The Experimental Investigations on Motion Features of Groundwater Flow near the Pumping Well

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Abstract: Using the 3D pumping test device, the author has completed a number of pumping tests about phreatic and artesian water and obtained a large amount of observational data. Experiments show that: as for both phreatic and artesian water, the water head variation of the observation wells, from the pumping well is far more higher and nearer than the lower, leading to significant groundwater cone of depression distribution around the underground water pumping well. At the same time, the water heads of different observation pointing at different heights of each observation well are higher to lower from top to bottom, which are characterized by showing that the water has a top to bottom motion component while groundwater has migration and accumulation from the surrounding water boundary to the pumping well, i.e. the water movement direction is inclined. The same is true for artesian water. An analysis found the result is that not only head pressure plays an important role, but also water gravity does this too. When the water is pumped, the artesian aquifer near the top roof has a stronger water flow near the supply source.

Keywords：3D, Pumping Test Device, Pumping Well, Groundwater Flow, Motion Features

Prologue

In recent years, the theory of groundwater flow system has obtained the unceasing development and it makes profound changes in groundwater science. While rethinking and reviewing on the groundwater flow problem of groundwater science in the past， trying to accept the theory of groundwater flow system at the same time, people could find or verify the source of the driving force of the groundwater flow, or find out the main factors influencing the formation and evolution of groundwater flow system. In nature, due to the limit of observation methods, observation den-sity and the spatial distribution of observation points and other many constraints, it’s difficult to achieve the above goals. Based on the above consideration, also in order to simulate field pumping test visually and facilitate teaching, the author designed and built the three-dimensional pumping test device specifically. The device sets an important precedent for the main pumping well aquifer medium field around the three dimensional dynamic water level observation of the finished pumping test in indoor. In addition, through the simple and preliminary pumping test, some unknown phenomenon or facts before are found. To the development of the groundwater movement theory and the practical teaching in groundwater science, it’s believed that it is of great significance. With such a short essay, some observations results and the author's analysis and discussion are presented. We regard both as a henceforth reference for the counterparts, and also sincerely hope readers to criticize the correction.

Introduction of the 3D Pumping Test Device

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The device is located in the ground floor of lab S2 in Shandong University of Science and Technology (Fig.1 and Fig.2). This reinforced concrete structure is 3.8 m in height (Fig.3 and Fig.4). Among them, the base is 0.6 m in height, base plate is 0.2 m in thickness, sand pool is 2.0 m in height and the top rail is 1.0 m in height. It covers about 90 m^2, of which, the width of the stairs is 3.7 m and the length of the device platform is 6.6 m in the east-west direction and 8.66 m in the south-north direction. The observation platform is 2.8 m in height, with 1 m high fence equipped on both sides in the east-west direction and connection against the wall in the south-north direction.

Five meters in length, the sand pool appears as a square in horizontal plane, with reinforced concrete wall (0.3 m) and water supply warehouse (tank) (0.2 m) on the four sides. And the four corners are poured in concrete. Within 4 m square sand pool, a stereo space volume of 32 m^3 is formed. A vertical pumping well is placed in the center of the pool. The diameter is 100 mm. The pipe is perforated apart from the unperforated section at the bottom of 5 cm, wrapped in gauze. In order to observe easily, a digital visual automatic hydraulic probe is installed in the pipe, with wires connected to the hydraulic readouts on the exterior wall.

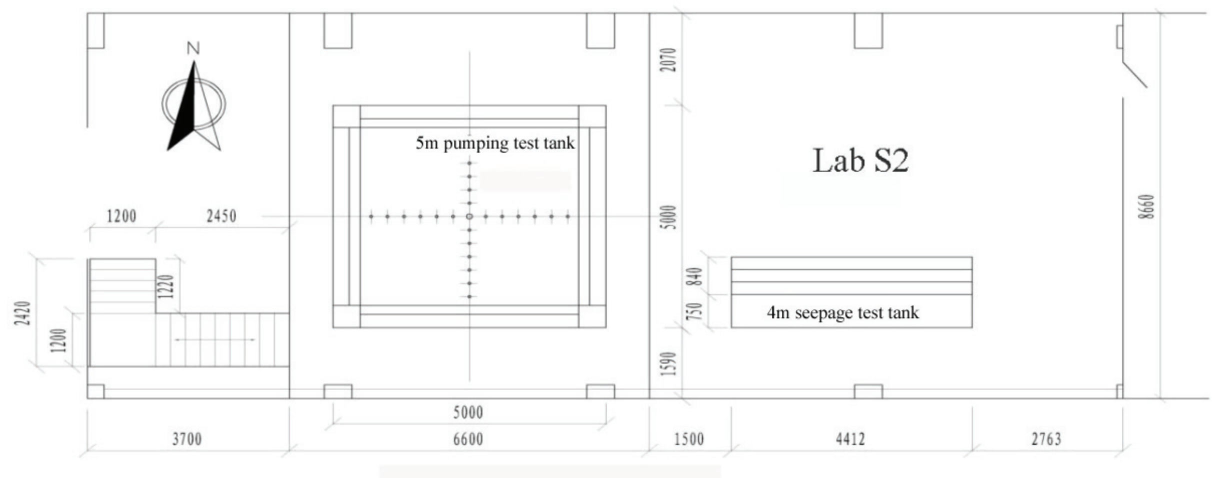

Fig.1 The Floor Plan of Pumping Test Device

There are 6 observation holes (Fig.1 and Fig.2) are installed in each direction (east, south, west and north) perpendicular to the water supply tanks. According to the position and the distance to the main well, the holes are named as South 1 (N1), South 2 (N2), East 1 (D1), East 2 (D2),... West 1 (X1), West 2 (X2),... North 1 (B1), North 2 (B2),..., the bigger the number is, the closer to the pumping main well is. The interval between each other (including the main well) is 30 cm.The first observation hole is 20 cm far from the water supply tanks. Each observation hole is 2 m in height, which is set 10 observation points (Fig.3) with equal intervals of 20 cm from top to bottom, named as No. 1, No. 2,..., and No.10. Based on the bottom of sand pool, the distance of each observation point above the pool separately is 10 cm, 30 cm, 50 cm, 70 cm, 90 cm, 110 cm, 130 cm, 150 cm, 170 cm and 190 cm from top to bottom respectively. Each observation point protrudes from the sand in the pool, with filter gauze prevent from the sand getting into. The water level can be exported from pipes in the observation wells to the lines of piezometers (Fig.4) side by side on the east and the west facades of the entire device. Therefore, the water level data of 240 points can be measured in the 3D space of sand pool at the same time. Because of the large amount of data, it is required to use video cameras to record while the water level of different observation points of each hole is observed in the pumping test. Then the data can be analysed and determined.

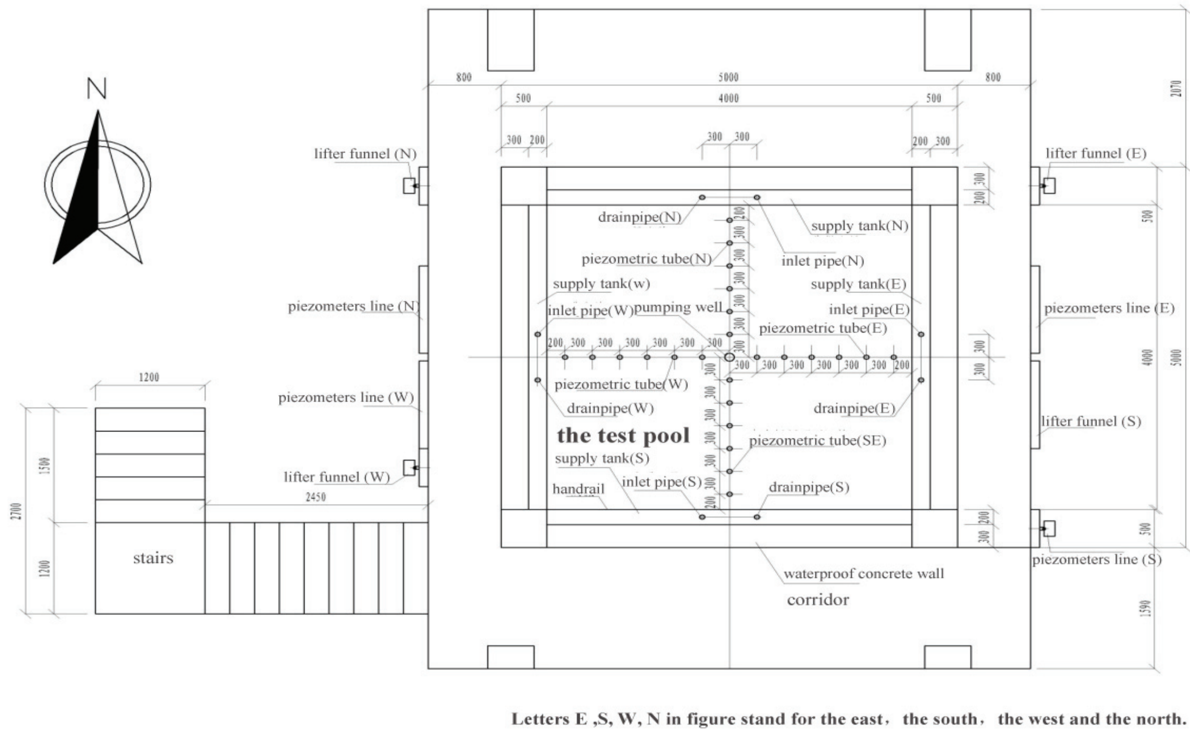

Fig.2 The Floor Plan of the Pumping Test Device

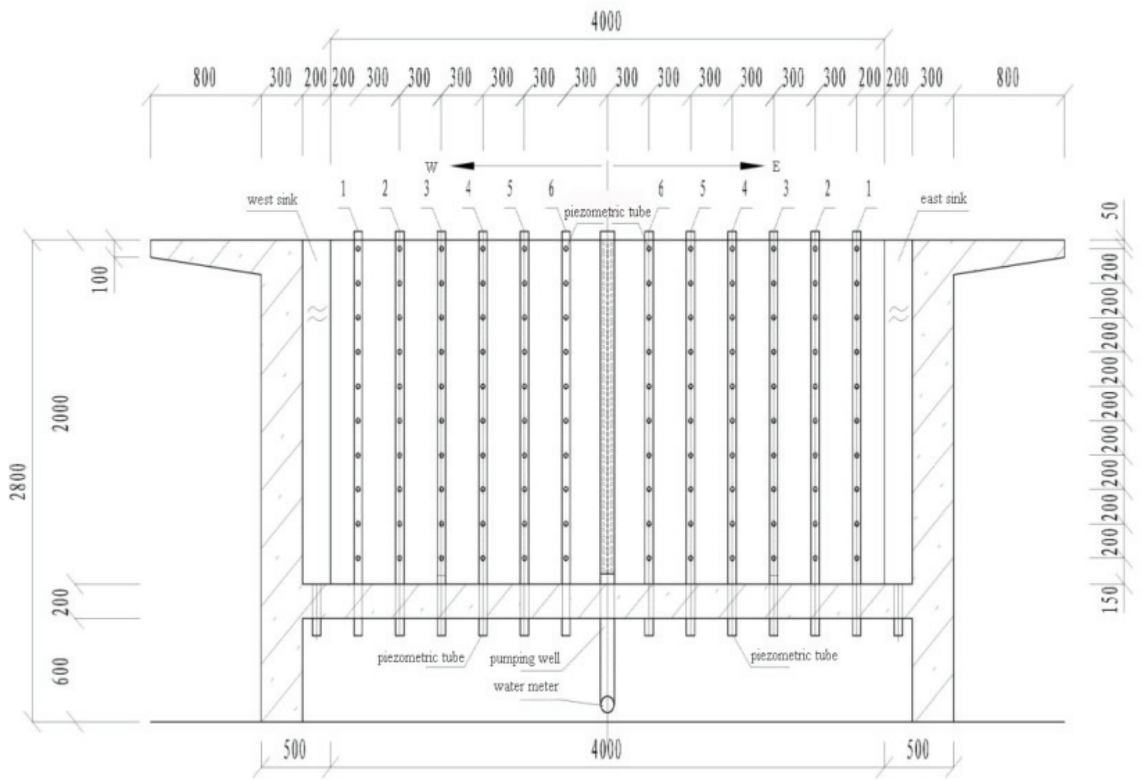

Fig.3 The Axial Profile of Pumping Test Device and the Distribution Profile of Pressure Taps of the Observation Hole in the Pumping Well

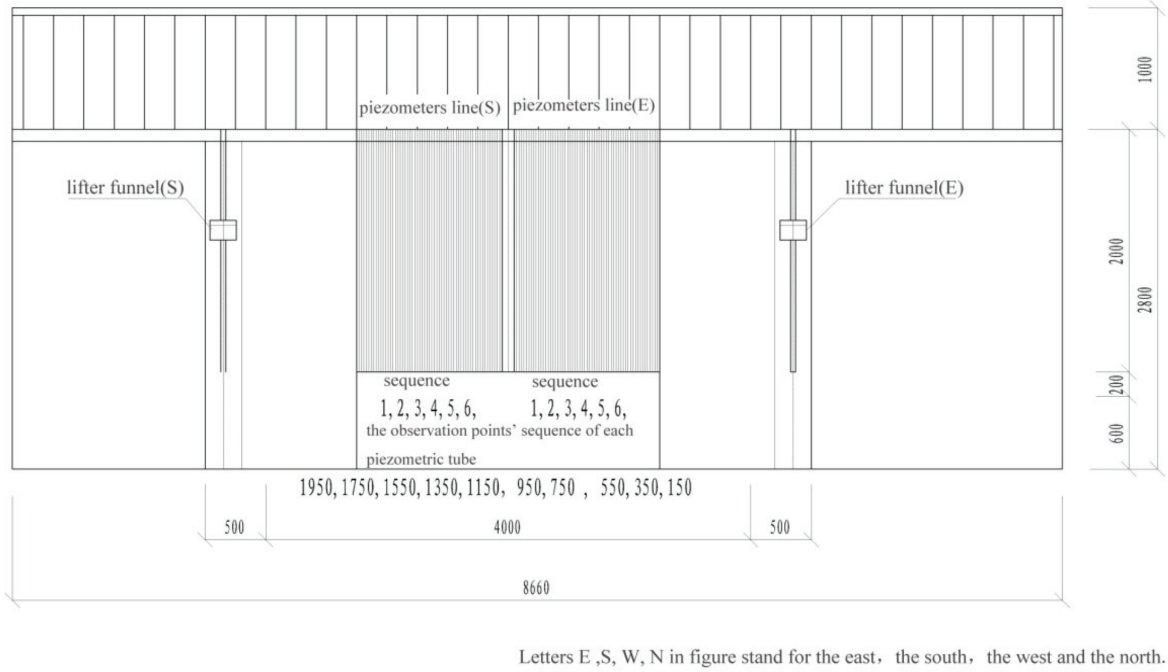

Fig.4 The East Elevation of the Pumping Test Device

The water supply and drainage system of the device is shown in Fig.5. Water is supplied from the bottom center of the supply tanks. Near the supply holes, drain holes are equipped, connecting to the flush water lifter funnels which are set in the four corners of the device. As the lifter funnels go up and down, water level of the four supply tanks can be controlled.

The quantity of pumping water can be read from the water meter (added). The result of pumping also can be achieved by drainage at the bottom of the pumping well, of which the water quantity can be measured by the water meter out of the outlet.

The water-bearing medium filled in the sand pool can be homogeneous or inhomogeneous sand or sandy soil. It can simulate unconfined water pumping test or confined water pumping test. The water-bearing medium can be tuned and adjusted depending on different experimental purposes.

As the water-bearing medium filled with water in sand pool is saturated, the pumping test can be carried out.

Results of the Pumping Test

Here are only two special situations introduced. Pumping test at constant rate is divided into unconfined water and confined water in the condition that the supply tanks keep equivalent water head boundary. And only the finally results of the steady state are introduced, and a brief analysis and discussion is made, especially on the unknown innovative conclusions.

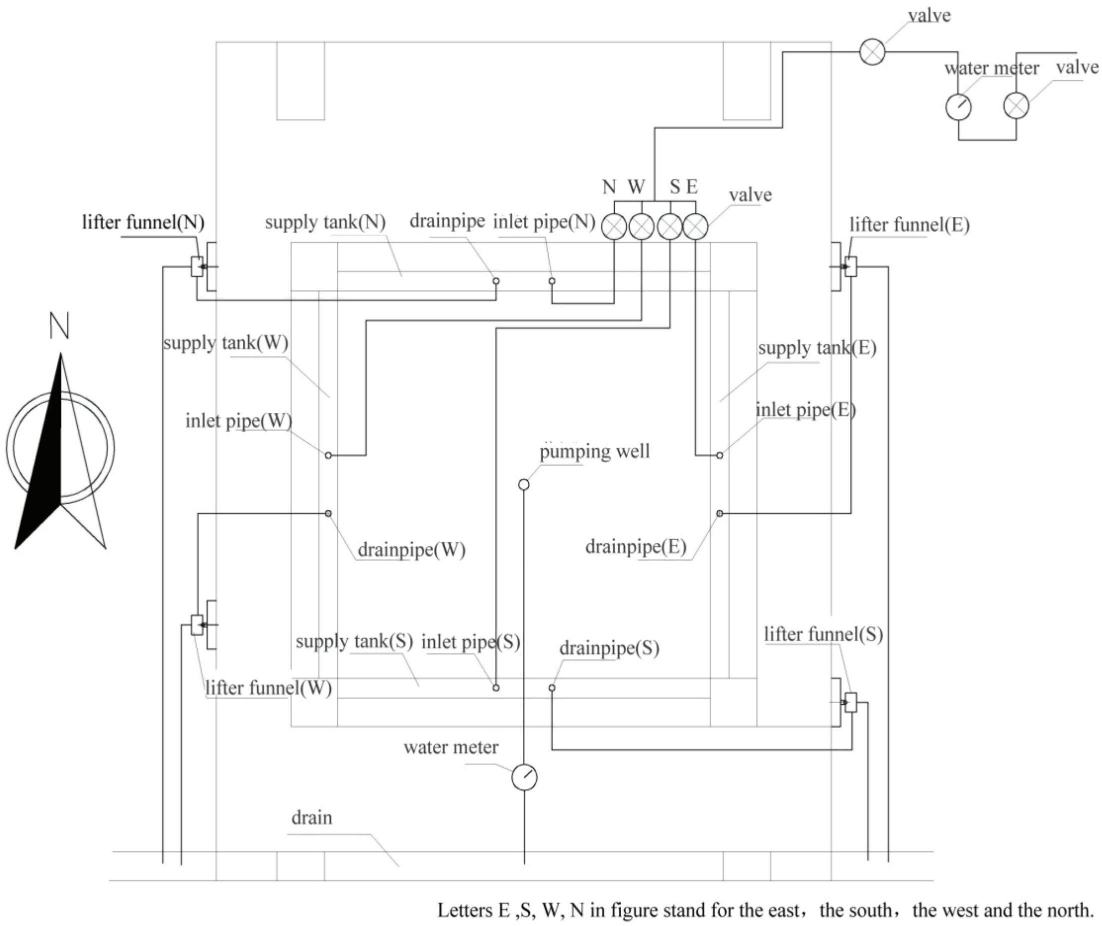

Fig.5 Water Supply and Drainage System Diagram of the Pumping Test Device

Unconfined Water Pumping Test

Within the pool filled with sand, water supply tanks filled with water, water head can keep equivalent and stable under the control of the flush water lifter funnels. Pumping from the main hole, the quantity of pumping water is 0.67 L/s. And the main hole water tends to be stable after 589 seconds. The stable water level is 1,280 mm (water level referred to in this article, is based on the bottom of the pool which is regarded as 0 mm, similarly hereinafter).

All the observed results of the four rows of the piezometers show that the water level observation results of corresponding observation holes around are identical with the corresponding observation points, with a same change law of axisymmetric centers on the pumping well. Therefore, take for example, water level changes of the six observation holes in the south of main well illustrate water level changes of unconfined water pumping in space under the condition of constant head recharge around the straight line.

As water lowering of the main pumping well, the water level of observation hole 6 near the pumping well falls first. Then the water lowering happens in other holes from the inside out successively. A groundwater cone of depression comes out around the main pumping well (Table 1 and Fig.6) while it achieves stability. The catch: the abscissa in Fig.6 is time slot rather than time. The corresponding relationship between time slot and actual time is shown in Table 2.

Since the sand pool’s small size and the distribution of constant head tanks around, water level of each point can become regional stability after a certain period of time when pumping. The water level in each hole after the stable condition is shown in Table 3.

Table 1 The Dynamic Water Level of Unconfined Water Pumping Test from Beginning to Stability in the Observation Point 8 of all Observation Holes

Time(s)	The Number of Observation Holes					
	N1	N2	N3	N4	N5	N6
0	1,810	1,810	1,810	1,810	1,810	1,810
1	1,810	1,810	1,810	1,810	1,810	1,795
2	1,810	1,810	1,810	1,810	1,810	1,790
3	1,810	1,810	1,810	1,810	1,810	1,780
4	1,810	1,810	1,810	1,810	1,810	1,770
5	1,810	1,810	1,810	1,810	1,810	1,765
6	1,810	1,810	1,810	1,810	1,800	1,765
8	1,810	1,810	1,810	1,810	1,795	1,740
10	1,810	1,810	1,810	1,805	1,790	1,730
12	1,810	1,810	1,810	1,800	1,780	1,720
15	1,810	1,810	1,810	1,795	1,770	1,705
18	1,810	1,810	1,805	1,790	1,760	1,690
21	1,810	1,810	1,800	1,780	1,755	1,680
24	1,810	1,810	1,795	1,780	1,750	1,670
29	1,810	1,805	1,790	1,770	1,740	1,660
34	1,810	1,805	1,790	1,770	1,735	1,655
44	1,810	1,800	1,785	1,760	1,725	1,640
54	1,810	1,800	1,780	1,760	1,720	1,635
64	1,810	1,800	1,780	1,755	1,720	1,630
94	1,810	1,795	1,775	1,750	1,710	1,620
124	1,810	1,795	1,775	1,745	1,710	1,620
154	1,805	1,790	1,770	1,740	1,705	1,615
214	1,805	1,790	1,770	1,740	1,700	1,610
274	1,800	1,785	1,765	1,740	1,695	1,610
394	1,800	1,785	1,760	1,730	1,690	1,605
589	1,800	1,780	1,760	1,730	1,685	1,605

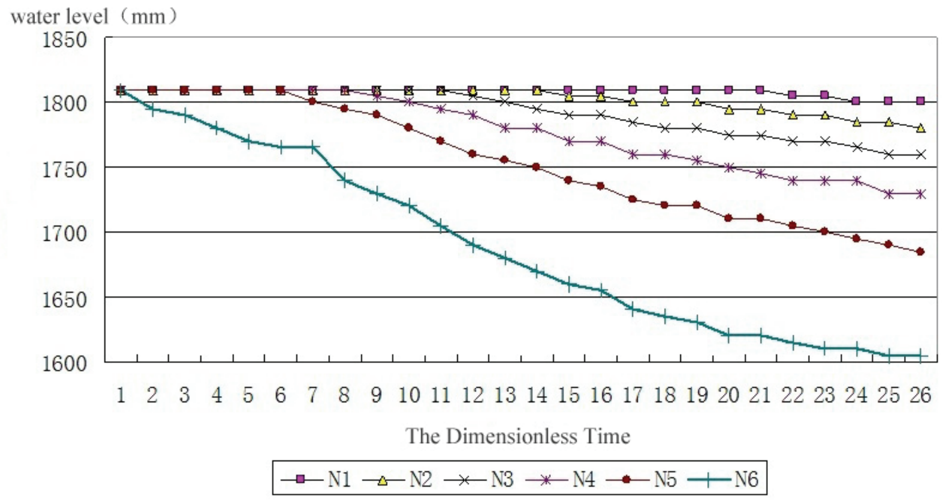

Fig.6 The Water Level Dynamic Curve of Point 8 in Each Observation Hole during Unconfined Water Pumping Test

Table 2 The Corresponding Table between Time Slot and Actual Time in Fig.6

Time Slot	1	2	3	4	5	6	7	8	9	10	11	12	13
Pumping Time(s)	0	1	2	3	4	5	6	8	10	12	15	18	21
Time Slot	14	15	16	17	18	19	20	21	22	23	24	25	26
Pumping Time(s)	24	29	34	44	54	64	94	124	154	214	274	394	589

Table 3 The Water Level in Each Hole after the Stable Condition of Unconfined Water Pumping Test (mm)

Time (s)	The Number of Observation Holes					
	N1	N2	N3	N4	N5	N6
0	1,810	1,810	1,810	1,810	1,810	1,810
1	1,810	1,810	1,810	1,810	1,810	1,795
2	1,810	1,810	1,810	1,810	1,810	1,790
3	1,810	1,810	1,810	1,810	1,810	1,780
4	1,810	1,810	1,810	1,810	1,810	1,770
5	1,810	1,810	1,810	1,810	1,810	1,765
6	1,810	1,810	1,810	1,810	1,800	1,765
8	1,810	1,810	1,810	1,810	1,795	1,740
10	1,810	1,810	1,810	1,805	1,790	1,730
12	1,810	1,810	1,810	1,800	1,780	1,720
15	1,810	1,810	1,810	1,795	1,770	1,705
18	1,810	1,810	1,805	1,790	1,760	1,690
21	1,810	1,810	1,800	1,780	1,755	1,680
24	1,810	1,810	1,795	1,780	1,750	1,670
29	1,810	1,805	1,790	1,770	1,740	1,660
34	1,810	1,805	1,790	1,770	1,735	1,655
44	1,810	1,800	1,785	1,760	1,725	1,640
54	1,810	1,800	1,780	1,760	1,720	1,635
64	1,810	1,800	1,780	1,755	1,720	1,630
94	1,810	1,795	1,775	1,750	1,710	1,620
124	1,810	1,795	1,775	1,745	1,710	1,620
154	1,805	1,790	1,770	1,740	1,705	1,615
214	1,805	1,790	1,770	1,740	1,700	1,610
274	1,800	1,785	1,765	1,740	1,695	1,610
394	1,800	1,785	1,760	1,730	1,690	1,605
589	1,800	1,780	1,760	1,730	1,685	1,605

To facilitate intuitive understanding of the situation, the data in table 3 is transformed to charts (Fig.7 and Fig.8).

In conclusion, a few interesting phenolmenon goes something like this:

(1) From the axial section of the pumping well to the water supply straight boundary, the water level in observation hole emerges that the depression near the pumping well comes first, then towards to the water supply boundary in turn, until finally get stability. The water level changes shows the start of, in line with the pumping of unsteady flow (in the case of further, such as water level change rate is similar or same to the Theis formula as well).

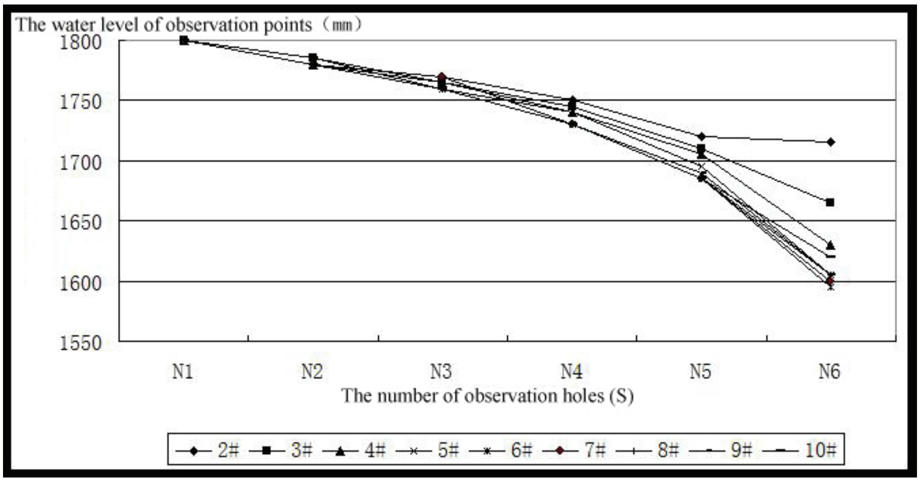

Fig.7 The Water Level of Each Observation Point in Each Observation Hole after Steady State during Unconfined Water Pumping Test (The Water Level of Main Well is 1,280 mm)

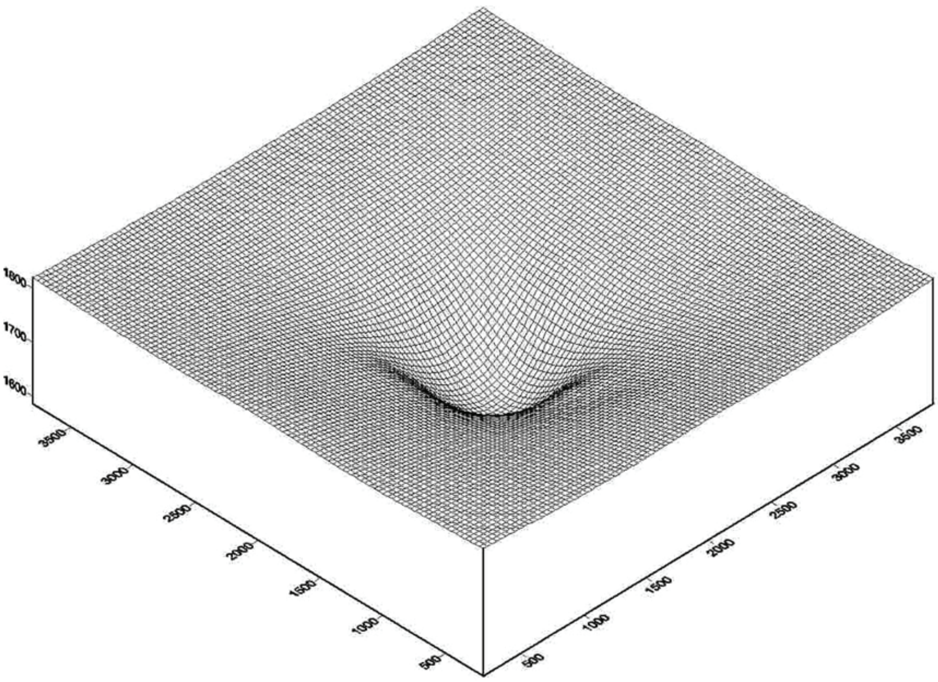

Fig.8 The 3D Distribution of Groundwater Flow in a Stable State of Unconfined Water Pumping Test

(2) To each observation hole, different observation point in water level is not equal. Usually, the higher the position is, the higher the water level is. This decision, the distribution of water level in a sand pool full of water is different in space. To the water movement of any point, there are two directions at the same time, toward the well and downward. Namely, the water movement inclines downward.

(3) However, there are exceptions. The water level of the observation points at the bottom of several observation holes near the pumping main well is higher than the point of minimum water level (the 7th counted upward). The analysis believes that the 5 cm unperforated section at the bottom of the main well affect the normal movement of the water flow. Water flow gets stagnant and energy-gathered. Then the local upward force appears. It is this reason that causes this phenomenon.

Confined Water Pumping Test

As well, this device can be used to conduct the confined water pumping test after some modification as follows. Dig out the sand on the surface to reveal the probe of the 5th observation point. Then spread out waterproof membrane above the 5th observation point counted upward (due to the small pressure difference, it's enough to use plastic film). Finally, dress and close the main well above. (In this test, cover a litter of sand over the plastic film first, and then release the air out of the pool from top to bottom until the device is full of water. According to the definition of confined aquifer, sand below the 5th observation point is confined aquifer and is in the saturated state. Later, conduct the pumping test and observe the water level of each observation point).

Likewise, after a period of pumping time, the water yield, the water level of the main well and each observation point get stable (Table 4). It can be found the water level of point No.1, No.2, No.3 and No.4 above the waterproof membrane keep constant (because it's free water in the state of full of water of which the water level is directly connected with the surrounding four water supply tanks). And the water level of the 6 water observation points under waterproof membrane appears regular changes (Fig.9 and Fig.10).

Table 4 The Water Level of Each Point in Each Observation Hole When Confined Water Pumping Test Stabilizes (cm)

Observation Hole / Observation Point	D1	D2	D3	D4	D5	D6	Water Level of the Main Well （cm）
No. 1	197.0	197.0	197.0	197.0	197.0	197.0	137.3
No. 2	197.0	197.0	197.0	197.0	197.0	197.0	
No. 3	197.0	197.0	197.0	197.0	197.0	197.0	
No. 4	197.0	197.0	197.0	197.0	197.0	197.0	
No. 5	197.0	197.0	196.5	195.2	194.8	192.0	
No. 6	196.9	196.2	195.0	193.2	190.5	182.0	
No. 7	196.8	195.9	194.2	192.0	188.5	177.5	
No. 8	196.7	195.5	193.8	191.0	186.0	175.0	
No. 9	196.6	195.5	193.5	190.0	185.0	173.0	
No. 10	196.5	195.2	193.0	189.5	184.0	173.5	

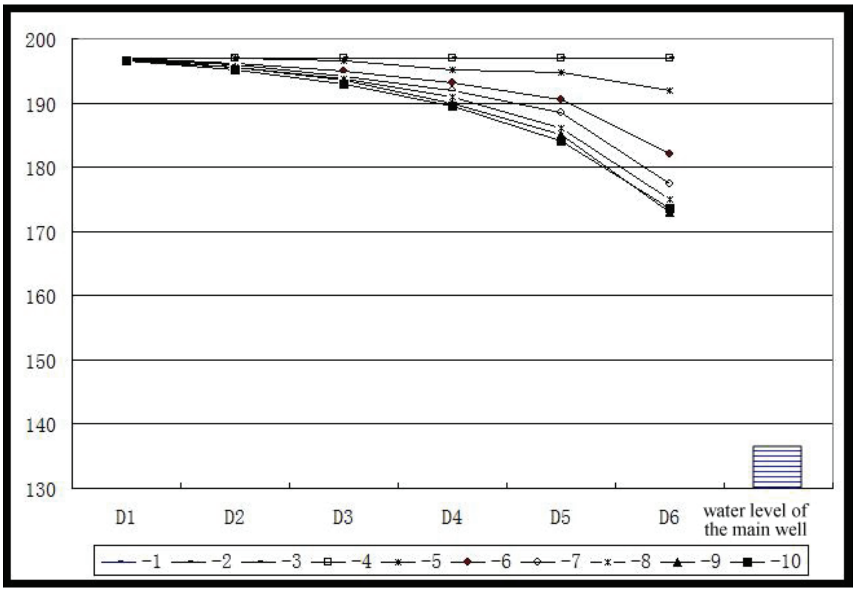

Fig.9 The Water Level of Each Observation Point in Each Observation Hole after Steady State during Confined Water Pumping Test (The Water Level of Main Well is 1,373 mm)

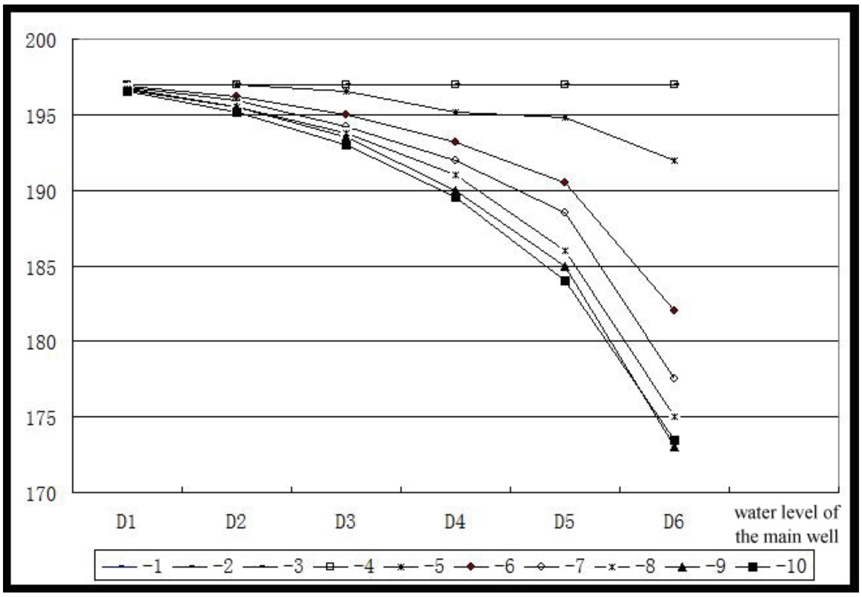

Fig.10 Detail View of Fig.9 (The Water Level of Main Well is 1,373 mm)

According to the water level of different points in different observation holes measured on the same level, a 3D space distribution characteristic pattern of the groundwater flow in the sand pool during the pumping test can be drawn (Fig.11).

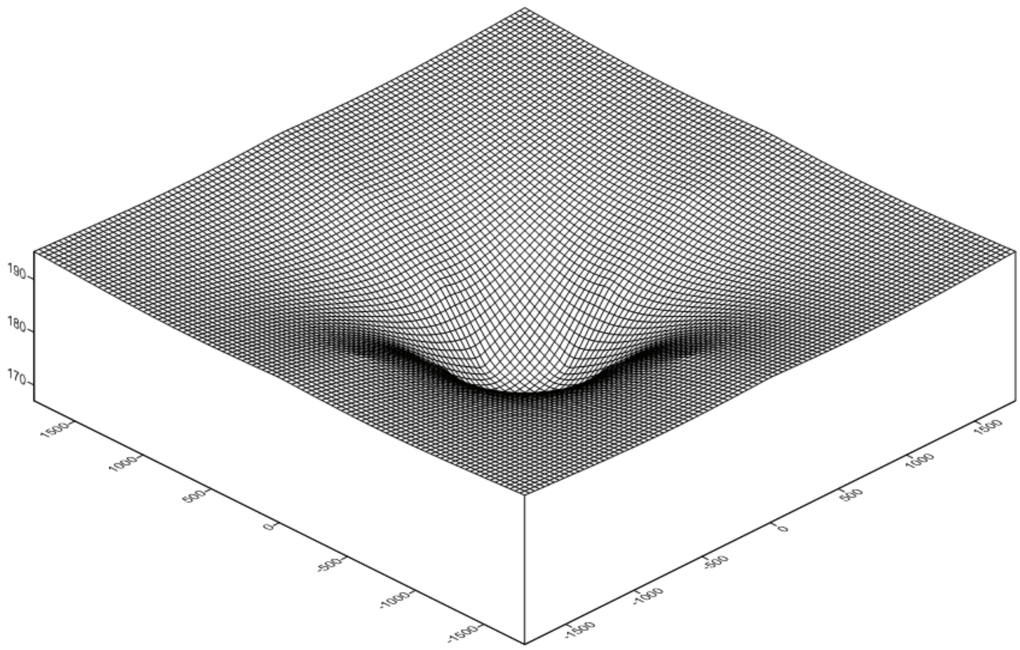

Fig.11 The 3D Distribution of Groundwater Flow in a Stable State of Confined Water Pumping Test

As the same case of the unconfined water pumping, groundwater cone of depression appears around the pumping well centered on the pumping main well. To water level on the same level of observation points, the closer the point to the pumping main well is, the lower the water level is, and vice versa.

According to the general theory, the groundwater flow should be to the moves toward the main well in the horizontal direction. However, as the same case of unconfined water, the water level of observation point is usually from high to low in each observation hole from top to bottom. It is indicated that the movement of the groundwater still inclines downward in the condition of confined water. Namely, the gravity still plays an important role.

The difference to the unconfined water is mainly reflected in one point that only the observation point 6 near the pumping main well appears the opposite on the top-down water gradually decline above. The water level of point 10 is a litter higher than point 9 at the bottom of point 6.And the rest all follow the trend that the above is higher than below.

To investigate the reasons, following conclusion is reached:

Firstly, the effect of gravity is indispensable. The downward force that plays a role all the time in the groundwater movement cannot be ignored.

Secondly, in the confined aquifer roof, near one side of the recharge boundary, there are strong currents more rapidly than other position. The currents point to the pumping well.

Thirdly, the function of blocking and lifting water flow is still reflected in the 5 cm unperforated pipe at the bottom of the main well during confined water pumping test.

Conclusions

Through the operation of the 3D pumping test device, it can be found that the device can realize the 3D dynamic water level observation of the saturated medium near the pumping main well full of water medium. Accord with the test, the spatial feature (3D) of the groundwater flow movement can be found that the groundwater movement inclines downward based upon the interaction of gravity and pressure. This kind of situation not only appears in the state of unconfined water, also in the condition of confined water. It follows that there is strong water flow passing through the roof accessory of the confined water aquifer during pumping. The closer to the recharge source, the stronger the water flow is.

References

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