ANALYSIS OF LAND SUBSIDENCE IN THE NOBI PLAIN*

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Abstract

The land subsidence in the Nobi Plain, central Japan, was examined in relation to groundwater level declining. The authors tried to examine, using several thousands of borehole materials, the complicated system in the groundwater basin which involves the subsurface stratigraphy, soil properties and so on, and to explore pumping amounts of groundwater and the declining process of the groundwater levels from data of water wells during a past few decades in the plain.

Using the above results, the authors successfuly obtained the numerical solution appropriate to the land subsidence up to the present, and they estimated the future land subsidence in the plain.

1 Underground Conditions of the Nobi Plain

There existed, during the Pliocene and early Pleistocen, a large sedimentary basin called Lake Tokai in the area which covers the present Nobi Plain, Ise Bay and their environs, central Japan. The tilting movements of the Nobi Plain Tectonic Block started to develop at the early stage of the middle Pleistocene. The movements have formed a westward dipping sedimentary sequence over 350 m in thickness. It overlies unconformably the sediments of Lake Tokai which is more than 1,000 m in thickness.

The subsurface stratigraphy of these sediments in the plain has been explored on the basis of borehole material obtained from several thousands of water wells and test borings. The geological succession of these sediments is shown in Table 1, and geological cross sections in Fig. 1.

The middle Pleistocene sediments and the younger are composed of an alternation of clay, sand and gravel beds. Change in sedimentary environments and climatic fluctuations of these sediments have been studied by means of the microfossil analyses of numerous boring core samples (Nobi Plain Quarternary Resarch Group, 1976).

Semiconsolidated fresh water lacustrine clay beds and fluvial sand and gravel beds are interbeded in the lower horizon of the Pleistocene sediments

Table-1 The Subsurface Stratigraphy in the Nobi Plain

		(Thickness)
HOLOCENE	NANYO FORMATION (H) *(loose upper sand bed and very soft marine clay bed)*	10- 60 m
PLEISTOCENE	NOBI FORMATION (N) *(alternation of sand and silt bed)*	10- 20 m
	DAIICHI GRAVEL BED (G1)	10- 30 m
	ATSUTA FORMATION (D3) *(upper sand and clay beds and unconsolidated lower marine clay bed)*	10-100 m
	DAINI GRAVEL BED (G2)	5- 30 m
	AMA FORMATION GROUP *(alternations of semiconsolidated sand, clay and gravel beds)*	30-100 m
	PRE-AMA FORMATION GROUPS *(alternations of semiconsolidated sand, clay and gravel beds)*	30- 70 m
PLIOCENE	TOKAI GROUP *(alternations of semiconsolidated clay, sand and gravel beds)*	200-1000 m
	M I O C E N E S E R I E S	
	P R E - T E R T I A R Y B A S E M E N T R O C K S	

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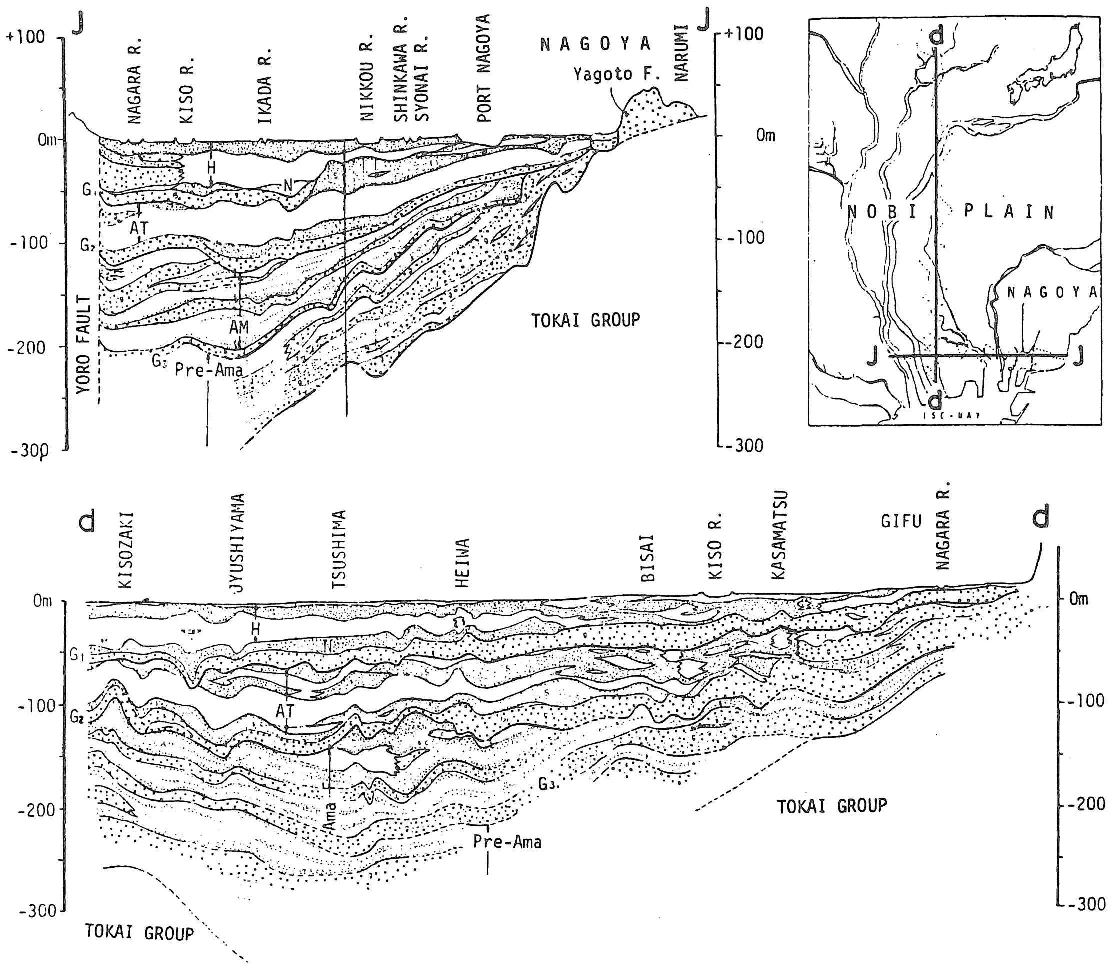


Fig. 1 Geologic Cross Sections of the Nobi Plain
H : Nanyo Formation (Holocene), N : Nobi F., AT : Atsuta Formation, Dotted : gravels, Fine dotted : sand, Blank : clay.

called Pre-Ama Formation Groups. Ama Formation Group and the younger sediments are composed of alternations of fluvial sand or gravel beds and unconsolidated marine clay beds, deposited under inner bay conditions. Each of these marine clay beds shows a sedimentary cycle from transgressive to regressive phase, and represents a relatively warm period, interglacial epock or interstadial. In colder periods, the gravel beds have been deposited as either terrace or river-bed gravels in the valleys formed during the period of low sea level falling. The river-bed gravel deposited in the bottom of the valleys during a maximum stage of sea level falling reaches 20 m or more in thickness. The terrace gravel beds are generally thinner than the valley bottom gravel beds. These two types of gravel beds are distributed under the almost whole area of the Nobi Plain. Buried topography such as hills, terraces and valleys formed in the lowering process of sea level is depicted in the base contour map of these gravel beds (in Fig. 2). These buried topography and types of gravel bed effect groundwater yield in this plain. The marine clay beds overlying the gravel beds have attained to more than 30 m in thickness in the valleys, and spread far and wide under the plain area except for the alluvial fan area, where the clay beds are thinning out and grading into sand or gravel beds (Fig. 3).

In the alluvial fan area, precipitation and surface water percolate downward through these permeable sand and gravel beds, and recharge groundwater in the Nobi Plain. Superficial sand bed, the upper member of Nanyo Formation, attaining to 15 m in thickness contains unconfined groundwater which is recharged directly from precipitation and infiltration of surface water. The gravel beds, interbeded in clay beds, G_1, G_2, and others, are artesian aquifers and supply a large quantity of groundwater. Before the pumping is largely developed, many flowing wells tapping into these gravel beds were found in most of all area of the Nobi Plain (Iida et al, 1976).

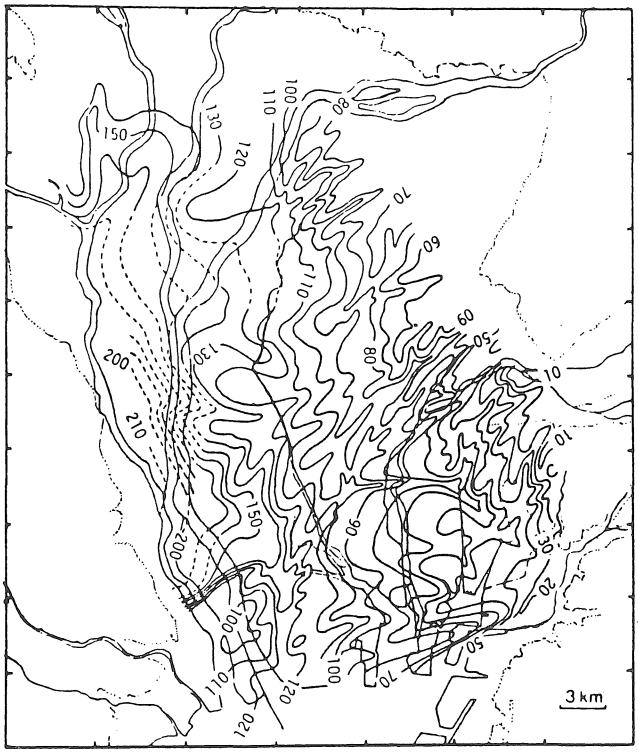


Fig. 2 Buried Topography Beneath G_2 Aquifer (contour lines below sea level in meter)

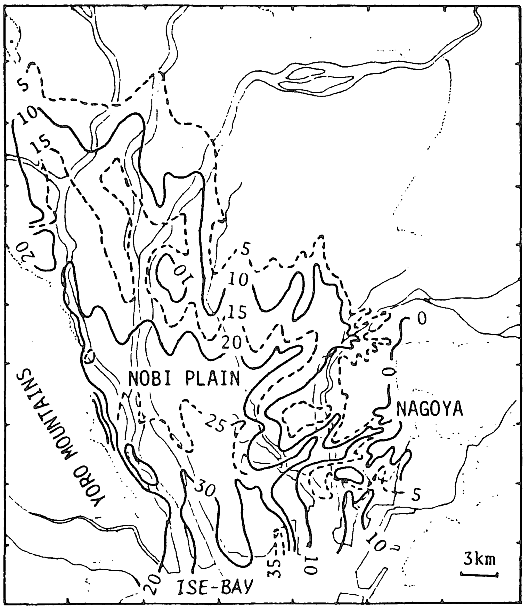


Fig. 3a Distribution of Thickness of the Holocene Marine Clay Bed, AL. (in meter)

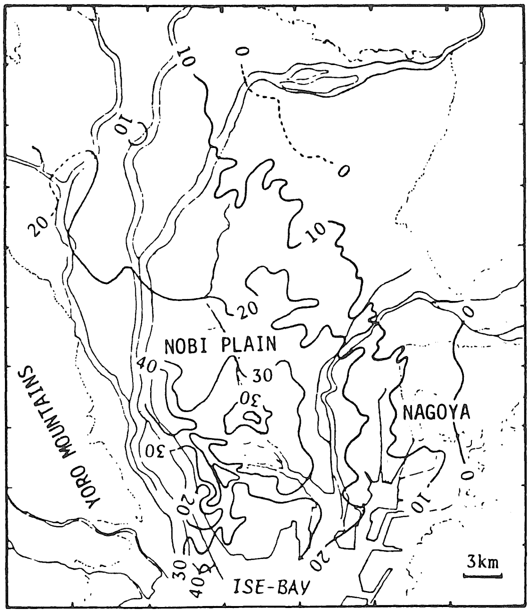


Fig. 3b Distribution of Thickness of the Lower Marine Clay Bed, D3L, in the Atsuta Formation (in meter)

2 The Increased Pumping of Groundwater and Downward Trend of the Groundwater Levels in the Nobi Plain

As the use of groundwater has grown in the Nobi Plain area, the wells tapping the artesian aquifers have been enormously multiplied during the last two decades, and recently about ten thousands and more wells are supplying over 3.7 million tons of water per day.

The pumping intensity, namely the pumping amount in a certain unit area which is a rectangle of 4.4 km^2 in this case, has been enlarged in the marginal zone (except for the western part) of this plain where urbanization and industrialization have been advancing (Fig. 4). In Ogaki, one of the industrial cities, located in the northern area of this plain,daily pumping intensity amounts to 100 thousands ton per 4.4 km^2. Fig. 5 explains increasing amounts of water supplied from each aquifer unit in recent years. The pumping amount from each aquifer in Fig. 5 was conveniently estimated in proportion to the thickness of each aquifer because many production wells are usually open to more than one aquifer. During the period from 1961 to 1965, the largest quantity of

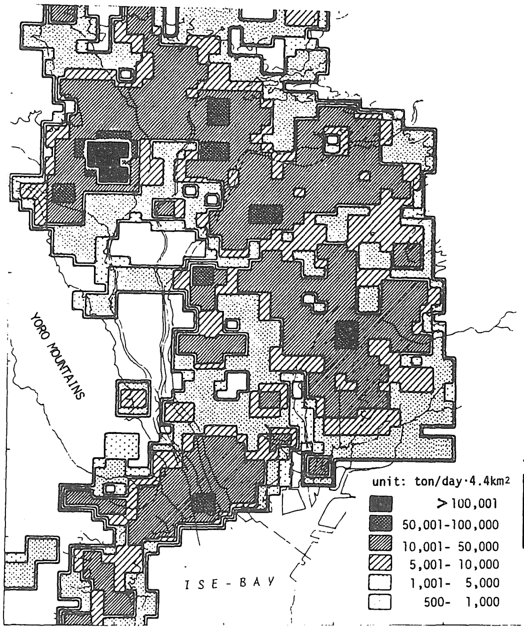


Fig. 4 Pumping Intensity from the Whole Aquifers in the Nobi Plain in 1973

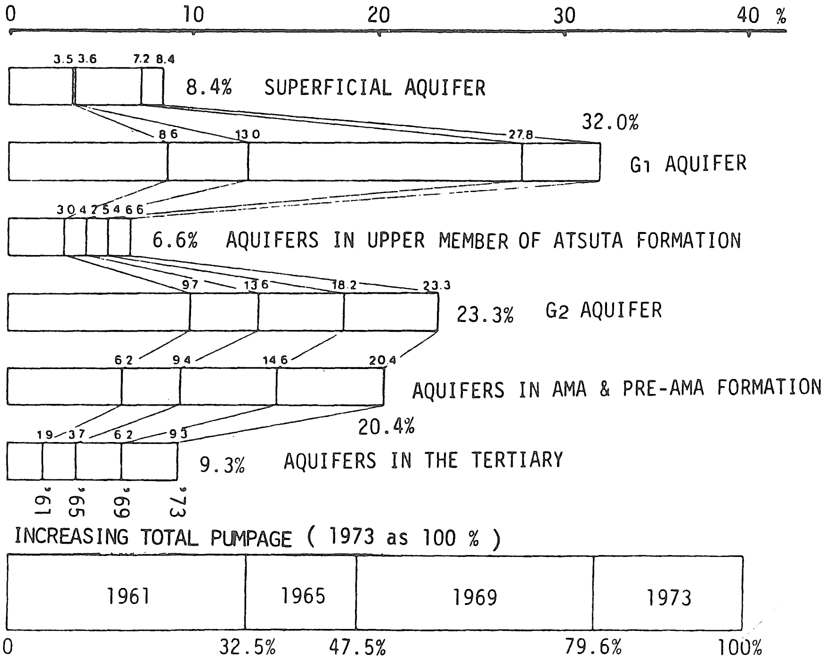


Fig. 5 Increasing Total Pumpage and Extraction Rate from Each Aquifer Unit in the Nobi Plain from 1961 to 1973

pumpage in this plain was from G_2 aquifer, and from 1965 to 1969 the largest supplying source was replaced by the shallower productive G_1 aquifer. The proportions of the pumping amount from each source, in 1973, are as follows, 8.4 % from superficial unconfined aquifer, 32.0 % from G_1 aquifer, 6.6 % from upper sand bed of Atsuta Formation, 23.3 % from G_2 aquifer, 20.4 % from

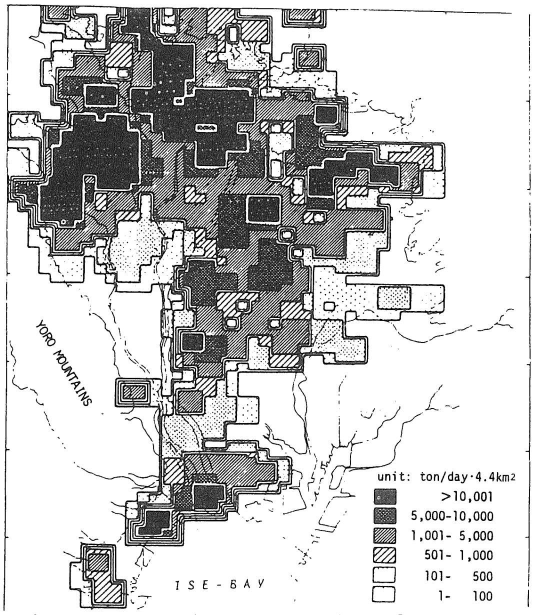


Fig. 6 Pumping Intensity from G_1 Aquifer in 1973

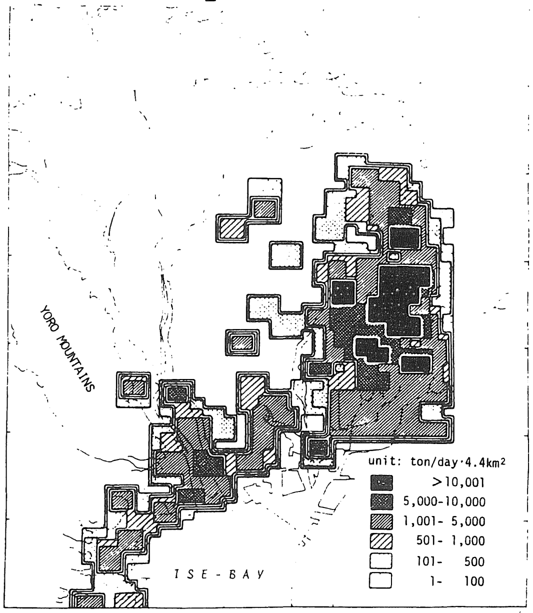


Fig. 7 Pumping Intensity from the Tertiary Aquifers in 1973

Ama and Pre-Ama Formation and 9.3 % from aquifers in the Tertiary. About 70 % of total pumpage in this plain, therefore, was withdrawn from the aquifers shallower than G_2.

Figs. 6 and 7 indicate the areal distribution of pumping intensity from each aquifer unit. The groundwater is intensively extracted from the shallower aquifers, namely superficial and G_1, in northern areas of the plain where they have a high recharge rate and where industrialization has increasingly developed recently. Fig. 6 shows pumping intensity of G_1 aquifer. The deeper aquifers than G_2 are used as the main water source in the south-eastern area of this plain. The use of Tertiary aquifers is shown in Fig. 7. G_2 aquifer is the source of the groundwater supply throughout the whole plain area. Deeper wells, exceeding 1,000 m in depth, tap the aquifers in the Pliocene or the underlying Miocene which is interbeded with clay, sand and gravels. Higher temperature water used for spas is extracted from these deeper wells.

As pumping water increases, the piezometric surfaces which were above the land surface before the World War II, have declined continuously except alluvial fan areas. The piezometric surfaces are lowered 40 m below sea level in intensively declined areas with the rate of 2 m per year (Kuwahara, 1976a).

The land subsidence occurs in the area where unconsolidated thick clay beds lie and intense declining of piezometric surfaces is observed. The subsidence rate ranges from 2 to 20 cm per year, and the total amount of subsidence during the period from 1961 to 1975 attains to 147 cm in an area of maximum subsidence (Iida et al, 1976). No appreciable subsidence has occured in areas where piezometric surface declining is little and/or coarse materials predominate.

3 The Analysis of Land Subsidence due to Groundwater Withdrawals

Data from the observation wells have indicated that the compaction of unconsolidated sediments above G_2 contributed largely (70-80 %) to the subsidence of land surface. Since the compaction rate of these sediments is closely related to the rate of decline of piezometric surfaces, the reduction of the artesian pressure evidently causes the land subsidence in the Nobi Plain. A reduction of artesian pressure results in an increase of grain-to-grain or effective stress on the skeleton system of the sediments which may cause compaction. The subsidence, therefore, depends upon the subsurface lithology and upon the magnitude and rate of artesian pressure reduction.

The processes of compaction of sediments due to the artesian pressure reduction were calculated based on the Terzaghi Consolidation Theory. We excluded the deeper sediments underlying G_2 from the calculation, because the details of artesian pressure reduction are not too clear in the deeper part and also the compaction in this part contributes only a little to the surface subsidence. The compaction of sand and gravel beds among the sediments overlying G_2 is also excluded from the calculation because both of these beds have much smaller coefficient of volume compressibility than clay beds. Unconsolidated soft marine clay beds, namely the lower member of Nanyo Formation (AL) and the lower member of Atsuta Formation (D3L), therefore, are taken into consideration.

Depth and thickness at any point of these clay beds are depicted by the subsurface information from thousands of materials of water wells and test borings. Fig. 3 shows isopack maps of clay beds. The data obtained from many undisturbed soil samples proved that most of these clay beds are normally consolidated, while the deeper beds are almost over-consolidated.

Compression index, Cc, varies vertically and horizontally in these clay beds and the values are closely related to the sedimentary facies. The value is the largest in the middle horizon which deposited in the maximum phase of transgression and is composed of finer materials. Lateral distribution of the mean Cc value calculated by averaging vertical variations, as shown in Fig. 8, reflects the sedimentary environment of clay bed.

Natural void ratio of clay, e_0 , has a close relation with the contents of clay fraction, sedimentary environments and the geological history of the sediments (Kuwahara, 1966). There are remarkable corelations between e_0 and Cc, as follows:

$$Cc = 0.5(e_0 - 0.5)$$

for AL (Kuwahara and Horiuchi, 1966, Ueshita and Nonogaki, 1970),

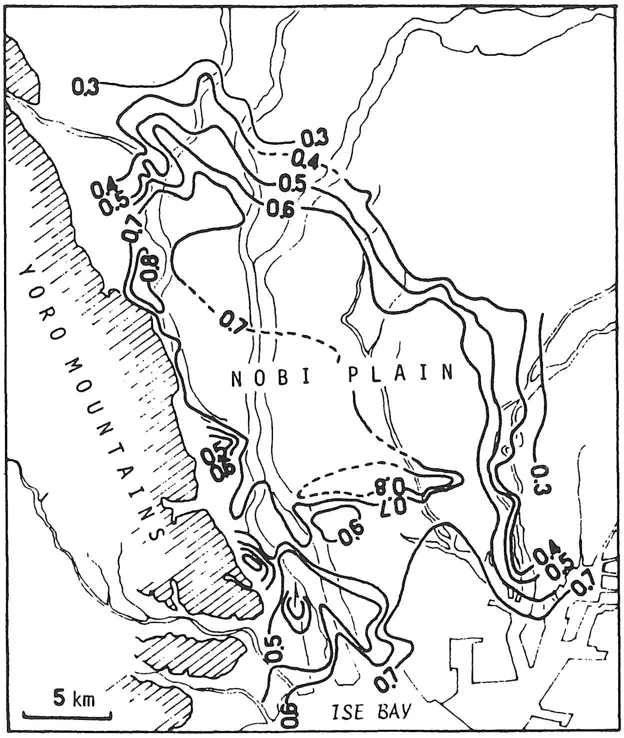


Fig. 8 Distribution of the Mean Cc Value in the Holocene Marine Clay, AL

$$Cc = e_0 - 0.5$$

for D3L (Kuwahara, 1976b).

The ultimate consolidation of the clay bed, S, is computed by equation (1);

$$S = \frac{Cc \cdot H}{1 + e_0} \cdot \log \frac{P + \Delta P}{P} \qquad (1)$$

where H : thickness of clay bed,
P : effective stress before the artesian pressure reduction,
ΔP : increase in effective stress by the artesian pressure reduction.
The value of e_0 in each clay bed used in the equation is computed from the corelations with Cc mentioned above.

Considering the increasing effective stress due to the continuous artesian pressure reduction, the rate of consolidation of the clay bed must be solved by the following consolidation equation under incremental loading (Schiffman, 1985 and Lumb, 1963);

$$\frac{\partial u}{\partial t} = Cv \cdot \frac{\partial^2 u}{\partial z^2} + R\ (z,\ t) \qquad (2)$$

where u : pore pressure at time t,
Cv : coefficient of consolidation,
z : distance from the surface of clay bed,
R : rate of incremental loading.
Equation (2) is not solvable unless the load increment is linear. In the case of non-linear load increment (non-linear artesian pressure reduction), the solution may be approximated by superposing two or more linear incremental conditions.

The process of artesian pressure reduction of each aquifer in the past, at various locations, is estimated from the recorded water levels in each artesian well (Kuwahara, 1976a).

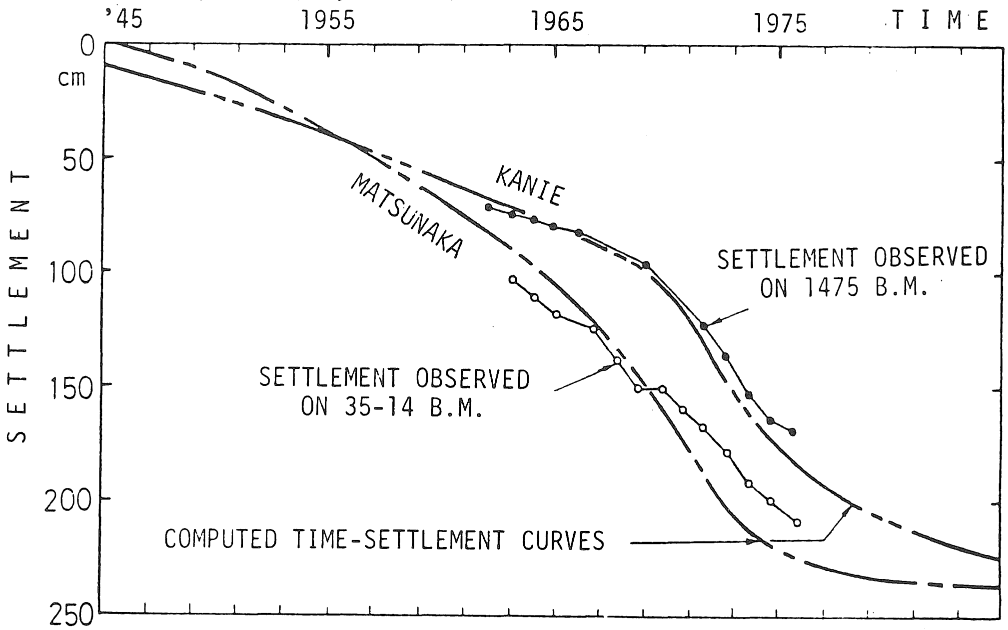


Fig. 9 Computed Rate of the Settlement of the Clays above G_2, Observed Settlement also Plotted

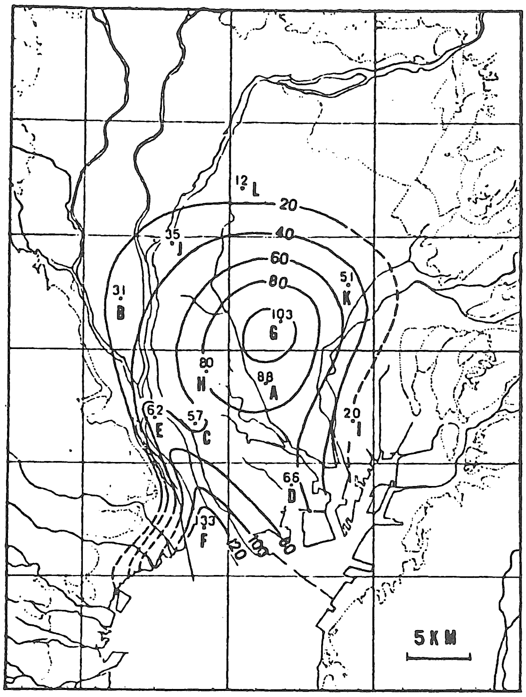


Fig. 10 Distribution of the Amount of Settlement Computed for the Clay Beds above G_2 from 1961 to 1973 (in cm)

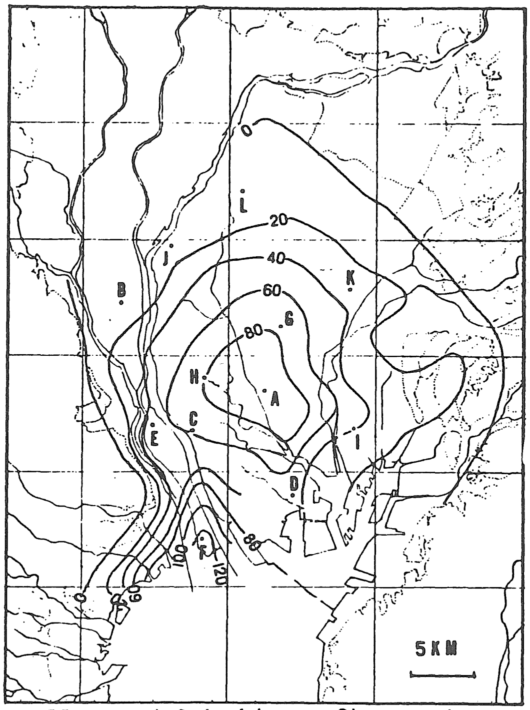
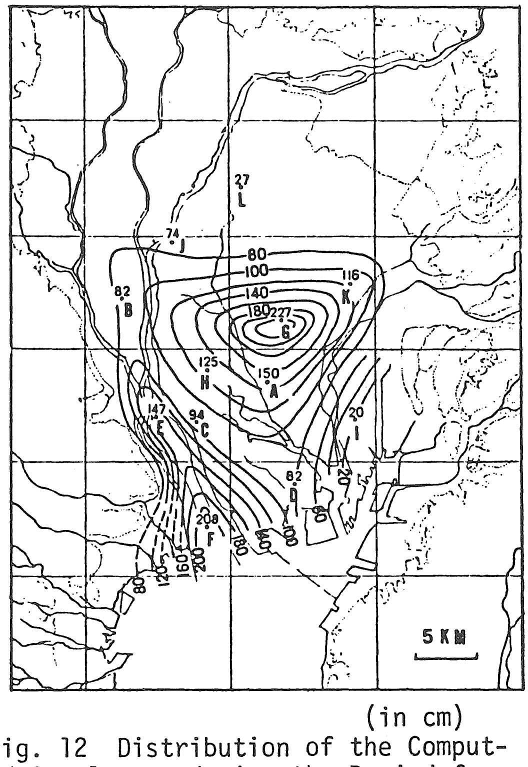


Fig. 11 Land Subsidence Observed from 1961 to 1973 (in cm)

The computed rates of consolidation at certain points where the informations of subsurface lithology, soil properties and the process of artesian pressure reduction are given, coinside with the results of repeated precise levelings of the bench marks on or near the computed points, as the examples in Fig. 9. It may be said that the computing method in this paper is effective to the analysis of land subsidence in the Nobi Plain.

The areal distribution of computed rate of settlement during the period from 1961 to 1973 (Fig. 10) is compatible with that observed (Fig. 11) during the same period in the Nobi Plain. The computed rate at point G is somewhat larger than the observed one, probably because of the incorrect records of the water level declining there.

The areal distribution of the computed settlement in this plain during the period from the year when all piezometric surfaces were at the ground level to 1973 is shown in Fig.12.



(in cm)

Fig. 12 Distribution of the Computed Settlement during the Period from the Year When Piezometric Surfaces were at the Ground Level to 1973

The settlement in core area of subsidence amounts to 2 m. These computed amounts are not inconsistent with the results from the leveling surveys in the past.

The same method is used to estimate the further subsidence in this plain under the several presupposed artesian pressure reduction conditions. The conditions are as follows: the groundwater levels are fixed in the 1973's levels in each aquifer (rate=0), the levels continue to lower in the same rates as in 1973 (rate=1), the lowering rate will decrease to 3/4 (rate= 3/4), decrease to 1/2 (rate=1/2) and decrease to 1/4 (rate=1/4).

The computed results, as given in Table 2, show that the residual settlement due to the time delay required for consolidation will attain to 70 cm in another decade, even if the artesian surfaces can be fixed at the 1973's levels.

Table 2 Computed Further Settlement of Clay Beds above G_2 from 1973 (in m)

Point \ R	TO 1978					TO 1983					SETTLEMENT TO ULTIMATE WATER LEVEL
	0	1/4	1/2	3/4	1	0	1/4	1/2	3/4	1	
A	0.465	0.619	0.756	0.884	0.981	0.697	1.105	1.370	1.462	1.566	3.419
B	0.062	–	–	–	–	0.110	–	–	–	–	4.320
C	0.172	0.195	0.219	0.240	0.264	0.276	0.340	0.408	0.466	0.530	3.852
D	0.235	0.301	0.324	0.365	0.403	0.372	0.552	0.613	0.725	0.831	3.325
E	0.180	0.198	0.220	0.236	0.248	0.291	0.340	0.403	0.449	0.480	3.960
F	0.216	0.356	0.492	0.612	0.724	0.257	0.605	0.944	1.244	1.526	3.829
G	0.087	0.113	0.132	0.154	0.175	0.116	0.183	0.239	0.289	0.342	1.112
H	0.176	0.209	0.249	0.286	0.323	0.266	0.368	0.470	0.566	0.665	5.300
I	0.045	0.073	0.101	0.127	0.151	0.047	0.116	0.182	0.246	0.304	4.337
J	0.005	0.029	0.039	0.057	0.071	0.011	0.057	0.097	0.142	0.178	1.733
K	0.001	0.030	0.057	0.086	0.111	0.001	0.070	0.135	0.199	0.258	0.386
L	0.000	0.010	0.018	0.027	0.036	0.000	0.022	0.043	0.063	0.082	0.586

The Table 2 also shows that the maximum settlement will reach 160 cm in the next decade, if the same rate of the surface lowering continues. If the artesian surfaces in main aquifers decline to the ultimate state, the further settlement resulted only from the sediments above G_2 will attain to 3 or 4 m in the southern and western areas of this plain.

In order to prevent the land subsidence in the Nobi Plain, it is indispensable to regulate the use of the groundwater without delay. To promote the regulation, the limit of groundwater use must be precisely computed from groundwater balance between discharge and recharge in this plain. The optimum policy must be taken to prevent the disasters induced by the subsidence and to maintain the groundwater resource. We are now computing the groundwater balance using the finite element method (Ueshita et al, 1976) as well as the finite difference method (Kamata et al, 1975).

Acknowledgments

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