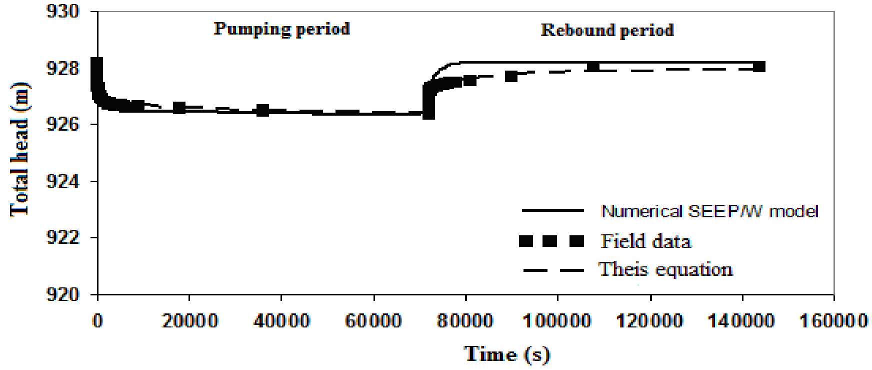

Figure 5. Comparison of analytical, numerical and field monitored hydraulic head as a function of time during dewatering and recovery periods in well No. D4W1.

ulation was considered for this problem. A steady state simulation was first performed to establish an initial condition for the transient analysis of the dewatering test. No flow boundary conditions were applied at the top and bottom boundaries of the model. A fixed-head boundary value equal to 928.19 m was specified at the right-hand side of the model. A flux boundary condition was assigned at the left side next to the dewatering well to take the dewatering rate into consideration. A transient simulation was then carried out to model dewatering test. The final prediction of the hydraulic head calculated during the well dewatering modelling was used as an initial condition for the simulation of the rebound process. The flux boundary condition was removed from the left-hand side of the model. To execute a transient simulation, 32 time steps were considered. Figure 5 compares the variations of total hydraulic head versus time during dewatering and recovery periods. The numerical results using g Theis analytical solution compared very well with field data associated with the well No.D4W1 at Sangan iron mine. The relative error between the two methods is less than 2%.

Case Study 3 - Prediction of the hydraulic head variations during groundwater recovery period (residual drawdown) in well No. 2W

The third case study deals with the modelling of groundwater rebound problem in a fully penetrated well, No. 2W, in a confined aquifer at Sangan iron mine under transient flow conditions. The aquifer had a hydraulic conductivity of 0.000093 m/s and a storativity of 0.000278. The initial hydraulic head was 1024.75 m. The dewatering rate was 0.0361 m^3/s and the well radius was 0.3048 m. The aquifer had a transmissivity of 0.00398 m^2/s.

A finite element mesh was constructed with 40 elements and 82 nodes in a single layer 40 m thick. An axisymmetric analysis was performed to model radial flow to the well. An infinite element was specified at the right end of the mode describing an infinite boundary for the confined aquifer. Figure 6 shows the finite element grid of the problem. 34 time steps were considered for the transient simulation of the well rebound process. The final estimation of the hydraulic head computed during the well dewatering modelling was used as an initial condition for the simulation of the recovery process. No–flow boundary conditions were applied at the top and bottom boundaries of the model representing impermeable layers in the aquifer. A fixed-head boundary value equal to 1024.75 m was specified at the right-hand side of the model.

Figure 7 compares the residual drawdown as a function of time during well rebound period, predicted by the SEEP/W model, those calculated by the Theis analytical solution and field data at 5 m of the pumping well axis. Table 1 outlines

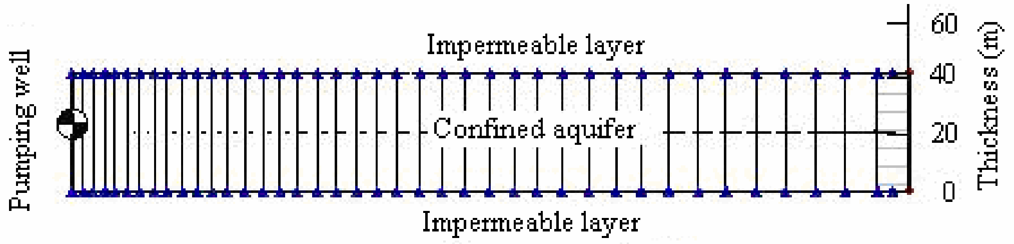

Figure 6. Finite element model of the problem

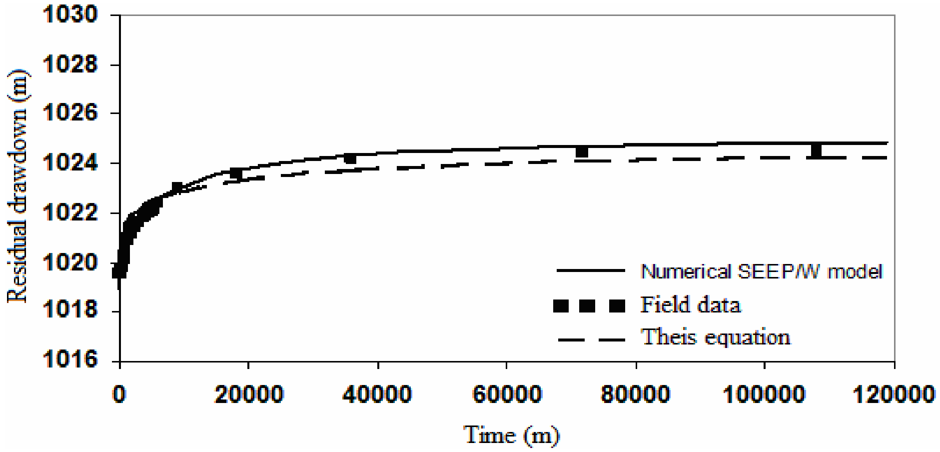

Figure 7. Comparison of analytical, numerical and field monitored residual drawdown as a function of time during rebound period in well No. 2W.

Table 1. Comparison of analytical, numerical and field monitored residual drawdown at 5 m of the well No.2W and relative errors.

Method	Residual drawdown (m)	Relative error (%)
Field Data	5.24	------
SEEP/W model	5.1	2.67
Theis solution	5.44	3.81

the residual drawdowns calculated by different methods at 5 m of the well axis and the relative errors.

Conclusion

Simulation of groundwater recovery process in the pumping wells provides valuable information to predict the rate at which post-mining lake forms. A two-dimensional axisymetric finite element model called SEEP/W was used to simulate the groundwater recovery process in wells entirely penetrated into a confined aquifer at Sangan iron mine. The accuracy of the model was evaluated by comparing the results obtained from Theis analytical solution and field data and a close agreement was achieved. The transient simulation of groundwater rebound showed that the recovery process would be very fast immediately after mine closure and cessation of dewatering program at Sangan mine due to the considerable difference in hydraulic heads imposed by dewatering. The results of such modelling can be used for designing an effective environmental management program in order to minimise environmental effects arising from the mining activity.

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