Memoirs of the Faculty of Engineering, Okayama University, Vol.25, No. 1, pp.59-69, November 1990

Pumping Test for Multilayered Aquifers

Iichiro KOHNO*, Makoto NISHIGAKI*, and Junji OKADA**

(Received October 31 , 1990)

SYNOPSIS

In this paper, we propose a method to determine the coefficients of permeability of the unconfined aquifer consisted of two different permeability layers. With mixing the conventional pumping test and falling head permeability test, the coefficients of permeabilitiy k_1 and k_2 were obtained. The validity of the proposed method is investigated by using the numerical simulation. As the results, it becomes apparent that the proposed method is applicable to real hydarulic problems.

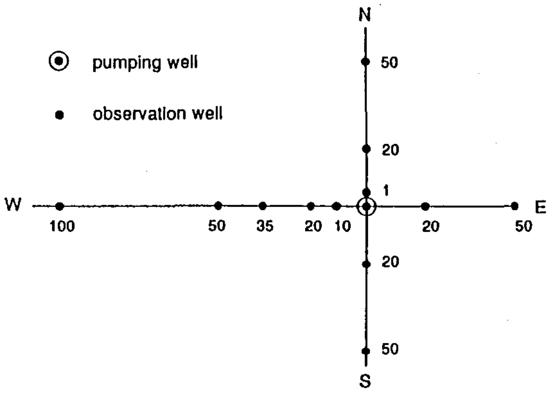
1. INTRODUCTION

To design improvement of clay foundations by dewatering method, we have to determine the exact hydraulic coefficients of aquifers. To measure the coefficient of permeability, in-situ permeability tests are usually carried out. However, in the case that the multilayers consists of aquifer as shown in Fig.1, it is quite difficult to analysis the puming test data by the conventional analytical method as theis' or Jacob's method. So we have the develop some analytical methods for these complex conditions. Fig.1 shows the aquifer consisted of two layers with different permeabilities. This case is very common case in the plain area in Japan. We try to analysis with mixing the conventional pumping test data and falling head permeability test data in the pumping well. The validity of the proposed method will be verify by the numerical analysis method of finite element.

---

* Department of Civil engineering

** Nakaboli Soil Corner Co.Ltd.



(numerals show distance from pumping well to observation well in , m .)

Fig.1 Plane of Arrangement of Pumping Well and Observation Wells.

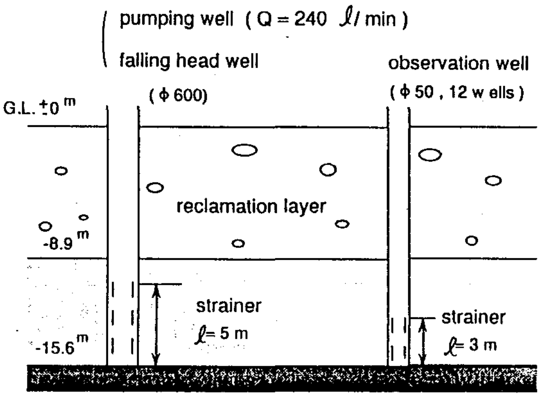


Fig.2 Cross Section of Arrangement of Pumping and Observation Well.

2. IN-SITU PERMEABILITY TEST

2.1 Experimental Method

Fig.2 shows the plane view of the arrangement of pumping and observation wells. Table 1 shows the specification of the pumping and observation wells. The pumping rate was measured by the time required to fill the vessel (capacity 60ℓ) placed under the end of the drainage pipe.

Table 1. Specification of Pumping and Observation Well.

item	pumping well	observation well
drilling diameter	1000mm	86mm
drilling machine	overall casing method	rotary boring machine
outer diameter of well casing	609.8mm	48.6mm
depth	15.6m	15.6m
strainer length	5m	3m
used mud	-	rester (commercial name)

Two types of in-situ permeability test were carried out as shown in Fig.3. In the first, the mean coefficient of permeability $\bar{k}$ of the unconfined aquifer as shown in Fig.1 was measured by the pumping well test with several observation wells. Next , the coefficient of permeability of the lower layer k_1 was obtained by the falling head permeability test in the pumping well.

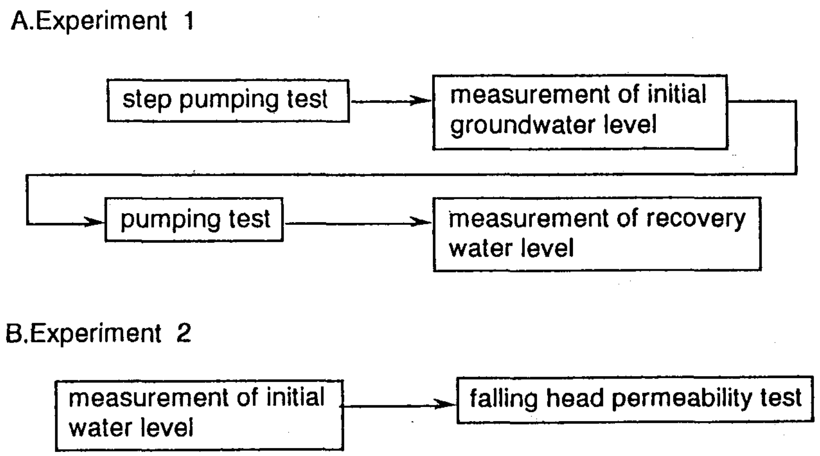


Fig.3 Flow Chart of in - situ Permeability Tests

2.2 Experimental Results

Fig.4 shows the relationship between the pumping rate and the drowdawn in pumping well. From these results, the optimum pumping rate was decided as 240ℓ /min. The relationship between time and ground water behaviours during pumping test are shown in Fig.5. Falling head permeability test result is also shouwn in Fig.6. In this case, that water was supplied by a large water cart.

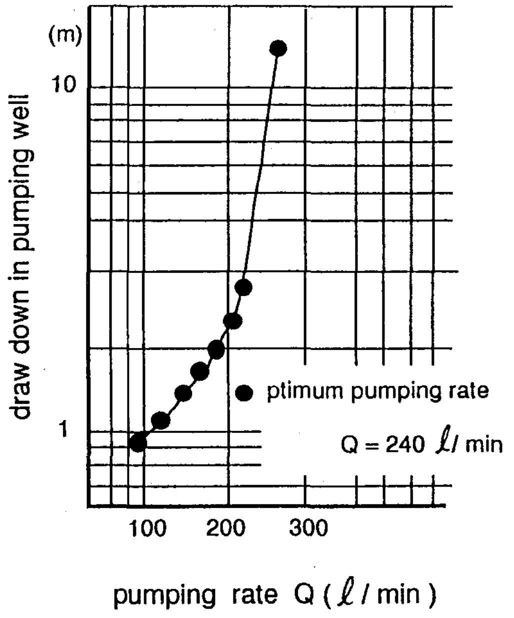


Fig.4 Step-Pumping-Test results

2.3 Determination Of The Coefficients Of Permeability

(1) Mean coefficient of permeability of the unconfined aquifer consisted of two layers

(a) Equilibrium method

Thiem's equilibrium equation can be expressed as follows:

$$k=\frac{2.3Q\log\left(r_j/r_i\right)}{\pi\left(h_j^2-h_i^2\right)} \qquad (1)$$

Where k ;coefficient of permeability

Q ;pumping rate

h_i, h_j ;water head at a distance r_i and r_j from pumpig well respectively

The calculated results are shown in Table 2. From these results, the co- efficient of permeability k is between 1.9×10^{-2} m/min and 2.7×10^{-2} m/min, and its avarage value $\bar{k}$ is 2.4×10^{-2} m/min.

Table 2. Coefficient of Permeability by Thiem's Equllibrium Equation.

direction	average coefficient of permeability k (m/min)	
N	1.92×10^{-2}	2.44×10^{-2}
W	2.65×10^{-2}	
S	2.37×10^{-2}	
E	2.01×10^{-2}	

(b) Nonequilibrium method

Theis nonequilibrium equation can be expressed as follows [1].

$$T=\frac{Q}{4\pi s}\int_u^{\infty}\frac{e^{-u}}{u}\,du=\frac{Q}{4\pi s}W(u) \qquad (2)$$

$$W(u)=\left[\frac{4\pi T}{Q}\right].s \qquad (3)$$

$$u=\left[\frac{S}{4T}\right]\cdot\frac{r^2}{t} \qquad (4)$$

where s : drawdown

Q: pumping rate

T: coefficient of transmissibility

S: coefficient of storage
r: distances of the obsevation well from pumping well
t: time

Table 3 shows the calculated results. The average coeffient of permeability $\bar{k}$ becomes 2.0×10^{-2} m/min.

Table 3. Coefficient of Permeability and Coefficient of Strage by Thels's Nonequilibrium Equation.

pumping time t (min)	165	225	405	585
coefficient of permeability k (m / min)	1.88×10^{-2}	1.67×10^{-2}	2.01×10^{-2}	2.29×10^{-2}
average coefficient of permeability k (m / min)	1.96×10^{-2}			
coefficient of strang S	3.77×10^{-2}	5.79×10^{-2}	5.46×10^{-2}	4.46×10^{-2}
average coefficient of strage S	4.87×10^{-2}			

(c) Recovery test method

From recovery test, permeability was obtained as $k=1.5 \times 10^{-2}$ m/min

(d) Average permeability

We can get average permeability $k=2.0 \times 10^{-2}$ m/min from above three methods ((a),(b)and(c)).

(2) The Coefficient Of Permeability Of The Lower Layer k_1

(a)Falling head permeability test

Coefficient of permeability of the lower layer k_1 was obtained by the falling head permeability test by using the pumping well. In this method, hydraulic conductivity k can be computed from the following equation:

$$k_1 = \frac{2.3\,Q}{2\pi L H} \log(L / r_w) \qquad (5)$$

Where Q: the recharge rate
L: length of the well screen
r_w : radius of pumping well
H : water head in well

The coefficient of permeability k_1 obtained for 5 minutes after stopping water supply is within the range of 2.1×10^{-3} m/min ~ 6.1×10^{-3} m/min and from these values, the average value $\overline{k_1}$ becomes 4.8×10^{-3} m/min.

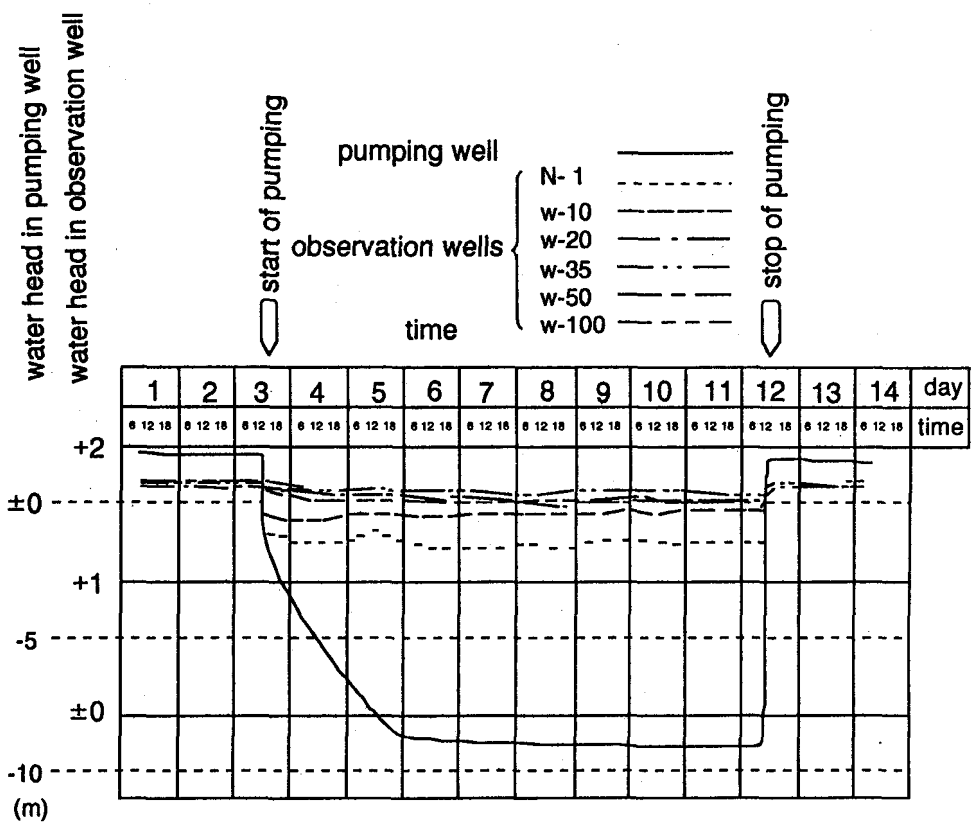


Fig.5 Relationship between Time and Growndwater Level in Pumping Test.

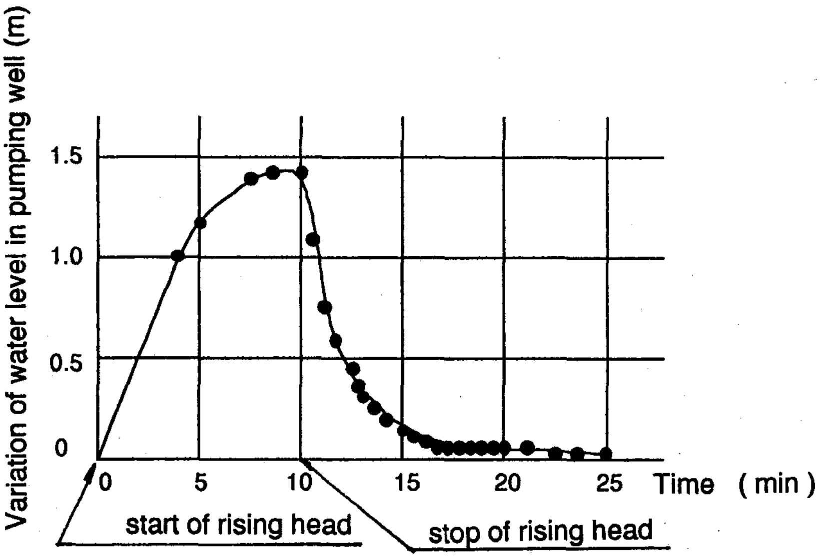


Fig.6 Relationship between Time and Water Level in Pumping well during Falling Head Permeability Test.

(b) Method based on difference in water head in and out well

The following expression are obtained[2]:

$$\overline{h_w} - h_w = \frac{Q^2}{8\pi^2 k_1^2} \cdot \frac{1}{\overline{r_w}^2 \cdot \overline{h_w}} \tag{6}$$

Where h_w: water head in pumping well

$\overline{h_w}$: water head in a piezometer at a distance $\overline{r_w}$ from the center of pumping well

From this method, the coefficient of permeability k_1 was obtained as $k = 2.1 \times 10^{-3}$ m/min.

(c) Average value

From these two methods ((a)and(b)), the average coefficient of permeability k_1 becomes 3.5×10^{-3} m/min.

(3) The coefficient of permeability of the upper layer k_2

The following equation was derived from Fig.7.

$$Q = k_1 \cdot 2\pi r \cdot m\frac{dh}{dr} + k_2 \cdot 2\pi r \cdot h \cdot \frac{dh}{dr} \tag{7}$$

Integrating with $h=h_1$ at $r=r_1$ and $h=h_2$ at $r=r_2$ we can derive an equation for the well discharge Q as follows:

$$Q = \frac{2\pi m k_1(h_2 - h_1) + \pi k_2(h_2^2 - h_1^2)}{2.3 \log r_2 / r_1} \tag{8}$$

where Q : the well discharge

r_1 and r_2: the respective distances of the piezometers from the well

h_1 and h_2: the restactive elevation of water levels in the piezometers

m: thickness of lower layer aquifer

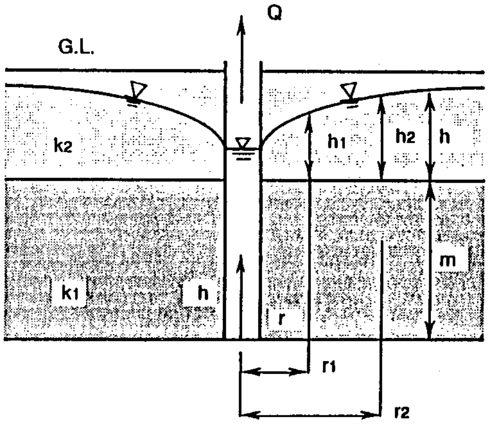


Fig.7 Model of drawdown of two layer aquifer

As the coefficient of permeability k_1 of the lower layer is 3.5×10^{-3} m/min, so the value k_2 of the upper layer is determined as $k_2 = 7.1 \times 10^{-3}$ m/min from Eq.(8).

3. NUMERICAL ANALYSIS

3.1 Numerical Model

To examine the validity of the proposed method to determine the coefficient of permeability in two layered aquifer systems, we applied the finite element method of the nonsteady seepage analysis in the saturated and unsaturated porous media[3]. Fig.8 shows element division (170 nodes and 208 elements). Each parameter of two layers, upper and lower, is shown in Fig.9. The flow chart of the seepage flow analysis is shown in Fig.10.

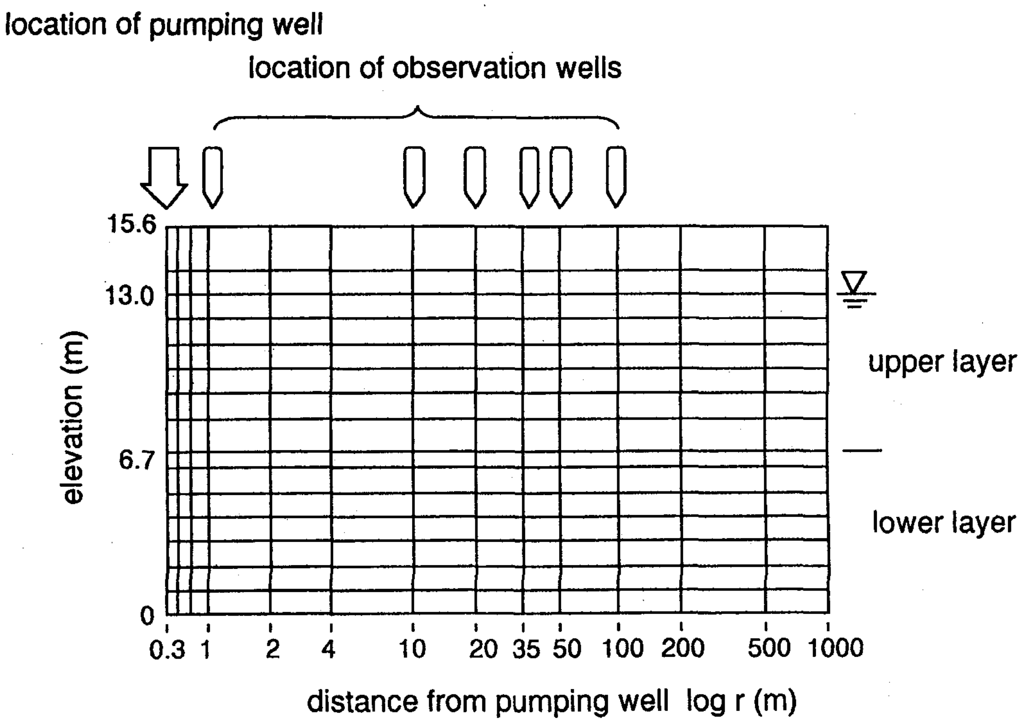


Fig.8 Element Divisions

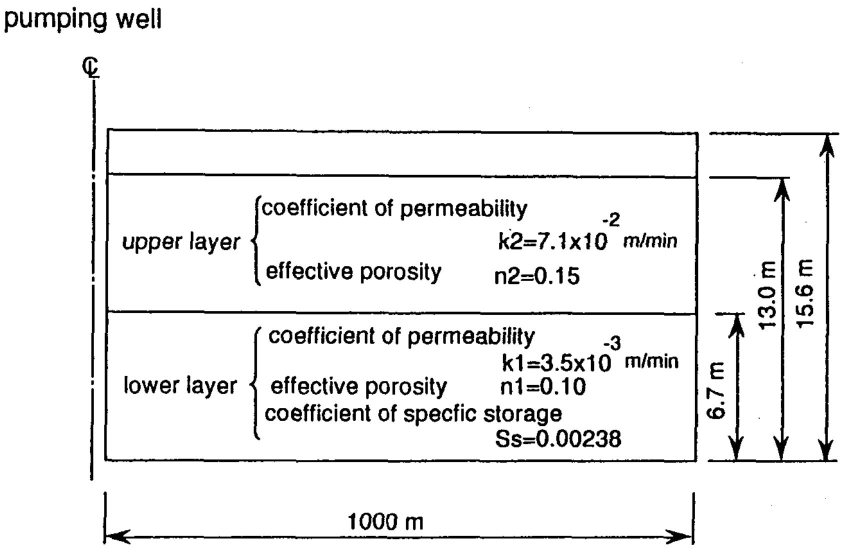


Fig.9 Constants of Aquifer

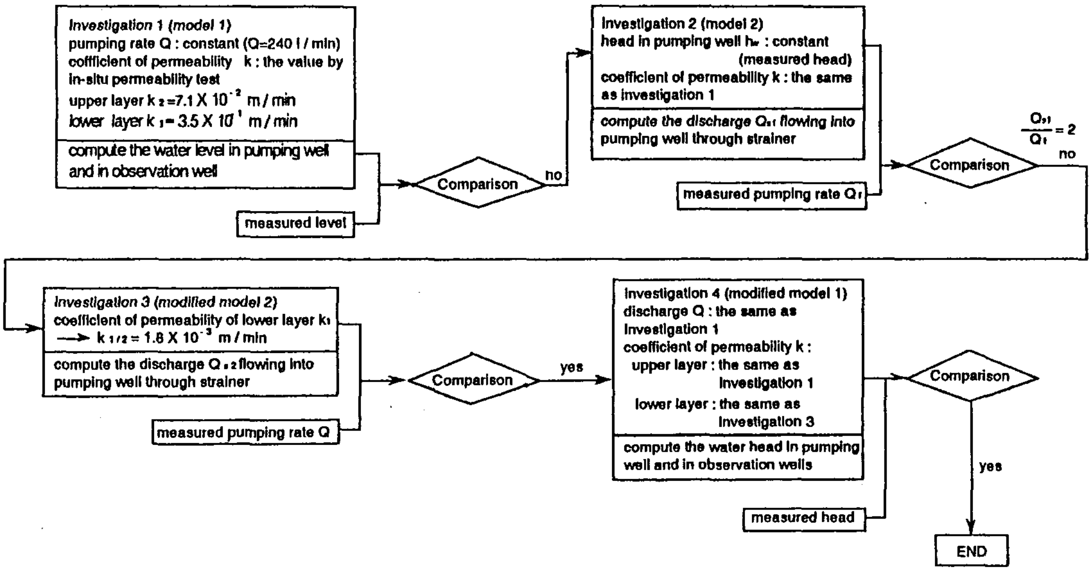


Fig . 10 Flow Chart of Seepage flow Analysis .

3.2 Numerical Results

1) Investigation 1

When the pumping rate was constant at the measured pumping rate, the numerical caluculated value of the drawdown in pumping well becomes about 5m. However its measured value was about 11m and is almost twice the calculated value.

2) Investigation 2

When the water head in puming well was constant at the measured draw- down , the caluculated value of the puming rate Q becomes 400ℓ/min, this is almost twice the measured value (240ℓ/min).

3) Investigation 3

Assuming that the lower layer in which the strainer of well was set was strongly influential in discharging, we calculated the pumping rate by using half value of the coefficient of permeability in investigation 2 ($k_1 = 1.8 \times 10^{-3}$ m/min) as the input data. Based on this assumption, the calculated value of discarge was obtained as Q=220ℓ/min. This value is almost equal to the measured value (Q=240ℓ/min). And then, we decided that the coefficient of permeability of the lower layer is suitable for half of the measured value.

4) Investigation 4

The calculated groundwater level with the half value of the measured coefficient of permeability of the lower layer investigated above is shown in comparison with the measured results in Fig.11. The agreement between computed and measured profiles in Fig.11 is considered satisfactory. But the computed values of the drawdown nearby the pumping well is smaller than the measured values. Therefore, it becomes apparent that the real coefficient of permeability of the upper layer is smaller than those values obtained by the pumping test.

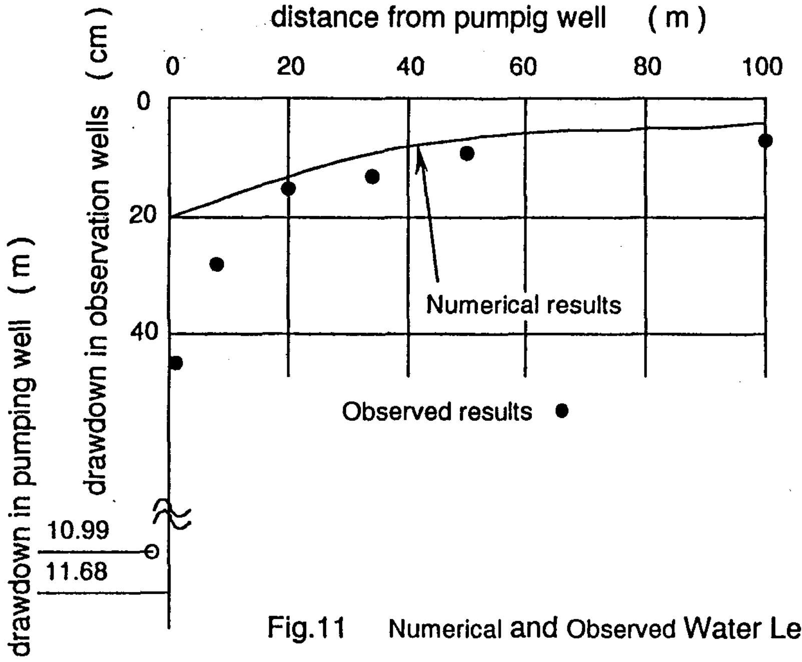


Fig.11 Numerical and Observed Water Level

4.CONCLUSION

The mean coefficient of permeability $\bar{k}$ of unconfined aquifer consisted of two layers with different permeabilities was obtained by the pumping test of the well with several observation wells. The coefficient of permeability of the lower layer k_1 was obtained by the falling head permeability test in pumping well. The coefficient of permeability of the upper layer k_2 was caluculated by using $\bar{k}$ and k_1.

The appropriateness of each coefficient of permeability obtained from these methods is judged by the seepage flow analysis. As the results, it is appear that the proposed method have enough applicability to real problems, but still there are lots of problems to improve in the case of multi-layered aquifer systems.

REFERENCES

[1]Kono,I. ; "Groundwater Engineering"(in Japanese) , pp.92-93,1989.
[2]Sakai,G.; "Applied Groundwater Hydrology" ,(in Japanese) , pp.165,1967.
[3]Onishi,Y., Nishigaki,M.; "The Analysis of Saturated and Unsaturated Seepage Flow Using the Finite Element Method, Procedure and Programing Explanation", (in Japanese) , 1981.