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GEOTECHNICAL PROPERTIES OF ARIAKE CLAY IN SAGA PLAIN-JAPAN

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This paper describes the geotechnical properties of Ariake clay found in Saga plain, a lowland in north of Ariake sea in Kyushu, Japan. It is attempted to discuss the geotechnical properties of Ariake clay up to the depth of 20 meters by using the data of 110 exploratory boreholes drilled in different places of Saga plain. Simple regression equations are developed for some index properties and multiple regression equations are developed to estimate unconfined compression strength, compression index, compression ratio, and preconsolidation pressure from index properties. The efficiency of equations are discussed statistically by using the analysis of variances.
Key Words : *Ariake clay, geotechnical properties, regression analysis*

1. INTRODUCTION

Saga plain, a lowland of less than 5 meters above mean sea level with an area of about 400 square kilometers, lies in north of Ariake sea (western area of Chikugo rive) in Kyushu, Japan (**Fig.1**). The tidal range of the Ariake sea is about 6 meters with a mean high water level of 2.89 meters. Therefore, several dikes are constructed to prevent flooding during heavy rainfalls. The tidal flat of Ariake sea, even now, develops 5-6 centimeters per year in thickness. Reclamation in the Saga plain has rapidly developed in past years by stepwise construction of dikes.

The soft Ariake clay is a very sensitive clay (Onitsuka, 1983)[1] deposited around the shore of the Ariake sea in northern Kyushu, Japan. The top soil of the Saga plain is also of this type. Its thickness is generally about 10 to 20 meters with a maximum value of 30 meters, a well known formation in Japan in which geotechnical properties have been studied by many authors (Onitsuka, 1983, 1988, Nakamura et al., 1985, Ohtsubo et al., 1988, Miura et al., 1988, koumoto, 1988) [1)~6)]. High sensitivity, low bearing capacity, and land subsidence due to the pumpage of ground water are some of the reasons that Ariake clay has become one of the most problematic soils in Japan.

This study used geotechnical properties of Ariake clay, from 110 boreholes in different places of the Saga plain, and geological considerations to present a general picture of Ariake clay up to the depth of 20 meters. Simple regression analysis is adopted between physical properties such as void ratio, e, natural water content, W_n, total unit weight, γ_t, and consistency limits. Various regression models are developed to estimate unconfined compressive strength, q_u, compression index, C_c, compression ratio, C_r, which is equal to $C_c/(1+e)$) and preconsolidation pressure, P_c, from more easily determinable soil index properties. The analysis of variance (F test) is used to determine the significance of fitness of equations.

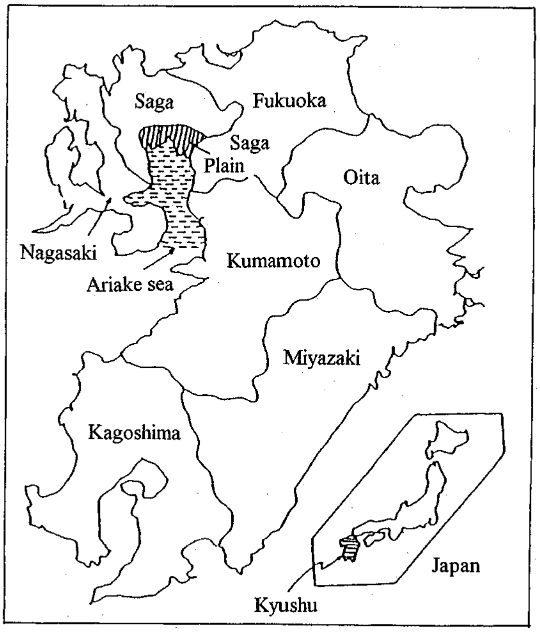

Fig.1 Location map of Saga plain

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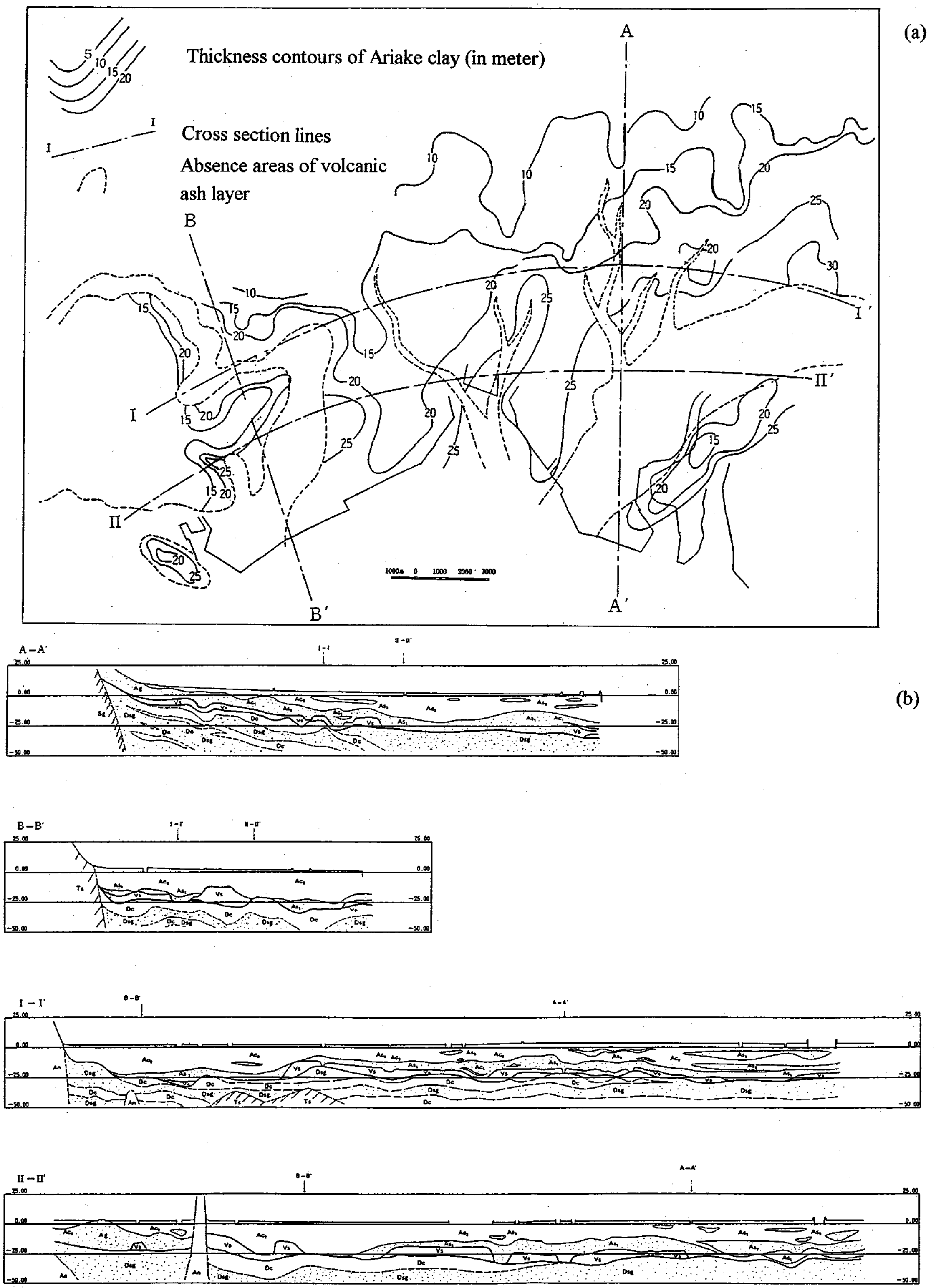

Fig.2 (*a*) Distribution of Ariake clay and volcanic ash layer in Saga plain, (*b*) Geological cross sections (after Iwao & Kouichi, 1985)[7]

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2. GEOLOGICAL CONDITIONS

Saga plain is geologically surrounded by Seburi mountain (Mesozoic granite and Sangun metamorphic rock and serpentinite) in the north, Minou and Chikuhi mountain (Sangun metamorphic rocks) in the east, Oninhanayama, Kishimayama and Taradake mountain (Paleocene sediments and Neogene to diluvial volcanic rocks) in the west, and finally Ariake sea in the south.

The Chikugo, Kase and Rokkoku are the main rivers that flow through the Saga plain and enter into the Ariake sea. The Kase river flows from the granite area with a large amount of drifting sand, and the bed of the river, in some places, is higher than the surrounding area.

There are thick unconsolidated sediments under Saga plain, which is divided into *A*, *B*, *C*, *D*, *E* and *F* formations (**Fig.2b**). The lower part of this unconsolidated sediments are undifferentiated diluvial *D*, *E*, ,and F formations, consisting of marine sand and silt, which were deposited in Plio-Plioctocene (**Fig.3**, step 1). The *C* formation overlaid diluvial layers and is a tuff bearing volcanic ash. This formation, the well known key bed in this area, has resulted from the activity of Aso volcano in upper Pliestocene. The sea level, at the *C* formation deposition period, was more than 100 meters lower than present level (**Fig.3**, step 2). After the *C* formation deposition, *B* and *A* formations were deposited in the Ariake sea when the sea level was about 6 meters higher than the present level (**Fig.3**, step 3). *B* formation (Shimabara bay formation) mainly composed of sand. *A* formation (Ariake clay) is the upper part of unconsolidated sediments, deposited in alluvial transgression and regression, and is mainly composed of very soft silt and clay with variable thickness (**Fig.2a**). River erosion, between steps 2 and 3 (**Fig.3**), caused the absence of the *C* formation in some areas in the Saga plain (**Fig.2a**).

3. GEOTECHNICAL PROPERTIES AND RELATIONS

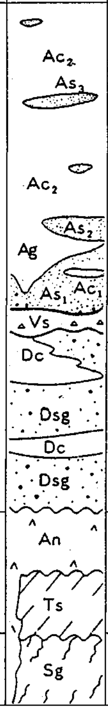
(1) Physical Properties

Clay minerals in Ariake clay, are montmorillonite, illite, hydro halloysite and metahalloysite (Onitsuka et al., 1976)[8]. The clay also contains a lot of diatom remains. Physical properties of Ariake clay up to depth of 20 meters are presented in **Table 1**.

Consistency limits of Ariake clay are shown in **Fig.4**. The Relation between plasticity index, *PI*, and liquid limit, *LL*, is as follow with high correlation coefficient of 0.96 :

$$PI = 0.73(LL - 22) \cdots\cdots (1)$$

L E G E N D



Age	Geol. Profile	Thickness	Formation Name	Remarks
Quaternary		10 ~ 25m	(A) Ariake clay	Ac_2: Silt, silty clay As_2, As_3: Sand lense
		5~ 15m	(B) Shimabara	As_1: Sand Ag: Agglomerate Ac_1: Clay
		0~10m	Yame (C)	Vs: Volcanic ash
			(D, E, F) Undiffrentiated diluvium layers	Dsg: Gravel and sand Dc: Clay
Tertiary			Volcanic rocks Kishima group	An: Andesite Ts: Tertiary kishima group
Paleozoic			Sangun	Sg: Sangun metamorphic rock

Fig.2 b Continue

that is very near to *A* line ($PI = 0.73(LL - 20)$).

Relations 2, 3 and 4 are founding relations between physical properties of Ariake clay accompanied with the correlation coefficients, *R*. These are shown in Figures 5, 6 and 7.

$$e = 0.142 + 0.02 W_n \qquad R = 0.98 \cdots (2)$$

$$\gamma_t = 1.788 - 0.814 \log e \qquad R = 0.95 \cdots (3)$$

$$\gamma_t = 3.05 - 0.797 \log W_n \qquad R = 0.96 \cdots (4)$$

These relations can be used rapidly for determining void ratio, *e*, and total unit weight, γ_t, of Ariake clay in the initial stage of soil investigations.

(2) Mechanical Properties

The mechanical properties of Ariake clay are presented in **Table 1**. The sensitivity of Ariake clay is mostly above 16, and it is indeed a very sensitive clay that may well be comparable with the quick clay in northern Europe (Nakamura et al., 1985)[3]. The sensitivity increases with the decrease in salt content of soil (Onitsuka, 1988)[2].

Multiple regression analysis was adopted to obtain the relations between mechanical and physical properties of Ariake clay, by assuming the mechanical properties as dependent variables and physical properties as independent variables. In multiple regression problems, we are usually

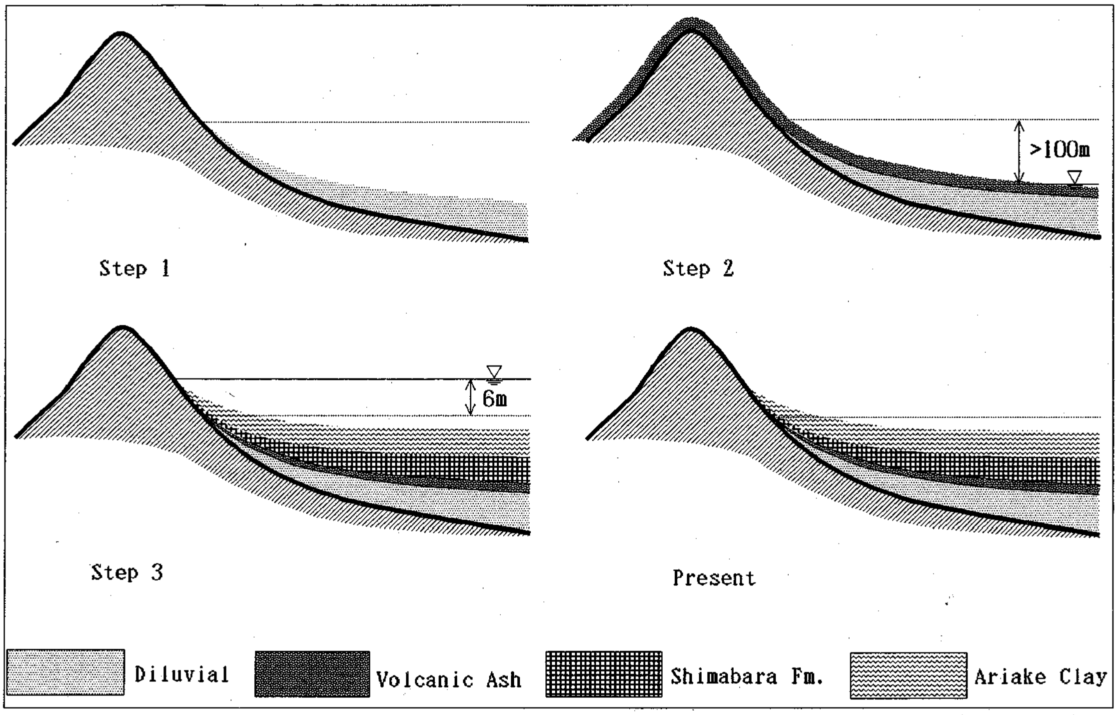


Fig.3 Sedimntation histrory of Quaternary unconsolidated deposits in saga plain

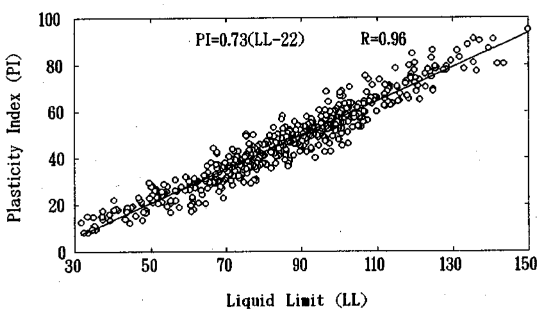


Fig.4 Consistency limits of Ariake clay

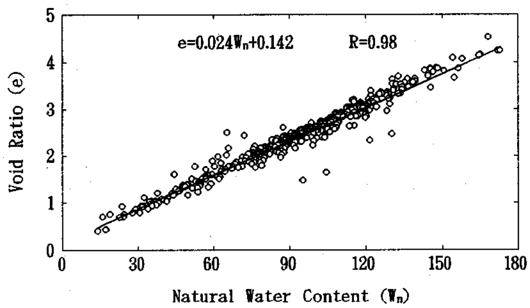


Fig.5 Void ratio (e) in relation to natural water content (W_n)

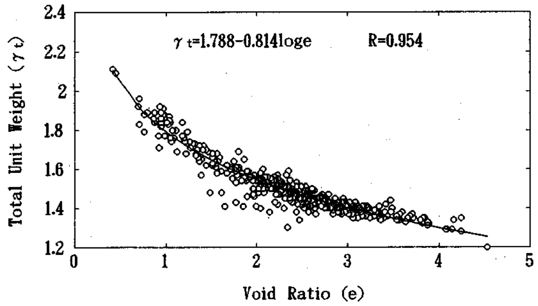


Fig.6 Total unit weight (γ_t) in relation to void ratio (e)

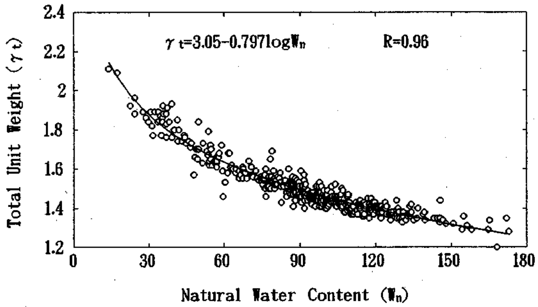


Fig.7 Total unit weight (γ_t) in relation to natural water content (γ_t)

interested in relative effectiveness of independent variables as predictors of the dependent variable (Davis, 1973)[9]. Independent variables are determined by examining the magnitude of the contribution of independent variables to dependent variable during the analysis. The magnitude of this contribution can be determined by F test. To determine the very best possible regression (in the sense of having the most significant F ratio) all possible combinations of the variables would have to be examined (Davis, 1973)[9].

Table 2 presents a summary of developed regression equations between unconfined compressive strength, q_u, compression index, C_c, Compression ratio, C_r, and preconsolidation pressure, P_c, with some soil index properties such as void ratio, e, natural water content, W_n, Liquid limit, LL, total unit weigth, γ_t, and depth. The independent variables in the regression equations are chosen on the basis of their correlation coefficients with the dependent variables.

a) Consolidation Parameters

The cost of consolidation test is high in comparison with those of many other common soil tests, and it is also time consuming. Therefore, many efforts have been made to estimate consolidation parameters from the more easily determinable soil properties. In the case of Ariake clay, several researchers have examined the possibility of predicting the compression index of Ariake clay from a knowledge of other soil properties, such as void ratio, e, natural water content, W_n, and liquid limit, LL (JSSMFE, 1959, Uchida & Mutsumoto, 1959, Yamaguchi et al., 1964, Kabeshima & Uta, 1969, Onituka & Yoshitake, 1985) [10)~14)]. **Table 3** presents a summary of published regression equations for prediction of compression index, C_c, of Ariake clay.

Various developed regression equations for determining the relation between compression index, C_c, and compression ratio, C_r, with void ratio, e, natural water content, W_n, Liquid limit, LL, depth, DEP, and the relation of preconsolidation pressure, P_c, with void ratio, natural water content, unconfined compressive strength, and depth are presented in **Table 2** and shown in **Figs. 8, 9, 10, 11.**

b) Unconfined Compressive Strength

Some hold the opinion that if water is present, an effective confining pressure exists, internally, in an unconfined compression test sample due to capillary effects and that these effects may effectively confine the sample just as if it were in situ. If this be correct, then it is also true that degree of saturation, grain size, stress cracks or fissuring and laboratory humidity would be very important considerations (Bowles, 1979)[15]. With this consideration, relation of unconfined compressive strength, q_u, with natural water content, W_n, total unit weight, γ_t, void ratio, e, and depth **(Fig.12)** have been studied and presented in **Table 2**. More than 90 percent of grain particles of test samples are finer than sieve No.200.

Table 1 Geotechnical Properties of Ariake clay

Soil properties	Value
Physical properties	
Specific gravity, Gs	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, I_L	0.04-4.64
Natural water content, W_n	12-173
Total unit weight, γ_t(gr/cm^3)	1.2-2.11
Mechanical properties	
Unconfined compression strength, q_u(kg/cm^2)	0.04-1.98
Compression index, Cc	0.19-2.81
Pre-consolidation pressure, Pc(kg/cm2)	0.12-2
Standard penetration value, N	0-5
sensitivity, St	>8, >16(most of Ariake clay)[3)]

4. DISCUSSION

Regression equations in **Table 2** are the result of different combinations of selected independent variables for estimating dependent variables without considering the relations between independent variables. The F test is used for each of the equations presented in **Table 2**. As a result some equations are not statistically accepted. Sample equations for each of the independent variables are illustrated in **Table 4**. For example, in equations that deal with all of selected independent variables (specified by + in **Table 2**), natural water content, W_n, must be omitted from these equations (and also void ratio, e, only from equation for unconfined compressive strength, q_u). The criterion for omitting the above mentioned parameters from equations is because their F values are smaller than the corresponding F values for 5% level of significance. The specified equations by * in **Table 2** are statistically accepted by the applied analysis of variance.

By considering of the statistically accepted equations in **Table 2**, it can be seen that simple regression models are enough for estimating unconfined compressive strength, q_u, compression index, C_c, compression ratio, C_r, and preconsolidation pressure, P_c. Although the coefficients of

Table 2 Summary of developed regrssion equation for compression index, C_c compression ratio, C_r, unconfined compression strenghth, q_u and preconsolidation pressure, P_c

Dependent Variable	Independent Variable(s)	Regression Equation	R	F Value	St. F Value*	No. of Data
	e	$Cc=0.612e-0.409$ (*)	0.858	644.2	3.842	232
	W_n	$Cc=0.015W_n-0.342$ (*)	0.833	522.6	3.842	232
	LL	$Cc=0.011LL+0.128$ (*)	0.506	79.3	3.842	232
	DEP	$Cc=1.265-0.02DEP$ (*)	0.194	8.9	3.842	232
	e, LL	$Cc=0.658e-0.002LL-0.334$ (*)	0.862	330.1	2.996	232
Cc	W_n, LL	$Cc=0.016W_n-0.002LL-0.288$ (*)	0.835	263.6	2.996	232
	DEP, e	$Cc=0.013DEP+0.64e-0.585$ (*)	0.866	342.1	2.996	232
	DEP, W_n	$Cc=0.013DEP+0.016W_n-0.522$	0.841	276.3	2.996	232
	e, W_n, LL	$Cc=0.639e-0.001W_n-0.002LL-0.344$	0.862	219.1	2.605	232
	DEP, LL, e	$Cc=0.011DEP-0.002LL+0.673e-0.512$	0.867	230.7	2.605	232
	DEP, W_n, e	$Cc=0.013DEP-0.001W_n+0.613e-0.587$	0.866	227.2	2.605	232
	DEP, LL, W_n, e	$Cc=0.011DEP-0.002LL-0.001W_n+0.631e-0.514$ (+)	0.867	172.5	2.372	232
	e	$Cr=0.096e+0.071$ (*)	0.691	210.6	3.842	232
	W_n	$Cr=0.002W_n+0.081$ (*)	0.671	190.1	3.842	232
Cr	LL	$Cr=0.002LL+0.159$ (*)	0.399	43.5	3.842	232
	DEP, e	$Cr=0.004DEP+0.106e+0.01$ (*)	0.719	122.4	2.996	232
	DEP, W_n	$Cr=0.004DEP+0.003W_n+0.019$ (*)	0.702	111.0	2.996	232
	DEP	$q_u=0.042DEP+0.061$ (*)	0.854	566.7	3.842	213
	γ_t	$q_u=1.571\gamma_t-1.859$ (*)	0.618	130.3	3.842	213
	W_n	$q_u=0.992-0.006W_n$ (*)	0.590	114.4	3.842	213
	e	$q_u=0.989-0.211e$ (*)	0.584	109.4	3.842	213
	DEP, γ_t	$q_u=0.036DEP+0.526\gamma_t-0.653$ (*)	0.871	329.4	2.996	213
q_u	DEP, W_n	$q_u=0.037DEP-0.002W_n+0.27$ (*)	0.866	314.2	2.996	213
	γ_t, e	$q_u=1.221\gamma_t-0.056e-1.201$	0.622	66.1	2.996	213
	e, W_n	$q_u=0.999-0.061e-0.004W_n$	0.595	57.422	2.996	213
	DEP, γ_t, e	$q_u=0.037DEP+0.674\gamma_t+0.025e-0.936$	0.871	219.6	2.605	213
	DEP, γ_t, e, W_n	$q_u=0.036DEP+0.631\gamma_t+0.086e-0.002W_n-0.850$ (+)	0.873	166.1	2.372	213
	DEP	$Pc=0.068DEP+0.117$ (*)	0.863	491.9	3.841	171
	q_u	$Pc=1.195q_u+0.159$ (*)	0.871	448.3	3.841	145
	e	$Pc=1.398-0.282e$ (*)	0.504	57.3	3.841	171
	W_n	$Pc=1.368-0.007W_n$ (*)	0.499	56.1	3.841	171
	DEP, q_u	$Pc=0.023DEP+0.835q_u+0.127$ (*)	0.889	268.8	2.996	145
	DEP, e	$Pc=0.063DEP-0.07e+0.338$ (*)	0.870	261.1	2.996	171
	DEP, W_n	$Pc=0.064DEP-0.001W_n+0.3$ (*)	0.868	256.1	2.996	171
Pc	q_u, e	$Pc=1.134q_u-0.068e+0.363$ (*)	0.881	245.3	2.996	145
	q_u, W_n	$Pc=1.139q_u-0.002W_n+0.337$ (*)	0.879	240.5	2.996	145
	e, W_n	$Pc=1.399-0.003W_n-0.174e$	0.506	29.0	2.996	171
	DEP, q_u, e	$Pc=0.02DEP+0.84q_u-0.047e+0.272$ (*)	0.894	186.5	2.605	145
	DEP, q_u, W_n	$Pc=0.839q_u+0.02DEP-0.001W_n+0.243$ (*)	0.892	183.6	2.605	145
	DEP, W_n, e	$Pc=0.064DEP+0.002W_n-0.148e+0.328$ (+)	0.871	174.5	2.605	171
	q_u, W_n, e	$Pc=1.137q_u+0.001W_n-0.104e+0.36$ (*)	0.881	162.9	2.605	145
	DEP, q_u, W_n, e	$Pc=0.839q_u+0.02DEP+0.001W_n-0.1e+0.266$ (+)	0.894	139.9	2.372	145

* 5% ($\alpha=0.05$) level of significance (+) See Table 4
(*) Statistically accepted relations

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Table 3 Summary of published regression equations for estimation of compression index, C_c, of Ariake clay

Reference	Equation
JSSMFE, Kyushu branch	Cc=0.013LL Cc=0.48(e-0.50) Cc=0.013(Wn-23)
Uchida & Matsumoto	Cc=0.029(LL-50) Cc=0.014(Wn-30)
Yamaguci et al.	Cc=0.02(LL-4) Cc=0.36(e-0.14)
Kabashima & Uta	Cc=0.02(LL-35) Cc=0.55e²/(1+e)
Onitsuka & Yoshitake	Cc=0.49(e-0.41) Cc=0.013(Wn-10)

Table 4 F value for different parameters of marameters of marked equations by (t) in table 2

Parameter	Depth (DEP)	e	Wn	LL	γt	qu	St. F value*
Cc	9.098	40.582	0.195	2.83			2.37
qu	332.07	2.081	2.85		9.97		2.37
Pc	346.51	3.618	1.104				2.6
Pc	16.668	2.584	0.82			84.463	2.37

* 5% (α=0.05) level of significance

regression are increased a little in some cases, by using multiple regression models, these improvements are not enough to warrant the use of multiple models. Also, it can be seen that developed regression models are in agreement with the nature of dependent variables in the view of soil mechanics.

5. CONCLUSION

Ariake clay is a very soft clay with N values near to 0, unconfined compressive strength less than 2 kg/cm^2 (mostly less than 1 kg/cm^2) and natural water content, in general, higher than liquid limit.

Physical (void ratio, total unit weight, plastic limio) and mechanical (unconfined compressive strength, preconsolidation pressure, compression index, compression ratio) properties of Ariake clay can be estimated with the useful, simple, and convenient presented relationships, knowing only natural water content, depth of sampling, and liquid limit. It has been shown that q_u, C_c, C_r, and Pc are best expressed by simple regression models, and using the multiple regression models did not

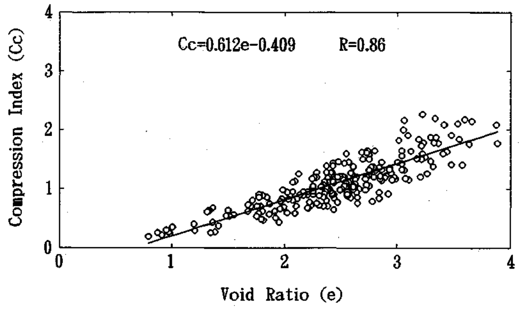

Fig.8 Compression index (C_c) in relation to void ratio (e)

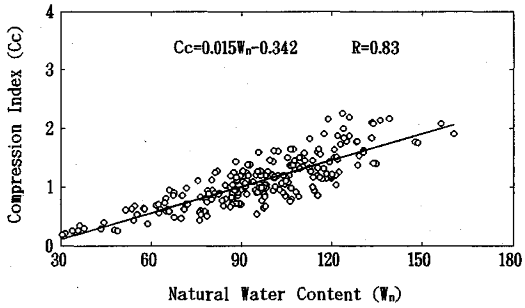

Fig.9 Compression index (C_c) in relation to natural water content (W_n)

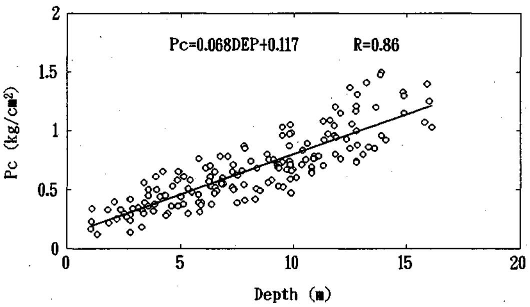

Fig.10 Pre-consolidation pressure (P_c) in relation to depth (DEP)

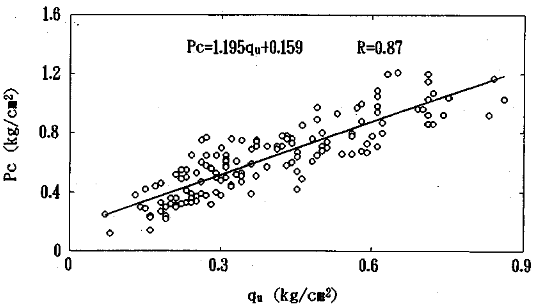

Fig.11 Pre-consolidation pressure (P_c) in relation to unconfined compression strength (q_u)

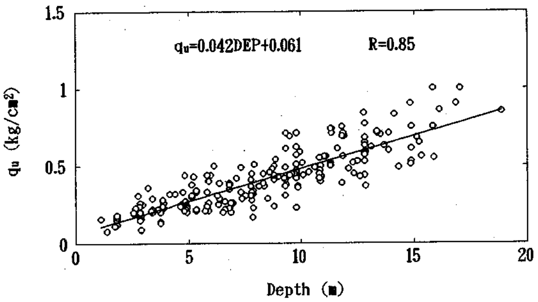

Fig.12 Unconfined compression strength (q_u) in reation to depth (*DEP*)

significantly improve the accuracy of the resulting regression models.

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佐賀平野における有明粘土層の地盤工学的特性

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この論文では，九州の有明海の北に広がる佐賀平野に分布する有明粘土層の地盤工学的特性が取り扱われている．佐賀平野の110本のコアから得られたデータのうち，深度20 m以浅の有明粘土層の地盤工学的性質について論じている．いくつかの特性値の説明に回帰分析が行われ，一軸圧縮強度，圧縮指数，圧縮比と先行荷重を説明するために重回帰分析が行われた．求められた回帰式は統計的に分散分析で検討された．