Study on Subsidence of the Nōbi Plain

Etude sur l'Affaissement de la Plaine de Nōbi

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SYNOPSIS The land subsidence of the Nōbi plain which is located in the central part of Japan was analyzed numerically with a large capacity computer. Desirable groundwater level to prevent the land subsidence was investigated by the one-dimensional finite element models which were formulated at several places in the subsiding area. The allowable withdrawal of groundwater which makes the piezometric levels of confined aquifers desirable condition was studied with the aid of a three-dimensional finite element model. Furthermore prediction of land subsidence relating to future withdrawal of groundwater was performed by using these models.

INTRODUCTION

The Nōbi plain is located in the central part of Japan as shown in Fig.1. This Alluvial plain has about 1300 km^2 in area and is underlain by the Alluvial, Pleistocene and Tertiary strata. Withdrawal of groundwater from this plain had been accelerated since 1950 and the piezometric levels of groundwater in deep confined aquifers dropped subsequently down to about 30 m below the ground surface in the coastal area of the plain in 1973. With lowering in the piezometric levels of confined aquifers, the land subsidence of this plain progressed and its speed was recorded more than 20 cm in 1973 at the most severly subsided area. However, the regulation of withdrawal of groundwater since 1974 dulled the subsidence. Although the land subsidence became smaller gradually, it is still observed at the rate of several centimeters a year in the coastal area. Geodetic survey showed that the area below the mean sea water level, which was 184 km^2 in 1961, had expanded to 274 km^2 in 1979.

Fig.1 The Nōbi plain

DESIRABLE GROUNDWATER LEVEL

The subsidence phenomena in the Nōbi plain resulted from decline of the piezometric levels of confined aquifers due to overwithdrawal of groundwater. The piezometric levels of confined aquifers must be recovered to the levels which do not cause the land subsidence. In order to solve such a subsidence problem, one-dimensional finite element consolidation models were used to find out the desirable groundwater level preventing the land subsidence.

In these models, groundwater flow in aquitards was assumed to be vertically one-dimensional toward the aquifers of which piezometric levels dropped down. As the displacement of soil can be also assumed to be vertical, the continuous equation of groundwater flow in a saturated aquitard can be expressed as follows;

$$\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z} \right) = -\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z} \right) \qquad (1)$$

where h denotes the piezometric head of groundwater, u denotes the vertical displacement of soil and k_z denotes the vertical permeability.

The equilibrium equation in a unit of saturated soil is also expressed as follows;

$$\frac{\partial}{\partial z}\left\{ E \frac{\partial u}{\partial z} + \gamma_w (h-z) \right\} + f = 0 \qquad (2)$$

where γ_w denotes the unit weight of groundwater, E denotes the modulus of elasticity of confined soil skelton and f denotes the body force.

Piezometric heads of confined aquifers were considered to be known because they could be observed by many observation wells in this plain. The piezometric levels of groundwater in confined aquifers in 1950 were assumed to be slightly higher than the ground level because of recorded circumstances.

In order to find out the groundwater level preventing land subsidence in the Nōbi plain, computations were performed in the cases of three observation wells at Matsunaka, Tsushima and Nakagawa where land subsidence was continuing at the rate of several centimeters a year. The Quaternary deposits were modeled for calculating the consolidation phenomena in aquitards caused by decreasing of piezometric levels of groundwater in confined aquifers. The piezometric levels in aquitards of the Quaternary deposits were calculated according to the piezometric levels of the 1st, 2nd and 3rd confined aquifers which were known in the one-dimensional models. The piezometric level of unconfined aquifer near ground surface was assumed to be constant and the Tertiary layer beneath the Pleistocene was assumed to be impermeable.

Calibration works of the models were done with data of the period from 1950 to 1977. Although seasonal fluctuations were seen in the actual piezometric levels of groundwater, the average trends were used in this analysis. The mean values of data from oedometer tests and pumping tests were used for the first calibrating computation and the most suitable parameters of the models were determined by modifying the parameters in order to fit the trial computations with observed values.

In the case of computation at Matsunaka, it was not necessary to modify the first estimated soil parameters in order to match calculated results with observed ones as shown in Fig.2. But in the other two cases, the first estimated parameters had to be modified to make the results consistent with observed data.

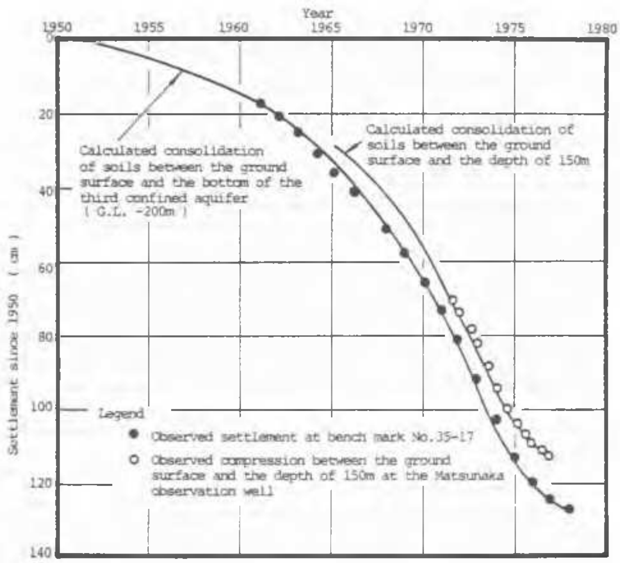

Fig.2 Comparison between the computed consolidation and observed one from 1950 to 1977

Fig.3 shows the results of the prediction of groundwater level preventing land subsidence. Those computations were performed under several kinds of recovery of groundwater level. The horizontal axis in Fig.3 is the assumed piezometric level of groundwater in 1985, the vertical axis of the upper figure is the settlement of ground surface from 1977 to 1985 and vertical axis of the lower figure is the land subsidence in 1985. Based on these results and experience in Japan, the authors consider that the groundwater level which is desirable to prevent the subsidence and also to make the land stable even in case of earthquake is about 10 m below the ground surface (Ueshita and Satō, 1980).

ALLOWABLE YIELD

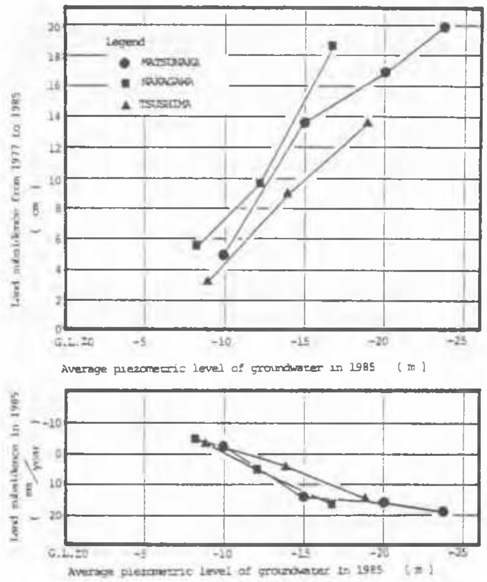

Fig.3 Prediction of land subsidence from 1977 to 1985 and the settlement in 1985

Although the concepts of allowable yield have been proposed by many hydrologists (Domenico, 1972), the authors define allowable yield in the Nōbi plain as the withdrawal of groundwater that will not cause the land subsidence. The land subsidence in this plain is still continuing at the rate of several centimeters a year. In order to find out the allowable withdrawal of groundwater which would not cause the subsidence in this plain, the authors made up a three-dimensional groundwater flow model (Ueshita et al, 1977, Satō et al, 1978). The fundamental equation of this simulation model is as follows, based on Darcy's law and the equation of continuity;

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)=s\frac{\partial h}{\partial t}+w \qquad (3)$$

Where k_x, k_y, k_z denote coefficients of permeability in x, y, z directions respectively, s denotes the specific storage and w denotes the withdrawal from the unit volume for the unit time.

The three-dimensional model of the Nōbi groundwater basin has about 1200 km^2 in area and contains the Alluvial and Pleistocene deposits as shown in Figs.4 and 5.

The Tertiary stratum beneath the Pleistocene was assumed to be an impermeable bed and the groundwater level of unconfined aquifer was assumed to be constant. The side boundaries of this model faced to the Ise bay and Nagoya city were assumed to be flux boundaries prescribed as follows;

$$q = \alpha\ (h - h_0) \qquad (4)$$

where h_0 denotes the piezometric head of groundwater of adjacent feed area, α denotes the seepage factor determined by the average permeability and distance from the feed area to this boundary and q denotes the groundwater charge through a unit boundary area for a unit time.

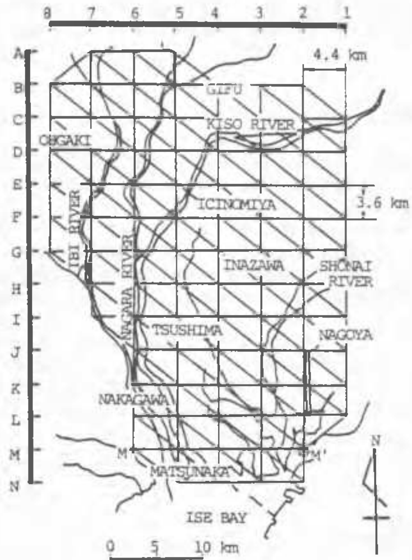

Fig.4 Three-dimensional finite element model for the Nōbi plain

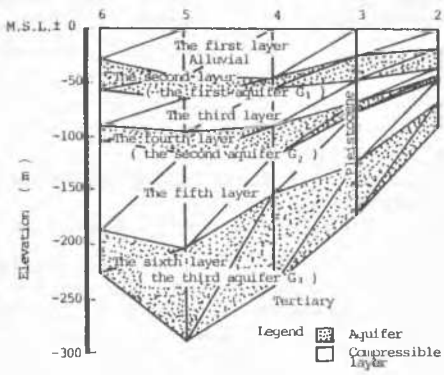

Fig.5 West-east section of the model (M-M' section in Fig.4)

In order to build up a simulation model of the groundwater basin, the soil parameters of confined aquifers were assumed with mean values of results of pumping-out tests and the ones of aquitards were assumed on the basis of results of oedometer tests. Those assumed soil parameters were modified until the computational results became similar to the observed ones.

Figs.6 and 7 show the results of calibration work. This groundwater model traces considerably the average trends of observed piezometric levels of confined aquifers as shown in Figs.6 and 7.

Allowable yield that would recover the piezometric levels of confined aquifers to desirable groundwater levels was investigated with this model. The computations were performed in five cases of future withdrawal, assuming as follows;

(a) Since 1978 the withdrawal of groundwater from the whole area would be kept at the yield of 1977.

(b) The yearly withdrawal of groundwater would be reduced by 20 percent of the yield of 1977 since 1978.

(c) Following the condition (b), the yearly

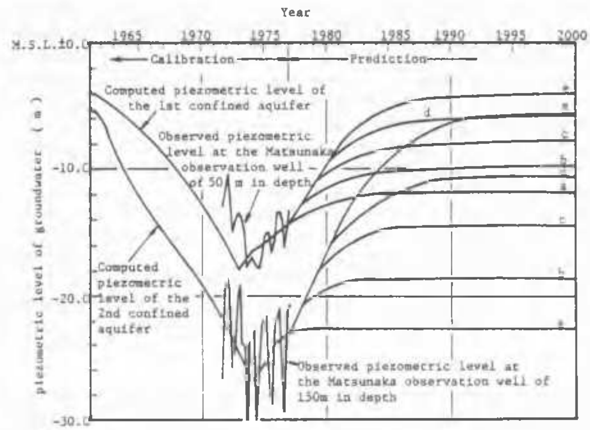

Fig.6 Results of calibration and prediction work for the site of the Matsunaka observation well by using the three-dimensional finite element model

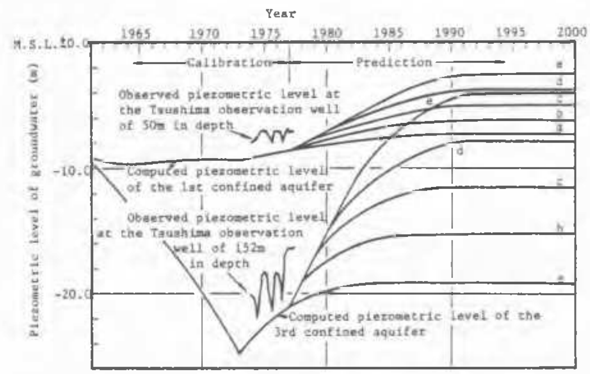

Fig.7 Results of calibration and prediction work for the site of the Tsushima observation well by using the three-dimensional finite element model

withdrawal of groundwater would be reduced by 40 percent of the yield of 1977 since 1979.

(d) Following the condition (c), the yearly withdrawal of groundwater would be reduced by 60 percent of the yield of 1977 since 1980.

(e) Following the condition (d), the yearly withdrawal of groundwater would be reduced by 80 percent of the yield of 1977 since 1981.

Results of these predictive analyses are shown in Figs.6 and 7. On the basis of these results it is concluded that the allowable yield in the Nōbi plain will be about a half of the yield of 1977.

PREDICTION OF LAND SUBSIDENCE

The rate of land subsidence decreased yearly since 1974 when the regulation of withdrawal of groundwater started in this plain (Iida et al, 1976).

Prediction of land subsidence by lowered piezometric levels due to the withdrawal of groundwater was performed by using the three-dimensional finite element model and the one-dimensional finite element models. The three-dimensional model was used to evaluate the relation between the withdrawal of groundwater and the piezometric levels in confined aquifers of the Nōbi groundwater basin. The one-dimensional models for several sites were used to predict the land subsidence in relation to change of the piezometric levels in confined aquifers calculated by the three-dimensional model. The three-dimensional model can not enough evaluate the time-dependent consolidation phenomena in aquitards because of limitation of the computer's capacity. On the other hand, the one-dimensional model having many divided elements in vertical direction can accurately compute the time-dependent consolidation phenomena in aquitards.

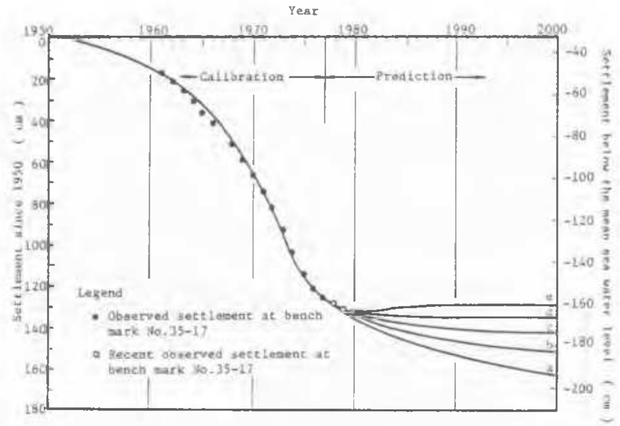

Fig.8 Results of calibration and prediction on land subsidence at Matsunaka

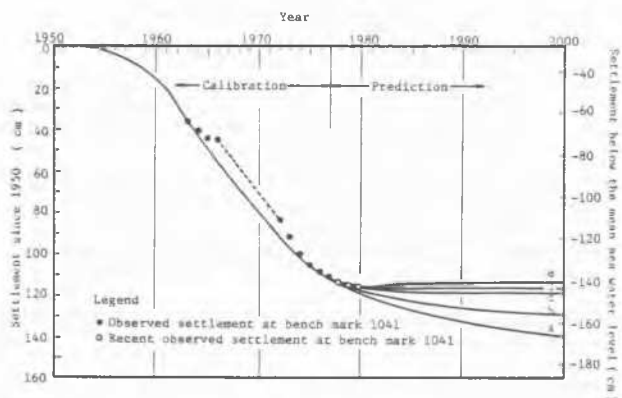

Fig.9 Results of calibration and prediction on land subsidence at Tsushima

Figs.8 and 9 show the computation by the calibrated models and the observed results at the bench marks near the Matsunaka and Tsushima observation wells. Predictive simulations of land subsidence were performed in five cases of future withdrawal which were already explained relating to Figs.6 and 7.

These figures show the future land subsidence in this plain relating to the future withdrawal of groundwater. The recent leveling results at these two bench marks were plotted in Figs.8 and 9 and compared with the prediction curves. Based on the comparison, it has been known that the land subsidence of the Nōbi plain is proceeding along the case of (c) as a result of many efforts of cutting the withdrawal.

CONCLUSIONS

The following conclusions were derived from the numerical analyses for the land subsidence of the Nōbi plain.

1) Desirable groundwater levels of confined aquifers preventing land subsidence are about 10 m below the ground surface, considering also the stability of the ground in case of earthquake.

2) Allowable yield of groundwater based on the desirable groundwater levels is about a half of the yield which was pumped up in 1977.

3) Land subsidence of the Nōbi plain is coming to an end along the prediction curve of a desirable case.

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