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Engineering characteristics of Ariake Clay (soft Quaternary deposits) from Saga Plain, Japan

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ABSTRACT

The Saga Plain of Kyushu, Japan, is surrounded by mountains and the inland Ariake Sea. It consists of lowland soft deposits of Quaternary age around the big inland Ariake Sea. The Ariake Clay shows great variation in material thickness, sensitivity, and softness. The top clayey soil is generally 10 to 20 m thick. Clay minerals are represented by montmorillonite, illite, hydro halloysite and metahalloysite with a lot of diatom remains. Natural disasters such as landslides, subsidence, liquefaction, and flooding are frequent due to its inherent weak engineering properties. These characteristics are linked with many engineering problems for further infrastructure development. In the paper, quantitative correlations from a vast soil test database are briefly presented for each geographical location.

INTRODUCTION

Many human and industrial civilisations are founded on the Quaternary plain in Japan due to the Japanese evolution of industry. The activity based on agriculture and textile industries changed to one based on ship building, automobile, and petrochemical industries about 50 years ago.

These new industries needed conveyances for material and products, industrial water, and a flat vast site. These demands dictated the use of Quaternary plains for industrial companies from the mountainous island in Japan. Differential settlement, low bearing capacity, land subsidence, slope instability, liquefaction, and high tidal wave were recognised in most of the industrial cities that are founded on soft soil of the Quaternary deposits. Appreciation of these problems requires an understanding of the geological history of the lowland. The lowland plain around the Ariake Sea is the typical case of these problems. Low bearing capacity, dense settlement, salt water intrusion, groundwater, subsidence, rise in sea level, and even tidal wave attacks are a few examples. To solve these problems for engineering applications, one must understand the basic geological characteristics of such Quaternary soft deposits in a lowland environment. The paper intends to enlighten these engineering geological aspects in order to benefit planners, engineers, and developers.

ARIAKE SEA

The Ariake Sea is a typical inland sea located on the northern part of Kyushu. Big mass of Mesozoic granite occupies the north side, and schist is detected at several points of deep underground around the Ariake Sea. Tertiary sediments and Tertiary-Quaternary volcanic rocks occur at the eastern and western sides of the Ariake Sea. This inland sea is connected to the Pacific Ocean at its southern end. The maximum tidal range of this sea reaches to 6 m under favourable topographical basin shape and astronomical cycle.

GEOLOGY

The Saga Plain (Fig. 1) is surrounded by mountains from three sides, and the inland Ariake Sea lies to the south of it. The Chikugo, Kase, and Rokkoku Rivers flow through the Saga Plain into the Ariake Sea. Alluvial processes of the Jyomon marine transgression formed the plain about 10,000 years ago.

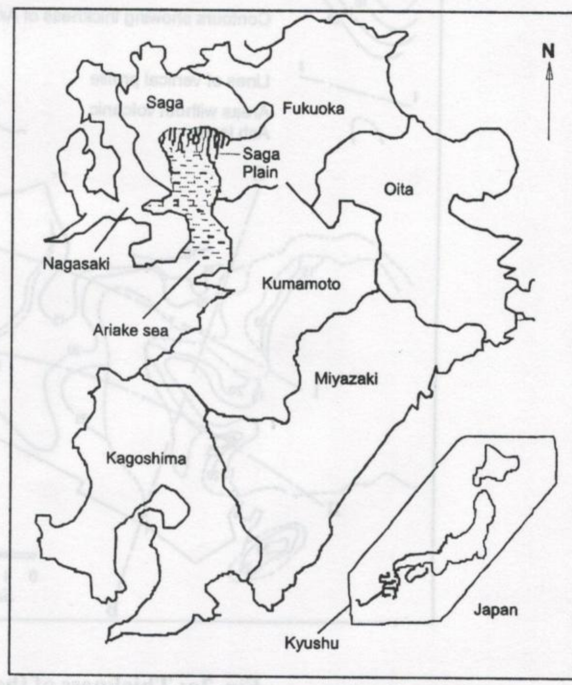

Fig. 1: Location map of the Saga Plain

Palaeogene sediments have accumulated on the schist and granite basement of this Japanese island. Two ENE trending faults named the Ohmati Fault and Yanagawa Fault appeared at this stage. The sandwiched block bounded by two faults started to sink gradually. At the same time, Palaeogene to Neogene sediments were deposited in the depression. At that time, andesitic volcanic deposits covered the island of Kyushu in several areas. The Tara and Unzen volcanic centres separated the west side of the Ariake Sea from the open sea at this stage. Finally, the whole area of Kyushu was covered by old Mt. Aso and Aira volcanic deposits. These deposits contained pyroclastic flow and welded tuff, and they also covered the Ariake Sea, which was a big valley (named the Ariake Valley) during the Würm glacial epoch. Many streams on the side of the Ariake Valley washed away the valley bottom and transported much of the pyroclastic material to the Ariake Sea from the hinterland. The pyroclastic material was transformed to smectite in the Ariake Sea giving rise to thick beds of the Ariake Clay (Fig. 2a).

A similar process was recorded at every plain around the Ariake Sea with varying scales and dimensions. The plains around the Ariake Sea, especially the Saga Plain, is characterised by the thick sediments that reach to 1,000 m. The cross-section of the upper part of the Saga Plain is shown in Fig. 2b. The flood plain deposits resulted from the Chikugo River produced sandy lenses. The western part is composed of uniform clay beds. The distribution of the washed out area indicates the presence of a river in Würm glacial epoch.

SOIL CHARACTERISTICS

The very fragile and soft Ariake Clay was deposited around the shore of the Ariake Sea. A typical vertical profile of it is shown in Fig. 3, and the geotechnical properties of it are summarised in Table 1. The top clayey soil is generally

Table 1: Properties of the Ariake clayey soil

Soil properties	Value
Physical characteristics	
Specific gravity, Gs (g/cm^3)	2.26–2.82
Clay content, (%)	10–81.5
Void ratio, e	0.4–4.53
Liquid limit, LL (%)	32–150
Plasticity Index, PI (%)	7–95
Liquidity Index, LI (%)	0.04–4.64
Natural water content, W_n (%)	12–173
Total unit weight, γ, (g/cm^3)	1.2–2.11
Mechanical characteristics	
Unconf. Comp. Strength, q_u (kg/cm^2)	0.04–1.98
Compression index, C_c	0.19–2.81
Pre-Consolidation press, P_c (kg/cm^2)	0.12–2
Standard Penetration value, N	0–5
Sensitivity, S	> 8–16

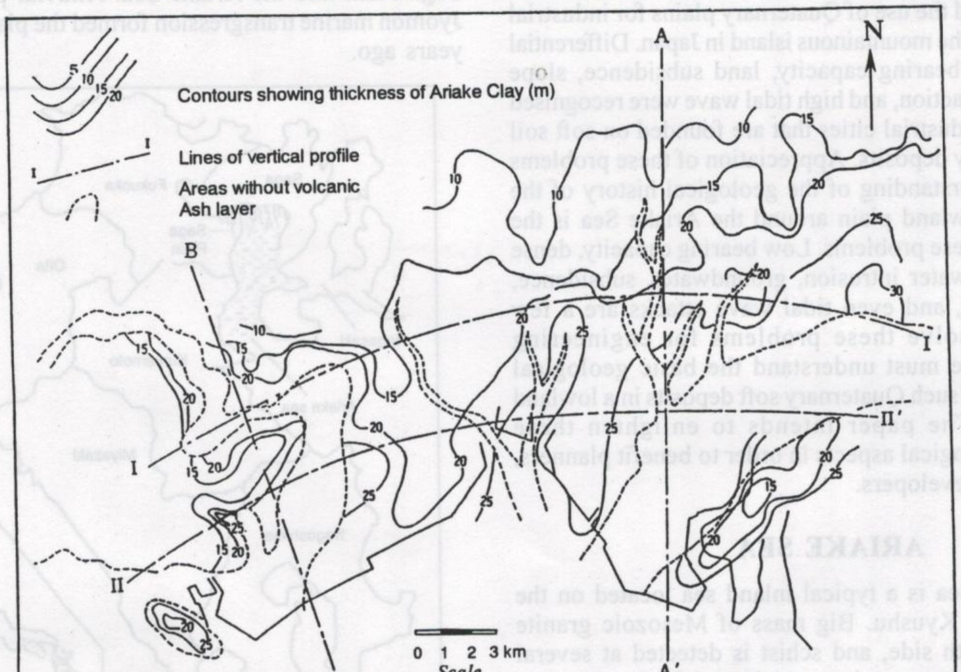

Fig. 2a: Thickness of the Ariake Clay in the Saga Plain

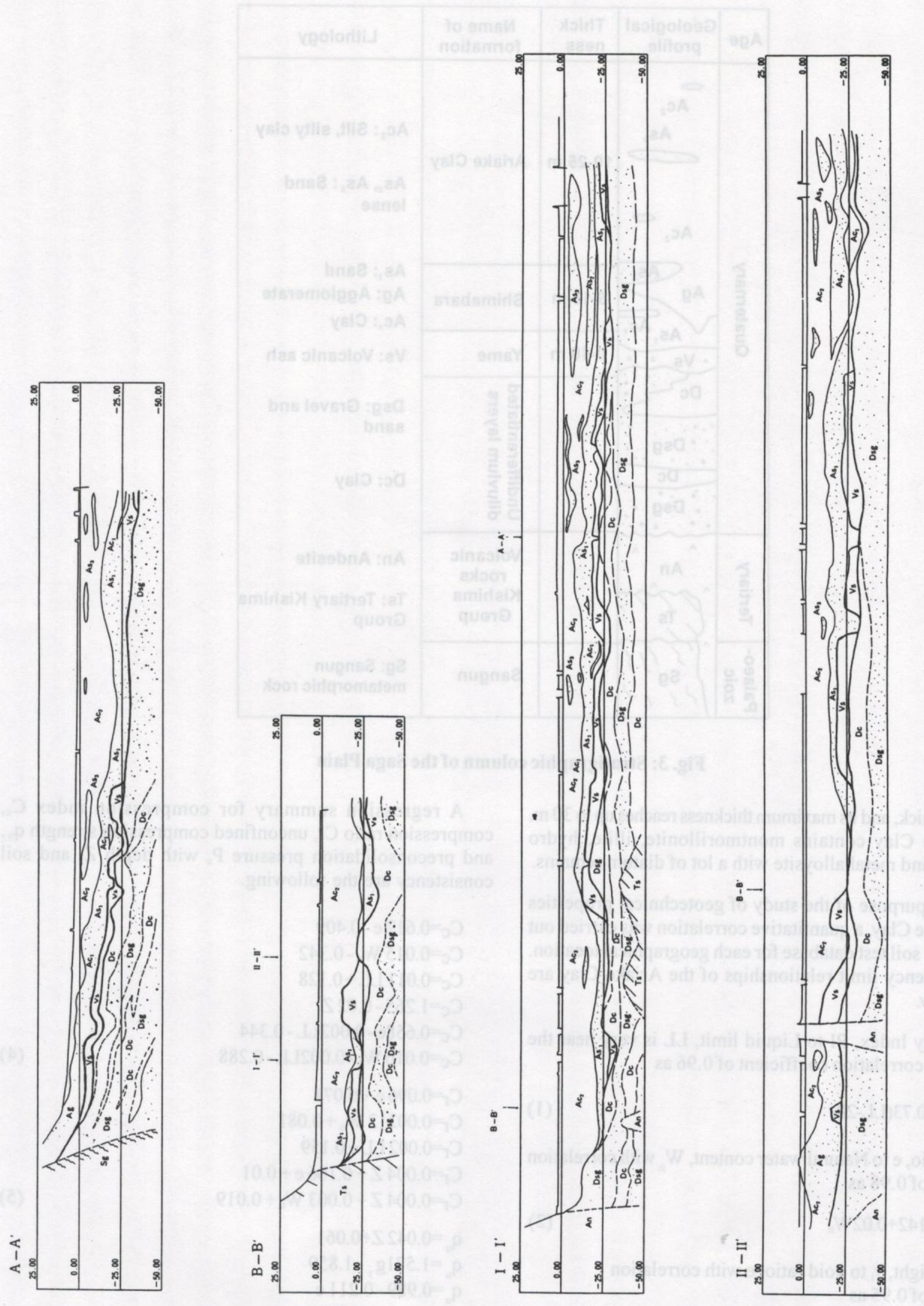

Fig. 2 b: Geological cross-sections along the Saga Plain –as indicated in Fig. 2a (After Iwao and Kouichi 1986): Ac_2: silt and silty clay, As_2, As_3: sand lenses, As_1: sand, Ag: agglomerate, Ac_1: clay, Vs: volcanic ash, Dsg: gravel and sand, Dc: clay, An: andesite, Ts: volcanic rocks of the Kishima Group, and Sg: Sangun Metamorphic Rock.

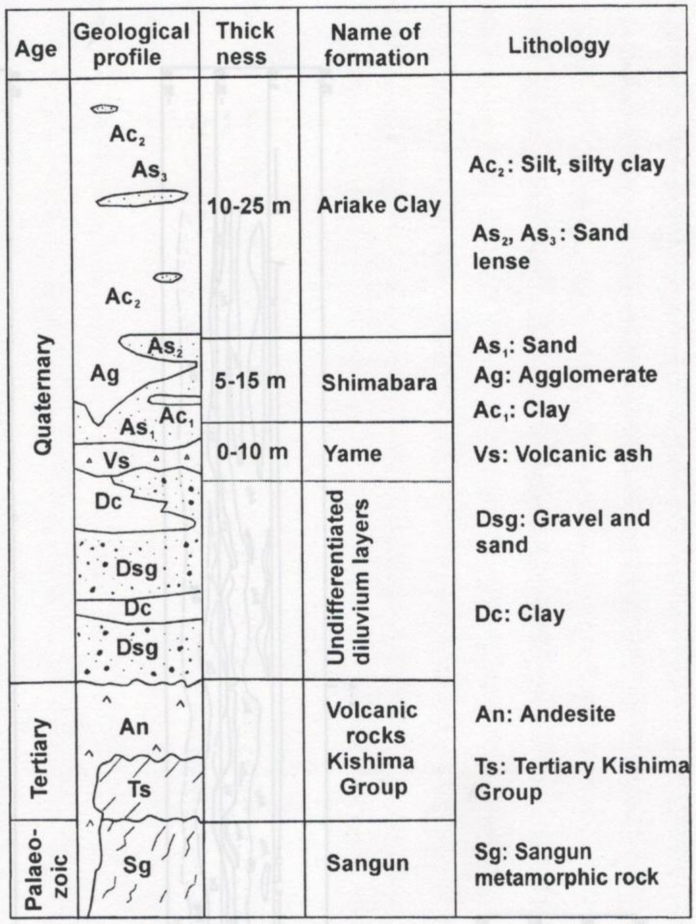

Fig. 3: Stratigraphic column of the Saga Plain

10 to 20 m thick, and its maximum thickness reaches up to 30 m. The Ariake Clay contains montmorillonite, illite, hydro halloysite, and metahalloysite with a lot of diatom remains.

For the purpose of the study of geotechnical properties of the Ariake Clay, a quantitative correlation was carried out from a large soil test database for each geographical location. The consistency limit relationships of the Ariake Clay are given below.

Plasticity Index, PI to Liquid limit, LL is very near the A-line with correlation coefficient of 0.96 as

$$PI = 0.73(LL-20) \tag{1}$$

Void ratio, e to Natural water content, W_n with correlation coefficient of 0.98 as

$$e=0.142+0.02W_n \tag{2}$$

Unit weight, γ_t to void ratio, e with correlation coefficient of 0.95 as

$$\gamma_t=1.788-0.814 \log e \tag{3}$$

A regression summary for compression index C_c, compression ratio Cr, unconfined compression strength q_u, and preconsolidation pressure P_c with depth Z, and soil consistency are the following.

$$
\begin{aligned}
C_c&=0.612\,e-0.409\\
C_c&=0.015\,W_n-0.342\\
C_c&=0.011\,LL+0.128\\
C_c&=1.265-0.02\,Z\\
C_c&=0.658e-0.002LL-0.344\\
C_c&=0.016\,W_n-0.002LL-0.288
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
C_r&=0.096\,e+0.071\\
C_r&=0.00212\,W_n+0.081\\
C_r&=0.002\,LL+0.159\\
C_r&=0.004\,Z+0.106\,e+0.01\\
C_r&=0.004\,Z+0.003\,W_n+0.019
\end{aligned} \tag{5}
$$

$$
\begin{aligned}
q_u&=0.042\,Z+0.061\\
q_u&=1.571g_t-1.859\\
q_u&=0.989-0.211\,e\\
q_u&=0.992-0.006\,W_n\\
q_u&=1.221g_t-0.056\,e-1.201
\end{aligned}
$$

$$q_u = 0.036\,Z + 0.526\,g_t - 0.653$$
$$q_u = 0.037\,Z - 0.002\,W_n + 0.27$$
$$q_u = 0.037\,Z + 0.674\,g_t + 0.025e - 0.936$$
$$q_u = 0.036\,Z + 0.631\,g_t + 0.086e - 0.002\,W_n - 0.85$$
$$q_u = 0.999 - 0.061e - 0.004\,W_n$$
$$q_u = 0.989 - 0.211e \quad (6)$$

$$P_c = 0.068Z + 0.117$$
$$P_c = 1.398 - 0.282\,e$$
$$P_c = 1.368 - 0.007\,W_n$$
$$P_c = 0.023\,Z + 0.0835\,q_u + 0.127$$
$$P_c = 0.063\,Z - 0.07\,e + 0.338$$
$$P_c = 0.064\,Z - 0.001\,W_n + 0.3$$
$$P_c = 1.134\,q_u - 0.068\,e + 0.363$$
$$P_c = 1.139\,q_u - 0.002\,W_n + 0.337$$
$$P_c = 1.399 - 0.003\,W_n - 0.174\,e$$
$$P_c = 0.02\,Z + 0.84\,q_u - 0.047e + 0.272$$
$$P_c = 0.02\,Z + 0.839\,q_u - 0.001\,W_n + 0.243$$
$$P_c = 1.137\,q_u + 0.001\,W_n - 0.104e + 0.36$$
$$P_c = 1.195\,q_u - 1.859 \quad (7)$$

ENGINEERING PROBLEMS

The engineering problems related to the Ariake Clay are quite diverse in nature. A short description of the important ones is given below.

Settlement and subsidence

The first evidence of land subsidence was recorded as a fissure in the rice field near the mountain foot. The subsidence was related to the over exploitation of the shallow aquifers by tube wells. These plains and reclaimed areas are apt to lack the surface water. Many farmers rushed to dig the wells. Industrial and agricultural water supply demanded to pump up more and more good-quality groundwater. The seasonal subsidence was found to be related to the intensity of pumping. For the protection of subsidence, restrictions were imposed on pumping of shallow groundwater from the Upper Pleistocene and Recent aquifers. However, pumping of deeper groundwater was permitted. But it caused further subsidence of the Neogene to Pleistocene aquifers. As a result, the embankment constructed for the protection of the area from high tides of the Ariake Sea hat to be raised (Khamehchiyan and Iwao 1994).

Slope stability and deformation

The Ariake Clay is very soft like a jelly or soft cream. It contains a lot of water and the following problems are often encountered.

1) Unequal loading causes uneven deformation. Embankment and filled ground deform into concave shapes. Strong bending resistance is necessary for the continuous footing of housing, because the traditional Japanese wooden houses are usually weak in bending. The deformation of ground can cause cracking of concrete in some cases.
2) Circular slip failure may occur during excavation or construction of embankment in some cases. This sliding may even break foundation piles.
3) Low bearing capacity and shear failure may occur locally.

Rise of sea level near lowland

The global warming and subsequent sea level rise are serious environmental problems in lowlands. From the history of the Quaternary Period, development of ice caps, melting, and global warming have greatly influenced the formation and stability of the lowland deposits. The fall and rise in sea level from glacial epoch to the present time have created a typical marine sediment environment. The marine sediments of clay and organic peat are very soft soils. Combined with groundwater and subsidence, the problem of sea water intrusion cannot be neglected. Salt content in clay greatly affects its sensitivity, softness, and other engineering properties.

Flooding and drainage

Land subsidence, flooding, and landslides triggered by rainfall are related topics to global warming and sea level rise in the case of island plains nearer the inland sea. The danger of flooding and problems of drainage increase in such locations. Flash floods and poor drainage in downstream plains may be hazardous invitations to many unwanted disasters. Beside slope instability problem in the hills, other problems such as slump failure, bank erosion, and dyke failure may happen at different locations downstream.

Tsunami or tidal waves

An inland Ariake Sea with small mouth can result in big tidal fluctuations with special dynamic currents called tsunamis. Banks and dykes in the lowlands will be subjected to dynamic wave attacks with higher potential when the sea level will rise higher. The depositional tidal flats like the Saga Plain will be subjected to significant tidal wave attacks. Depending upon the tide level, the area may fall into supratidal, intertidal, and subtidal zones. Geological processes of erosion, deposition, wave attack, sediment transportation, and sea water intrusion will pose serious problems.

DISCUSSION AND CONCLUSIONS

Engineering geological characteristics of the Ariake Clay were analysed on a database with respect to horizontal expanse, thickness, hinterland geology, and fundamental mass movement processes. The geology of hinterland was characterised by pyroclastic flows from the Old Aso Volcano in Pleistocene time. The transgression and regression affected the soft sediments.

The Ariake unconsolidated clay is very thick, soft, and sensitive. Engineering problems such as low bearing capacity and high rates of settlement are predictable from the low values of SPT, very low value of N (i.e., near to 0), average unconfined compressive strength q_u<1 kg/cm^2, and high water content (in general, higher than the liquid limit). These characteristics are linked with many problems in engineering construction, such as excessive settlement, low bearing capacity, land subsidence, slope instability, slump, liquefaction, salt water intrusion, flooding and drainage, rise in sea level, and tidal wave attacks.

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