Problems of subsidence and their mitigation in Saga Plain, Japan

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Abstract Saga Plain is a lowland affected by 6 m tides of the Ariake Sea. The plain is underlain by 15-40 m of soft, compressible and highly sensitive marine (Ariake) clay below which aquifers of water bearing strata exist. Land subsidence started about 35 years ago due to groundwater withdrawal. Subsidence of the order of 80 cm to 1 m has been observed. The rate of subsidence accelerated to 16 cm year$^{-1}$ due to an extremely hot summer and great demand for water in 1994. Medium and heavy structures built on piles bearing on dense gravel layers lead to large differential settlements between pile supported structure and the surrounding ground due to land subsidence. This paper summarizes the geotechnical characteristics of Saga Plain, and the variety of ground improvement techniques adapted to mitigate problems arising from subsidence.

INTRODUCTION

The Ariake Sea is located near the centre of Kyushu, the southern most main island of Japan. It is a large bay (Fig. 1) covering an area approximately 1700 km$^2$, with a central axis of length of about 98 km, of an average width of 18 km and a depth of 20 m. The characteristic feature of the Ariake Sea is the vast tidelands exposed at low tide. The Saga-Shiroishi Plain of today is formed either by natural action of alluvial rivers and tidal currents or by reclamation of land from the sea. The original coastline is believed to be approximately 20 km inland from the present one. Reclamation work in this area dates from 1185 AD (Watanabe, 1988). The different stages of reclamation are depicted in Fig. 1. Typhoons that strike the area during the post monsoon period (July-September) each year, have posed a serious threat to the dikes. Consequently, the design and construction of these dikes are modified from the conventional vertical wall type to a gently sloping embankment that can soften the impact of oncoming waves.

GEOLOGY

The Saga Plain is surrounded (Oshima, 1988) in the north by Mesozoic granites and a small amount of metamorphic rocks, in the east by Sangun metamorphic rocks, in the
the west by Palaeogenic sediments, diluvial volcanic rocks, diluvial terraces and alluvial fan, and in the east by the small hills of Kishimayama. The alluvial delta less than 4 m in altitude, is underlain by unconsolidated sediments.

The Saga lowland consists of an alluvial delta, with the limit of the tidal river stretching as far out as the root of the delta region. The south of Saga lowland is reclaimed land making the best use of top set of the delta in the tidal flat, by drainage. The succession of unconsolidated sediments are divided into A, B, C, D, E and F formations (Fig. 2). Formation A is Ariake clay deposited in alluvial transgression and regression and it consists mainly of soft silt and clay occasionally accompanied by sand. Formation B is a diluvial marine deposit, mainly composed of sand. C formation is a pumice-bearing volcanic ash formation formed about 33 000 years ago, from the pyroclastic flows from Mt Aso. Marine sands and silts constitute formations D, E and F (undivided diluvial beds). Formation F has compact silts and fossils of wood. All the formations are inclined from the land to the sea with inclination increasing downward, indicating compression of the basin in the early stages of deposition of the thick unconsolidated deposits.

GEOTECHNICAL PROPERTIES

The Ariake clay deposits vary in thickness from 15 to 42 m. Based on the fossil assemblages investigated, it is surmised that the clay layers in the top 10-11 m were deposited under marine environment while the lower layers were formed under brackish conditions (Ohtsubo et al., 1988). Smectite is the predominant mineral which exists along with vermiculite, illite and kaolinite, in the clays. The geotechnical and chemical properties from a typical site in Saga Plain is shown in Fig. 3. The liquid limit and the plasticity index vary in the ranges 60-125 and 25-80 respectively. The natural water content ranging between 80-140 is higher than the liquid limit. Liquidity index value could be high as 2.5. The sensitivity of the soil is less than 100 in the top 10 m but could be as high as 500 or more at depths below 10 m. Thus, the clays can be classified as quick or extra quick according to Rosenquist's (1953) classification and salt leaching is identified as the primary cause for the sensitivity of the clays (Fig. 4). The salt concentration in the pore water ranges between 0.05-1.08 g l⁻¹ for extra quick
clays and 1.02-10.4 g l⁻¹ for quick clays. The undrained strength of the clays could be as low as 5 kPa near the ground surface and increases with depth to a value of about 25 kPa at 15 m.

The compression index, \( C_c \), of Ariake clay ranges between 0.5 and 2.5, and the coefficient of consolidation from 3.5*10⁻¹ to 1.5*10⁵ cm² day⁻¹ (Sanaka, 1990). The values of \( S_u \), the undrained strength, \( q_c \), the cone penetration resistance, \( S_{uv} \), the field vane and \( q_u \), the unconfined compression strengths together with \( \sigma_y' \), the preconsolidation stress from standard oedometer test are presented in Fig. 5 from Hanzawa et al. (1990). The undrained strength of upper clay increases linearly with depth while that of lower clay increases more rapidly with depth. The preconsolidation stress, \( \sigma_y' \), agrees closely with the effective overburden stress, \( \sigma_{vo}' \), particularly for the upper clay indicating that it is in normally consolidated state. \( \sigma_y' \) values for the lower clay layer are some what greater than \( \sigma_{vo}' \) at its lower end. The variation of \( S_u \) with depth is consistent with that of \( \sigma_y' \) with depth.
SUBSIDENCE

When groundwater had been pumped out from the sand layer, the first aquifer, the sea water had intruded into it increasing the Cl ion content to a value above the permissible one. Subsequently, groundwater from the second and third diluvial layers is being utilized for domestic, agricultural and industrial purposes. The quality of groundwater from the third aquifer in Shiroishi area appears to be affected.

As a consequence of groundwater pumping, Saga Plain is subjected to subsidence due to induced consolidation of soft normally consolidated Ariake clay (Miura et al., 1988). Even though subsidence initiated from 1950s, precisely monitored values from the year 1971 for Saga and Shiroishi districts are shown in Fig. 6. The settlements

![Fig. 5 Undrained strength ($S_u$), yield stress ($\sigma_y'$) and sensitivity ($S_i$) from unconfined, field vane, oedometer and cone penetration tests (after Hanzawa et al., 1990).](image-url)
observed from 1971 to 1988, are of the order of 30 cm in Saga and 80 cm in Shiroishi. The movement of the ground level corresponds to that of the groundwater level with a small time lag, the rates being more during the summer months because of increased pumping rates. In periods of small rainfall, the subsidence rate per year has been as high as 10 cm in Saga and 13 cm in Shiroishi. Saga Plain has experienced in 1994 the severest summer for the last 50 years with the maximum temperature reaching a record level of 40.6°C. The movement of groundwater and ground levels from June to December 1994 are depicted in Fig. 7 and compared with those for the year 1978 which was the next most severe summer. In Shiroishi area, while the groundwater level fell by about 20 m, the subsidence has been nearly 18 cm in four months.

**DAMAGE DUE TO SUBSIDENCE**

Most of the structures in Saga Plain have been built on piles that are made to rest on the dense sand/gravel layers below the soft clay. However, because of subsidence,
serious differential settlement appears between the pile supported structures and the surrounding ground. A typical example is a box culvert and the approach roads on both sides of the culvert, the different settlements in this case reached 80 cm because of an overlay of asphalt concrete which was added occasionally to reduce the differential settlement. The piles are also subjected to down drag.

FLEXIBLE AND COMPATIBLE FOUNDATIONS

The basic principle of the flexible foundation system is that the structure deforms in conformity with the differential settlement of the ground, which is reinforced by floating foundations (Miura & Madhav, 1993). Two foundation types, viz. timber pile-grid system (Type A) and improved soil column-grid system (Type B), are adopted. Type A foundation system (Fig. 8) uses timber piles as skin resistance piles with a geogrid reinforced granular pad on top to serve as a pile cap and to restrain lateral displacements. Camber provided minimizes excess differential settlements.

In Type B foundation system, improved soil-lime columns of 1 m diameter are made by the Dry Jet Mixing (DJM) method (Fig. 9), a mechanical method of mixing quicklime with clay in situ. The area of the soil-lime columns is 30% of the total area of the ground. A reinforced granular base course with a single layer of polymer grid and with camber is provided as in the Type A system.

To make the structure (sluice way in this case) flexible, its body is separated into several blocks which are connected by flexible/multilayer rubber joints. Figure 10

![Fig. 8 Floating timber pile-reinforced granular fill system.](image1)

![Fig. 9 DJM column-reinforced granular fill system.](image2)
confirms that the settlements of the structure and the ground are compatible and consistent.

**CONCLUSIONS**

The lowlands reclaimed from the tidal range of Ariake Sea, Japan, are subjected to subsidence due to groundwater withdrawal. The Ariake clay whose thickness varies from 15 to 40 m is very soft, highly compressible and extremely sensitive due to leaching of salts from the pore water. Subsidence of the order of 80-100 cm causes large differential settlements especially adjacent to structures built on end bearing piles. A new flexible and compatible foundation system consisting of timber piles or DJM columns and polymer grid reinforced granular fill, are shown to function extremely well.

**REFERENCES**


