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THE EFFECT OF GAS BUBBLE FORMATION ON THE PHYSICAL AND ENGINEERING PROPERTIES OF RECENTLY DEPOSITED FINE-GRAINED SEDIMENTS

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ABSTRACT

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Sediments in the anoxic reaches of the Veerse Meer, a tideless basin in the southwest Netherlands, possess certain physical properties which are directly dependent upon the geochemical environment in which they are accumulating. High values of water content and correspondingly low values of bulk density (unit weight) and shear strength were observed in sediments deposited in low oxygen to anoxic waters (−12 m to −20 m depth). Plasticity increased regularly with depth with highest plasticity found in the most highly reduced sediments at −20 m.

One-dimensional consolidation analyses showed rapid consolidation and almost complete lack of rebound. Stress-strain diagrams show little or no reloading curves and are typical of underconsolidated or remolded sediments in which interparticle bonding is minimal.

Gas generation and bubble ebullition with swelling is believed to retard normal gravitational consolidation and inhibit fabric development through continual agitation and physical manipulation of sediment particles. Both conditions (i.e., underconsolidation and remolding) exist as a direct result of methanogenesis.

INTRODUCTION

Interest has been sharply focussed on the potential of anoxic sediments to generate various gases through the activities of anaerobic bacteria. Aspects of these sediments that have been considered include the petroleum potential (Emery & Rittenberg, 1952; Emery & Hoggan, 1958; Rashid, Vilks & Leonard, 1975), early diagenetic effects (Nissenbaum, Presly & Kaplan, 1972; Hammond, 1974), the effect on the transmission of acoustic signals (Wood & Weston, 1964; Hampton & Anderson, 1974; Schubel & Schiemer, 1974; Keen & Piper, 1976; Westneat & Porter, 1976), and the various geochemical and microbiological mechnisms responsible for methane production (Reeburgh, 1969; Kaplan, 1974; Martens & Berner, 1974; Berner & Goldberg, 1976).

It has been suggested that methanogenesis may affect the mass physical and engineering characteristics of the sediments, causing underwater slope instability and mass movements (Whelan, 1974; Whelan, Coleman, Suhayda & Garrison, 1975 Richards & Parks, 1976; Roberts, Cratsky & Whelan, 1976). However little quantitative data are available concerning the behavior of recently deposited anoxic sediments under stresses, and that information which exists has generally been derived from studies not directly applicable to gassy sediments (Harrison, Lynch & Altschaeffl, 1964), although Schubel & Schiemer (1974) demonstrated that gassy sediments of Chesapeake Bay had compressibilities two orders of magnitude greater than similar non-gassy sediments.

The purpose of this paper is to present the results of a study designed specifically to examine the mass physical and engineering characteristics of gassy sediments and to show how methanogenesis affects sediment stability. To convert the units of density and pressure used in this paper into SI units, multiply g/cm^3 by 1,000 to get kg/m^3, and multiply kg/cm^2 by 9.80665 to get N/m^2.

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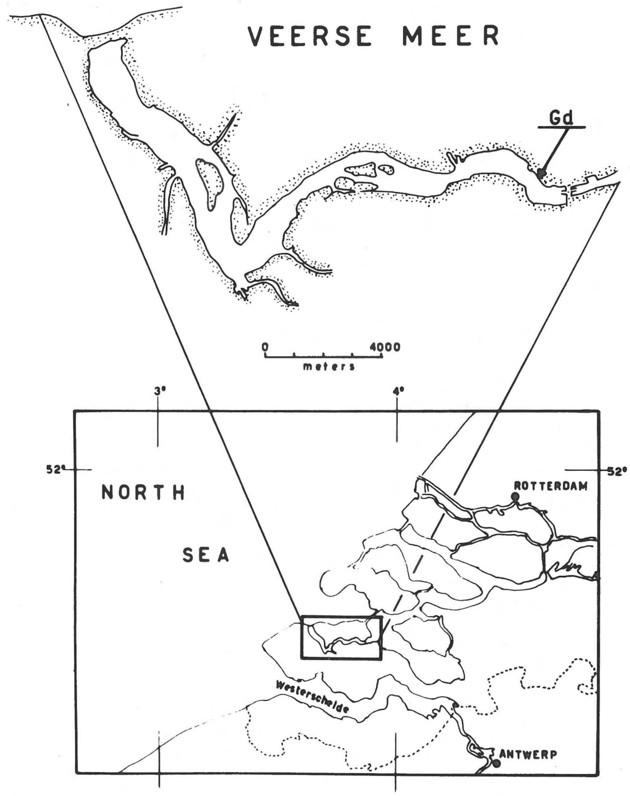

Fig. 1
General location map of the Delta region of the southwest Netherlands. The Veerse Meer is an enclosed segment of the Ooster Schelde.

Background and Setting

The sediments were obtained from the Veerse Meer, a brackish water lake in the southern Netherlands (Fig. 1). It was formerly a segment of the tidal Ooster Schelde, presently a sea arm and former mouth of the Schelde estuary. The Veerse Meer was closed from tidal activity in 1961 as a part of the Delta Plan of the Dutch government.

During a study of Delta region sedimentology, several areas of the Veerse Meer were found to be anoxic and given particular attention (Faas & Wartel, 1976). Other studies concerning the biological impact of closure of the Veerse Meer had been conducted (Vaas, 1970; Beeftinck, Daane & de Munck, 1971; Bakker, 1972), but no previous work had been directed toward the bottom sediments.

Procedure

This paper is based upon both field and laboratory analyses. Physical properties measured in the laboratory, according to established ASTM procedures included liquid and plastic limits, natural water content, and bulk density (unit weight). *In situ* shear strength measurements were made in the upper 10-12 cm of the sediment bed by SCUBA divers, using a hand-held shear vane. Eh and pH measurements were performed in the field on cores extracted by SCUBA divers, by inserting electrodes into predrilled holes in the core liner. The instrument used was a Radiometer millivolt meter, type PHM-29, using a combined glass-calomel electrode, type GK 2311C. Measurements were made immediately after the cores were brought out of the water to minimize environmental effects. Analyses of organic carbon were performed following the procedure of Walkley & Black (1934); carbonate carbon was determined using the Schiebler-Dietrich calcimeter (Heyer *et al.,* 1968). Particle size analyses were performed with the ASTM 152H hydrometer (Bouyoucos, 1962) using Calgon as the dispersing agent. Sediments were kept at their natural moisture content throughout the physical analyses to maintain the natural conditions and no attempt was made to remove organic matter.

GENERAL SEDIMENTOLOGY OF THE VEERSE MEER

The sediments range from sand to clayey silt (Shepard, 1954). Sands are found in regions where oxidizing conditions prevail, with clayey silts in anoxic regions (Fig. 2).

Underwater slope profiles were measured by SCUBA divers in several anoxic regions. The Gebroken Dijk (Gd) site is characteristic of these regions (Table I). It has a steep slope, beginning at –3 m, which becomes concave between –8 and –10 m. The shallower, upper slope reflects a relict tidal flat feature remaining since 1961 (Fig. 3). Fine-grained sediments are accumulating within the concave portion of the profile. Penetration measurements show an accumulation

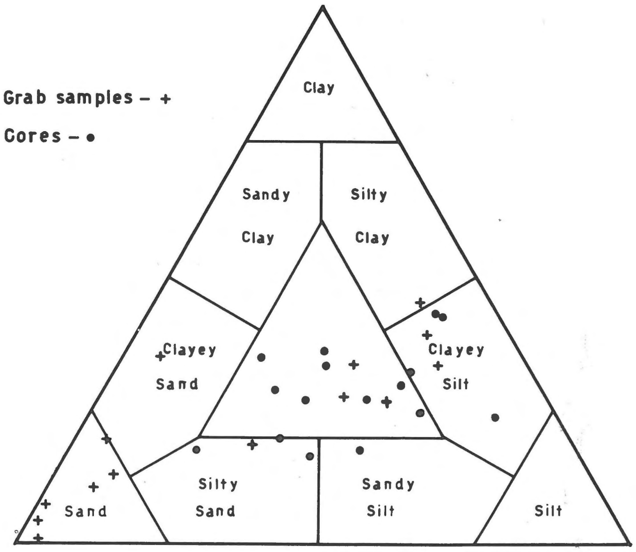

Fig. 2
A Shepard ternary diagram showing the general size distribution through the Veerse Meer, based upon Shipek samples.
Also shown are samples from cores taken from the Gebroken Dijk (Gd). A marked reduction in sand content is seen in these samples.

D(m)	pH	Eh	C carb (%)	C org (%)
– 5	W 8.3	+ 99		
	M 8.0	– 24	1.16	0.80
– 8	M —	—	1.56	1.53
– 8.5	W 8.1	+109	—	—
	M 7.9	–116		
–11	M —	—	1.44	1.50
–12.5	M —	—	1.44	1.50
–15	M —	—	1.65	1.15
–20	W 7.7	– 51		
	M 7.2	–226		

W = Water immediately above mud
M = Mud

Table I.
Eh, pH, carbonate carbon and organic carbon for sediment/water interface samples from the Gebroken Dijk site, June 1975. The sediments become more acidic with depth, and Eh values reach a minimum of –226 mv at –20 m. Organic carbon averages 1.22% and carbonate carbon averages 1.45%.

of as much as 1.5 m of anoxic sediment at depths of –20 m with greater thicknesses (as much as 2 m as shown by echo soundings) occurring within scour pits and depressions on the relatively flat channel floor. The general effect is to subdue relict relief and flatten the entire channel floor.

X-ray diffraction analysis of surface samples taken along the Gd slope indicates that illite is the dominant clay mineral, followed by kaolinite and smectite in about equal abundance, and chlorite, the latter occurring in most of the samples. Analysis of cores from the anoxic reaches showed that these minerals persist to a depth of at least 45 cm in the sediments. All cores exhibited a bubbly texture, described in detail later in this paper.

MASS PROPERTIES

Water contents (% dry weight) of 50 cm long cores taken along the bottom slope at the Gd site vary between 66.2% and 196.3% (Fig. 4). Bulk density is very low, ranging between 1.16 g/cm^3 to 1.42 g/cm^3. In nearly every case, the upper 5-10 cm could not be adequately tested due to the tendency for the material to flow. *In situ* shear strength measurements in the upper 10-20 cm decreases downslope, with minimum values (22.5 g/cm^2) being recorded between –12 and –13.5 m (Fig. 4).

The sediment is considered to be of low sensitivity (S_t = 1.00 – 2.00). Sensitivity is the ratio between the undisturbed shear strength and the strength of the remolded sediment (Terzaghi & Peck, 1948). It was measured *in situ* with the diver-held shear vane. The shear vane is carefully inserted in the sediment bed and a measurement is made; then the vane is rotated in place several times. After a delay of one minute, a measurement of the remolded shear strength is made. Extra-sensitive clays (S_t greater than 8.00) are those in which the sediment structure is changed from flocculent to dispersed and in which the remolded shear strength is markedly reduced. The Gd samples, being of low sensitivity, indicate little strength difference between the undisturbed and remolded sediment. It should be understood that shear strength values measured in this fashion are not directly comparable with values obtained under controlled laboratory conditions.

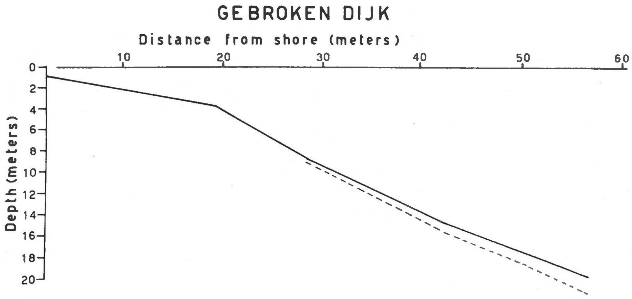

Fig. 3
Underwater slope profile at Gebroken Dijk (Gd). Dashed lines indicate thickness of fine-grained, gassy, sediment, measured by penetration of diver-held probe.

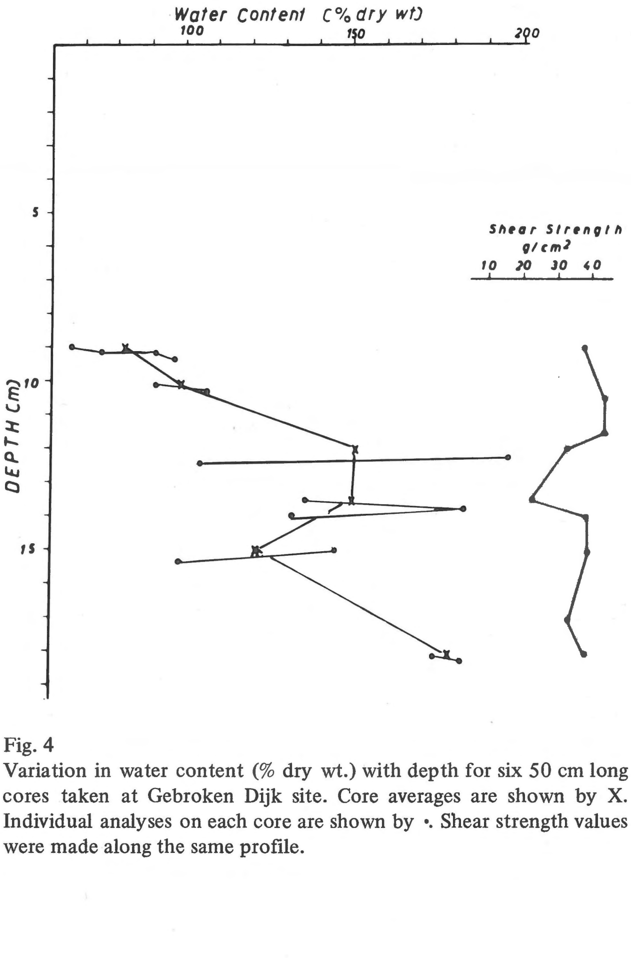

Fig. 4
Variation in water content (% dry wt.) with depth for six 50 cm long cores taken at Gebroken Dijk site. Core averages are shown by X. Individual analyses on each core are shown by •. Shear strength values were made along the same profile.

The sediments are classified for engineering purposes (Fig. 5), as "Inorganic Clays of High Plasticity." This classification utilizes the relationship between the sediment liquid limit (the water content at which the sediment first exhibits liquid behaviour) and the plasticity index (the range of water content through which the sediment behaves plastically). Atterberg limits show that the degree of plasticity of the sediments changes significantly with depth (Fig. 5). Sediments from –9 m plot closer to the line separating medium from high plasticity. Higher plasticity is found in sediment samples taken from depths greater than –13.5 m, with highest plasticity found in sediments from –18 m.

CONSOLIDATION ANALYSES

One-dimensional consolidation testing in engineering studies is used to obtain data useful in predicting rates and amounts of settlement of structures founded on clay. The data have been used by the marine geologist in geotechnical studies of recent marine sediments (Richards, 1961; Keller & Bennett, 1968; Miller & Richards, 1974); numerous studies of consolidation (compaction) of fine-grained sediments are presented by Rieke & Chilingarian (1974), and Hamilton (1976) has recently examined the phenomenon in DSDP cores.

The two most important sediment properties furnished by a consolidation test are (1) the compression index, C_c, which indicates the compressibility of the specimen, and (2) the coefficient of consolidation, c_v, which indicates the rate of compression under a load increment. Much of the interpretation of consolidation testing is based upon the void ratio versus log of pressure (e-log p) curve. The void ratio (e = volume of voids/total volume of sample) determined at the 100% primary consolidation for each load increment are plotted against that load increment to form an e-log p curve. Each sediment tested in a consolidation test will have a unique curve. For a thorough treatise on consolidation theory, the reader is referred to Taylor (1948) and Terzaghi & Peck (1948).

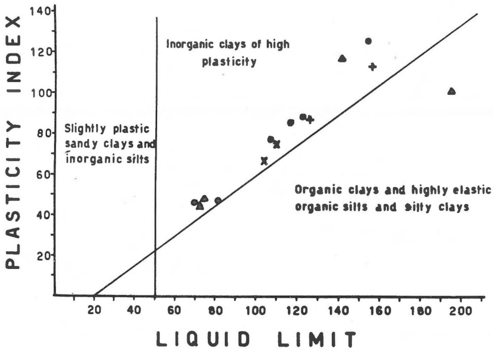

Fig. 5
Engineering classification of Gebroken Dijk sediments according to their rheological behavior. Sediment becomes more plastic down slope, with deepest samples showing highest plasticity.

	Unit Weight γ (g/cm³)	W(% dry wt)	Porosity η (%)	Degree of Saturation S_r (%)
Core 1 – Sample 1	1.24	154.4	81.9	91.9
Core 1 – Sample 2	1.23	119.3	79.2	84.3
Core 2 – Sample 1	1.21	188.1	84.4	93.5
Core 2 – Sample 2	1.35	100.8	75.0	90.5
Core 3 – Sample 1	1.23	153.2	82.0	90.5
Core 3 – Sample 2	1.37	110.6	75.9	94.7

Average Atterberg limits for the samples tested are:
W_L = 148.4 (s = 30.2)
W_P = 35.3 (s = 6.6)
I_P = 100.8 (s = 13.6)

Table II.
Mass physical properties and Atterberg limits of Gebroken Dijk cores used for one-dimensional consolidation analyses.

In June 1975, four sediment cores (50 cm long and 10 cm in diameter) were extracted from –12 m depth at the Gd locality, using SCUBA techniques. Table II shows the original water content and unit weight of each of the samples tested. One core was extruded, split, and carefully described. Three were immediately taken to the 'Laboratorium voor Grondmechanica van de Rijksuniversiteit Gent' and two samples from each core were selected for one-dimensional consolidation analysis. Figure 6 shows the intervals sampled and the resulting e-log p curves. The test apparatus was an Engineering Laboratory Equipment Ltd. fixed ring oedometer (ELE 28–205) with a 10:1 ratio position capable of loads to 144 kg. Loading began with 0.079 kg and was doubled every 24 hours to a final load of 2.528 kg/cm². The samples consolidated rapidly, averaging 11.72 minutes (s = 4.33) to achieve 90% consolidation, determined by the square root of time fitting method (Lambe, 1951). Through the duration of the tests, void ratios were reduced an average of 53.4% (s = 6.7%) ranging between 63.0% and 44.8%.

Compression indices (C_c) averaged 1.08 (s = 0.34), ranging from 0.70 to 1.62 (Table III). The virgin compression curves are generally linear, but two samples from 10-12 cm showed concave profiles, making C_c difficult to determine. Rebound is practically non-existent (C_s = 0.08, s = 0.05). The coefficient of consolidation, c_v, was determined using the square root of time fitting method and averaged 12.4×10^{-4} cm²/s (s = 19.5×10^{-4} cm²/s).

DISCUSSION

The sediments studied at Gebroken Dijk are typical of those being deposited in other anoxic regions of the Veerse Meer. The bubble texture of the sediments has a significant effect on the mass physical and engineering properties of the

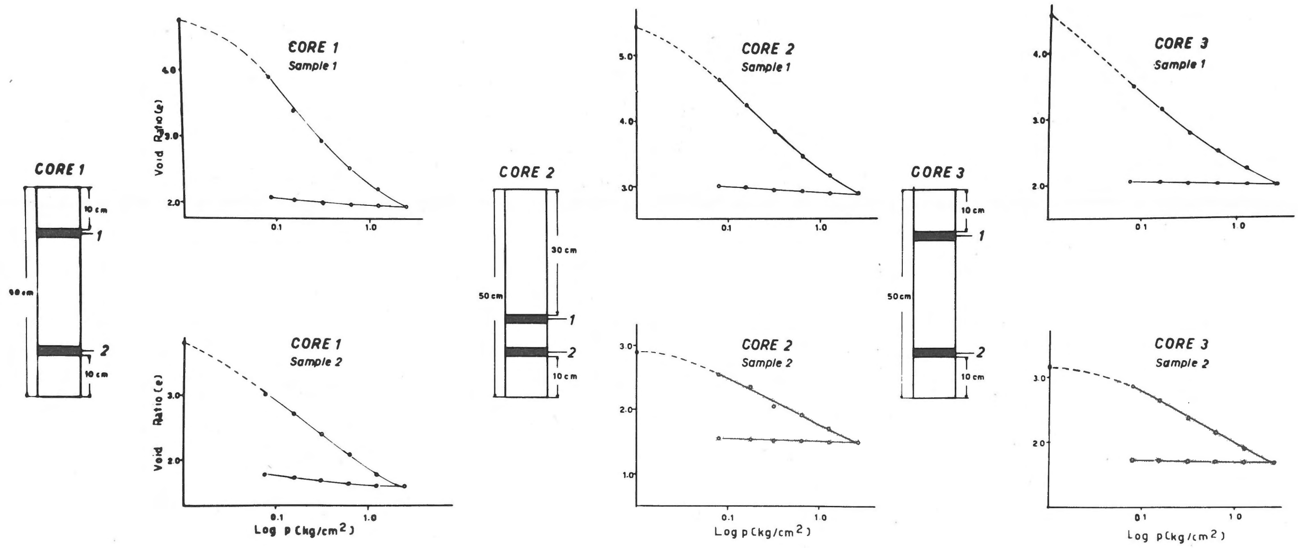

Fig. 6
Stress-strain (e–log p) diagrams for cores 1, 2, and 3 taken from –12 m.

sediments. The sediments are filled with voids, yet possess a degree of cohesion. Bubble spaces within the upper 20 cm have various dimensions, from several mm in diameter to infinitesimal size. Below 20 cm, an isotropic bubble texture is developed which continues to at least 50 cm (core length). Each void, or bubble space, is separated from its neighbour by a wall of relatively firm sediment. A moisture content gradient extends from the edge of the void towards the interior of the wall, becoming more moist approaching the adjacent void. Thus, there are "dry walls" between each void space and a horizontal anisotropic water content distribution is quite characteristic. These drier zones appear as soil "peds" and possess a blocky texture. However, upon disturbance, these drier regions rapidly acquire a smooth, "peanut-buttery" texture as water re-enters this sediment.

In general, analyses indicate the sediments possess a loose, porous structure which facilitates rapid drainage of interstitial waters. Compression appears to be totally "primary" as the virgin compression curve is linear in all but one sample. Primary compression is due to drainage of pore water, because of the hydrostatic excess pressure (Terzaghi, 1925), as opposed to "secondary" compression, a process which occurs without appreciable pressure in the pore water. The differentiation of the two forms of compression has been discussed thoroughly by Crawford (1966). In spite of the varying opinions concerning the validity of separating the two processes, this paper will utilize the classical Terzaghi concept.

The sediments from 38-40 cm possess a flatter virgin compression curve than the uppermost samples. This may be

Core	1 st.	2nd.	3rd.	4th	s 5th	6th	Avg. c_v	C_c	C_s
1-1	4.3×10^{-3}	9.1×10^{-4}	8.8×10^{-4}	6.1×10^{-4}	2.7×10^{-4}	---	13.94×10^{-4}	1.62	0.14
1-2	2.78×10^{-3}	3.78×10^{-4}	3.54×10^{-4}	4.8×10^{-4}	2.96×10^{-4}	2.33×10^{-4}	7.53×10^{-4}	1.04	0.14
2-1	6.90×10^{-3}	6.72×10^{-4}	3.92×10^{-4}	2.92×10^{-4}	3.15×10^{-4}	1.95×10^{-4}	14.61×10^{-4}	1.28	0.06
2-2	3.18×10^{-3}	5.08×10^{-4}	1.23×10^{-3}	3.18×10^{-4}	3.95×10^{-4}	1.85×10^{-4}	9.69×10^{-4}	0.70	0.04
3-1	9.43×10^{-3}	3.27×10^{-4}	7.81×10^{-4}	5.16×10^{-4}	1.31×10^{-4}	---	22.46×10^{-4}	1.03	0.05
3-2	4.67×10^{-3}	4.1×10^{-4}	6.2×10^{-4}	3.2×10^{-4}	6.3×10^{-4}	---	13.30×10^{-4}	0.78	0.05
x	5.21×10^{-3}	5.34×10^{-4}	7.10×10^{-4}	4.23×10^{-4}	3.40×10^{-4}	2.04×10^{-4}	13.57×10^{-4}	1.08	0.08

Table III.
Coefficients of consolidation (c_v), compression indices (C_c), and rebound indices (C_s) for all samples tested. Coefficients of consolidation for each loading increment are shown in columns 1-6, and the average coefficient for each core in column 7. Average consolidation coefficients for each load increment are found at the base of columns 1-6. Data are in cm^2/s.

attributed to the more uniform bubble texture and lower initial water content. In general, the consolidation coefficient, c_v, for each load increment is reduced by as much as 50% from the corresponding load increment in the higher sample, indicating a large change in the rate of consolidation (Table 3). Compression indices are similarly reduced (C_c = 1.04, 0.70, and 0.78) and the percent of void volume reduction is less (58.0%, 48.0%, and 44.8%). At this level, voids are primarily filled with water. The applied load is transferred immediately to the water-filled spaces and reduction in volume is closely related to permeability and drainage of interstitial waters.

The upper samples from each core possess e-log p curves distinctly different from the lower samples. Core 1-1 is difficult to explain inasmuch as it shows a slight reloading curve and has a concave virgin compression curve. An approximate coefficient of consolidation is 1.62, much greater than core 2-1 (1.28) and core 3-1 (1.03). The latter two samples show only a very slight reloading curve. The concave virgin compression curves (cores 1-1 and 3-1) result from initial rapid drainage into the various sized pores. Flattening of the lower part of the curve occurs after the larger pores have collapsed and the smaller, water-filled pores begin to resist the applied load. Drainage is restricted and the curve approaches linearity, similar to samples from 30-40 cm.

All samples show a significant lack of rebound. The swelling index (Table III) averaged 0.08. This is interpreted to indicate that the sediment particles are so totally disoriented that they have no capacity to develop a rigid framework upon release of load. They are inelastic with respect to their position on the Casagrande Plasticity Chart (Fig. 5) and the lack of rebound supports this.

Consolidation Coefficients

The rate of settlement of a substrate under load is dependent on the permeability of the sediment, its initial and successive void ratios, its compressibility, and the distance through which the pore water must travel. The coefficient of consolidation, c_v, relates the various parameters and is defined as:

$$c_v = \frac{K(1+e)}{a_v \gamma_w}$$

where

c_v = coefficient of consolidation
K = coefficient of permeability
e = void ratio
a_v = coefficient of compressibility
γ_w = unit weight of water

The coefficient is difficult to calculate and is usually evaluated from time-consolidation readings under each load increment. Table III shows the coefficient for each load increment.

Considerable variation is observed between load increments and between samples. In every case, the greatest rate of consolidation occurs with all succeeding loads, but they generally maintain a relatively constant rate until the final load which results in a reduced rate of consolidation. The average coefficient of consolidation is 13.57×10^{-4} cm^2/s.

Data on rates of consolidation are available for deep sea sediments taken from the Atlantic and Mediterranean (Richards & Hamilton, 1967) and some unpublished work by the senior author from the York River of lower Chesapeake Bay (Table IV).

A greater range in consolidation coefficients is seen in the Gebroken Dijk samples than for the marine and estuarine samples and the grand average is approximately 47% greater than the marine samples. The range of averages exceeds those of the marine sediments and corresponds partially with the York River, generally indicating more rapid consolidation in any case.

The differences in rates of consolidation may simply be due to the difficulty involved in testing such sediments and Richards & Hamilton (1967) have discussed the problems involved in using coefficients of consolidation for predictive purposes. However, it seems clear that real differences in sediment structure are at least partially responsible for the differences in the observed rates of consolidation. These differences may be attributed to the depositional environment from which the samples were taken. In the deep sea, a stable energy environment and low depositional rates would allow better particle alignment and packing to occur at the sea bed. Brittle bond development would be likely to occur (assuming no bioturbation) and recrystallization would strengthen the sediment and reduce permeability. Consolidation of such a sediment, depending as it does on permeability and compressibility, would be likely to be fairly slow. In the York River, the fluctuating tidal environment would create a fabric with less well-oriented particles under a greater depositional rate. Flocculated aggregates of various orders

All samples – Range:	
Richards & Hamilton, 1967	2.3 to 33.8×10^{-4} cm^2/s
York River, 1969	1.3 to 73.0×10^{-4} cm^2/s
Veerse Meer, 1975	1.3 to 94.3×10^{-4} cm^2/s
Average of Core Averages:	
Richards & Hamilton, 1967	9.2×10^{-4} cm^2/s
York River, 1969	11.9×10^{-4} cm^2/s
Veerse Meer, 1975	13.6×10^{-4} cm^2/s
Range of Averages:	
Richards & Hamilton, 1967	4.0 to 15.8×10^{-4} cm^2/s
York River, 1969	4.1 to 21.5×10^{-4} cm^2/s
Veerse Meer, 1975	2.0 to 52.0×10^{-4} cm^2/s

Table IV.
Comparison of coefficients of consolidation of samples from the deep sea (Atlantic and Mediterranean), estuary (York River, southeastern Virginia), and tideless basin (Veerse Meer).

(Krone, 1963) would impart a high degree of permeability to the sediments, at least within the upper 1-5 m until overburden pressures compacted them. The rate of consolidation should be higher for sediment from this environment than from the deep sea.

In the Gebroken Dijk sediments an additional factor, methanogenesis, is operating. Bubbles and voids exist throughout the entire sediment column, providing pathways for rapid drainage of the pore waters. In addition, the ebullition of gases prevents the formation of brittle bonds by continuous particle agitation. Expansion of gases as they move upward through the sediment into lower pressure regions may physically move sediment perticles, resulting in a dilatancy effect. Such an effect has been observed in clean sands, resulting in flowage (Monroe, 1969). The rate of consolidation of such a disoriented, permeable fabric is greater than in sediments from either deep sea or normal estuarine environments.

The e-log p analyses are similar to those made on laboratory remolded specimens, i.e., little or no reloading curve, linear virgin compression curve, insignificant rebound curve. These curves are also typical of underconsolidated sediments. Natural sediments possess both brittle bonds (recrystallization, precipitates in crystalline and gel form), as well as Van der Waals bonds (net forces of attraction between adjacent particles). Laboratory remolded sediment possess only Van der Waals bonds (Kenney, 1968). It is not possible to determine the magnitude of disturbance and breakage of brittle bonds in a natural sediment during sampling and processing of the sample. However, recognizing the problems, extreme care was taken with respect to the Gd sediments and it seems likely that some factor other than sampling disturbance has contributed to the remolded aspect of these sediments. That factor is believed to be the process of methanogenesis and the ebullition and expansion of gases which, in passing upward through the sediments (Martens, 1976) from their point of origin, disturb the sediment particles and inhibit the formation of a cohesive sediment fabric (i.e., brittle bonds), leading to an underconsolidated or remolded sedimentary deposit.

SUMMARY AND CONCLUSIONS

Study of sediments in anoxic reaches of the Veerse Meer of the southwest Netherlands supports the suggestion by Whelan (1974) that methanogenesis in fine-grained sediments leads to physical instability. *In situ* measurements of shear strength made by SCUBA divers showed a decrease downslope into anoxic waters. The greatest accumulation of sediment occurred at the base of the slope, associated with highest water contents, lowest shear strength, and the development of a bubble texture created by methanogenesis. Atterberg limits show the sediments become more plastic toward the base of the slope. The index of sensitivity (S_t) averages about 1.4, defined as "insensitive," and indicates that little difference exists between the undisturbed and remolded strength. This is attributed to a lack of "brittle" bonding and is suggested to be the result of gas generation in the sediments.

One-dimensional consolidation analyses indicate:

1. that consolidation is all primary
2. that a reloading curve is developing below 40 cm
3. that rebound is practically non-existent
4. that consolidation is rapid ($c_v = 13.57 \times 10^{-4}\ \mathrm{cm^2/s}$).

The e-log p curves represent either underconsolidated or remolded sediments. Both conditions may apply as gas generation in the upper 30 cm causes an overburden deficiency due to numerous void spaces. Below 30 cm development of a slight reloading curve may signify a decline of methanogenesis and the beginning of bond development. However, the linearity of the virgin compression curve and lack of rebound resemble remolded sediments.

Comparison of coefficients of consolidation from deep sea, and normal estuarine environments indicate the anoxic sediments consolidate more rapidly. This is believed due to the gas generation and ebullition with gas bubble expansion which inhibits geochemical bond development.

The total overall effect of methanogenesis in newly deposited sediments is to inhibit bond formation and fabric development, to a greater or lesser degree, depending on the intensity of the process. The effect of methanogenesis on previously deposited sediments is to disrupt the developed fabric through gas bubble generation and swelling and to cause weakening of the sediment.

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