Research Article

Dynamic and Static Reserve Recharge Characteristics of a Dewatering Well Seepage from an Aquifer Bottom by Sand Tank Seepage Experiment

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Ground water inflow from an overlying aquifer happens frequently in underground engineering; for properly controlling ground water during construction, the most important tasks are to assess the possibility and the probable water inflow, which depends on the ground water recharge characteristics. However, less work has been carried out on this topic. In order to study the water inflow variation characteristics including dynamic replenishment and static reserve release from a submersible aquifer, sand-tank seepage experiments on a dewatering well seepage from an aquifer bottom under the conditions of different water pressure heads inside the dewatering well (P) were designed and performed. The results show that (1) when the dewatering beginning, the water inflow increases to a peak value rapidly and then decreases following a first-order exponential decay function. In the initial phase, the water inflow is mainly composed of static reserve release, which decreases quickly with time also following a first-order exponential decay function. Meanwhile, the recharge of dynamic replenishment quickly increases with time following a first-order exponential growth function, which mainly forms the water inflow in the quasi-steady state. (2) The equal time of dynamic and static reserve release and the quasi-steady state time both present a first-order exponential decay function with the decrease of P. (3) The peak water inflow should perform at the beginning of dewatering which presents a little late after the beginning of dewatering and increases with the decreasing of P following a linear function. The results will play important references for water inflow prediction and calculation from overlying aquifers for underground projects.

1. Introduction

Many underground constructions are threatened by overlying aquifers, rivers, lakes, or reservoirs during extraction [1–6]. Groundwater inflows to underground shafts, drifts, mines, and tunnels can cause severe problems, both in practical and economical terms [7, 8]. Unexpected inflows lead to poor working conditions, reductions in safety standards, and costly delays in excavation and operations. The inflow into tunnels can affect the short- and long-term stability of the excavation and therefore increase the risk of failure and lead to higher cost of construction. For reliable estimation, the inflow rate to underground constructions is important, which makes it possible to accurately design the drainage system and anticipate the environmental impacts on water resources and human activities as a result of underground water level and settlement of the aboveground buildings [9, 10]. Drilling dewatering wells from the underground mines’ tunnels upward into the overlying aquifer are applied in many underground constructions for dewatering and depressurization of overlying aquifers [11–13].

Many models consisting of analytical, empirical, and numerical approaches have been proposed to predict groundwater flow into underground constructions or dewatering wells [14–19]. However, prediction of possible groundwater inflow using analytical and numerical tools...
often failed due to given hydrogeological assumptions, simplification, and groundwater inflow dynamic variation with time [20]. Actually, the water inflow mainly depends on the ground water recharge; for most underground projects, the sources of water inflow during excavation can be divided into static reserve release and dynamic replenishment [21, 22]. Making a thorough investigation of recharge characteristics is quite necessary for accurately predicting water inflow. Based on the system dynamics theory, a double-exponential decay model to describe the water-inflow process of roof aquifer with the working face extraction was proposed [23], the results indicated that the characteristics of water-inflow process were controlled by the dynamic and static inflows, and the dynamic recharge was the main controlling factor. A prediction method combining the static reserve amount with the dynamic recharge amount was adopted for the prediction of water inrush in the working face, which indicated that when the total drainage amount from the borehole was greater than the static reserve amount in the aquifer and the residual water amount in the borehole was equal to or less than the dynamic recharge amount, the drainage effect of the roof sandstone aquifer was good [24].

It indicates that dynamic and static reserve recharge characteristics are important for accuracy estimation water inflow from overlying aquifers into underground constructions, which are very difficult to monitor in situ with less research data; not only that, there is neither reference on the seepage characteristics by sand tank seepage experiment in lab. However, experiment based on sand tank is an effective and general method to study underground water...
seepage characteristics and hydraulic gradient variation [25–27]. In this paper, a sand tank model is designed and constructed, and sand with a permeability coefficient of 0.138 cm/s is filled inside the model. The aquifer in the sand tank is uniform and isotropic. By changing the water pressure head inside dewatering well, the relationship between the water inflow, dynamic replenishment, static reserve release, and the drawdown in the dewatering process is analyzed, which can provide some references for the prediction of water inflow.

2. Experiment Preparation

2.1. Experimental Devices and Materials. The sand seepage experimental device was fabricated from steel plates and acrylic sheets, representing a 60° sector, i.e., a 1/6 portion of a circular flow system for saving experimental materials. The radius and inside-height of the tank are 210 cm and 70 cm separately, as shown in Figures 1 and 2 [13]. The outer boundary water head was maintained at the elevation of 20–60 cm above the bottom of the sand-tank, and water was supplied into the sand-tank from a water inlet tank. The overflowing water and the well discharge were collected in overflow outlet tank and dewatering outlet tank for cyclic utilization. To measure the hydraulic pressure, 96 piezometers with water-level monitoring tubes were installed in six layers at different elevations and distances from the dewatering well, which were recorded using a camera. Two bottom water inlet ports were set at the sand tank bottom to saturate the sand, during the tank saturation, the rising water level in the tank allowed for air escaping upward from the sand, which reduced the volume of entrapped air [28]. The water pressure heads $P$ inside the dewatering well can be monitored by the water-level monitoring tube inside the well. In the process of infiltration, water tends to flow from the smooth surface of the boundary rather than through the sand layer at the boundary. In order to solve
this problem, a layer of 5 mm thick soft water-proof sponge was affixed on the side wall and the bottom.

In the study, an aquifer thickness of 58 cm which is formed with river sands was filled in the sand tank, the radius and height of the dewatering well are 6 and 8 cm, respectively, and the boundary water table was kept at 58 cm as shown in Figure 2. $P_0$ is constant head boundary, $P$ is water pressure head inside the dewatering well, and $S$ is drawdown in Figure 2. The well-cover is permeable to allow vertical permeation and replenishment. The water was cyclically utilized in the test process by three water pumps and water tanks, the water inflow was real-time monitored by three flow gauges, and the piezometer tubes were recorded by a camera.

A stable permeability of the seepage sands is the key factor for the experiment. River sands were used in this experiment, which were washed firstly then air-cured. The silty-fine sands and large particles were sieved, because the silty-fine sands may flow out with water which will affect the sand permeability. The sand tank is uniformly filled with sand, and the sand gradation is shown in Table 1 and Figure 3. The particle diameter of 0.25-0.5 mm occupies 28.33%, and that of 0.5-1 mm occupies 54.9%. It is indicating that the sand belongs to medium sand; through Darcy seepage test, its permeability coefficient is 0.138 cm/s.

2.2 Experimental Process. First of all, a 5 mm thick waterproof sponge was adhered inside sand tank, which used to reduce the effect of boundary seepage; the dewatering well with radius of 6 cm and height of 8 cm was set at the center as shown in Figure 2. To prevent migration of sand particles into the testing wells, 1 mm radius holes with 4 mm pitches were made in the well screens and tops, and the well screens were wrapped up by stainless steel filters with 0.25 mm diameter openings and 0.18 mm diameter steel wire; then, the sand is filled uniformly. After the completion of the filling, the water slowly recharges from the bottom water inlets in order to eliminate the air as much as possible. After

| Table 2: Table of quasi-steady state water inflow and peak flow under different well pressure heads. |
|----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| $P$ (cm)        | -8            | -6            | -4            | 0             | 13            | 23            | 33            | 45            |
| $S$ (cm)        | 51.0          | 49.5          | 48.0          | 42.0          | 28.0          | 22.0          | 14.0          | 6.0           |
| Peak flow (ml/s)| 149.43        | 145.18        | 130.94        | 120.80        | 106.15        | 80.78         | 44.63         | 19.91         |
| Water inflow in quasi-steady state (ml/s) | 80.61 | 78.44 | 76.29 | 75.63 | 67.06 | 52.89 | 38.08 | 19.05 |

Figure 6: Water inflow variation with $P$ and $S$: (a) relationship between $P$ and water inflow; (b) relationship between $S$ and water inflow.

| Table 3: Dynamic and static reserve change table. |
|----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| $P$ (cm)        | -8            | -6            | -4            | 0             | 13            | 23            | 33            | 45            |
| $S$ (cm)        | 51.0          | 49.5          | 48.0          | 42.0          | 28.0          | 22.0          | 14.0          | 6.0           |
| Dynamic replenishment at quasi-steady state (ml/s) | 78.05 | 75.77 | 74.1 | 72.91 | 64.19 | 50.45 | 36.89 | 18.9 |
| Quasi-steady static reserve release (ml/s) | 2.88 | 2.85 | 2.34 | 2.72 | 2.66 | 2.68 | 1.03 | 0.024 |
saturation, the water is drained and resaturated 4 to 6 times to ensure the consolidation and settlement of the sand layer and permeability’s stability. The pressure stabilizing tank was maintained to the stable water head of 58 cm. Before carrying out the experiment, the water heads in all piezometer tubes should also be 58 cm.

A dewatering pipe with diameter of 25 mm and length of 150 cm was set at the bottom of the dewatering well, which generating a height difference $H$ between the end of the pipe outlet and the position of the well bottom, as shown in Figure 1. When the water completely filled the pipe, the air is discharged. When dewatering begins, the value on the pipe outlet can control the water inflow; if the water inflow is large, the water quickly passes through the pipe; the water recharged from the sands around the well is limited, which may cause a negative pressure head in the well. The closed environment can be destroyed through the air vent at the upper of the well, so as to achieve zero water pressure head dewatering. The well pressure head inside dewatering well can also be changed by controlling the valve at the outlet.

The initial water table mainly depends on the sand tank size; the initial pressure head inside the dewatering well was divided into relatively average parts to design the different water pressure heads inside the dewatering well in the experiment. Eight water pressure heads inside dewatering well of 45 cm, 33 cm, 23 cm, 13 cm, 0 cm, -4 cm, -6 cm, and -8 cm in the experiments were carried out to study the corresponding actual water level drawdown, water inflow, dynamic and static reserve recharge characteristics, etc.

### 3. Results and Discussions

In actual dewatering project, the rate of drawdown generally decreases with time; the extension of cone of depression presents very slowly. When the rate of drawdown performs being so small as it is difficult to monitor its change in short time, the flow in the cone of depression can be seen as steady state; this state can be defined as a quasi-steady state.

In essence, the sand-tank model belongs to a finite aquifer with lateral recharge. When the cone of depression caused by the dewatering well extends to the lateral recharge boundary and the lateral recharge is equal to the drainage amount, it can reach a stable state. In this paper, when the numeric value of the piezometer tubes shows no change within 5 minutes, and the ratio of static release of reserves to dynamic replenishment is less than 0.05, it can be considered to be a quasi-steady state. The water inflows in the following analysis are in a quasi-steady state.

#### 3.1. Water Inflow Changes under Different Well Pressure Heads

The relationship between the change of water pressure head inside the dewatering well ($\Delta P$) and the drawdown of water level ($S$) is approximately linear which following a fitting function $y = -7.367 + 0.846 \times S$ with $R^2 = 0.99$, as shown in Figure 4. Though the water level drawdown above the well increasing with the well pressure head reducing, however, their variations at different high positions above the well are different, as the dewatering well is a non-complete well. The permeability coefficient of the well wall and well cover is much greater than that of the sand layer, which results in the obviously hydraulic jump phenomenon. A saturated water zone may be formed around the well wall to maintain the pressure in the well; however, when the water inflow is large, the interior of the dewatering well is not a full well; a vacuum space is formed in the upper part of the dewatering well. The atmospheric pressure cannot pass into inside of well through the water pressure in the aquifer. That is why the negative pressure formed.

The water inflow from the dewatering well presents a first increases to the peak very quickly and then generally reduces to a stable value process under different $P$ as shown in Figure 5. From the peak water inflow to quasi-steady state water inflow, it changes with time following a first-

![Figure 7: Dynamic replenishment variation under quasi-steady state: (a) variation of dynamic replenishment with $P$; (b) variation of dynamic replenishment with $S$.](image-url)
order exponential attenuation function such as $Q = a \exp (-b \cdot t) + c$. It also can be seen that the peak flow and quasi-steady state water inflow gradually increase with the decrease of $P$ and the increase of $S$ above the well as shown in Table 2. When the well pressure head is 45 cm, the peak flow is 19.91 ml/s, and the quasi-steady water inflow is 19.05 ml/s; the peak flow is similar to the quasi-steady water inflow. When the well pressure head decreases to -8 cm, the peak flow becomes 149.43 ml/s, and the flow seems to be stable also increases to 80.61 ml/s, which are a lot of variability. It indicated that $P$ had an important influence on water inflow.

The peak water inflow changes linearly with $P$ and $S$ with $R^2 = 0.975$ and 0.95; the quasi-steady water inflow follows a first-order exponential variation law with $P$ and $S$ with $R^2 = 0.995$ and 0.99 as shown in Figure 6, which is consistent with the single exponential attenuation model of borehole water inflow [23, 29]. Water inflows from different types of aquifers may have different fitting curves for water inflow with drawdown, such as linear function, logarithmic function, and power function [30].

3.2. Variation Characteristics of Dynamic Replenishment and Static Reserve Release under Different $P$. The water inflow is
Table 4: Fitting formula of dynamic replenishment and static reserve release.

| P (cm) | S (cm) | Fitting formula of static reserve release | Fitting formula of dynamic replenishment | $R_j^2$ | $R_d^2$ |
|--------|--------|------------------------------------------|-----------------------------------------|--------|--------|
| -8     | 51     | $Q_s = 2.47 + 145.6 e^{(-0.00703t)}$      | $Q_d = 76.6 - 64t e^{(-0.00738t)}$      | 0.95   | 0.96   |
| -6     | 49.5   | $Q_s = 2.87 + 140.31 e^{(-0.00873t)}$    | $Q_d = 73.37 - 62.73t e^{(-0.00847t)}$ | 0.99   | 0.98   |
| -4     | 48     | $Q_s = 2.53 + 126.6 e^{(-0.00608t)}$     | $Q_d = 73.14 - 60.73t e^{(-0.00746t)}$ | 0.98   | 0.97   |
| 0      | 42     | $Q_s = 2.57 + 115.86t e^{(-0.0057t)}$    | $Q_d = 72.77 - 58.62t e^{(-0.00712t)}$ | 0.96   | 0.96   |
| 13     | 28     | $Q_s = 2.68 + 101.47t e^{(-0.00751t)}$   | $Q_d = 61.02 - 49.54t e^{(-0.00615t)}$ | 0.94   | 0.94   |
| 23     | 22     | $Q_s = 2.92 + 76.82t e^{(-0.00899t)}$    | $Q_d = 48.87 - 40.37t e^{(-0.00725t)}$ | 0.93   | 0.94   |
| 33     | 14     | $Q_s = 1.22 + 40.22t e^{(-0.00647t)}$    | $Q_d = 34.29 - 26.25t e^{(-0.00844t)}$ | 0.95   | 0.95   |
| 45     | 6      | $Q_s = 0.027 + 18.28t e^{(-0.00915t)}$   | $Q_d = 18.87 - 14.17t e^{(-0.00915t)}$ | 0.94   | 0.94   |

Table 5: Parameter error analysis.

| $Q_{de}$ | $Q_{do}$ | $Q_{do} - Q_{de}$ | Fitted value | Errors | $Q_{je}$ | $Q_{jo}$ | $Q_{je} - Q_{jo}$ | Fitted value | Errors |
|----------|----------|-------------------|--------------|--------|----------|----------|-------------------|--------------|--------|
| 75.77    | 10.71    | 65.06             | 62.73        | 3.71%  | 2.85     | 145.18   | 142.33            | 140.31       | 1.44%  |
| 74.1     | 9.17     | 64.93             | 60.77        | 6.85%  | 2.34     | 130.94   | 128.6             | 126          | 2.06%  |
| 73.1     | 10.5     | 62.6              | 58.62        | 6.79%  | 2.4      | 120.8    | 118.4             | 115.86       | 2.19%  |
| 64.19    | 12.47    | 51.72             | 49.54        | 4.40%  | 2.66     | 106.15   | 103.49            | 101.47       | 1.99%  |
| 50.45    | 6.89     | 43.56             | 40.37        | 7.90%  | 2.68     | 80.78    | 78.1              | 76.82        | 1.67%  |
| 36.89    | 12.3     | 24.59             | 26.25        | 6.32%  | 1.03     | 44.63    | 43.6              | 40.22        | 8.40%  |
| 18.9     | 4.79     | 14.11             | 14.17        | 0.42%  | 0.024    | 19.91    | 19.886            | 18.28        | 8.79%  |

Figure 9: Integrals of static reserve release and dynamic replenishment with $P = -6$ cm.

Replenishment at quasi-steady state and should be zero at the real steady state.

The dynamic replenishment varies with the well pressure head also follows a first-order exponential attenuation model with $R^2 = 0.995$. And with the drawdown, it shows a first-order exponential growth law with $R^2 = 0.98$ as shown in Figure 7. It indicates that the dynamic replenishment has strong correlation with $S$ and $P$.

Three groups of dynamic and static reserve variations with time are selected which the well pressure heads are 45 cm, 0 cm, and -6 cm separately and are shown in Figure 8. It can be found that the variation trends of dynamic and static reserves are consistent under three different $P$. The static reserve release decreases from the peak point to a value tending to zero following a first-order exponential decay law. The dynamic replenishment increases from 0 to a stable value following a first-order exponential growth law. It is found that the change trend can be described by a first-order exponential model; the results are consistent with the actual water discharge experiment and the relevant research on the variation of double exponential water inflow [23, 31]. The fitting formula and parameters are summarized, as shown in Table 4.

By fitting the dynamic and static reserve release with different $P$ reduction values over time, it is found that they all obey the first-order exponential change law:

$$Q_j = Q_{jo} + (Q_{jo} - Q_{je}) \times e^{-at}.$$  (1)
3.3. Analysis of Balance Time of the Dynamic Replenishment and Static Reserve Release. In the whole dewatering process, the static reserve release decreases from the peak value to zero, and the dynamic replenishment gradually increases from 0 to a stable value. When the quasi-steady state is reached, the static reserves basically maintained at a value tending to zero, and the water inflow is mainly recharged by the dynamic replenishment.

The time when the dynamic replenishment is equal to the static reserve release indicates that the main components of the water inflow will be changed, and the dynamic replenishment will play a main role in the recharge of the water inflow.

The equal time and water inflow are summarized in Table 6; it can be seen that the time when the dynamic replenishment is equal to the static reserve release changes regularly with the changes of $P$ and $S$. When $P=45$ cm and $S=6$ cm, the equal time is 41 s. When $P=-8$ cm and $S=51$ cm, the equal time is 125 s. The mutual influence relationship is further analyzed and fitted, and the results are shown in Figure 12. The equal time of dynamic and static reserve release according to the first-order exponential reduces with the increase of $P$ and presents the first-order exponential growth law with the increase of $S$ both with $R^2 = 0.99$.

In the actual engineering drainage water, due to the continuous extension and development of the boundary of the cone of depression and the continuous increase of the falling depth with time, the groundwater will always be in an unstable state when there is no other stable recharge source. Quasi-steady state time is great significance for prediction stable water inflow. The quasi-steady state time under different $P$ and $S$ is shown in Table 7.

Quasi-steady state time increases with the decrease of $P$ and the increase of $S$; both can be described using first-order exponential model.
Table 6: Equal time and flow rate of different P and S.

| P (cm) | 45  | 33  | 23  | 13  | 0  | -4 | -6 | -8 |
|--------|-----|-----|-----|-----|----|----|----|----|
| S (cm) | 6   | 14  | 22  | 28  | 42 | 48 | 49.5 | 51 |
| Equal time (s) | 41 | 14 | 63 | 73 | 98 | 117 | 121 | 125 |
| Equal water inflow (ml/s) | 9.8 | 19.4 | 19.7 | 37.5 | 41.8 | 49.7 | 51.5 | 52 |

Figure 12: Time of dynamic replenishment equal to static release of reserves: (a) equal time change with P; (b) equal time change with S.

Table 7: Quasi-steady state time with P and S.

| P (cm) | 45  | 33  | 23  | 13  | 0  | -4 | -6 | -8 |
|--------|-----|-----|-----|-----|----|----|----|----|
| S (cm) | 6   | 14  | 22  | 28  | 42 | 48 | 49.5 | 51 |
| Quasi-steady state time (s) | 153 | 355 | 403 | 492 | 549 | 554 | 579 | 599 |

Figure 13: Variation of quasi steady state time with P and S: (a) quasi-steady state time change with P; (b) quasi-steady state time change with S.
order exponential function with $R^2 = 0.98$, as shown in Figure 13.

4. Discussions

Water inflow variation with time and its maximum inflow are great important for underground constructions. For stabilized boundary conditions such as in this paper, the static reserve release process is the main reason for the water pressure head change; actually, the static reserve release rate directly affects the water pressure head change rate and the water inflow. The difference between the phreatic line in the initial and quasi-steady state is caused by the change of the static reserve. Certainly, the dynamic replenishment is an important component of the water inflow, which is greatly affected by the boundary conditions and mainly forms the water inflow in the quasi-steady state. Thus, this study results will provide an important reference for the underground constructions.

5. Conclusions

(1) The water pressure head variation inside the dewatering well has an approximately linear function with the drawdown above the well center. The peak water inflow changes linearly with $P$ and $S$ with $R^2 = 0.975$ and 0.95; the quasi-steady water inflow follows a first-order exponential variation law with $P$ and $S$ with $R^2 = 0.995$ and 0.99

(2) The trend of dynamic and static reserves with time can also be described by first-order exponential model, dynamic replenishment with time is a first-order exponential growth law, $Q_d = Q_{de} - (Q_{de} - Q_{jo}) \times e^{-at}$, and static reserve release with time is a first-order exponential decay law, $Q_s = Q_{jo} + (Q_{jo} - Q_{de}) \times e^{-at}$. The ratio of static reserve release to dynamic replenishment decreases with the increase of $P$ following a linear function

(3) The equal time of dynamic and static reserve release and the quasi-steady state time both present a first-order exponential reduce with the increase of $P$ and a first-order exponential growth law with the increase of $S$

These results are great useful for water inflow prediction in underground constructions including its change with time. More complicated boundary conditions should be carried out for dewatering from an aquifer bottom to study its seepage characteristics.

Data Availability

The datasets generated from the authors’ seepage test, which are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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