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LAND SUBSIDENCE DUE TO SEASONAL PUMPING OF GROUNDWATER IN SAGA PLAIN, JAPAN

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ABSTRACT: In lowlands comprised of soft ground, land subsidence due to excessive groundwater pumping causes many problems, including damage to roads and structures, and an increased risk of flood due to the reduced drainage capacity of the system. Subsidence in Saga Plain, Japan, has been caused by fluctuating groundwater levels due to summer pumping for agriculture and winter recharge. The nature of land subsidence due to these groundwater level fluctuations is the focus of this paper. The characteristics of land subsidence and groundwater level were identified in both the Holocene clays and Pleistocene aquifer that form the hydrological system of the Saga Plain.

INTRODUCTION

Land subsidence due to groundwater pumping occurs as a result of consolidation with an increase in effective stress of the clay layers adjacent to the pumped aquifer due to decreased pore water pressure from excessive groundwater withdrawal. Groundwater has some excellent properties, such as constant temperature in all seasons and high water quality due to natural purification. In regions where there are no water restrictions regarding the use of groundwater and the resource is freely available, groundwater could be actively used for water supply. The effects of subsidence due to excessive groundwater use become a factor when extensive lowland areas are affected, with the risk of damage such as the differential settlement of roads and structures, and an increased risk of flood due to a reduction in the drainage capacity of the system.

Land subsidence in soft ground is caused by periodic variations in groundwater level, such as when groundwater is pumped in summer for agricultural purposes, as is the case for the Saga Plain (Harada et al. 1983; Miura et al. 1986; Sakai et al. 1996; Hachiya et al. 1998), and in winter for melting snow (primarily from roads), as occurs in Muikamachi, Niigata, Japan (Iwata et al. 1990; Sekiya et al. 1998). In both cases, groundwater levels return to the equilibrium level in the "off" season, within annual variation. In particular, in Saga Plain, significant subsidence damage occurred when there was a 1 to 2 month period of a high rate of groundwater withdrawal during the drought of 1994. It is known that such subsidence is dependent on not only an increase in effective stress in the clay, but also on the cyclic effect of consolidation of the clay due to seasonal fluctuations in groundwater level (Iwata et al. 1990; Tohno et al. 1989; Yasuhara 1995; Sakai 1997).

The Saga Plain is a typical lowland, reclaimed from the Ariake Sea in northern Kyushu, Japan. Many geotechnical problems have arisen due to the characteristics of the clay formations (Ariake clay formation and Hasuike formation), which are from 10 m to 30 m thick, upon which the Saga Plain is founded. The clay formations are very soft and highly compressible, making them highly susceptible to severe differential settlement and ground subsidence due to groundwater withdrawal (Miura et al. 1988). However at present, the

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utilization of groundwater is essential to maintain the socioeconomic activity of the region, although plans to secure new water resources as an alternative to groundwater are well under way.

This paper describes the features of land subsidence in Saga Plain over 24 years, including the drought of 1994. The depth distribution of groundwater level and settlement due to groundwater level fluctuation are then examined using newly acquired data.

LAND SUBSIDENCE IN SAGA PLAIN

Land Subsidence due to Seasonal Pumping of Groundwater

In Saga Plain, the cumulative subsidence has reached 123 cm over the past 38 years (1960-1998) and the area affected by subsidence has extended to 324 km^2. Soft clay layers, 10 m to 30 m thick with high water content and high compressibility, are present in the surface strata of Saga Plain, making the area highly susceptible to land subsidence by the lowering of the groundwater level. Groundwater has been widely utilized in the area because most rivers in the Saga Plain are affected as far as the middle parts by saltwater intrusion from the Ariake Sea.

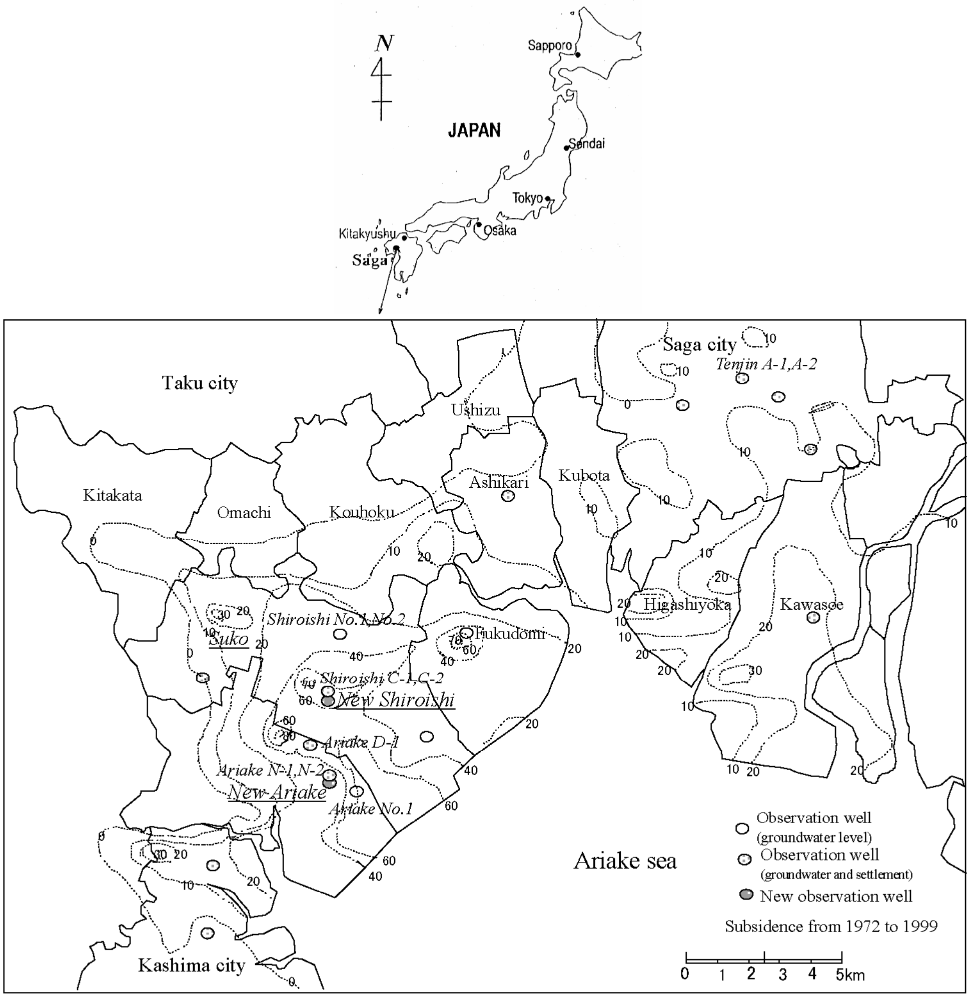


Fig. 1 Saga Plain and land subsidence observed in Saga Plain from 1972 to 1999

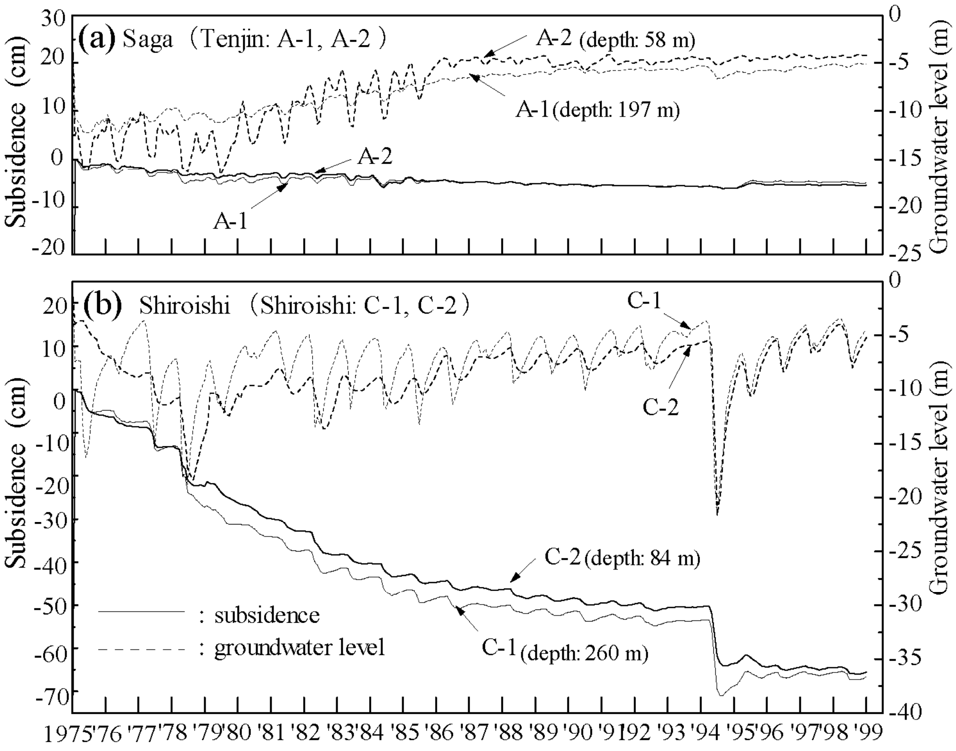


Fig. 2 Fluctuation of groundwater level and subsidence measured at observation wells in Saga and Shiroishi

A survey of 17 locations and 23 observation wells, as shown in Fig. 1, and leveling using bench marks were conducted to clarify the state of land subsidence and groundwater level fluctuation in the Saga Plain (Saga Pref., 1981-1998). Figures 2(a) and 2(b) show typical groundwater levels and land subsidence in both the Saga and Shiroishi districts (1975 to 1998). The Saga Plain is commonly divided into two districts; "the Saga district" and "the Shiroishi district", comprising the east and west parts of the Saga Plain, respectively. In the Saga district (extending from the eastern shore of the Chikugo river to the western shore of the Ushizu river and to the mouth of Rokkaku river), groundwater extraction, mainly for industrial use, has decreased significantly from late 1970's due to groundwater utilization regulations imposed by Saga Prefecture in 1974. The groundwater level observed at wells A-1 and A-2 (Tenjin, Saga city), appears to have recovered well, and has fluctuated within only 1 m in recent years, as shown in Fig. 2(a).

In the Shiroishi district, the demand for water has increased, primarily for agricultural as well as residential supply, due to land reclamation, brackish river water, and the limited extent of natural irrigation by natural flow. Therefore, the high dependence on groundwater for water supply and agriculture prevails in the Shiroishi district. Groundwater is primarily pumped from Pleistocene series rocks at a depth of around 100 m. This aquifer is overlain by the soft clay layer (Holocene series), which is prevalent as the upper layer in the Shiroishi district (Environment Agency et al. 1990). The subsidence at observation wells C-1 and C-2 (Shiroishi) in the Shiroishi district has continued irreversibly due to the periodic change in groundwater level, which is depressed in summer and then recharged to almost original levels in winter, except for several years during and following the drought of 1994, as shown in Fig. 2(b). Rapid subsidence in 1994 occurred during the drought as a result of the severe depletion of the aquifer due to the extreme level of pumping. Groundwater pumpage in the Shiroishi district is almost entirely attributable to agricultural and residential supply, according to the yearly pumpage statistics by sector, as shown in Fig. 3 (Saga Pref. 1970-1998). In particular, pumpage for agriculture increases markedly in years with low precipitation, whereas residential supply remains almost constant. The recorded pumpage for agriculture in the droughts of 1978 and 1994 were 11,994,000 m^3 and 16,009,000 m^3, respectively. Thus, the fluctuation in agricultural pumpage almost exclusively represents the overall pumpage fluctuation in the Shiroishi district.

In the Shiroishi district, it has been reported that the expected maximum subsidence due to the primary consolidation of the Holocene clay layers is only 76.5 cm, which would occur when the clay layers are completely dewatered (Miura et al. 1986). However, subsidence has

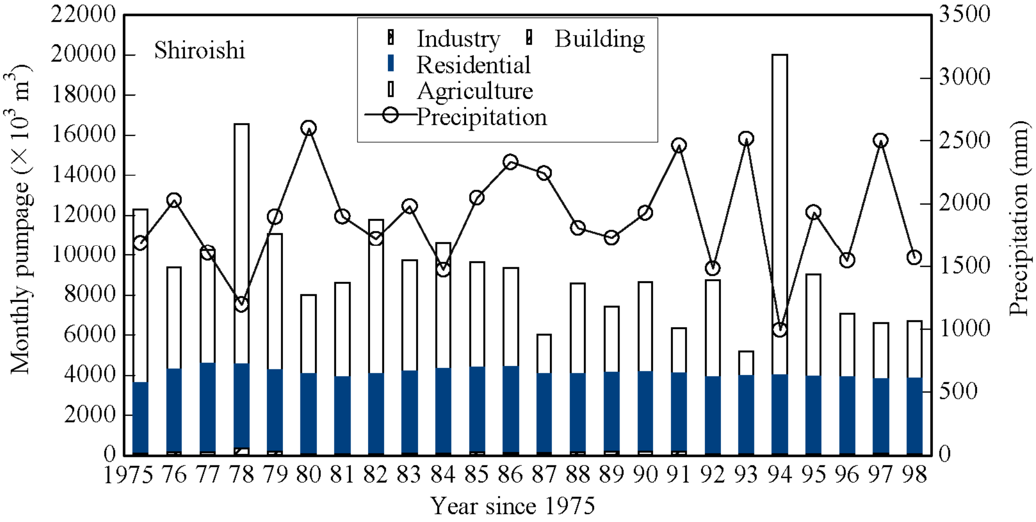


Fig. 3 Fluctuation of annual pumpage by sector in Shiroishi

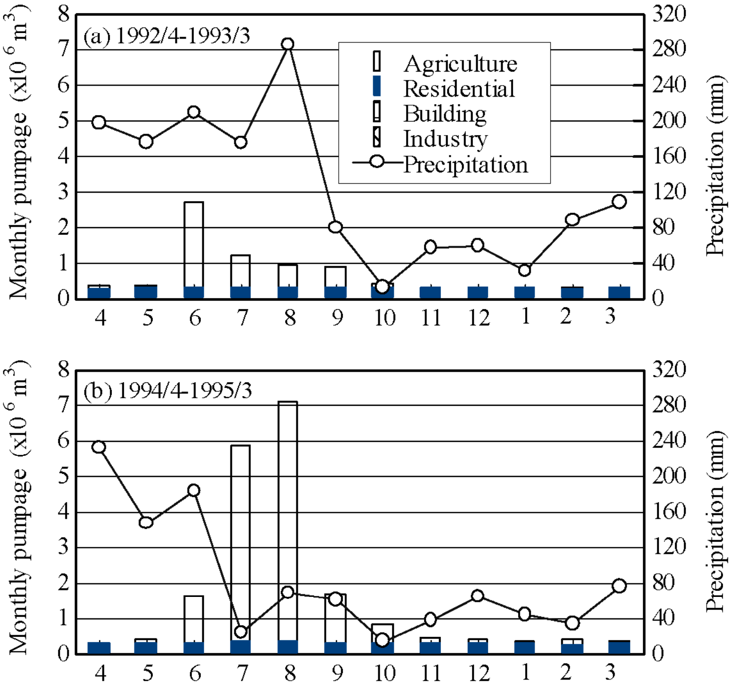


Fig. 4 Monthly pumpage by sector in Shiroishi

already reached as much as 123 cm in certain areas. It appears that subsidence is caused not only by the cyclic consolidation of the Holocene clay layers due to seasonal fluctuations in groundwater level, but also the compression of the Pleistocene aquifer itself.

Land Subsidence in 1994 Drought

Severe subsidence damage occurred in western Japan as a result of the 1994 drought, the summer of which brought high temperatures (maximum 39.6 °C) and the lowest rainfall for the last hundred years (Saga Prefecture 1996; Hachiya et al. 1996). Figure 4 shows a comparison of the relationship between monthly pumpage by sector and precipitation for 1992 and the same period during the drought of 1994 in the Shiroishi district. The monthly pumpage for agriculture increased rapidly during July and August in 1994 due to the lack of precipitation. The groundwater level dropped sharply after June 1994, recording the lowest value on record (-22 m at C-1, Shiroishi) in early September, as shown in Fig. 2(b).

A subsidence of about 16 cm occurred at that time, and has not reversed significantly in contrast with the groundwater level recovery at C-1, Shiroishi. The stratum composition in C-1 and C-2, Shiroishi, is composed of 19 m Holocene clay at the upper layers and Pleistocene aquifer below that. Also, subsidence at the observation wells was measured as settlement of the base of the well with respect to the surface. Thus, the 5 cm difference in subsidence between C-1 and C-2, with depths of 260 m and 84 m, respectively, represents the additional component of settlement in the Pleistocene aquifer. This implies that compression of the Pleistocene lithology between 84 m and 260 m contributes to about 30% of surface subsidence in addition to the consolidation settlements of both the overlying 19 m Holocene clay and the Pleistocene aquifer above 84 m. This is surprising given the very low compressibility of the Pleistocene aquifer.

Local Differential Settlement in Suko

The severe subsidence damage in the Shiroishi district in 1994 included subsidence at the foot of the hilly Kishima district, where a ridge of elevated terrain runs north-south for about 300-340 m in the western region of the Saga Plain (Saga Pref. 1996; Hachiya et al. 1996). The

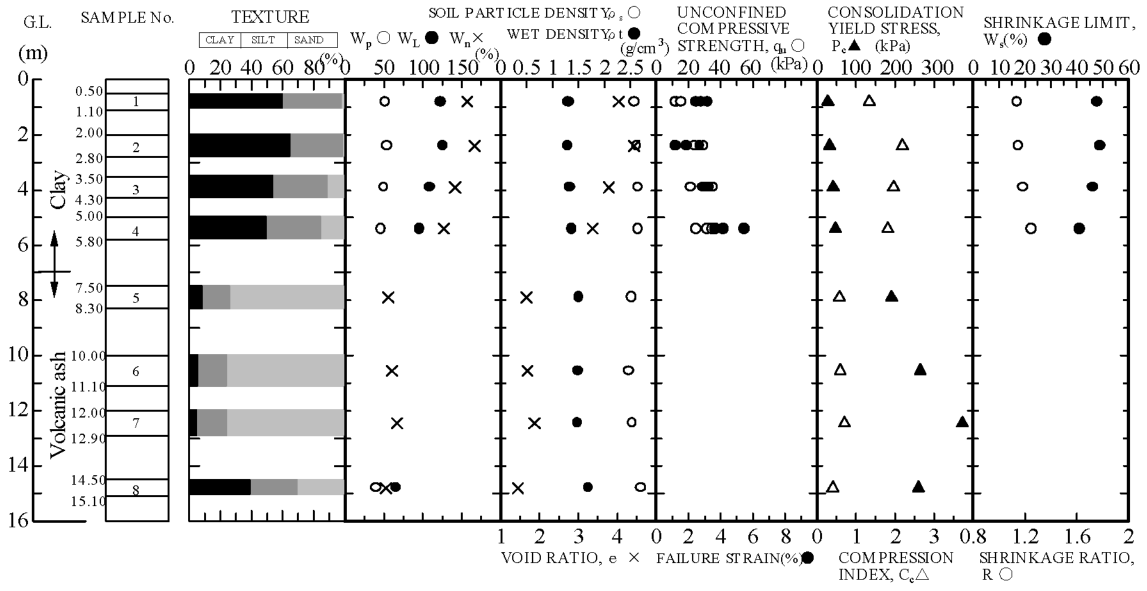
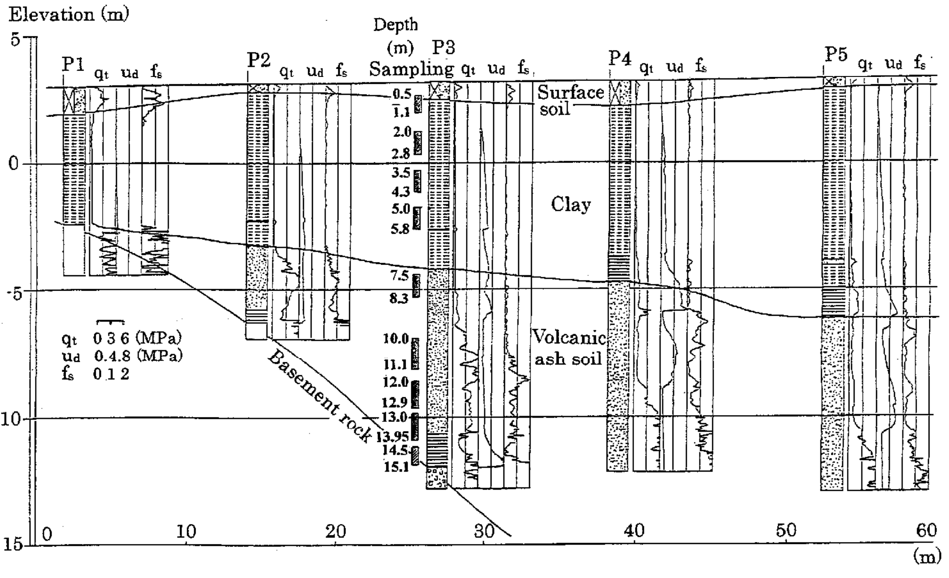


Fig. 5 Soil properties in Suko area

Suko area is located at the foot of this ridge, specifically at the base of a hill that extends for about 41 m and is elevated about 3 m above the surrounding area. The maximum subsidence in this area in 1994 was estimated to be about 30 cm, and represents differential settlement. Subsidence in the Suko area has been minimal, except for the major effects of the drought of 1994, and remains negligible in periods of average rainfall.

Figure 5 shows geotechnical properties obtained by using samples bored at a site 25 m from the foot of the hill in the Suko area, as shown in Fig. 6(a). The soils are composed of soft clay and volcanic ash. The main geological feature to note here is that the clay layer tilts and gradually thickens away from the hillside, as determined from five piezocone data. The clay-rich nature of the ground makes this area susceptible to subsidence with the lowering of the groundwater level. The clays have the high water content, high void ratio, and comparatively high compression index of the ground. The subsidence of the clay layer in the 1994 drought is likely to have occurred as a result of inadequate recharge of the underlying aquifer, as inferred from the depressed level of water in a pond at the foot of the hill. The subsidence in this area becomes more severe approaching the hill, even though the clay layer thins in this direction.



(a) Geological profile of Suko area

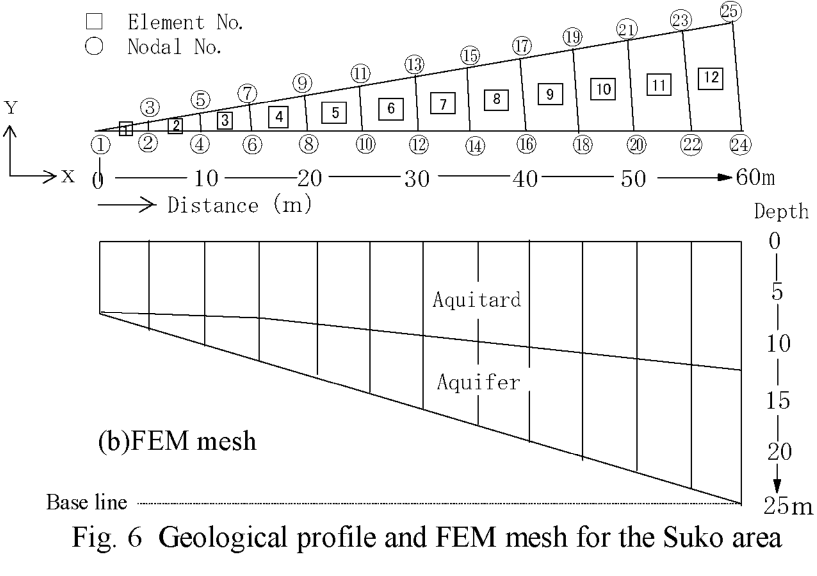


Fig. 6 Geological profile and FEM mesh for the Suko area

Table 1 Parameters for analysis

Aquitard	Wet density ρ_t (g/cm^3)	Void ratio e_0	Compression index $(C_c)_0$	Cofficient of consolidation C_v (m^2/day)
	1.33	4.0	1.8	0.05
	$S_s = m_v\gamma_w \Rightarrow m_v = 0.434C_c/(1+e_0)\sigma'_v, C_c = \alpha(C_c)_0$ α=1.0($D \leqq$7 m), 0.7(7<$D \leqq$9), 0.4(9<$D \leqq$11), 0.1(11<D) D: Depth (m)			
Aquifer	Coefficient of permeability, k (m/day)	Specific storage coefficient, S_s (1/m)	Young's modulus E (kPa)	
	1.5	0.001	2x10^4	

A FEM analysis of the settlement in this area for a lowered groundwater level was carried out in order to examine this phenomena. Figure 6(b) shows the analytical mesh used, comprised of a clay layer (aquitard) and volcanic ash layer (aquifer), inclined away from the hill. The aquitard was divided equally in 20 layers. The greatest thickness of each layer, farthest (60 m) from the hill, was assumed to be 11 m and 13 m, respectively (12 elements and 25 nodes). A quasi three-dimensional groundwater flow analysis was performed for a lowering of the groundwater level in the aquifer at nodes ①-③ on the hillside. The time increment used in this analysis was one day (24 hrs). The calculation was repeated until the convergence condition of 1 mm maximum head error was satisfied, using half the time increment. The magnitude of subsidence was calculated in each time step. Table 1 lists the analytical parameters used, as derived from the soil properties in Fig. 5 and the coefficient of permeability obtained from a permeability test. The compression index C_c of the clay layer was decreased in steps with depth, D (see α in Table 1).

Figure 7 shows the calculated results based on a situation in which the groundwater level is lowered by 10 cm per day. The pressure heads at the hillside decrease 1, 2 and 3 m after 10, 20 and 30 days, respectively. The degree of subsidence decreases away from the hill, and differential settlement is obvious. The subsidence characteristics of the ground in this region are strongly influenced by the inclination and thickness of the clay layer, and the degree of water level depression. An additional analysis was conducted assuming that the compression index of the clay layer remained constant with depth, revealing that the degree of subsidence was higher at the immediate foot of the hill, resulting in a local convexity that deepened over a period of days.

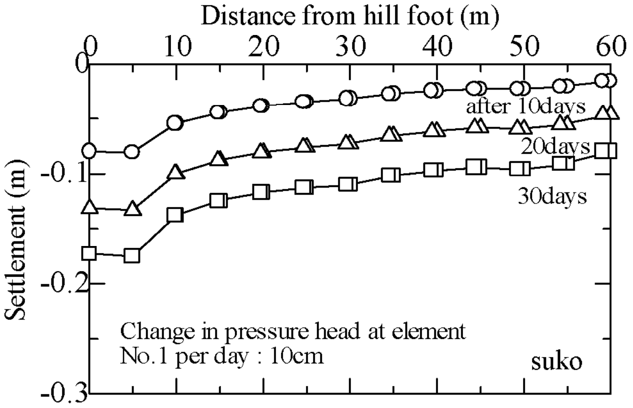


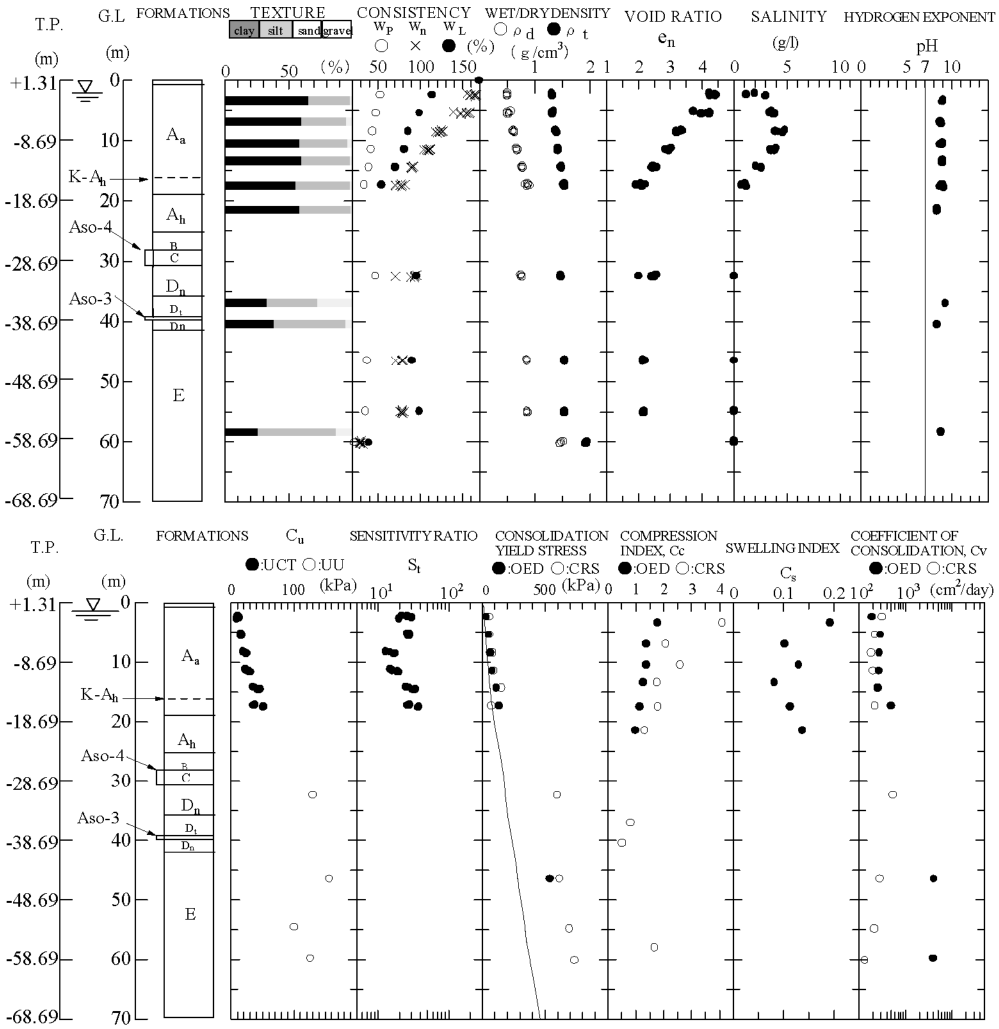
Fig. 7 Calculated surface settlement

FIELD MEASUREMENTS OF GROUNDWATER LEVEL AND SETTLEMENT

Soil Properties in the Shiroishi district

Recently, a new Quaternary geological formation in the Saga Plain has been established by Shimoyama et al. (1994). The Takagise formation and the Ariake clay formation are marine strata, representing the elevated sea level in the late Pleistocene and early Holocene eras. The Holocene clay, 10 m to 30 m thick, present in the upper strata of the Saga Plain is divided into two categories; marine clay and non-marine clay, called Ariake clay formation and Hasuike formation, respectively. The Ariake clay formation contains shell fossils as an indicator of a marine depositional environment.

Figure 8 shows the soil properties obtained from data from the new Ariake observation well drilled in the Shiroishi district in 1996. The upper layers of this site consist of 26 m of Holocene clay (Ariake clay and Hasuike). At greater depth are the Mitagawa formation, Aso-4, the upper part of the Nakabaru formation, the Takagise formation, Aso-3, the lower part of the Nakabaru formation, and the Kawasoe formation (Shimoyama et al. 1994). The natural



Akahoya tephra (K-A$_h$: 6.3 ka), Aso-4 tephra (85 ka), Aso-3 tephra (120 ka)
A$_a$: Ariake clay formation (marine), A $_h$: Hasuike formation (non-marine), B: Mitagawa formation,
C: Aso-4, D$_n$: Nakabaru formation, D $_t$: Takagise formation, E: Kawasoe formation

Fig. 8 Soil properties at the new Ariake observation well water content in the upper clay layers is greater than the liquid limit, and the void ratio is 4.0 or more near the surface. The salinity of the marine-deposited Ariake clay is lower at the top and bottom of the stratum due to leaching. Unconfined compressive strength increases with depth, and the sensitivity ratio is high at between 20 and 60. The compression index of the upper clay layer increases with proximity to the surface, and is 10 times greater than the swelling index. The overconsolidation ratio in the lower clay layer increases gradually with depth, up to 2 to 3 below 30 m, whereas the upper clay layer is slightly overconsolidated. Tohno et al. (1992) reported in a boring survey to a depth of 200 m in 1992, overconsolidation ratios of 1.0-1.4 to a depth of 110 m, and about 2 below 150 m at the Fukudomi town office, northeast Shiroishi district.

New Observation Wells

New observation wells have been drilled at two locations in the Shiroishi district in a zone of high subsidence, as shown in Fig. 1. A cross-sectional view of the new Ariake observation site, which consists of eight observation boreholes of various depths, is shown in Fig. 9. In the clay layer, four pore-water pressure cells have been installed in four wells with depths of 5, 10, 15 and 21 m. In the Pleistocene aquifer 26 m below ground level, four observation wells have been installed, with depths of 92.4, 81.0, 56.5 and 28.2 m in order to measure the groundwater level and subsidence at each depth. A similar set of wells was established at the new Shiroishi observation well site.

The observation system employed is a measurement system for obtaining groundwater levels and subsidence at various depths, as follows; The instruments installed at the two new observation well sites included four borehole water-level gauges, four settlement gauges, four pore-water pressure gauges, and two thermometers, for each site. The data obtained at the well sites with these instruments is recorded by a data-logger and transferred to a personal computer at Saga University via a telephone line. A similar observation system has already been implemented at the Ariake well site in Saga Prefecture (Tohno 1997).

Seasonal Changes in Groundwater Level and Settlement due to the Pumping of Groundwater

Figures 10(a) and 11(a) show the fluctuation of groundwater levels at the new Ariake and Shiroishi observation well sites between June 1, 1996 and December 31, 1998, respectively. The groundwater level has been converted into the elevation (T.P.) from pore-water pressure data in the clay layer and borehole water-level data in the Pleistocene aquifer. The groundwater level decreases due to agricultural water pumping in summer, and recovers in

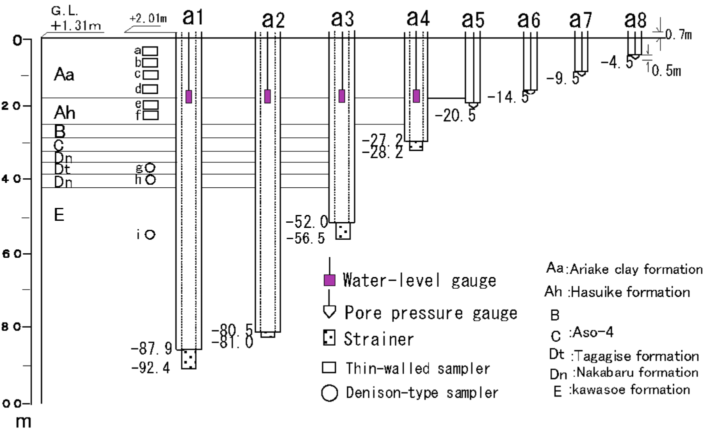


Fig. 9 Schematic new observation wells

winter. The lowering of the groundwater level at the new Ariake observation wells reaches a maximum of 12-13 m. The deepest of the clay layer wells exhibits a special feature of groundwater level fluctuation; it is small and has a 2 month lag in variation compared with that for the aquifer. The fluctuation of the groundwater level differs annually, and is dependent on rainfall in the Shiroishi district. From the relationship between the fluctuation in groundwater level at the new Ariake observation wells and precipitation between June 1, 1997 and September 30, 1997, as shown in Fig. 12, it was observed that the groundwater level tended to drop when rainfall was insufficient for agriculture, and recovered during subsequent rainfall.

The fluctuation in groundwater level at the new Shiroishi observation wells has the same tendency as at Ariake. However, the fluctuation is suppressed by less than half that at Ariake, because of fewer pumping sites and a lower pumpage in the vicinity of the new Shiroishi

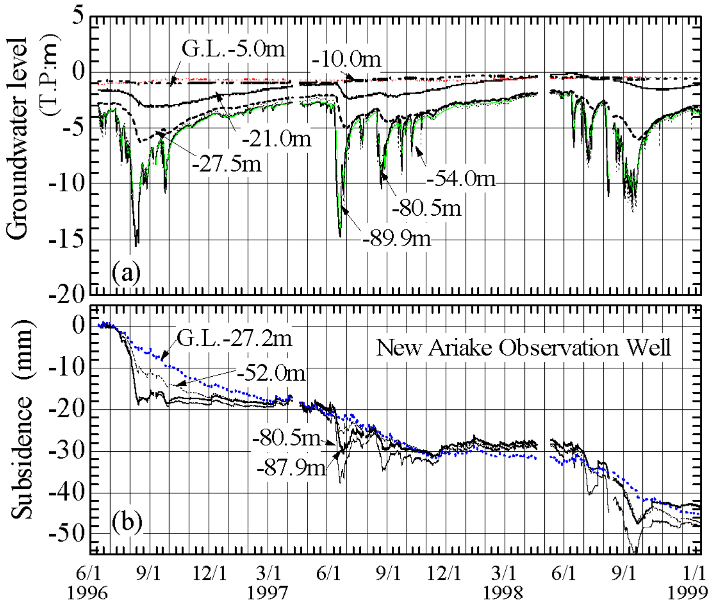


Fig. 10 Observed groundwater level and subsidence at new Ariake observation well site

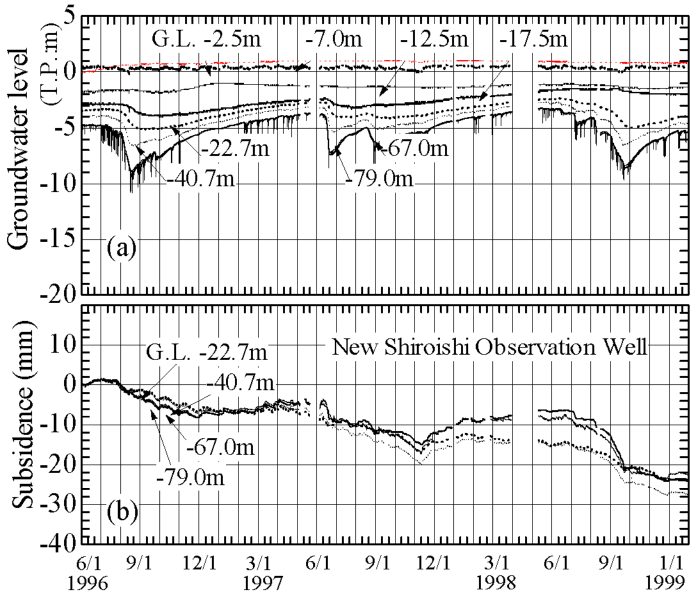


Fig. 11 Observed groundwater level and subsidence at new Shiroishi observation well site

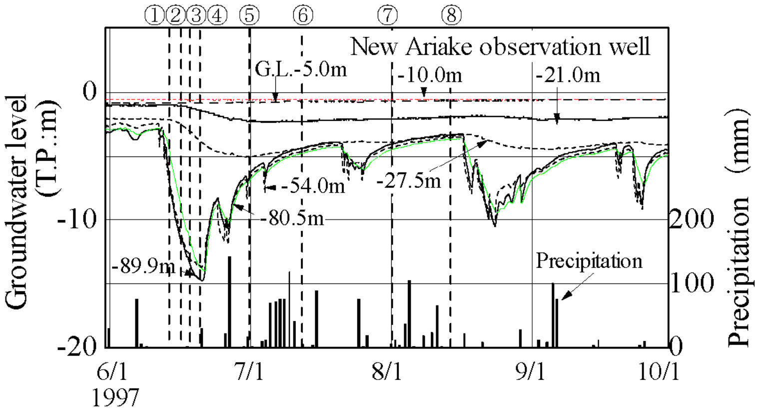


Fig. 12 Comparison of precipitation and groundwater level fluctuation

observation site.

Figures 10(b) and 11(b) show the ground subsidence at the new Ariake and Shiroishi observation sites. The subsidence is that of the base of the well with respect to the surface. Subsidence at the new Ariake observation site occured rapidly following the lowering of the groundwater level after the middle of July, 1996, subsiding 18 mm at -87.9 m depth by the middle of August. The ratio of settlement of the clay layer (-27.2 m) to that of the aquifer (-87.9 m) was 30% during August, and increased to 86% by the end of December. The subsidence of layers shallower than 52 m gradually approaches that of the lower layers, despite the fact that the Pleistocene aquifer exhibits minor inflation due to groundwater recharge. Thus, the behavior of surface subsidence with the suppression and recovery of the groundwater level is a combination of rapid reactions to groundwater level fluctuations in the Pleistocene aquifer and the slower response of pore pressure in the Holocene clays. The subsidence in 1997 and 1998 have similar features to the subsidence in 1996 at the Ariake site, and although the subsidence at the new Shiroishi observation site is less because the magnitude of groundwater level fluctuations is smaller, it exhibits the same tendency as the subsidence at Ariake.

Distribution of Groundwater Level and Settlement in Depth

The depth distribution of pore water pressure in 1997 at the new Ariake observation site is shown in Fig. 13(a). On June 12, 1997, the pore water pressure was lower than the hydrostatic pressure in the Pleistocene aquifer. From this state, pore water pressure decreased further due to seasonal groundwater pumping, with the lowest levels on June 19. Thereafter, the pore water pressure distribution gradually returned to previous levels, reflecting the recovery of the groundwater level. The magnitude of the fluctuation in pore water pressure increases with depth, to a maximum at 50 m to 60 m, below which the degree of fluctuation is constant. The distribution of pore water pressure in the clay layer is shown well-informed by Fig. 13(b). Pore water pressure in the lower clay layer is influenced by water pressure changes at greater depths, although the changes are negligible near the surface. However, the gradual delayed decrease in pore water pressure in the clay layer, even after the groundwater level in the Pleistocene aquifer has begun to recover, is apparent due to the time delay of changes in pore water pressure in the clay layer.

Figure 14 shows the distribution of relative settlement in relation to depth at the new Ariake observation site. The relative settlements were plotted incremental settlements of three observation wells with depths of 88 m, 52 m, and 27 m from ground level, based on data from June 12, 1997. Settlement in the Pleistocene aquifer below 26 m was greatest on July 1, 1997;

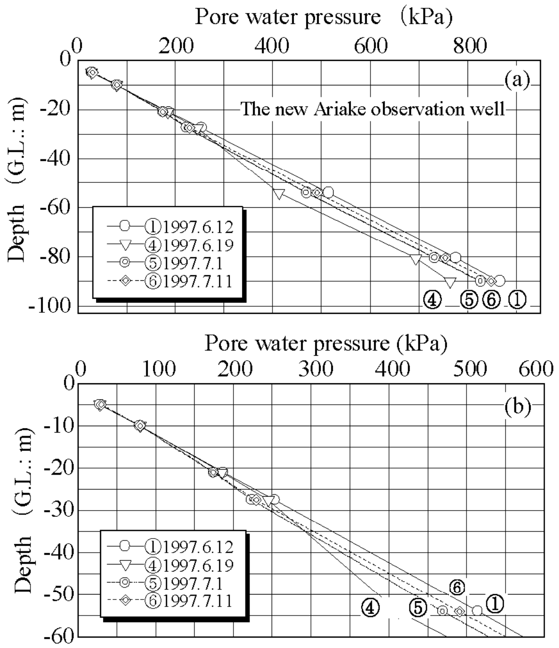


Fig. 13 Depth distribution of pore water pressure

12 days after the groundwater level reached its lowest on June 19, 1997 as shown in Fig. 14, while the settlement of the clay layer has yet to become noticeable. By the end of the observation period, however, the fraction of surface subsidence attributable to the clay layer has increased considerably after the inflation of the Pleistocene aquifer following with the recovery of the groundwater level.

Compressibility of Ground During Groundwater Level Fluctuations

The consolidation characteristics of the clay layers (Holocene Ariake clay formation and Hasuike formation) in the Saga Plain have been obtained from the examination of many soil samples. In the Saga Plain, where groundwater is pumped from a depth of 50 m to 200 m on a seasonal basis, it is important to clarify the compression characteristics of not only the Holocene clays but also the Pleistocene aquifer to the fluctuation in groundwater level.

In this paper, the compression characteristics of the Pleistocene aquifer were examined using the observation results of groundwater level fluctuation and subsidence at the new Ariake observation well site. The following methods were adopted here as a method of estimating the compressibility of certain layers. The layers in the new Ariake observation well were divided into three categories, based on composition, as shown in Fig. 8, and groundwater level fluctuation; (a) the upper layer, consisting of the clay layers (the Ariake clay formation and the Hasuike formation) to a depth of 26 m, (b) the intermediate layer, consisting of the Mitagawa formation, Aso-4, the upper part of the Nakabaru formation, the Takagise formation, Aso-3, and the lower part of the Nakabaru formation, between 26 m and 41 m in depth, and (c) the bottom layer, consiting of the Kawasoe formation below 41 m depth. The distributions of pore water pressure and settlement of the intermediate and bottom layers were established using the observed values for the period of groundwater level suppression during June 13-21, 1997, as shown in Fig. 15. The average compression strain in each layer of the Pleistocene aquifer was calculated from these distributions. The difference in the compression strain between the intermediate and bottom layers decreases with groundwater withdrawal, with the strain of the intermediate layer being slightly higher than that of the bottom layer.

The parameter $(m'_v)_{\Delta t}$ $(=(\Delta\varepsilon_v/\Delta u)_{\Delta t})$, expressed as the ratio of compression strain ($\Delta\varepsilon$) of each layer and the pore water pressure change (Δu) over time increment (Δt), is used to evaluate the compressibility of each layer over time. It should be noted that $(m'_v)_{\Delta t}$ differs from the coefficient of volume compressibility in that the pore water pressure change (Δu) is the value at the measurement point and does not account for the all areas in the layer. Two scales are defined for Δt; over the period of a single day, and over a number of days. The value of $(m'_v)_{\Delta t}$ for the period of groundwater level suppression during June 13-21, 1997, is plotted in Fig. 16. The value of the intermediate layer is greater than that of the bottom layer, and both values tend to increase when the groundwater level lowers. This means that the settlement of both the intermediate and bottom layers is delayed due to the influence of clay layers in the Pleistocene unit. That is, the pore water pressure distribution in the Pleistocene unit is not uniform, exhibiting internal variations due to the existence of clay layers. The value of $(m'_v)_{\Delta t}$ for August 1-10, 1996, also exhibits the same tendency. From these values, the compressibility is determined to be $1\sim3\times10^{-6}$ m^2/kN for the intermediate layer and $0.5\sim2\times10^{-6}$ m^2/kN for the bottom layer during periods of lower groundwater levels.

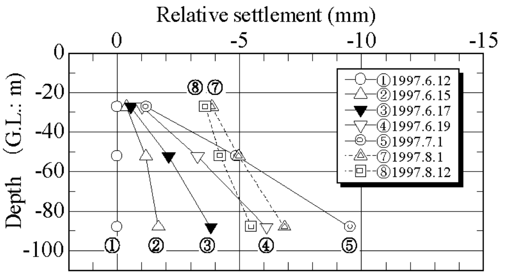


Fig. 14 Depth distribution of relative Settlement

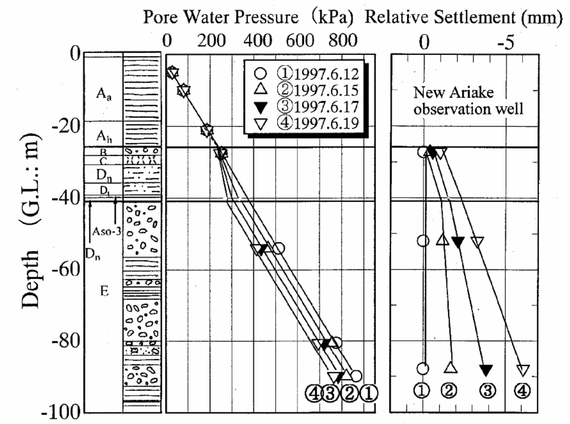


Fig. 15 Layer divisions used for compressibility

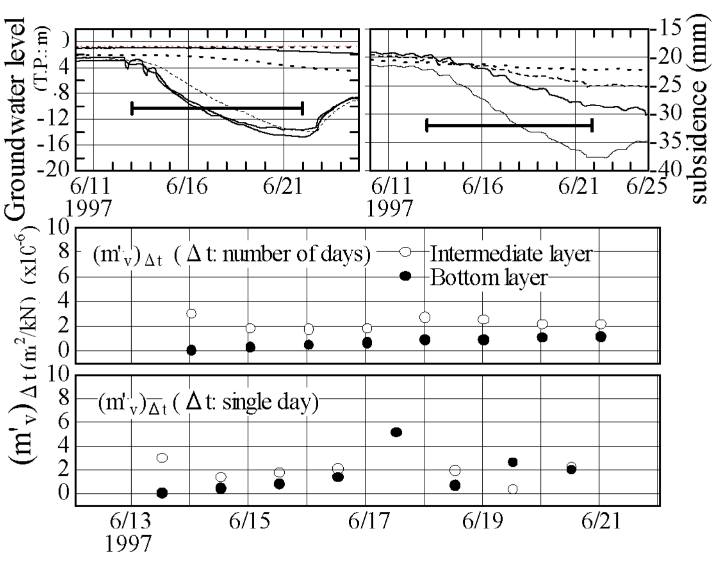


Fig. 16 Compressibility of Pleistocene aquifer with lowering groundwater level

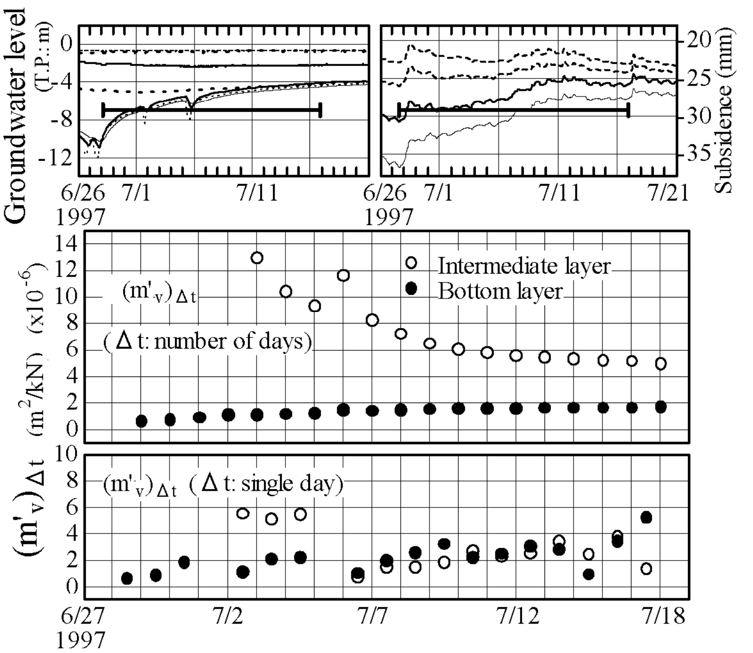


Fig. 17 Compressibility of the Pleistocene aquifer with recovery of groundwater level

Figure 17 shows the compressibility of the Pleistocene aquifer during the recovery of the groundwater level between June 28 and July 17, 1997. The value of $(m'_v)_{\Delta t}$ in the intermediate layer over this period is considerably greater than that of the bottom layer, and exhibits a tendency to decrease over time. From such behavior it is inferred that both subsidence and rebound occur simultaneously in the intermediate layer in the first stage of the recovery of the groundwater level due to the delayed consolidation of the clay layers within it. The compressibility during the recovery of the groundwater level over the period of a single day is $1\sim3.0\times10^{-6}$ m^2/kN in the intermediate layer and $0.5\sim3\times10^{-6}$ m^2/kN in the bottom layer, in reference to the values obtained for June 28 to July 17, 1997 and August 15 to19, August 19 to September 4, and November 5 to December 9, 1996.

CONCLUSIONS

Through this study, the nature of land subsidence due to the seasonal pumping of groundwater in the Saga Plain was clarified. The results can be summarized as follows:

1. Nature of regional land subsidence in the Saga Plain: The ground surface of the Saga Plain is comprised of soft saturated clays (Holocene) ranging from 10~30 m in thickness, making the region highly susceptible to subsidence as a result of lowering the groundwater level. The groundwater in Shiroishi is utilized for residential water supply, which has a fixed pumpage throughout the year, and for agriculture, which is utilized only in the summer. Thus, the groundwater level fluctuates from a low in the summer due to agricultural pumpage, to a high in the winter due to recharge. This fluctuation causes cyclic consolidation of the geological strata, which in turn causes land subsidence. In particular, a rapid subsidence of 16 cm was caused when the groundwater level lowered to 22 m during the drought of 1994. This subsidence was attributable not only to the consolidation of the Holocene clay (Ariake clay formation and Hasuike formation), but also the compression of the Pleistocene aquifer, even though the compressibility of the aquifer is small.
2. Land subsidence at the foot of hill during the drought: A maximum settlement of 30 cm

was estimated at the foot of a ridge of hills in the Shiroishi district during the 1994 drought. No subsidence has occurred in this region, even though the surface layer is comprised of soft clay with a large void ratio and high compressibility. The clay layer is inclined and thickens away from the hill. A subsidence analysis of the hillside (Suko district) for depressed groundwater level was carried out and revealed that there is a danger of a large local differential settlement when the groundwater level is lowered in hilly areas.

3. Depth distribution of ground subsidence and groundwater level: (a) Pore water pressure distribution: The pore water pressure in the new Shiroishi and Ariake observation wells is below hydrostatic pressure even during the winter recharge. The fluctuation of the groundwater level due to groundwater pumping in the summer is uniform below 50 to 60 m. The variation in pore water pressure of the Holocene clay decreases with proximity to the surface, and the groundwater level in the upper part of the clay layer remains almost constant. The pore water pressure in the lower layers of the Holocene clay decreases gradually with a delay attributable to the low permeability of the layer. The pore water pressure continues to decrease, even when the groundwater level in the Pleistocene aquifer has begun to recover. Pore water pressure in the clay layer follows groundwater level slowly, and so at any time the overall head height is a combination of the rapid response of groundwater level and the slow response of pore water pressure of the clay. (b) Subsidence depth distribution: The subsidence of the Pleistocene aquifer due to the depression of the groundwater level in the summer greatly surpasses the subsidence of the overlying Holocene clay. However, over time, the proportion of subsidence attributable to the Holocene clay increases, with a maximum in December when the recovery of the groundwater level has also reached a peak. (c) Compression characteristics of the Pleistocene aquifer with respect to groundwater level fluctuation: The Pleistocene aquifer, based on data from the new 90 m Ariake observation well, was divided into two layers; one in which the groundwater level fluctuation is uniform (the bottom layer), and one that has a reduced groundwater level fluctuation (the intermediate layer), as determined from the depth distribution of pore water pressure and geology. The compressibility parameters $(m'_v)_{\Delta t}$ of the two layers at each time step during the lowering and recovery of the groundwater level were calculated using the average compressive strain of each layer, as obtained from the observed depth distribution of pore pressure and subsidence. There is a time delay between the settlement of the two layers, alluding to the existence of a clay-rich layer (the intermediate layer) that differs in permeability from the sandy aquifer (the bottom layer), which exhibits rapid response to groundwater level changes. The compressibility of the intermediate layer during the lowering of the groundwater level is slightly greater than that of the bottom layer.

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REFERENCES

Environment Agency, Niigata Prefecture, Kyoto Prefecture, and Saga Prefecture (1990). Inventory report on the groundwater yield. 171-313. (in Japanese)

Hachiya, Y., Kitajima, J., and Jinno, K. (1996). Land subsidence in Saga Plain due to water shortage in 1994. J. Groundwater Hydrology. 39(3): 181-191. (in Japanese)

Hachiya, Y., Miura, N. and Sakai, A. (1998). Characteristics of land subsidence in Saga Plain. Improvement of Soft Ground. Asian Institute of Technology: 9-22.

Harada, K. and Yamanouchi, T. (1983). Land subsidence in the Saga Plain, Japan, and its analysis by the quasi-three-dimensional aquifer model. Geotech. Engrg. 14: 23-54.

Iwata, S. and Tohno, I. (1990). Land subsidence caused by pumping for snow melting in Muika-machi, Niigata prefecture. Research Report form the National Institute for Environmental Studies, Japan. 127: 1-84. (in Japanese)

Miura, N., Isagai, K., Sakai, A., and Tohno, I. (1986). Land subsidence and quality of groundwater in Saga Plain. Tsuchi-To-Kiso. JSSMFE. 34(11): 13-18. (in Japanese)

Miura, N., Taesira, Y., Sakai, A., and Tanaka, M. (1988). Land subsidence and its influence to geotechnical aspects in Saga Plain. Proc. Intl. Symp. on Shallow Sea and Lowland, Saga: 151-158.

Saga Prefecture (1970-1998). Subsidence investigation report at Shiroishi plain. (in Japanese)

Saga Prefecture (1981-1998). General condition of land subsidence. (in Japanese)

Saga Prefecture (1996). Urgent investigation report of water shortage (subsidence) damage. (in Japanese)

Sakai, A., Miura, N., Tohno, I., and Hachiya, Y. (1996). Land subsidence caused by seasonal pumping up of groundwater. J. Groundwater Hydrology. 38(4): 269-278. (in Japanese)

Sakai, A. (1997). Effects of the applied loading time on one-dimensional cyclic consolidation. Proc. China-Japan Joint Symp. on Recent Development of Theory & Practice in Geotechnology, 69-74.

Sekiya, K. and Tohno, I. (1998). Land subsidence due to groundwater withdrawal for melting snow in Niigata prefecture. Proc Intl. Symp. on Lowland Technology: 521-528.

Shimoyama, S., Matsumoto, N., Yumura, H., Takemura, K., Iwao, Y., Miura, N., and Tohno, I. (1994). Quaternary geology of the low-land along the north coast of Ariake bay, west Japan. Research Report of the Faculty of Science, Kyushu University. 18(2): 103-129. (in Japanese)

Tohno, I., Iwata, S. and Shamoto, Y. (1989). Land subsidence caused by repeated loading. Proc. 12th Intl. Conf. on SMFE. 3: 1819-1822.

Tohno, I., Endo, K. and Yasuhara, K. (1992). The geological environment and compression characteristics of quaternary deposits in the Shiroishi plain, Saga, Japan. Proc. 27th Japan National Conf. on SMFE: 77-78. (in Japanese)

Tohno, I. (1997). Present state of land subsidence in Saga Plain and monitoring of subsidence with new observation system at Ariake, Saga, Japan. Research Report from the National Institute for Environmental Studies, Japan. 135: 77-84. (in Japanese)

Yasuhara, K. (1995). Consolidation and settlement under cyclic loading. Proc. Intl. Symp. on Compression and Consolidation of Clayey Soils, Hiroshima: 979-1001.