北海道大学工学部研究報告
第152号（平成2年）

Bulletin of the Faculty of Engineering
Hokkaido University. No. 152 (1990)

On the Development of Experimental System of Groundwater Flow

Noriyasu KATOH*, Masuyuki UJIHIRA*
Kiyoshi HIGUCHI* and Masamitsu NEGISHI**

(Received June 30, 1990)

ABSTRACT

In the scale model study on groundwater flow, it is required to measure the changes of heads of many points in the model as fast as possible. Authors have developed an experimental system which consists of experimental vessel, pressure sensors, A/D converters and a personal computer. As the result of the test of this system, it was confirmed that the time to measure the hydraulic heads of several tens of points and the time to print out the processed data on the plotter at arbitrary time were 0.5 second and 3 minutes respectively. It is considered that this system would be available to evaluate the unsteady flow of groundwater because of its high speed measuring and processing ability.

1. Introduction

At the working sites in underground of coal mine, metal mine and moutain tunnel,it is not rare case that groundwater flows out suddenly or rapidly to the working face. For example, 2 m^3/min of groundwater flowed out into the working face in an inclined shaft in Yubari Shin Coal Mine, and 30 m^3/min of groundwater flowed out from the fractured zone in a tunnel driven through Rokkou Mountains in Hyogo Prefecture.[1)2)] In these working sites where great amount of ground water continued to flow out, it was necessary to decide whether an other roadway or tunnel for water drainage should be driven or only water drainage boreholes should be drilled. There are many cases that the fractured zone has been formed almost vertically. In these cases, it is able to establish the two dimentional vertical model for an approximation of these fractured zones. In this reason, an experimental system has been developed to evaluate the changes of groundwater level, the changes of hydraulic head and velocity of flow and the quantity of water flow toward the working face.

In this paper, the experimental system of groundwater flow, an example of experimental results obtained from the system and the results of FEM analysis are described.

2. Law of Similarity

It is necessary to satisfy a law of similarity in the scale model study. However, it is impossible to satisfy the law of similarity on all physical parameters, when the scale model

* Safety Eng., Dept. of Mineral Resources Development Eng.

** Geology and Rock Mechanics Section, Civil Eng. Research Inst., Hokkaido Development Bureau

study on hydraulic phenomenon is carried out. Generally, Reynolds Law is applied between prototype and model in the scale model study of groundwater flow.[3)4)5)]
Reynolds number is defined as follow.

$$Re = V \cdot L/\nu \tag{1}$$

where, V : fluid velocity
L : length
ν : dynamic viscosity
Experimental model is considered to be similar to prototype, when Reynolds number of the prototype equals to that of the model.
It is given by

$$R_{ep} = R_{em} \tag{2}$$

where, suffix p and m mean prototype and model respectively.
Equation(1) is substituded into equation(2) and the following equation is deduced.

$$\begin{aligned} V_p \cdot L_p/\nu_p &= V_m \cdot L_m/\nu_m \\ &= \alpha_v V_p \times \alpha_L L_p/\alpha_\nu \nu_p \end{aligned} \tag{3}$$

where, α_v : scale factor of velocity
α_L : scale factor of length
α_ν : scale factor of dynamic viscosity
Accordingly, the following equation is deduced.

$$\alpha_v \times \alpha_L/\alpha_\nu = 1 \tag{4}$$

As the fluid used in this experimental model is as same as that of prototype, the α_ν equals to 1. So the equation(4) is transformed as follow.

$$\alpha_v \times \alpha_L = 1 \tag{5}$$

Using the equation(5), it is able to lead some scale factors that give influences to the experimental results. These scale factors are shown in Table 1.

Table 1 Scale factors for scale model experiment of groundwater flow.

	Dimension	Scale Factor
Length	L	$\alpha_L = \alpha_L$
Dynamic Viscosity	L^2T^{-1}	$\alpha_\nu = 1$
Fluid Velocity	LT^{-1}	$\alpha_V = 1/\alpha_L$
Time	T	$\alpha_T = \alpha_L^2$
Permeability Coefficient	LT^{-1}	$\alpha_K = 1/\alpha_L$
Flow Quantity	L^3T^{-1}	$\alpha_Q = \alpha_L$

3. Experimental System

In accordance with Table 1, the scale factor of time is 1/40000, when the scale factor of length is established to be 1/200. This means that one second in the model is suited to 40, 000 seconds in the prototype. Therefore it is necessary to do the measurement of hydraulic heads within one second at least, when the experiment of groundwater flow is carried out.

For the reason as mentioned above, the experimental system of the groundwater flow which consisted of pressure sensors, A/D converters and a personal computer was developed.

3.1 Outline of the System

The experimental apparatus is shown in Fig. 1. The height of the apparatus is 75 cm, the horizontal length is 125 cm, and the thickness is 15 cm, and the transparent acryl boards are attached to the front and back sides. Then one water drainage hole is mounted. It is a cylindrical strainer of which diameter is 2.5 cm and length is 14.5 cm respectively. Water tanks are mounted to the both ends of the apparatus. The function of the water tanks is to fix the boundary conditions. And, 49 pressure sensors are put to measure the hydraulic head at each point. The outputs from sensors are inputed to the two A/D converters which are built in a personal computer.

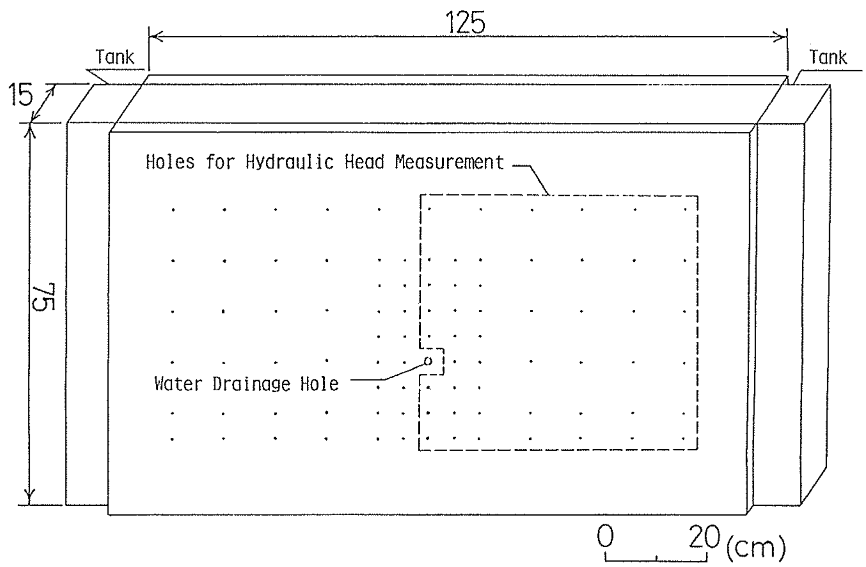

Fig. 1 Experimental apparatus and arrangement of the holes for measurement of hydraulic heads.

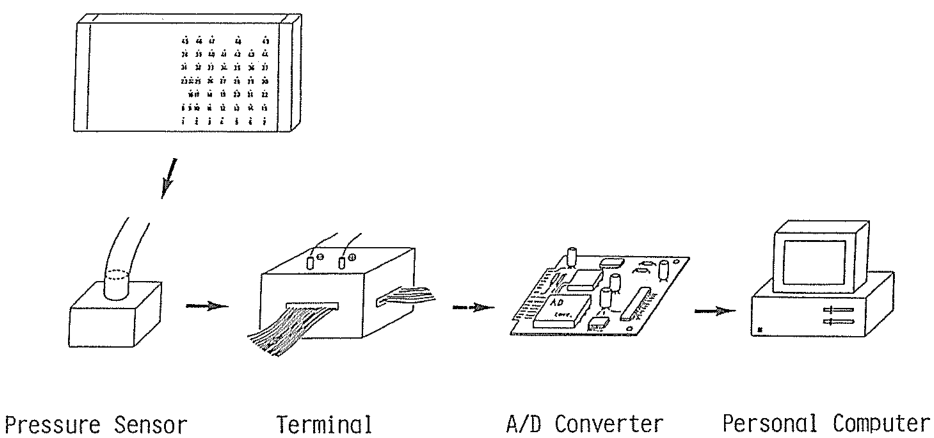

Fig. 2 Flow diagram of experimental system.

The flow diagram of the hardware of this experimental system is shown in Fig. 2 and the photo of the experimental apparatus is shown in Fig. 3.

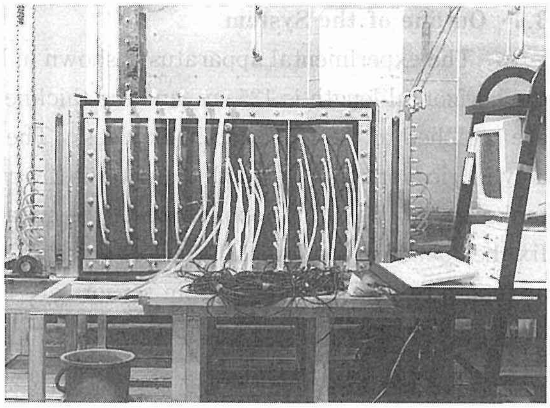

Fig. 3 Photograph of experimental apparatus.

As shown in Fig. 2, the outputs from sensors are led to a terminal, inputed to the computer and processed. The characteristic curve of the pressure sensor is shown in Fig. 4. It shows the relation between the output voltage of sensor and hydraulic head. The A/D converter has a resolving ability of 4096 bits. As the range of the head that is necessary to be measured in this experiment is from 10 cm to 100 cm, output voltage of the sensor is restricted from 1.1 V to 1.3 V. So, the resolving ability of this A/D converter is 0.55 cm in the hydraulic head.

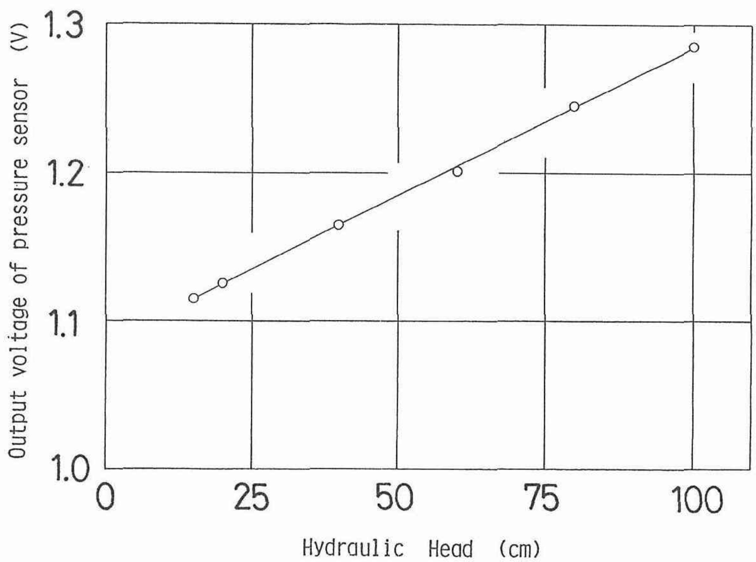

Fig. 4 Characteristic curve of pressure sensor.

3.2 Program for Measurement and Data Processing

The flow chart of the program for measurement is shown in Fig. 5. The function of this program is described as follows.

(1) Read the initial output voltage of all pressure sensors before beginning of experiment, (2) read the time to measure from floppy disk, (3) set the clock in the computer to 0 : 0 : 0, (4) begin the measurement ; open the water drainage hole at the same time, (5) read the time from the clock ; read the output voltage of all pressure sensors when the command to

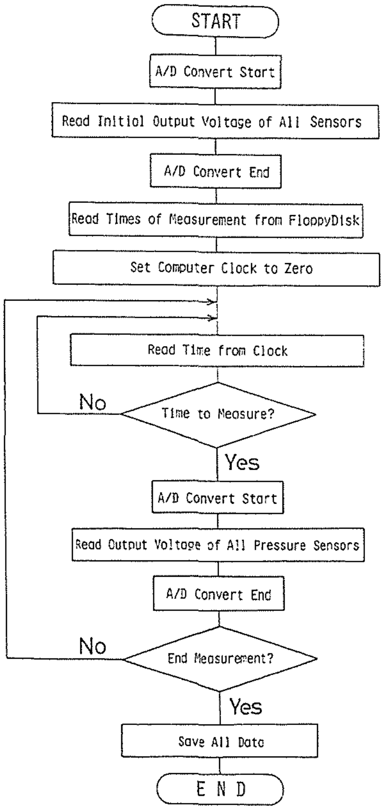

Fig. 5 Flow chart of program for measurement.

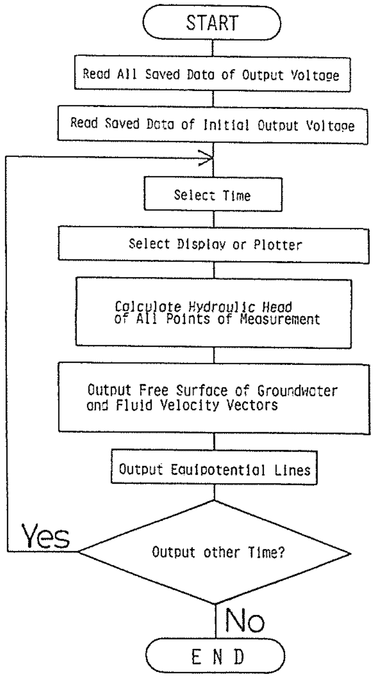

Fig. 6 Flow chart of program for data processing.

measure is transmitted, (6) go to (5), if the measurement is not finished, (7) save the all data to floppy disk.

The flow chart of the program for processing the data is shown in Fig. 6. The function of this program is described as follows.

(1) read the all saved data from floppy disk, (2) appoint the time to output and select a display or a plotter for an output device, (3) calculate the hydraulic heads of all measuring points of the time in accordance with the relation given in Fig. 4, (4) output all equipotential lines, fluid velocity vectors and a free surface of groundwater.

4. Experiment of Groundwater Flow

The experimental procedures and the results are described in the following sections.

4.1 Experimental Procedures

The experiments of groundwater flow are carried out as following procedures.

(1) Fill the model material that has a fixed permeability coefficient to the appointed level of the apparatus, and place a fixed quantity of water, (2) leave it for more than 24 hours and put out the air entrained in the material, (3) open the water drainage hole and measure the heads

by using the program for measurement as described in 3.2, (4) the quantity of water flowed out is measured at constant time intervals.

4.2 An Example of Experiment

The case that a crosscut was driven against an ore vein of water permeable which spread 250 m horizontally and 130 m vertically was established as a prototype of experimental example.

The level of initial surface of groundwater was established to be 130 m from the impermeable basement, the position of crosscut reach was established to be 60 m from the impermeable basement and 125 m from right and left ends. Scale factors of length, time, density of the fluid, permeability of the material, velocity of the fluid, quantity of the flowing out fluid into the crosscut roadway are shown in Table 1.

Scale factors of physical properties applied to the model are shown in Table 2. The sand of which permeability coefficient was 1.03×10^{-4} (m/s) was used as the model material. This value of permeability corresponds to 0.52×10^{-6} (m/s) in the prototype.

Table 2 Scale factors practically given in an experiment of groundwater flow.

	Dimension	Scale Factor
Length	L	$\alpha_L = 1/200$
Dynamic Viscosity	L^2T^{-1}	$\alpha_\nu = 1$
Fluid Velocity	LT^{-1}	$\alpha_V = 200$
Time	T	$\alpha_T = 1/200^2$
Permeability Coefficient	LT^{-1}	$\alpha_K = 200$
Flow Quantity	L^3T^{-1}	$\alpha_Q = 1/200$

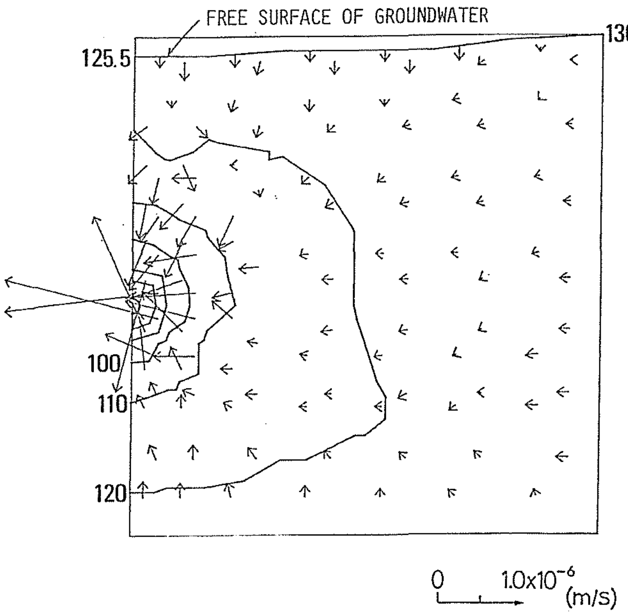

Fig. 7 State of groundwater flow on 20th day from the start of water drainage.

Fig. 7 and Fig. 8 show the results of the experiment. These figures were printed out automatically on the plotter. The time that is necessary for processing and printing out the groundwater level, equipotential lines and fluid velocity vector at an arbitrary time is less than 3 minutes. At here, the numerical values in the figures are magnified to the prototype scale in accordance with Table 2.

Fig. 7 shows the state of groundwater flow on the 20 th day from beginning of the water drainage. As shown in this figure, the fall of the free surface of groundwater is 4.5 m on the upper part of the crosscut. Equipotential lines are distributed closely around the crosscut in the shapes of circle or ellipse, and almost vertically and roughly in the range far from the crosscut. Groundwater is flowed out from all directions around the crosscut.

Maximum value of the fluid velocity vector is 1.70×10^{-6} (m/s) and the quantity of water flow is 3.81 (m^3/hour) at this time.

Fig. 8 shows the state of groundwater flow on the 360 th day from the beginning of the water drainage. As shown in this figure, the fall of the free surface of groundwater is 30 m on the upper part of the crosscut. Distribution of the equipotential lines becomes rougher even around the crosscut than that shown in Fig. 7. Maximum value of the fluid velocity vector is 1.00×10^{-6} (m/s) and the quantity of water flow is 3.96 (m^3/hour) at this time. At the time, the flow has become steady flow and the state of the flow did not change hereafter.

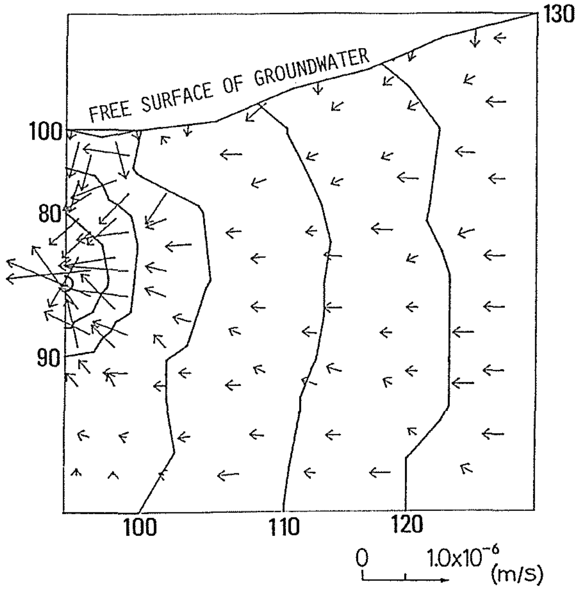

Fig. 8 State of groundwater flow in 360th day from the start of water drainage.

As above, it has been confirmed that the hydraulic heads of fluid flow can be measured within the interval of 0.5 second and the state of the flow can be displayed accurately in response to the model structure and material.

5. Numerical Calculation of Groundwater Flow

The procedures of FEM analysis and the results are described in the next sections.[6)]

5.1 Procedures of Calculation

Fig. 9 shows the model of FEM This model has 89 elements and 107 nodes. The initial hydraulic head is given to the nodes of the right hand end as the boundary condition. Permeability coefficient is set to be uniform and to have no anisotropy in the model.

In this numerical calculation, the initial surface of groundwater is set to be 130 m from the impermeable basement. The position of crosscut is set to be 60 m from the impermeable basement. These conditions are quite same as those of the experiment mentioned above.

5.2 Calculated Results

Fig. 10 and Fig. 11 show the results of the numerical calculation.

Fig. 10 shows the state of groundwater flow on the 20 th day from beginning of the water drainage. As shown in this figure, the fall of the free surface of groundwater is 16.7 m on the upper part of the crosscut. This value is 12.2 m larger than that obtained from experiment. Equipotential lines are distributed closely around the crosscut and the shape is circle. Maximum value of the fluid velocity vector is 3.07×10^{-6} (m/s) and the quantity of

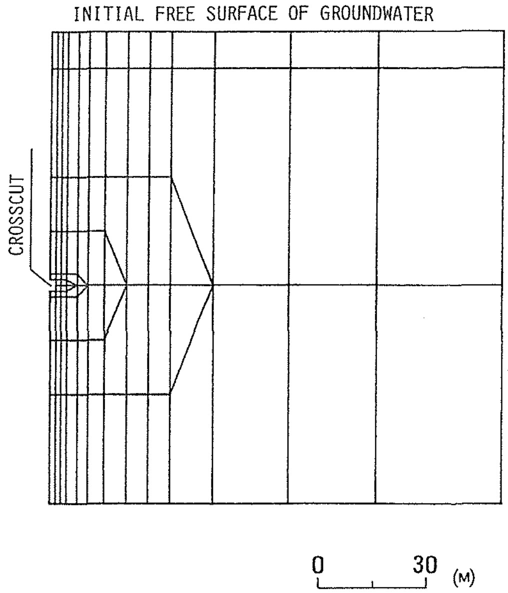

Fig. 9 Finite element model and arrangement of crosscut.

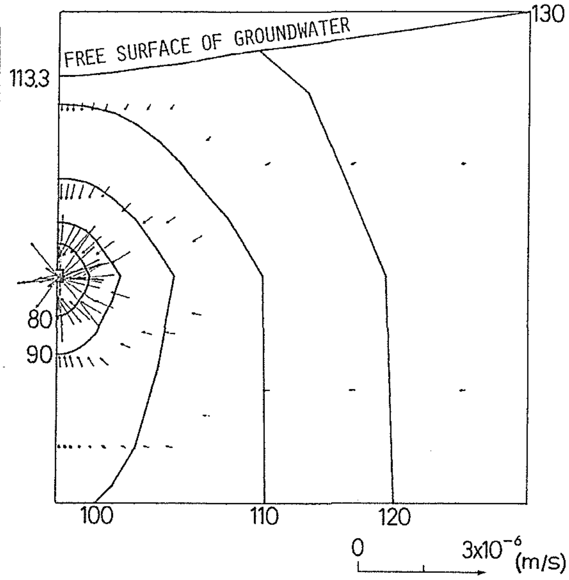

Fig. 10 State of groundwater flow in 20th day from the start of water drainage.

water flow is 5.64 (m^3/hour) at this time. The velocity and the quantity are 1.8 and 1.5 times larger than those obtained from experiment respectively.

Fig. 11 shows the state of groundwater flow on the 360 th day from the beginning of water drainage. At here, the fall of the free surface of groundwater is 39.7 m on the upper part of the crosscut. Maximum value of the fluid velocity vector is 2.62×10^{-6} (m/s) and the quantity of water flow is 4.58 (m^3/hour). These values are also larger than those obtained from experiment. At this time, the flow of the water has become steady flow.

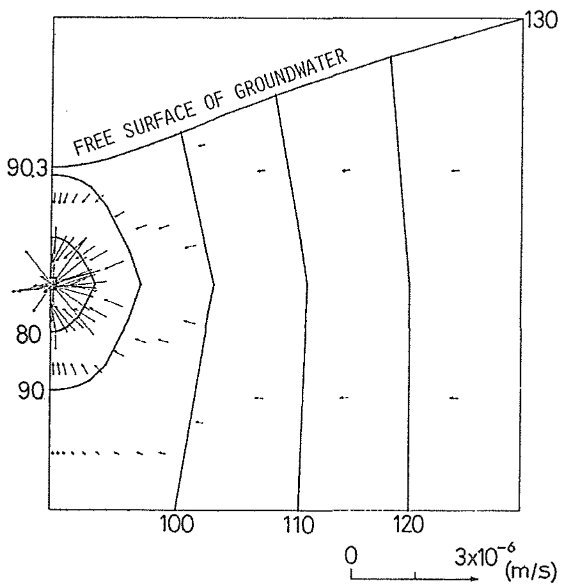

Fig. 11 State of groundwater flow in 360th day from the start of water drainage.

Fig. 12 shows the relation between the distance from crosscut to the free surface of groundwater and the time lapse from the beginning of water drainage. As shown in this figure, within 30 days from the beginning of water drainage, the falling rate of the free surface of groundwater of the calculated result is larger than that of the experimental result. But, after about 60 th day, the both rates are almost equal.

On 360 th day when the state of the flow has become steady, the fall of the free surface of groundwater is 30 m in the case of experiment and 39.7 m in the case of calculateion.

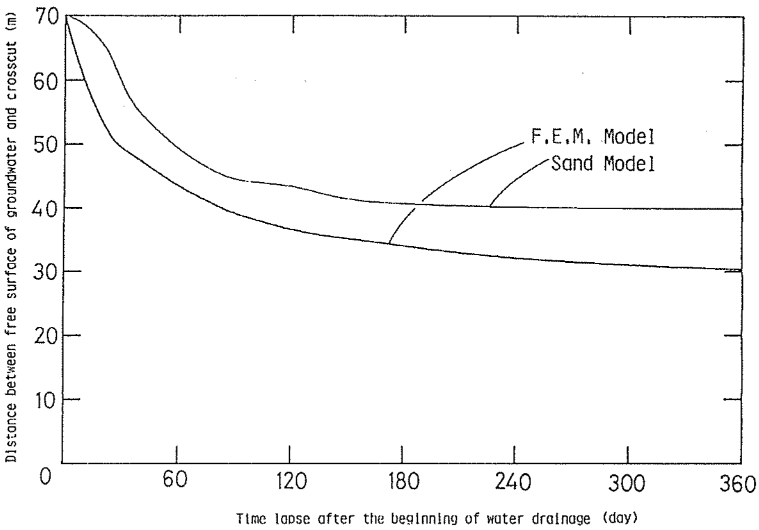

Fig. 12 Changes of the level of groundwater surface in accordance with time lapse.

Difference between these fall values have become smaller than that in the initial stage of water drainage.

Generally, there is the tendency that the values of fall of the free surface of groundwater and the fluid velocity are evaluated larger in the FEM analysis in comparison to those in the case of scale model study. It is considered that the results obtained from experiments should be used in addition to those obtained from numerical analysis, when the prediction of the state of groundwater flow against the prototype is required.

6. Conclusion

The results obtained from the study are as follows.

(1) Authors have developed an experimental system of groundwater flow which consists of experimental vessel, pressure sensors, A/D converters and a personal computer. Then, it was confirmed that the heads of the 49 points could be measured within 0.5 second, and the time that is necessary for processing and printing out the groundwater level, equipotential lines and fluid velocity vector at an arbitrary time was less than 3 minutes.

(2) It was found that this experimental system was available for the evaluation of the state of groundwater flow in the two dimentional fractured or fissured zone.

(3) It is desirable that experimental study should be carried out in addition to numerical analysis, when the prediction of the state of groundwater flow against the prototype is required.

REFERENCES

1) *Yubari Shin Coal Mine Co.Ltd., Countermeasures against the flowing out of groundwater in the driving of inclined shaft in Yubari Shin Coal Mine (in Japanese),Colliery Engineering, No.2, pp.*8−11 (1973)

2) *Y. Ashida et al., Examples of construction of moutain tunnels (in Japanese), Kougakusya Publisher, pp.* 128−135 (1977)

3) *D.W.Hobbs,Scale Model Studies of Strata Movement around Mine Roadway, Int.J.Rock Mech.Mining. Sciences, pp.*101−127 (1965)

4) *M. Ujihira,N. Katoh,T. Morikawa, On the Prediction of the Changes of Underground Water Level in a Metalliferous Vein in Drift Driving (in Japanes), Hokkaido Geotechnics* '90, *pp.*28−34 (1990)

5) *Sachio Harada, Fluid Engineering (in Japanese), Maki Syoten Publisher pp.*67−75 (1965)

6) *Y. Ohnishi, H. Shibata, M. Nishigaki, Finite Element Analysis of Seepage Flow in regularly jointed Rock Mass, Numer. Methods Geomech., Vol.*2, *pp.*673−680 (1985)