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Mechanical properties of soft organic Dhaka clay

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Abstract

A 132 kV transmission tower was planned for construction at a location in Dhaka city. Eight boreholes were drilled at the location. It was found that 8 to 9 m of the sub-soil consist of soft organic clay of high plasticity. Liquid limit and plasticity index of the organic clay samples were in the range of 72 to 94% and 42 to 57%, respectively. Natural moisture content and initial void ratio of the samples were in the range of 46 to 83% and 1.16 to 2.01, respectively. Strength, compressibility, swelling and permeability properties of undisturbed samples were evaluated. Unconfined compressive strength of the samples indicated that these are very soft. The values of compression index were found to vary between 0.33 and 0.59 while swelling index varied between 0.02 and 0.13. The coefficient of consolidation and permeability of the samples were also determined from the consolidation test. Permeability change index (C_k) was determined from approximate linear e-logk relationships. C_k and the ratio of C_c/C_k varied between 0.22 to 0.55 and 0.98 to 1.54, respectively. Permeability parameters (n, C) were also determined from approximate linear $\log_{10}e$—$\log_{10}[k(1+e)]$ relationships. The relation, $k = C\, e^n/(1+e)$ can be used to predict permeability- void ratio relation for organic soils of Dhaka. Attempts were made to correlate compression index and natural moisture content with initial void ratio. These correlations were compared with those reported for alluvial and coastal soils of Bangladesh.

Keywords: Soft organic clay, undrained shear strength, deformation, compressibility, permeability.

1. Introduction

Soft organic soil as foundation material causes serious problems to structures. Although a considerable part of Bangladesh is covered by organic soil, the capital city Dhaka contains organic soil at some locations only. A 132 kV transmission tower was planned for construction at a location where the sub-soil has been found to be highly organic (BRTC, 1998).

Geological and geotechnical characteristics of soils of different regions of Bangladesh have been studied by many researches. Morgan and McIntire (1959) and Hunt (1976) had investigated geological characteristics of soils of different regions of Bangladesh. Ameen (1985) and Bashar (2000) investigated the geotechnical characteristics of the Dhaka clay. Islam (1999) and Hoque and Islam (2000) reported the anisotropy of Dhaka clay. Serajuddin et al. (2001) reported characteristics of uplifted Pleistocene deposits in Dhaka city. Some research works have been performed on coastal and regional soils, such as Serajuddin (1969), Amin et al. (1987). Mollah (1993) reported the geotechnical characteristics of the sub-soil of the deltaic alluvial plains of Bangladesh to provide a useful guideline for development planning. A few works have been reported in the literatures about the soft soils of Bangladesh, such as Kabir et al. (1992 and 2000); Razzaque and Alamgir (1999), Siddique et al. (2002) and Islam et al. (2003). Apart from Bangladesh soils, a lot of works are available in the literature which dealt with the charcterization of soft clays and soft organic clays (Parry and Nadarajha, 1974; Mesri and Godlewski, 1977; Cox, 1981; 1985; Patrick et al., 1992; Allman and Atkinson, 1992; Siddique and Clayton, 1999; Diaz-Rodriguez and Santamarina, 2001; Chai and Miura, 2002).

It is clear that the available literature regarding local soils do not give a comprehensive picture of geotechnical characteristics of organic soils of Bangladesh. Rather most of the works previously done were concentrated on Dhaka clay and some coastal soils, none of which are problematic to the same extent as the soil of the present study. For proper design and construction of the civil engineering structure on such problematic soils, proper geotechnical characterization of the subsoil is necessary. However, consolidation characteristics of organic soil are rather complex. This paper presents the undrained stress-strain-strength, compressibility, swelling and permeability characteristics of soft organic clay samples of the proposed site.

2. Geology of Dhaka

Bangladesh can be divided into three major physiographic units namely, (i) the tertiary hill formations, (ii) the Pleistocene terrace, and (iii) the recent flood plains. Nearly 85 percent of Bangladesh is underlain by quaternary sediments consisting of deltaic and alluvial deposits of the Ganges, Brahmaputra and Meghna rivers and their numerous tributaries. The deltaic deposits are sediments that are deposited on the active delta, which is defined as the area south of the Ganges River and mostly west of the Meghna estuary. Most of the delta is less than 15 metres above mean sea level. According to the study of Morgan and McIntire (1959), there are two major areas of Pleistocene sediments, commonly known as the Modhuphur tract and Barind tract. The Madhupur block lies between the Jamuna and Old (18th century) Brahmaputra channels and 6 to 30 metres above mean sea level. Modhupur tract is bounded by faults; they appear to be uplifted and structurally complex; the Madhupur block has been tilted eastward (Morgan and McIntire, 1959). All or part of the clay is depositional. Most of the oxidized clay is now considered to be the product of weathering (the residuum) and, therefore, a relict paleosol. Residuum is defined as material derived by in-place chemical weathering of clastic sediment with no appreciable subsequent lateral transport. Patches of residuum also overlie gently dipping Tertiary units in the Fold Belt, including the Lalmai Hills, Comilla area.

Dhaka is situated on the southern tip of a Pleistocene Terrace, called the Madhupur Tract. Two characteristics units cover the city and surroundings, viz. Madhupur clay of Pleistocene age and alluvial deposits of Recent age. The Madhupur clay is the oldest sediment exposed in and around city area, having characteristic topography and drainage. The moisture content and liquid limit result shows that Madhupur clay is normally consolidated to slightly overconsolidated.

The clay has intermediate to high plasticity. The major geomorphic units of Dhaka are: the high lands or Dhaka terrace, the low lands or flood plain, depression and abandoned channels. Low-lying swamps and marshes located in and around the city are other topographic feature. The soil deposits in Dhaka city mainly consists of alluvial silt and clay; marsh clay and peat and Madhupur clay residuum.

The subsurface sedimentary sequence in Dhaka, up to the explored depth of 300 m, shows three distinct entities: one is the Madhupur clay formation of pleistocene age and is characterized by reddish plastic clay with silt and very fine sand particles. This Madhupur clay formation uncomfortably overlies the Dupi Tila formation of Pleistocene age composed of medium to coarse yellowish brown sand and occasional gravel. The incised channels and depression within the city are floored by recent alluvial flood plain deposits and is further subdivided into lowland Alluvium and high land Alluvium. A description of soil profile over Dhaka is provided by Ameen (1985).

3. Review on previous investigations

A number of research works were conducted in the past to evaluate undrained shear strength, stiffness, permeability, and compressibility of intact and reconstituted samples of Dhaka clay. A very brief description of few of these research works is given below.

Ameen (1985) investigated the undrained shear strength and stiffness characteristics of isotropically and K_0-consolidated reconstituted Dhaka clay (LL= 44, PI= 21). Ameen (1985) reported that the undrained strength ratio (s_u/σ'_v) of isotropically consolidated Dhaka clay ranged from 0.31 to 1.56 for overconsolidation ratios of 1 to 9, while the value of s_u/σ'_v for K_0-consolidated Dhaka clay varied from 0.19 to 2.7 for overconsolidation ratios of 1 to 24; where s_u and σ'_v are undrained shear strength and vertical effective stress, respectively. Undrained strength ratio for both isotropically and K_0-consolidated reconstituted Dhaka clay increased with increasing overconsolidation ratio. Ameen (1985) also found that the value of s_u/σ'_v obtained for K_0-consolidated Dhaka clay in normally loaded state is close to value of obtained from the Skempton's (1948) relationship. Ameen (1985) suggested that naturally occurring Dhaka clay is overconsolidated due to the process of desiccation. The value of K_0 remains essentially constant and equal to 0.46 for reconstituted Dhaka clay in normally loaded state. The value of K_0 increases from 0.46 to 3.23 with the increase in OCR from 1 to 12.

Siddique (1986) investigated the compressibiliy properties of reconstituted Dhaka clay (LL= 40, PI= 20). The values of compression index (C_c) and void ratio at 1 tsf vetical stress were found to be 0.28 and 0.84, respectively. Siddique and Safiullah (1995) reported coefficient of permeability values of reconstituted Dhaka clay. Coefficients of permeability of reconstituted Dhaka clay were determined directly from constant head permeability tests and indirectly from incremental loading one-dimensional consolidation tests. For normally consolidated Dhaka clay, coefficient of permeability (k) determined from constant head test varied between 0.74×10^{-10} and 7.35×10^{-10} m/s for the void ratio and dry density of the samples in the range of 0.51 to 0.84 and 14.2 to 17.4 kN/m^3, respectively. It was found that the values of the coefficient of permeability determined from the constant head test are higher than those found from consolidation test. Void ratio-permeability relationship for Dhaka clay was also investigated by

Siddique and Safiullah (1995). It was found that permeability decreased with decreasing void ratio and that e -log k relationships are non-linear.

Uddin (1990) investigated the undrained shear strenth, compressibility and expansibility of reconstituted Dhaka clay (LL= 43, PI= 20). It was found that stress-strain curve for normally consolidated reconstituted Dhaka clay tested to undrained compression showed no defined peak. It was found that for both isotropically consolidated and K_0-consolidated, normalized Young's Modulus increases with increasing OCR. A comparative study showed that Dhaka clay possesses a lower value of K than that of some other clays. Uddin (1990) also reported that for reconstituted Dhaka clay, under K_0 stress condition, the compression index (C_c) and swelling index (C_s) determined from e versus log σ'_v curve are 0.25 and 0.025, respectively. Under isotropic stress condition compression index (C_c) and swelling index (C_s) were found to be 0.278 and 0.038, respectively.

Islam (1999) investigated the strength and deformation anisotropy of Dhaka clay (LL= 46, PI= 19). The existence of strength anisotropy was clearly noticeable in reconstituted compacted Dhaka clay irrespective of moulding moisture content and compaction effort. The coefficient of anisotropy, defined as the ratio of strength of vertical specimen to that of a horizontal specimen, was varied from 0.75 to 1.25 in unconfined compression and unconsolidated direct shear tests, while it was between 0.6 and 1.08 in unconsolidated direct shear tests on soaked samples. It was found that unconfined compressive strength is maximum for the horizontal specimen, while it is minimum for the vertical specimen. Compaction effort had influences on anisotropy, which was found to be dependent on test types. The strength of reconstituted and field clays was approximately isotropic in horizontal plane. The strength was, however, anisotropic for specimens trimmed from a vertical plane at different orientations. The coefficient of anisotropy was mostly to that in compacted clays. However, the coefficient for undisturbed clay varied between 1.01 (i.e., isotropic) to 1.55 (i.e., anisotropic). Deformation properties e.g., compression index (C_c), swelling index (C_s) and coefficient of volume compressibility (m_v) and coefficient of permeability (k) obtained from one-dimensional consolidation tests on reconstituted Dhaka clay were directionally independent in a vertical plane. Natural clay was, however, anisotropic both in deformation and hydraulic characteristics. The indices C_c and C_s were maximum in vertical direction. The value of coefficient of permeability in horizontal direction, however, was higher than that in vertical direction.

4. Field investigations

A total of eight boreholes were drilled vertically at this site using wash boring technique. Wash borings of small diameter (approximately 100 mm) were drilled by water flush aided by chiselling. The depth of each borehole was 20 m below existing ground level. The density and stiffness characteristics of the sub-soil layers in the boreholes were measured by performing Standard Penetration Test (SPT) at 1.5 m intervals by means of standard 50.8 mm outside diameter split-spoon sampler. Disturbed and undisturbed samples were collected from the boreholes. A split-spoon sampler was used to obtain the disturbed samples in conjunction with the Standard Penetration Test. Undisturbed samples were also retrieved from cohesive layers of the boreholes by pushing conventional 76 mm external diameter thin-walled Shelby tubes. A typical bore log is shown in Fig. 1. A study of the eight borelogs and soil samples revealed the characteristics of the soil at the site. The soft soil consists of very soft to soft clays of high plasticity and organic clays of high plasticity up to a depth of 4.5 to 9.5 m below the existing ground level. In three boreholes (BH-1, BH-3 and BH-5), approximately 1 m thick layer of loose to medium dense fine sandy silt exists below the soft clay layer. N values obtained from SPT were in the range of 0 to 4 for the soft layer. A layer of dense to very dense fine silty sand layers of about 10.5 to 15.5 m thick have been encountered below the soft clay layer.

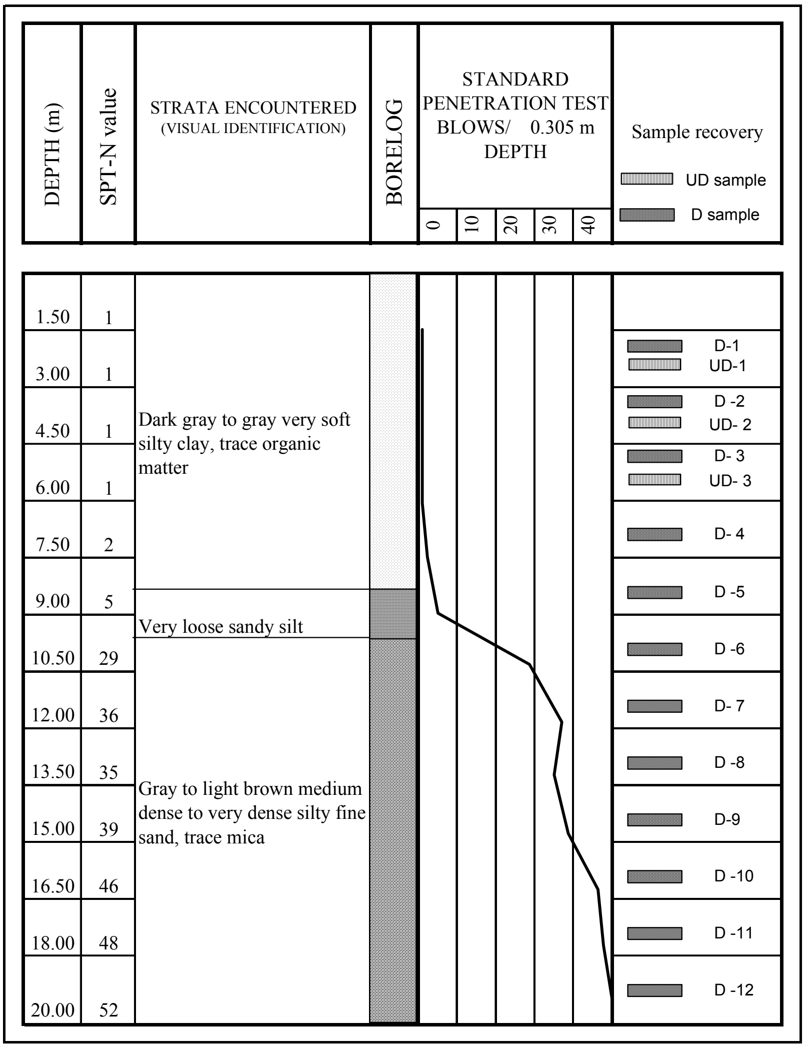

Fig. 1. Typical borelog at the site

5. Laboratory investigations

A detailed laboratory investigation was carried out on soil samples collected from the boreholes drilled at the site. The laboratory-testing program consisted of carrying out specific gravity, liquid limit, plastic limit, particle size analysis, unconfined compression and one-dimensional consolidation tests.

5.1 Physical and index properties

The values of specific gravity, natural moisture content, initial void ratio, dry unit weight and proportions of clay, silt and sand fractions are summarized in Table 1. Soil description is also provided in this table. Specific gravity (G_s) of soil samples varies between 1.94 and 2.53. Natural moisture content ranges from 46 to 83%. Initial void ratio of the samples is in the range of 1.16 to 2.01. Dry unit weight varies from 7.9 to 10.8 kN/m^3. Clay, silt and sand fractions vary from 41 to 63%, 33 to 57% and 2 to 6%, respectively. The values of liquid limit (LL), plastic limit (PL) and plasticity index (PI) of the samples are summarized in Table 2. The values of LL, PL and PI vary from 72 to 94%, 30 to 46% and 42 to 57%, respectively. Using the results of limit values, soil samples have been classified according to the Unified Soil Classification System (USCS). Classifications of the samples are also shown in Table 2. It has been found that out of the eight samples tested, two are clays of high plasticity (USCS Symbol is CH), while the rest six samples are organic clays of high plasticity (USCS Symbol is OH).

Table 1
Physical properties and grain size distribution of samples

BH No./ Sample No./ Depth	Soil description	G_s	w_n (%)	Initial void ratio	Dry unit Weight (kN/m^3)	% Clay	% Silt	% Sand
BH-1/ UD-2/ 4.0-4.5 m	Dark grey clay	2.47	46	1.63	10.8	54	40	6
BH-2/ UD-3/ 5.5-5.95 m	Grey clay	2.53	51	1.30	10.7	62	33	5
BH-3/ UD-2/ 4.0-4.45 m	Soft clay	2.49	83	2.01	7.9	63	35	2
BH-4/ UD-2/ 4.0-4.5 m	Organic clay	2.44	65	2.00	8.8	41	57	2
BH-5/ UD-2/ 4.0-4.45 m	Organic clay	2.49	73	1.78	8.7	59	38	3
BH-6/ UD-2/ 4.0-4.45 m	Dark organic clay	1.94	71	1.16	8.6	55	40	5
BH-7/ UD-2/ 4.0-4.45 m	Organic clay	2.35	75	1.97	8.2	51	45	4
BH-8/ UD-3/ 5.5-5.95 m	Organic clay	2.34	72	1.38	8.3	56	41	4

Note: G_s= Specific graivity; w_n= Natural moisture content

5.2 Unconfined compressive strength

Eight unconfined compressive strength tests were carried out on undisturbed samples. For each test on a sample, three specimens were prepared, which were sheared in compression up to failure. Typical compressive stress versus axial strain curves are presented in Fig. 2. From the stress-strain data, compressive strength (q_u) and axial strain at failure (ε_f) were determined. A summary of the test results is presented in Table 3. The average value of q_u varied in the range 6 to 38 kPa. Water content and dry density of the samples tested were in the range of 46 to 83% and 8.2 to 10.8 kN/m^3, respectively. Based on the values of undrained shear strength, which is half of the unconfined compressive strength for clays, clays are classified in accordance with BS 5930, which is shown in Table 3. Undrained shear strength, were found to vary from 3 to 19 kPa, while axial strain at failure, ε_f varied between 10 to 15%. It indicates that elongation for soft organic soil is very high. According to BS 5390, all the samples tested were very soft. Undrained shear strength ratio (s_u/σ_v') of the samples were in the range of 0.07 to 0.45.

Table 2
Index properties and classification of samples

BH No./ Sample No./ Depth	Soil Description	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Classification of soil (ASTM D2847, 1989)
BH-1/ UD-3/ 5.5-5.95 m	Grey clay	72	30	42	CH
BH-2/ UD-2/ 4.0-4.45 m	Soft clay	88	31	57	CH
BH-3/ UD-2/ 4.0-4.45 m	Organic clay	85	37	48	OH
BH-4/ UD-2/ 4.0 4.45 m	Organic clay	84	37	47	OH
BH-5/ UD-2/ 4.0 4.45 m	Dark organic clay	85	38	47	OH
BH-6/ UD-2/ 4.0 4.45 m	Organic clay	83	37	46	OH
BH-7/ UD-3/ 5.5-5.95 m	Organic clay	94	46	48	OH
BH-8/ UD-3/ 5.5-5.95 m	Organic clay	85	40	45	OH

Note: CH = Clay of high plasticity; OH= Organic clay of high plasticity

5.3 Compressibility and swelling properties

Compressibility properties of eight samples were determined from incremental loading one-dimensional consolidation test. Consolidation tests were carried out on samples of 63.5 mm diameter and 25 mm high using a stress increment ratio of 1, (i.e., a load ratio of 2). The vertical stresses applied during consolidation were 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa and 800 kPa. The samples were also allowed to swell under stresses of 200 kPa, and 10 kPa. Duration of each loading step was twenty-four hours. During all these tests drainage was permitted from top and bottom of the sample. For each loading step, deformation was recorded by a dial gauge at specified time intervals.

Table 3
Summary of unconfined compression test results

BH No./ Sample No./ Depth	Average water content (%)	Average dry density (kN/m^3)	Average value of q_u (kPa)	Average value of s_u (kPa)	Average value of ε_f (%)	s_u/σ_v'	Consistency
BH-1/ UD-2/ 4.0-4.5 m	45	10.8	32	16	10	0.38	Very soft
BH-2/ UD-3/ 5.5-5.95 m	46	11.1	28	14	15	0.25	Very soft
BH-3/ UD-2/ 4.0-4.45 m	77	8.2	10	5	15	0.12	Very soft
BH-4/ UD-2/ 4.0-4.5 m	62	8.9	14	7	15	0.17	Very soft
BH-5/ UD-2/ 4.0-4.45 m	70	8.7	14	7	15	0.17	Very soft
BH-6/ UD-2/ 4.0-4.45 m	70	8.8	6	3	15	0.07	Very soft
BH-7/ UD-2/ 4.0-4.45 m	68	8.9	38	19	12	0.45	Very soft
BH-8/ UD-3/ 5.5-5.95 m	70	8.7	24	12	15	0.21	Very soft

Time - deformation curves were plotted for each pressure increment and from these plots times corresponding to 50% consolidation, i.e., t_{50} were determined using Casagrande's Curve Fitting Method (Das, 1983). Coefficients of consolidation (c_v) and coefficient of volume compressibility (m_v) were calculated for each stress increment.

A typical void ratio versus logarithm of effective vertical stress plot and coefficient of consolidation versus logarithm of effective vertical stress plot is presented in Fig. 3. Compression index (C_c) of the samples was determined from the slopes of the loading portion of the void ratio versus logarithmic of pressure curves. A summary of compressibility and swelling parameters of the samples are shown in Table 5. The values of C_c of the samples have been found to vary between 0.33 and 0.59. The value of C_s ranged from 0.02 to 0.13. Coefficient of compressibility (m_v) of samples varied between 0.14×10^{-4} to 5.10×10^{-4} m^2/kN. Figure 4 shows the variation of m_v with effective vertical stress. It can be seen that m_v decreases with the increase of vertical effective stress. The coefficient of consolidation (c_v) varied between 0.10 and 17.30 m^2/year. It indicates that coefficient of consolidation is very low, which are typical of soft clay behavior. Figure 5 shows the variation of c_v with the increase of effective vertical stress. It can be seen that c_v decreases with the increase of effective vertical stress.

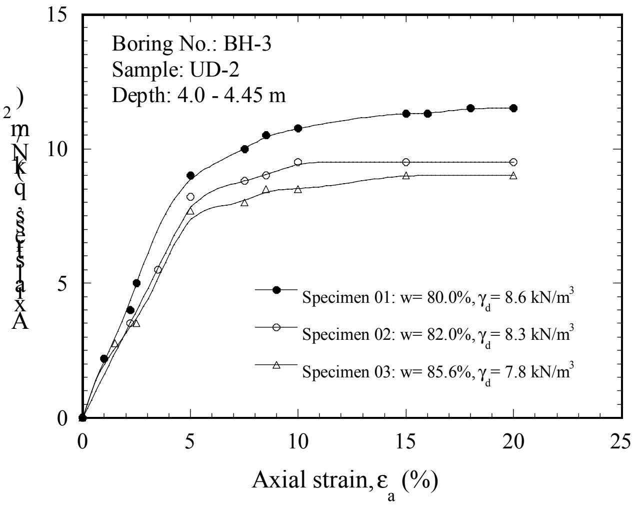

Fig. 2. Typical compressive stress versus axial strain curve of a sample in unconfined compression test

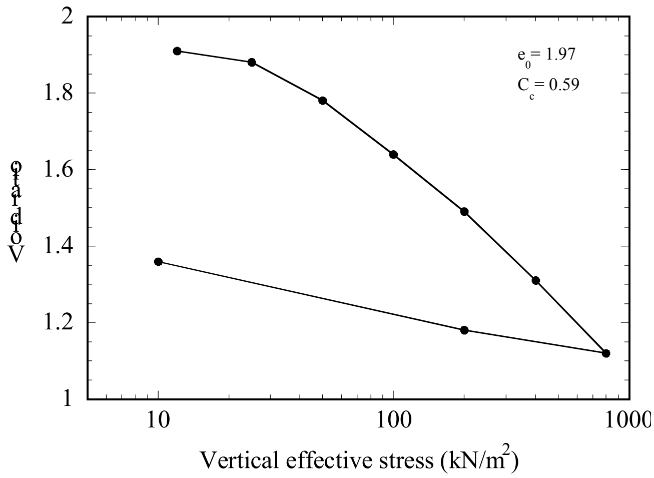

Fig. 3. Typical void ratio versus logarithmic of effective vertical stress

5.4 Permeability properties

Coefficient of permeability of the samples was determined indirectly from one-dimensional consolidation tests. The coefficient of permeability (k) of samples were computed using the following equation (Taylor, 1948).

$$k = c_v m_v \gamma_w \tag{1}$$

where, c_v = coefficient of consolidation; m_v = coefficient of volume compressibility; γ_w = unit weight of water.

A summary of the range of permeability values of the soil samples are presented in Table 5. The coefficient of permeability (k) range between 1.74 x 10^{-10} and 1.15 x 10^{-7} m/sec. It indicates that permeability is very low, which are typical of soft clay behavior. Figure 6 shows the relationship between permeability and vertical effective stress. It is seen that permeability decreases with the increase of vertical effective stress.

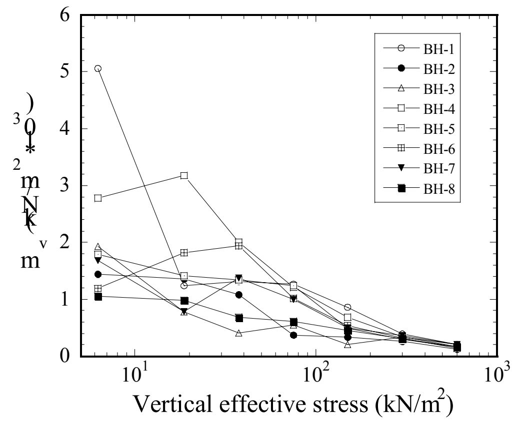

Fig. 4. Coefficient of volume compressibility versus vertical effective stress

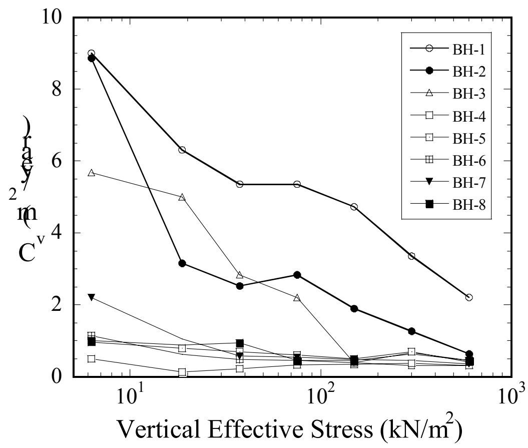

Fig. 5. Coefficient of consolidation versus vertical effective stress

For clays, Taylor (1948) suggested the following empirical linear relation between the logarithm of permeability (k) and the void ratio (e):

$$\log k = \log k_0 - \frac{e_0 - e}{C_k} \tag{2}$$

where C_k is permeability change index, which is the slope of linear e versus log k relationship and e_0 and k_0 are the in situ void ratio and in situ permeability, respectively. This type of relationship has become a common way of expressing the variation of permeability of clays with void ratio. The relationship is generally valid for a range of void ratio changes encountered in engineering practice (Meshri and Rokhsha, 1974).

Tavenas et al. (1983) report that from a practical point of view, the relationship represented by Eq. (1) is excellent for initial void ratios less than 2.5 and for volumetric strains of practical interest in engineering problems.

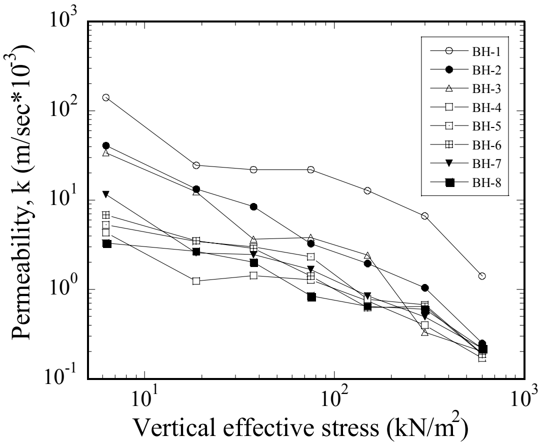

Fig. 6. Coefficient of permeability versus vertical effective stress

The relationship between void ratio and permeability (e-log k) has been presented in the Figure 7 for eight samples of soft soils. Approximately linear relationship has been obtained for all the organic samples. The values of C_k of the samples were determined from void ratio versus log k plots. The value of C_k have been found to vary between 0.22 and 0.55 for the soft organic Dhaka Clay samples. The values of C_k of the samples are shown in Table 6. The approximately linear relationships between void ratio and logarithm of permeability has been found to apply to other reconstituted clays (Lambe and Whitman, 1969; Siddique and Clayton, 1999) and has been shown to extend to high void ratios in very soft sedimented clays (Been and Sills, 1981). The ratio of compression index to permeability change index, i.e., C_c/C_k has also been presented in Table 6. C_c/C_k for the soft organic Dhaka clay varied between 0.98 and 1.54. Berry and Wilkinson (1969) reported for many soils C_c/C_k often lies within the limits of 0.5 and 2.0, while Mesri and Rokhshar (1974) observed that the experimental values of C_c/C_k very between 0.5 and 5.0. Permeability change index (C_k) for London clay is 0.54 and the value of C_c/C_k is 1.02 (Siddique and Clayton, 1999).

Samarasinghe et al. (1982) suggested a model to predict permeability of normally consolidated clays. The relationship is as follows:

$$k = C \frac{e^n}{1 + e} \tag{3}$$

where, C is a constant in the same unit as k and n is a constant depending on the type of soil. Eq. (3) can be rewritten as follows:

$$\log\left[k\left(1 + e\right)\right] = n \log e + \log C \tag{4}$$

Eq. (4) shows that a plot of log [k (1+e)] versus log e results in a straight line, of which n is the slope and log C is the vertical intercept. Samarasinghe et al. (1982) termed n and C as permeability parametrs. Table 7 shows permeability parameters of different soils reported by different reseearchers. Eq. (4) has also been found to be suitable to represent permeability – void ratio relationship in natural and reconstituted clays (Tavenas et al., 1983; Raymond, 1966; Siddique and Safiullah, 1995; and Ansary et al., 1999).

Table 4
Summary of one-dimensional consolidation test results

Borehole No./ Sample No./Depth	Water Content (%)	Initial void ratio	m_v (10^{-4} m^2/kN)	c_v (m^2/year)	C_c	Cs
BH-1/ UD-3/ 5.5-5.95 m	48	1.63	0.20 to 5.10	1.60 to 17.30	0.52	0.05
BH-2/ UD-2/ 4.0-4.45 m	50	1.30	0.15 to 5.07	1.60 to 25.00	0.34	0.02
BH-3/ UD-2/ 4.0-4.45 m	80	2.01	0.21 to 1.94	1.30 to 3.15	0.54	0.09
BH-4/ UD-2/ 4.0 4.45 m	67	2.00	0.17 to 2.78	0.13 to 0.50	0.52	0.13
BH-5/ UD-2/ 4.0 4.45 m	70	1.78	0.16 to 1.78	0.16 to 0.95	0.46	0.10
BH-6/ UD-2/ 4.0 4.45 m	69	1.16	0.14 to 1.93	0.10 to 0.55	0.33	0.08
BH-7/ UD-3/ 5.5 5.95 m	76	1.97	0.21 to 1.68	0.30 to 2.20	0.59	0.13
BH-8/ UD-3/ 5.5-5.95 m	70	1.38	0.16 to 1.05	0.47 to 1.02	0.43	0.08

Note: C_c= compression index; m_v= coefficient of volume compressibility; c_v= coefficient of consolidation.

Figure 8 shows the relationship between $\log_{10}e$ and $\log_{10}[K(1+e)]$. Approximately linear relationship has been obtained between $\log_{10}e$ and $\log_{10}[K(1+e)]$ for all the samples. Permeability parameters n and C have been determined for all the eight samples. The values of n and C are presented in Table 8. It is seen that the values of n and C are in the range of 4.8 to 13.0 and 0.09 x 10^{-10} to 11.2 x 10^{-10} m/sec.

5.5 *Correlation between C_c and e_0*

Attempts have been made to correlate compression index (C_c) and initial void ratio (e_0) obtained from this study with those for other regional and coastal soils of Bangladesh. The relation between C_c and e_0 has been compared with other relationships provided for other coastal and regional soils of Bangladesh (Amin et al., 1987; Nishida, 1956;

Serajuddin and Ahmed, 1967). A plot of C_c versus e_0 is shown in Fig. 4. The best fit relationships, as proposed by the four authors, have been presented. Correlations provided by Amin et al. (1987), Nishida (1956) and Serajuddin and Ahmed (1967) are presented in Eqs 5, 6, 7 and 8, respectively.

$$C_c= 0.42(e_0-0.34) \tag{5}$$

$$C_c= 0.33(e_0-0.35) \tag{6}$$

$$C_c=0.54(e_0-0.35) \tag{7}$$

$$C_c=0.44(e_0-0.36) \tag{8}$$

where, C_c is compression index and e_0 is initial void ratio.

Table 5
Coefficient of permeability determined from one-dimensional consolidation test

Borehole No. / Sample No./Depth	*Coefficient of permeability* k (m/sec)
BH-1/ UD-3/5.5-5.95 m	1.42×10^{-9} to 2.85×10^{-8}
BH-2/ UD-2/4.0-4.45 m	6.45×10^{-10} to 1.15×10^{-7}
BH-3/ UD-2/4.0-4.45 m	2.05×10^{-10} to 1.98×10^{-8}
BH-4/ UD-2/4.0 4.45 m	1.74×10^{-10} to 4.30×10^{-9}
BH-5/ UD-2/4.0 4.45 m	2.03×10^{-10} to 5.40×10^{-9}
BH-6/ UD-2/4.0 4.45 m	2.04×10^{-10} to 3.40×10^{-9}
BH-7/ UD-3/5.5 5.95 m	2.06×10^{-10} to 1.18×10^{-8}
BH-8/ UD-3/5.5-5.95 m	2.30×10^{-10} to 3.41×10^{-9}

Table 6
Values of C_k and C_c/C_k

Parameter	BH-1	BH-2	BH-3	BH-4	BH-5	BH-6	BH-7	BH-8
C_k	0.36	0.22	0.55	0.62	0.62	0.33	0.42	0.40
C_c/C_k	1.44	1.54	0.98	0.20	0.16	1.00	1.40	1.08

The relationship proposed by Nishaida (1956) is for undisturbed clays and that for Serajuddin and Ahmed (1967) is for fine-grained soils of Bangladesh. Amin et al. (1987) proposed the relationships for coastal soils of Bangladesh. From Fig. 9, it is seen that the relationship between C_c and e_0 of this study can be well represented by the equations proposed by Amin et al. (1987). The relationships proposed by Amin et al. (1987) are the relations for two different zones: Zone A and Zone D, as defined by Amin et al., 1987) of the coastal area of Bangladesh. Zone A is Barisal district of Bangladesh. Natural moisture content of the Barisal soil is 28 to 57%. Liquid limit and plasticity index of the Barisal soil are 24 to 57% and 22 to 37%, respectively. Clay content of the soil is 0 to18% and undrained shear strength (s_u) is 8 to 75 kPa. Zone D is Sandwip district of

Bangladesh. Natural moisture content of the Sandwip soil is 26 to 46%. Liquid limit and plastic limit of the Sandwip soil are 25 to 47% and 21to31%, respectively. Clay content is 0 to 26% and undrained shear strength (s_u) is 12 to 84 kPa.

The relationship between C_c and e_0 of the organic samples tested in this study can be expressed by the following Equation.

$$C_c = 0.25\,(e_0 + 0.194) \tag{9}$$

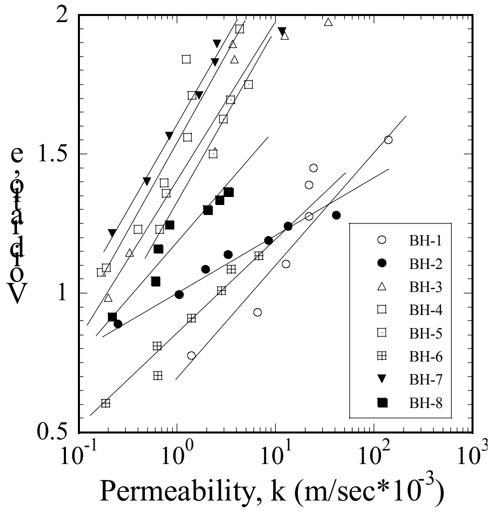

Fig. 7. Void ratio versus permeability

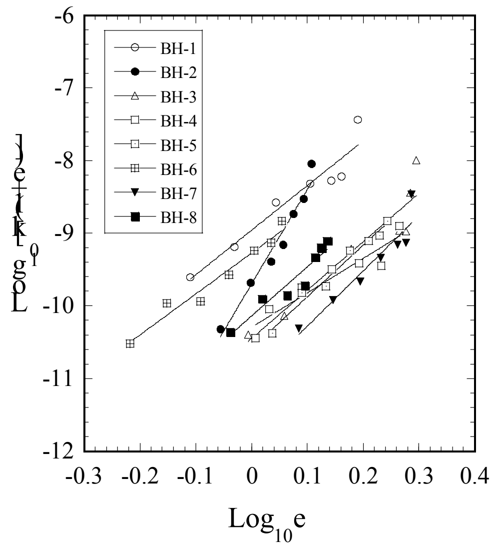

Fig. 8. *Log [K(1+e)]* versus *Log e* plots for Dhaka soft clay

5.6 *Correlation between e_0 and w_n*

Attempts were also made to correlate the relationship between e_0 and natural water content. Correlations for e_0 and w_n provided by Amin et al. (1987) has been presented in Eqs. 10 and 11. Equations 10 and 8 are the relationships between e_0 and natural water content for the soils of Zone A and Zone D as described by Amin et al. (1987). These relationships along with the relationships obtained in this study have been presented in Fig. 10. In Fig. 10, the data points indicate the relationship of e_0 and w_n of this study. It is clear from the figure that although the data points are scattered, the relationship between e_0 and water content, w_n can be well represented by the relationship proposed by Amin et al. (1987) for the soils of Zone A.

$$e_0= 0.245\ (w_n+0.54) \tag{10}$$

$$e_0= 0.0137\ (w_n+3.092) \tag{11}$$

where, e_0 is initial void ratio and w is natural water content in percent.

Table 7
Values of permeability parameters of different soils derived from consolidation test (logt fitting method)

Soil	n	C (10^{-10} m/sec)	Remarks
Don Valley Clay[1]	4.8	29.0	Reconstituted samples
New Liskeard Clay[1]	4.9	4.0	Reconstituted samples
Greyish Sandy Clay[2]	5.2	77.0	Reconstituted samples
Gazipur Clay[3]	5.1	355.0	Reconstituted samples
Dhaka Clay[4]	4.7	12.0	Reconstituted samples
G1[5]	3.3	7.2	Reconstituted samples
G3[5]	2.1	13.0	Reconstituted samples
KA[5]	1.7	12.6	Reconstituted samples
M[5]	3.9	16.1	Reconstituted samples
G1[5]	6.1	38.2	Undisturbed samples
G3[5]	3.1	11.6	Undisturbed samples
KA[5]	6.5	255.3	Undisturbed samples
M[5]	6.4	179.5	Undisturbed samples

Note: 1: Raymond (1966); 2: Samarasinghe et al. (1982); 3: Siddique (1986); 4: Siddique and Safiullah (1995); 5: Ansary et al. (1999)

6. Conclusions

A study of the eight borelogs and soil samples revealed the characteristics of soil at a site in Dhaka city. The soft soil consists of very soft to soft clays of high plasticity and organic clays of high plasticity up to a depth of 4.5 to 9.5 m below the existing ground level. In three boreholes approximately 1 m thick layer of loose to medium dense fine sandy silt exists below the soft clay layer. N values obtained from SPT were in the range of 0 to 4 for the soft layer.

Specific gravity, natural moisture content, initial void ratio, dry unit weight ranges from 1.94 to 2.53, 46 to 83%, 1.16 to 2.01 and 7.9 to 10.8 kN/m^3, respectively. Clay, silt and sand fractions are 41 to 62%, 33 to 57%, and 2 to 6%, respectively. Liquid limit, plastic limit and plasticity index are in the range of 72 to 94%, 30 to 46% and 42 to 57%, respectively.

Table 8
Values of permeability parameters of different soils derived from consolidation test (logt fitting method)

Borehole No./ Sample No./Depth	n	C (10^{-10} m/sec)	Correlation Coefficient
BH-1/ UD-3/ 5.5-5.95 m	6.1	11.2	0.957
BH-2/ UD-2/ 4.0-4.45 m	13.0	2.01	0.979
BH-3/ UD-2/ 4.0-4.45 m	6.7	0.35	0.943
BH-4/ UD-2/ 4.0 4.45 m	4.8	0.26	0.944
BH-5/ UD-2/ 4.0 4.45 m	7.1	0.26	0.988
BH-6/ UD-2/ 4.0 4.45 m	5.6	5.37	0.980
BH-7/ UD-3/ 5.5 5.95 m	7.6	0.09	0.946
BH-8/ UD-3/ 5.5-5.95 m	6.8	0.74	0.954

Low specific gravity, very low dry density, high natural moisture content, high initial void ratio, and high liquid limit indicate that the soil samples are very soft and contain organic matter. According to, Unified Soil Classification System (USCS), the soils have been found to be clays of high plasticity (CH) and organic clays of high plasticity (OH).

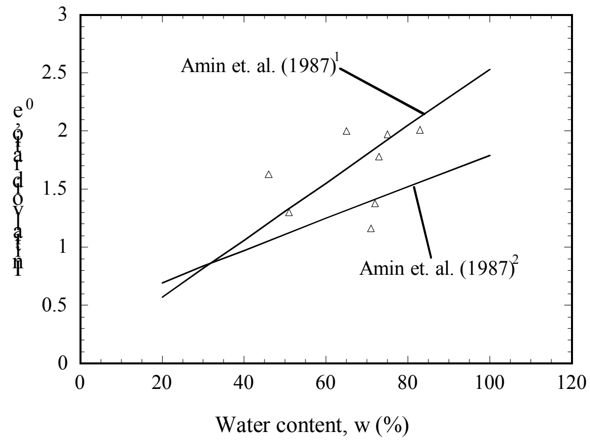

Fig. 9. Compression index, c_c versus initial void ratio, e_0 relationship

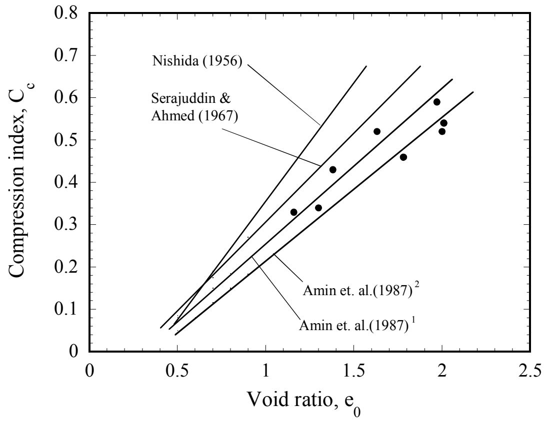

Fig. 10. Initial void ratio, e_0 versus water content relationships

Unconfined compressive strength is in the range of 6 to 38 kPa, which indicates that the clays are very soft. Compression index, C_c of the samples is in the range of 0.33 to 0.59. It indicates that the soils are highly compressible. Coefficient of consolidation and coefficient of permeability are in the range of 0.10 to 25.0 m^2/year and 1.74 x 10^{-10} to 1.15 x 10^{-7} m/sec, respectively. It indicates that effect of consolidation and the permeability is very low, which are typical of soft and organic clay.

Approximately linear e-log k relationship has been obtained for all eight samples of soft organic Dhaka Clay. Permeability change index has been found to vary in the range of 0.22 to 0.55. The ratio of C_c/C_k of this clay has been found to vary in the range of 0.98 to 1.54, which lies within the limits reported by other researchers.

Approximately linear $\log_{10}e$—$\log_{10}[k(1+e)]$ relationships have been obtained for organic samples of Dhaka clay. The relationship $k = C\ e^n/(1+e)$ as proposed by Samarasinghe et al. (1982), therefore, can be used to predict permeability- void ratio relation for organic soils of Dhaka. Permeability parameter n and C have been found to vary between 4.8 to 13.0 and 0.09 X 10^{-10} to 11.2 X 10^{-10} m/sec.

Correlations between compression index (C_c) and initial void ratio (e_0) and e_0 and natural moisture content (w_n) has been established. It has been found that these correlations compare reasonably well with existing similar correlations for coastal and regional soils of Bangladesh.

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Notations

C	permeability parameter
C_k	permeability change index
C_s	swelling index
C_c	compression index
c_v	coefficient of consolidation
e	void ratio
k	coefficient of permeability
LL	liquid limit
m_v	coefficient of volume compressibility
n	permeability parameter
PL	plastic limit
PI	plasticity index
t_{50}	time corresponding to 50% consolidation
γ_w	unit weight of water
s_u	undrained shear strength
σ_v'	effective vertical stress