Numerical Analysis for Prediction as to Influence of Digging a Tunnel on Groundwater

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Summary

This paper describes monitoring of the in-valley discharge and underground water level at the place where the tunnel will be constructed and also, the numerical analysis for prediction applying the Tank Model and Linear Filter Method to calculate the prediction.

The application of these analyses has actually allowed the change of underground water level to be grasped and more effective information system to be established by comparing the real-time monitoring data with the real-time calculation of prediction.

1 Introduction

Since many people are living in the narrow plains in Japan, the case that both environmental protection and tunnel development being carried out in closing area get entangled with each other is farther increasing. Especially, the problem of water-related environment has great influence.

When excavating a tunnel in the mountains, it is often apprehensive that this tunnel has the function of gathering water, which may cause the shortage of water in the rivers. The reduction of water in the rivers will decrease the number of underwater organisms and also, the number of ground ones flocking to obtain water. Moreover, there is a risk that plants may be withered away.

The tunnel itself should be constructed with waterproof lining system in order to make invalid the tunnel's action of gathering water. In addition, it becomes necessary to do sufficient monitoring for checking the change of surface water.

Noise and exhaust gas are disliked in a city and its suburbs, so that a road and the like are frequently installed underground. The tunnel to be examined here is also one of them, and a road tunnel through under the hills saved as the place of civilian's recreation.

Since the reduction of surface water was worried due to tunnel passing, its continuous survey was performed to measure the change of water amount on and under the ground for several years before starting to construct the tunnel.

At the time of actual tunnel construction, however, it is required to perform the fulltime environmental monitoring to grasp the situation of the surrounding hydrogical environment during the tunnel construction on the basis of the observation of in-valley discharge on the ground, the observation of underground water level and the observation of geology with the complete measures so as not to allow the surrounding hydrogical environment to be changed by digging a tunnel.

It is important to make prediction in the environmental monitoring. The numerical ground flow analysis is often made by means of the finite element method (FEM) to make prediction for water leakage caused from the tunnel when it is dug. There are three analyzing methods: (1) vertical two-dimensional ground water FEM, (2) quasi three-dimensional ground water FEM and (3) three-dimensional ground water FEM.

And also, there is a simple predicting method of viewing the discharge by use of the Tank Model and Linear Filter with the measurement at site.

Thus, this thesis will describe the method of predicting the influence on underground water and ground water when the tunnel is dug using the Tank Model and Linear Filter analysis.

1.1 Project Oriented Information Integrated Construction (IIC)

The present writer has been suggesting the project oriented IIC to advance the smooth flow of

information in the life cycle of project.
The examination content of water environment attendant on the tunnel digging work to be newly provided in the IIC is shown by the hatches in Fig. 1.

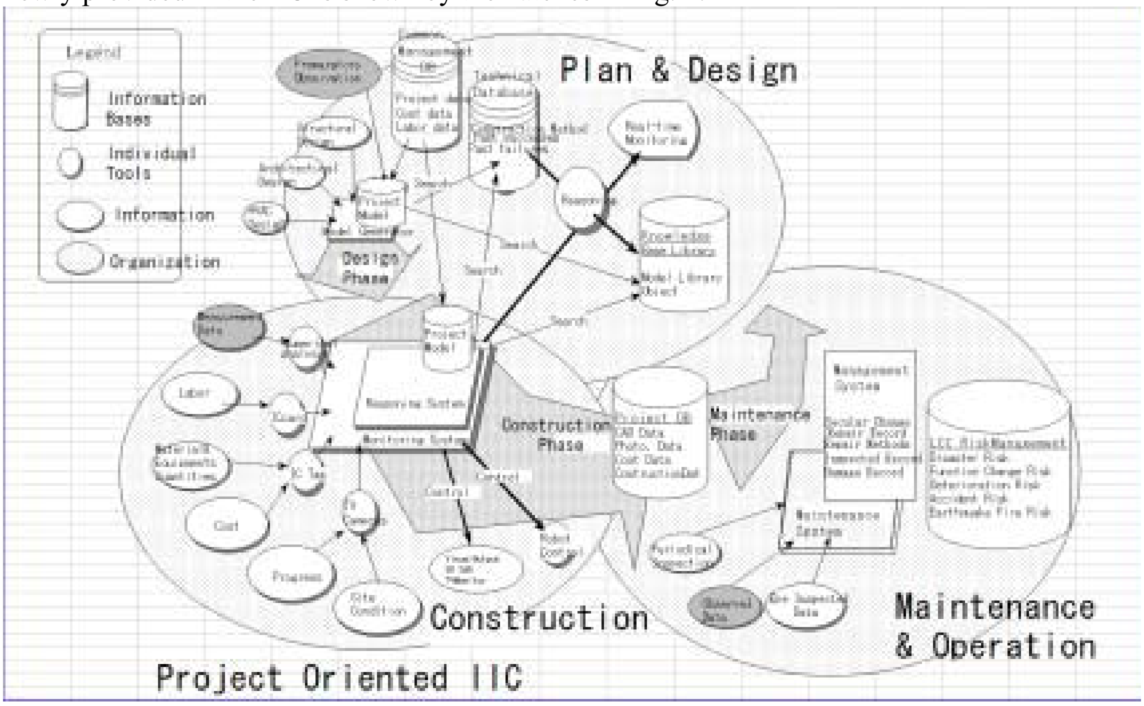


Fig.1 Project Oriented IIC

The actual work procedures are described as follows:After sufficiently checking, in the search and design stages in Fig. 1, the annual precipitation and water volume of river, the flux of springs, the underground water level and the change of river environment by measurement or visual judgment, these values that will be measured at the time of work execution should be predicted from the above data. There is no problem if work is carried out within the range of predicted values. Otherwise, if a trouble that the actual values are largely out of these predicted ones occurs during construction, it should be interrupted to consider countermeasures. And then, if there is no problem after the completion of tunnel construction while the continuous observation is performed for some years, the estimate that the tunnel construction has been completed without any trouble and the natural environment has been also maintained will be given.

1.2 Measures for Environmental Protection

In the construction of tunnels and/or underground cavities, it is known as the troubles that the underground water veins are cut off during construction and a newly constructed tunnel becomes an aqueduct, which does not resume the underground water level even after the completion of construction and causes the reduction of water in the ground rivers. In order to prevent such troubles, the tunnel itself should be constructed with the consolidation waterproof system so as not to make it the aqueduct. At the same time, when digging the high-permeability ground as an example, it is necessary to take countermeasure to prevent water leakage occurring from ground around the tunnel by applying consolidation grout before digging work.
In the tunnel construction introduced here, it takes measures from the beginning of construction plan that the consolidation waterproof lining is integrated into the structure of tunnel so that the water level of small ground rivers is not lowered, and the ecology is not turned into others and the natural scene is not changed by the set water level. Further, the application of consolidation

grout is planned around the tunnel in the high-permeability geological area so as to decrease springs flowing from the tunnel.
The waterproof tunnel is integrated with the consolidation grouting and water-tight concrete lining with water protection sheet.

2 Preliminary Surveys and Development of Prediction Formula

2.1 Preliminary Survey

Before the start of tunnel construction, the detailed survey of geology and underground water was made, the level of springs flowing from the tunnel was predicted, and the tunnel construction method and consolidation measures were examined.
The preliminary survey is important to take such measures, so that the precipitation and in-valley discharge were measured for a long term. In addition, the survey of geology at the tunnel unveiled the existence of part of high-permeability ground.
The preliminary survey to secure the actual measuring values such as the in-valley discharge was carried out 5 years before starting the tunnel construction.
The content of preliminary survey is as follows:
(1) Survey of in-valley discharge: 20 stations
(2) Survey of flowing springs amount: 20 stations
(3) Survey of underground water level by boring work: 5 stations
(4) Survey of water level of a well at hill-top
(5) Visual survey of important scene protecting object, i.e., small waterfall: 3 stations
(6) Basic survey of temperature and precipitation
At the main observing points among them, the surveyors use the method that the above content is measured every hour with an automatic printing recorder.

2.2 Ground Observing Points at the Construction Phase

The important points should be selected from these observing points when a tunnel is being dug, automatic measuring work should be done with measuring instruments, and countermeasures should be taken for the lowered underground water level and the change of in-valley discharge. Thus, 14 points of measuring the discharge and the underground water level were selected in addition to 1 point of measuring the temperature and precipitation as the basic survey.
The observing points are shown below.
(1) Survey of in-valley discharge: 5 stations
(2) Survey of flowing springs amount: 4 stations
(3) Survey of underground water level by boring work: 4 stations
(4) Survey of water level of the well at hilltop

2.3Outline of Predicting Method

The tunnel described here is constructed with the consolidation waterproof system and watertight concrete lining so as to avoid influence on the surrounding underground water environment attendant on the tunnel digging work, and “Environmental Monitoring” is also done to check any influence. When checking the existence and degree of any influence that may be exerted due to the tunnel digging work, they should be confirmed according to the level of decrease from “Normal Value” as to the underground water level, the in-valley discharge and the ground springs amount to be monitored. However, since these observed values always change due to influence of weather conditions, especially precipitation, it is difficult to set the specified values as control ones. Therefore, the predicted values should be calculated in consideration of the change of precipitation, so that comparing the predicted values with the observed ones allows influence of digging a tunnel to be examined.
Hereupon, the 2 methods of “Tank Model” and “Linear Filter Analysis” that enable the underground water level and the in-valley discharge to be predicted according to the change of

actual precipitation should be used for daily control to judge the existence of influence of digging a tunnel. In these both methods the relations between precipitation and observed values (the underground water level, the in-valley discharge, etc.) are perceived from the past observed data and then, the forecasting values in consideration of the change of precipitation are gained by entering the observed value of precipitation into the obtained model.
Either method is based on a model in which real phenomenon has been simplified. The Tank Model is often used to predict the flows of river including rain, and in recent years, it is also used for numerical analysis for prediction of flowing pollution objects with its high frequency of application and is excellently accurate in analysis.
First "Tank Model" is descried and then "Linear Filter Analysis" is described below.

2.4Description of Tank Model

Fig. 2 shows the flow chart of Tank Model. Its simple description will be given according to the items in figure.

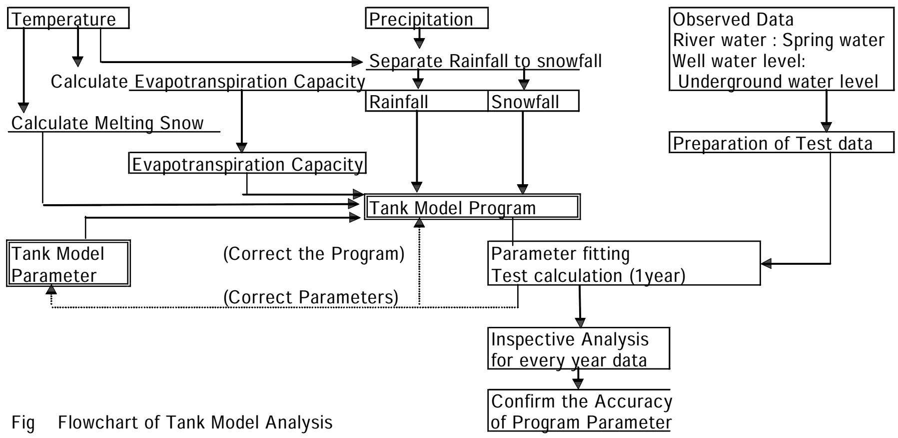


Fig.2 Flowchart of Tank Model

2.4.1Common work

Weather data is created to examine common data.
1) As to precipitation, it would be observed at the measuring point of temperature and precipitation at hilltop. Since the precipitation was measured every hour in preliminary observation, it is edited per 20 minutes for application. Fallen snow amount and thaw snow amount were calculated from the relations between precipitation and in-valley discharge.
As a result, it was presumed that almost of precipitation became ground snow coverage as snowfall during winter. And also, it was presumed that this snow coverage was gradually flowing out as thaw snow water. In this case, the judgment of snowfall and the calculation of thaw snow amount are carried out by use of temperature.

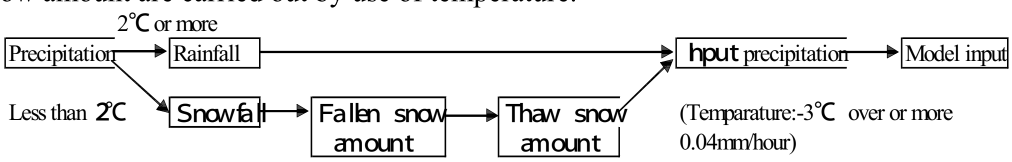


Fig. 3 How to examine model input and precipitation

In judgment of snowfall as shown in Fig. 3, snowfall and rainfall should be separated for less than 2 centigrade and 2 centigrade or more of temperature, respectively.
Supposing that the thaw snow mainly occurs from under fallen snow ground, the thaw snow

shall happen frequently and its amount at the bottom of fallen snow shall become 1.0mm/day (0.04mm/hour), when the average ground temperature goes up to –3centigrade.
2) As to temperature, it should be observed using the temperature data at the measuring point. This temperature was used to judge fallen snow or thaw snow and presume evapotranspiration amount.
3) The evapotranspiration amount seasonally changes according to quantity of solar radiation and temperature. In this case, the application of Thornthwaite method calculates the average value of potential evapotranspiration amount by months and enters it into the Tank Model.
The evapotranspiration amount here is obtained from fully wet ground, and it becomes rather small when a little water is under the soil. As to the Tank Model, its top tank is called the soil water one. Since the evapotranspiration amount becomes smaller if a small quantity of water remains in the top tank by subtracting the maximum potential evapotranspiration amount from the quantity of water in the soil water tank, it can indicate the actual evapotranspiration amount.
The potential evapotranspiration amount to be calculated by the Thornthwaite method is as follows:

$Et = 1.6 \, (10T/I)^{a}$ Formula 1-1

$I = \Sigma \, (Ti/5)^{1.514}$ $i = 1\text{-}12$ (Month) Formula 1-2

$a = (492390 + 17920I - 77.1I^{2} + 0.675I^{3}) \times 10^{-6}$ Formula 1-3

where, Et is the potential evapotranspiration amount (cm/month).
T is the monthly average temperature (Centigrade).
I is the heat index.

The above-mentioned three formulas are available for the monthly average temperature: 0 to 26.5 centigrade.
When the monthly average temperature is less than 0 Centigrade, "Et = 0" should be assumed.
Since the average temperature is not more than 26.5 Centigrade in these parts, no compensation is made for high temperature.
Finally, "Et" is multiplied by "the correction value for daytime" by months according to the latitude of observing point.
Correction value for daytime is distributed in winter 0.84 and in summer 1.24.
In addition, since the evapotranspiration amount calculated by the Thornthwaite method is the daily average value by months, the evapotranspiration amount is created per 20 minutes for application.

- No evapotranspiration occurs in the nighttime or without solar radiation.
  Supposing that evaporation occurs between sunrise and sunset, the daily evapotranspiration amount is equally divided within that time.
- The time of sunrise and the time of sunset are used with both times of Tokyo by months rounded off at a unit of hour.

Time of sunrise, which changes from 4 o'clock to 7 o'clock, and time of sunset, which changes from 17 o'clock to 19 o'clock, is used to calculate evapotranspiration amount

2.4.2 Creation of weather data and its results

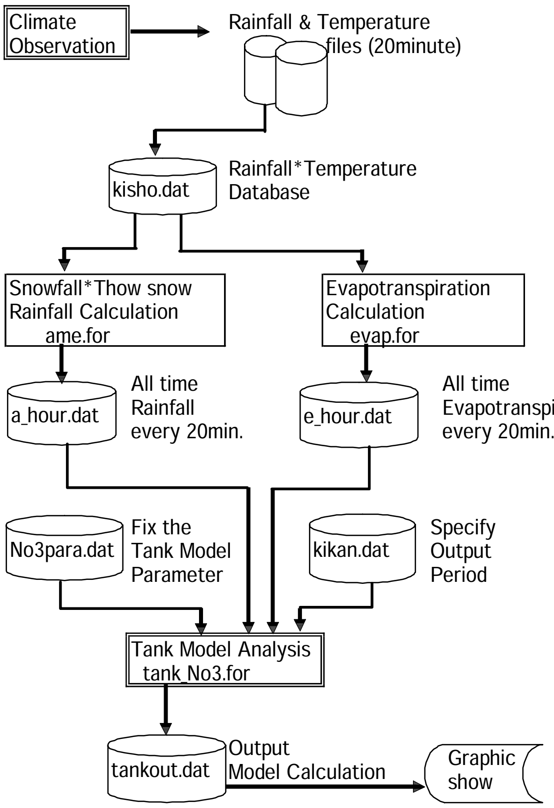
The weather data per 20 minutes was created for 5 years from 1995 to 1999 on the basis of the method described in the previous section. And also, the weather data by days and by months was created and examined in order to view the time change and tendency of weather. As a result, the obtained features are as follows:

- The precipitation greatly changes by years, which mainly depends on the precipitation in much rain period of July and August, and the precipitation in the low water season is almost the same quantity every year except 1998 as a year of especially much snowfall.

- Excepting 1998, the snowfall amount is often in majority of precipitation in January and February and the yearly snowfall amount – less than 100mm – is not so much.
- A great change of temperature and evapotranspiration amount by years is not found. The temperature falls to 6 centigrade below zero in winter and there is the influence of snowfall and fallen snow.

2.4.3 Real-time processing of weather data

The real-time processing flow of weather data is as follows:



Flowchart for Real-time Analysis of Climate Data

Fig.4 Flowchart for Real-Time Analysis of Climate Data

The outline of input/output file for programs to be used in the real-time processing flow is described in items 1) and 2) below.

1) The program name "ame.for" shall be coded to create the precipitation data for model input.
The input data file "kisho.dat" shall be used to enter the real-time data of precipitation and temperature transmitted from the measuring point every 20 minutes.
The output data file "a_hour.dat" shall cope with the precipitation for model input for the complete period.

2) The program name "evap.for" shall be coded to create the evapotranspiration amount data for model input.
In this case, the input data file includes data of date and time added to the real-time data of weather. This input data file shall be "tempreal.dat".
The output data file to calculate the maximum potential evapotranspiration amount for model input shall be "e_hour.dat".
With the abovementioned structure of model, a calculation is made according to the flow chart.

2.4.4 How to examine the Tank Model

Mr. Masami Sugawara (1975) suggested the Tank Model to explain the time change of discharge and water level in catchments area. This method means that "some tanks with orifices (runoff holes) are placed in the catchments area to forecast the the flows of a river, using both precipitation and runoff from the tanks. In other words, the discharge from the runoff hole made at the bottom of individual tank and the discharge from its side face are considered infiltration water and surface water discharge, respectively. The sum of discharge from the side face of each tank is regarded as the flows of a river." This Tank Model allows the fine parameters to be set in consideration of assumptive flows and has been actually used for water discharge analysis.

Since the influence of fallen snow and thaw snow was to be considered in the target area, a snow tank was also installed to separate thaw snow amount becoming water from snowfall amount. And also, the basic structure was timely changed according to the characteristics of change of in-valley discharge and underground water level at the observing points. As shown in Fig. 5 in details, it added the changes such as the increase of number of tank racks and the extension of flow and infiltration holes.

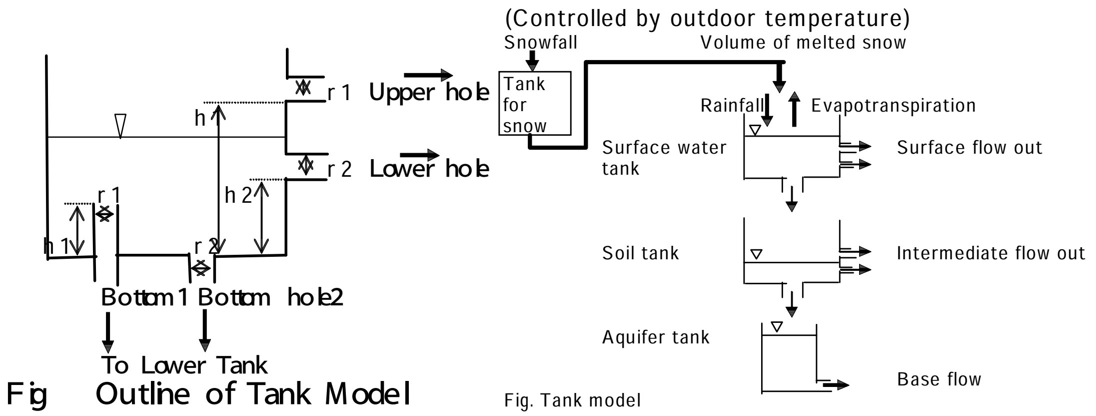


Fig. 5 Outline of Tank Model

2.4.5 Setting of catchment area

The catchments area is determined in consideration of the at-site geography and geology. The catchments area is enclosed with a ridge and precipitation gathers round it. The catchments area is determined every point of measuring the in-valley discharge.

On measuring of spring flow amount, its value is calculated by specific discharge comparing with the in-valley discharge at the observing point.

2.4.6 Analysis of underground water level

Many research results have been gained for the relations between precipitation and in-valley discharge or springs discharge by the use of Tank Model and also, it is known that the accuracy of prediction is high. On the other hand, there are a few searches for the underground water level and precipitation. Here, described are the results of Tank Model having forecasted the relations between underground water level and precipitation.

The Tank Model is made every one of all measuring points. Hereunder, the measuring point B-1 at the boring hole is described as an example.

Fig. 6 shows the variation graph of underground water level at the point B-2 from 1994 to 1999. After examining the relations of this data and precipitation, the Tank Model structure and parameters were also examined. This method is that the number of tank racks and flow holes is determined and also, the factor of flow holes and their height are calculated so that the underground water level calculated by the Tank Model becomes considerably close to the same observed while adjusting them with the application of trial-and-error method. The structure of

Tank Model made in this way is a series of four racks.
The relations of observed value and forecasting value obtained as the result of having calculated them with the parameters set for the Tank Model, as shown in Fig. 6, are brought into very excellent correlation.

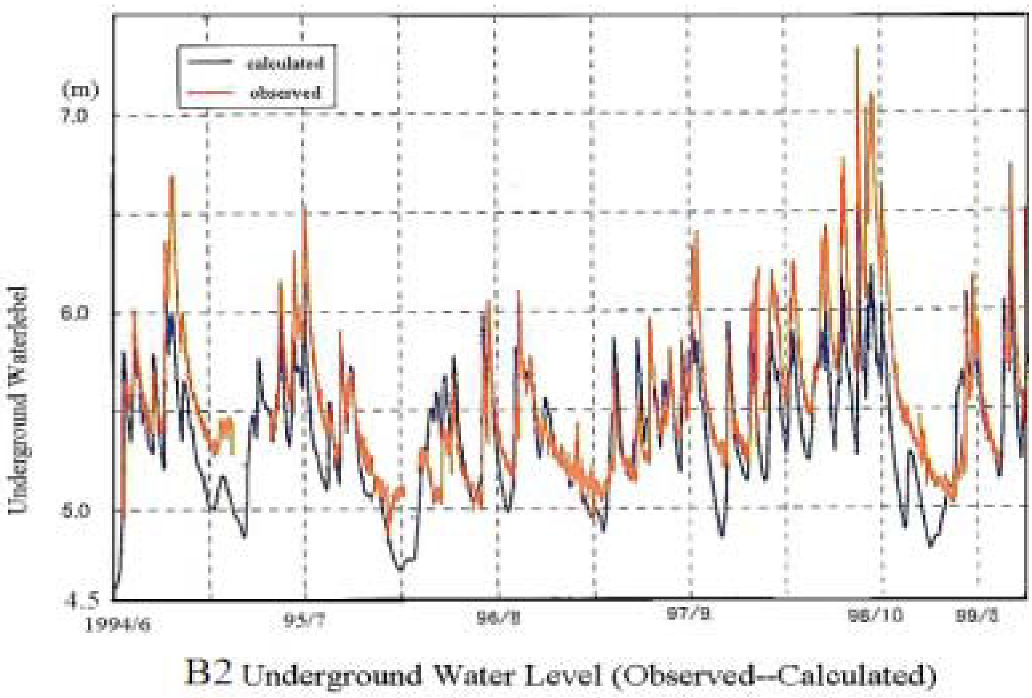


Fig.6 Underground Water Level Observed vs. Calculated (B-2)

As described above, all tank models at 14 stations are settled individually.

2.5Outline of Linear Filter Analysis

As to the linear filter analysis, only its simple outline is described.
Where R(t) is precipitation and Q(t) is in-valley discharge (the same method is applicable to the water level).

$Q(t) = F(\tau) \cdot R(t-\tau)$ Formula 2-1

It is supposed that the relations above can be established. Here, $F(\tau)$ is the linear response function of discharge against the unit precipitation, and the mark [•] shows convolution. In other words, the discharge at a certain time shall be able to indicate as the response over the other to the previous individual precipitation. According to this method, calculating the filter F(t) makes it possible to calculate the discharge at any moment from the observed value of precipitation.
The difference between the discharges (displayed as $Q^{cal}(t)$) calculated in this way and the actual observed value of discharge ($Q^{obs}(t)$):

$\Delta Q = Q^{cal}(t) - Q^{obs}(t)$ Formula 2-2

or, the difference between the tendency of change of discharge to be forecasted from the calculated value and that of observed value should be a factor to check if it affects the digging work. This analysis is applicable to not only the in-valley discharge but also the underground water level (hydraulic pressure) and springs discharge on ground surface. The observed data for a specified period is required to set the model parameters (filter of this analysis) as well as the

aforementioned Tank Model. It is also necessary to check the applicability of analysis every observing item in advance since the linearity is not always made for the response of precipitation according to the observing items.
In addition, the results of having tried to reproduce the observed values for the hole B-2 by both "Tank Model" and "Linear Filter Analysis" show a good correlation.
Both analyses cannot reproduce the observed values completely, but they grasp well the characteristics of change of observed values, which means high practicability of them. (Fig. 14)
The numerical analysis for prediction has been set through such preparation processes.

3 Measurement and Data Analysis during Construction

In the tunnel construction, the already described 14 observing points should be determined and the in-valley discharge springs discharge, underground water level and water level of well should be measured at these observing points. Further, if the spring flows into tunnel from the underground, it should be also measured.

3.1 Measuring System

3.1.1 Ground surface measuring system

The basic ground surface measuring items are precipitation and temperature. The change of ground water and the change of underground water level and well can be measured by the flow meter and water level gauge. Since it is necessary to measure them at the same time, the on-line measuring system was used.
Fig. 7 shows the block diagram of on-line measuring system.

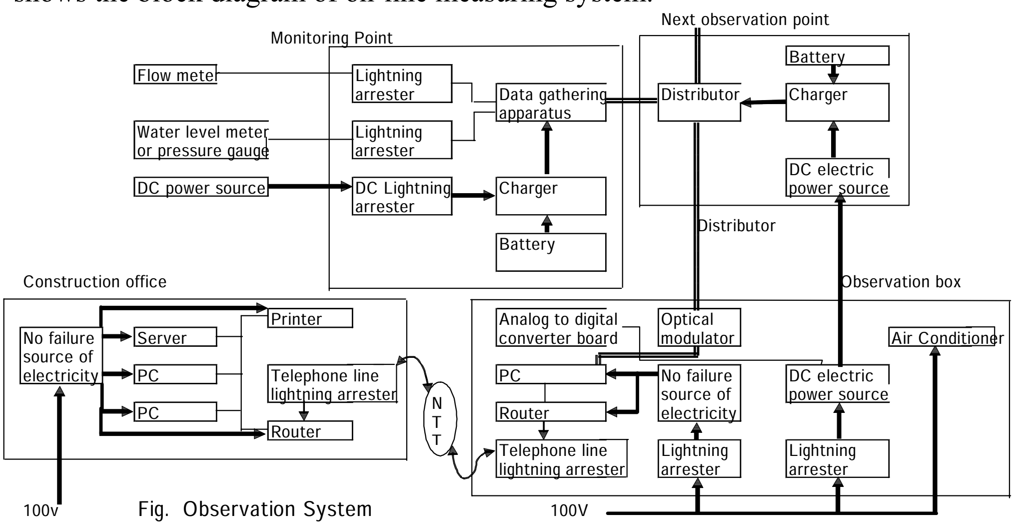


Fig. 7 Observation System

3.1.2 Underground measuring system

In order to measure the leakage from ground into the tunnel at the same time with the ground surface measuring work, the real-time measurement is taken with the catchments measure and triangular notch installed.

3.2 Data Control and Display System

The underground water level and in-valley discharge are observed at 14 observing points
on the ground. This observing data is measured every 20 minutes, is collected into the computers in the observation boxes A and B, and is also transferred into the computers in the at-

site office through the dedicated lines. The measurement data collected in the observation boxes is computed and then, it is consolidated into the data control base.
The daily data control is performed by checking if the discharge and underground water level to be observed have correlation with the prediction formulas obtained from the observation data of precipitation and temperature at the regular time.

3.2.1 Surver function of data control

This function is to receive the data collected in the observation boxes A and B with the two-line computer system through the dedicated lines at the specified time intervals and store and accumulate this data as the original data into the server system. At this time, the collection of data is carried out independently through A and B operation routes to secure it. This two-line computer system that the data collection line of observation boxes is separated from the computer network line of the at-site office prevents the failure or trouble of one computer system affecting the other and protects the computer network line to let nothing enter from outside

3.2.2 Data control and display functions

This data control and display system has the following subsystems:
1) Input and display function of tunnel construction progress:
This function displaying the tunnel construction progress has closer relation to the leakage amount in a tunnel, allows the information of such tunnel construction progress to be entered and displayed, and enables the display of past record.
2) Ground observing data computing and displaying function:
This function is to display the observed data on ground every observing point, compute the measured value, the change condition with the passage of time and the speed of change at the time of measuring operation, and display them by numeric characters and figures.
3) Underground leakage computing and displaying function:
This function is to compute the measured value, the change condition with the passage of time and the speed of change at the time of measuring the leakage in a tunnel and display them by numeric characters and figures.
4) Input and display function of observed data of tunnel cut face:
This function is to enter and display the photos of tunnel cut face, create the development of crack and geological condition, and display the three-dimensional geology.
5) Input and display function of pre-boring information:
This function is to record and display the boring work to be started from cut face of tunnel for the geological survey and forward underwater survey and display the information of already bored places.
6) Input and display function of information of consolidation grout:
This function is to enter and display the results of consolidation grout to be carried out by application of pre-boring holes and boring work around a tunnel and display the pressure of final grout and its amount distribution.
7) Input and display function of predicted values:
This function is to enter and display the predicted values of water level and water amount at the measuring points by using the Tank Model and Linear Filter Analysis, display the comparison between observed values and predicted values, and display the change condition with the passage of time.
8) Correlation display function:
This function is to display the correlation between observing data and position of tunnel cut face and also the correlation between geology and observing data.
As abovementioned, the data control and display system is integrated with many functions. When a sign of change of observed water amount and underground water level is found to examine in the daily control, the items relating to the underground water level, in-valley

discharge, springs amount, position of tunnel cut face and geology that are the water environment data until now are retrieved from the data control base and all information is totally examined, which can determine propriety of digging a tunnel.

3.3 Results of Data Observation

At the same time of starting the construction of tunnel, data was collected by the real-time monitoring system at 20-minute intervals. Figs. 8 shows a part of its results.
The results of observation are monthly observed records. These observed records are indicated in comparison with the underground water level on the basis of precipitation.
The measured records refer to the underground water level B-1.

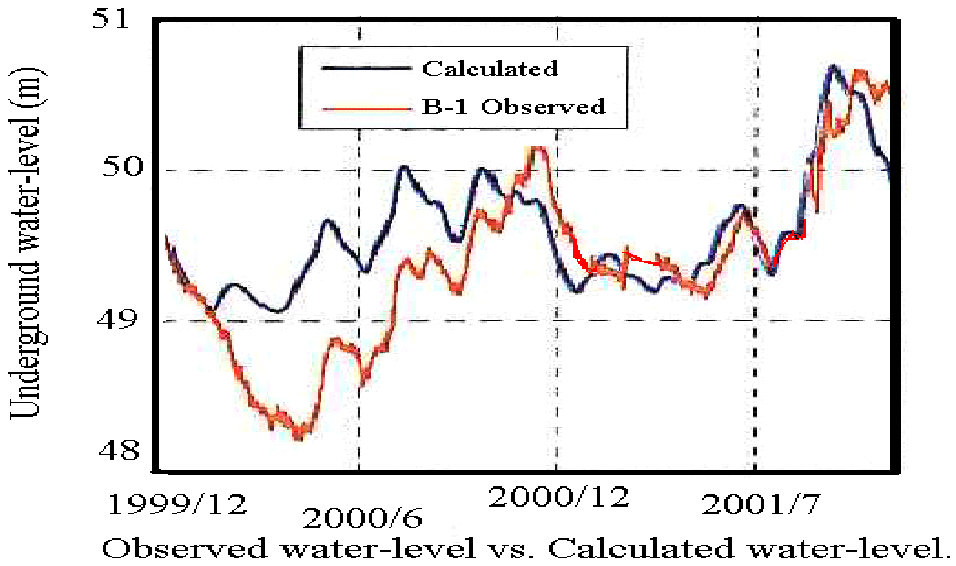


Fig. 8 Observed Water Level vs. Calculated Water Level at Construction

An example of data observation at the time of trouble of underground water is described below. The depths of underground water level are measured at the observing point B-2 in this tunnel. Here, the rapid decrease of observed values was found just before the tunnel cut face reach to the point. On the other hand, since it indicated that the predicted values by both Tank Model and Linear Filter Analysis do not decrease, the cause of decrease of underground water level was supposed to be digging of tunnel. At this time, digging of tunnel was stopped, amount full of consolidation grout from the cut face of tunnel was executed to protect leakage water inflow to the tunnel. Tunnel excavation was postponed until the underground water level will increase at the starting level.

4 Conclusion

It is difficult to grasp the phenomenon occurring during tunnel construction only by observing the underground water level and discharge. In general, they are assessed after the completion of construction. Recently, the application of complex three-dimensional FEM is now increasing so as to avoid troubles and to take some countermeasures before the construction of tunnel.
In order to perform the three-dimensional analysis like this, it is necessary that the correct geological conditions along the tunnel have been obtained, and it needs the coefficient of permeability on ground, geography and geology, vegetation on ground, and distribution, flowing direction and speed of existing underwater, including the meteorological observation. However, the Tank Model and Linear Filter Analysis perform the numerical analysis for prediction from the existing observed data relating to the weather, underground water level and

ground discharge etc., set them as the standard values, carry out the at-site monitoring observation during construction, and take some countermeasures for trouble to be assumed when the monitoring results are out of the predicted values.

As to the ground discharge, the prediction formulas by the Tank Model are excellent assessed, but there are only few cases that it has been applied to the prediction of change of underground water level, including that in the tunnel. It has been described above that the sufficient prediction can be carried out even during digging of the tunnel by means of the two simple analyses for prediction. It is also supposed that the better analysis can be suggested by using the infiltration analysis such as the three-dimensional FEM at the same time.

The reflection and reconsideration are that the water to be used for the digging machines to construct the tunnel is mixed with the leakage in the tunnel and the accuracy of observation becomes poor, so that the obtained data is found to be invalid. Obtaining more correct leakage in the tunnel will improve the accuracy of monitoring further.

Since effective monitoring is executed by comparing the observation with the prediction, the analysis like this will be expected to perform as many times as possible.

5 Acknowledgments

The present writer will express heartfelt thanks to Mr. Saitou (Kokusai Kogyou Co., Ltd.,) for his help to analyze tank model parameters.

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