22. CONSOLIDATION CHARACTERISTICS OF SEDIMENTS FROM LEG 31 OF THE DEEP SEA DRILLING PROJECT

P.K. Trabant, W.R. Bryant, and A.H. Bouma, Department of Oceanography,
Texas A&M University, College Station, Texas

INTRODUCTION

The importance of determining consolidation characteristics and associated geotechnical properties of sediments obtained by the Deep Sea Drilling Project is twofold: first, these properties provide an additional tool for the understanding of depositional processes and the history of sediment accumulation within ocean basins; secondly, the data provide engineering criteria for the design of foundations, sediment-bearing capacity, and slope-stability problems.

In recent years the geologist, studying the change of soft deep-sea sediment to indurated marine sedimentary rock, has allied himself with the field of soil mechanics to better understand certain of these processes (Hamilton, 1959). Prior to drilling the experimental Mohole off Guadalupe Island in 1961, studies of the geotechnical properties of marine sediments were limited to those recovered from shallow sampling depths permitted by standard gravity-coring devices. Project Mohole permitted such studies as those by Hamilton (1964) and Moore (1964) of the mass physical properties of marine sediments to a depth of 170 meters.

With the advent of DSDP in 1968, the possibility of retrieving samples up to 1000 meters beneath the sea floor became a reality. Although the project has elucidated many aspects of sea-floor spreading, stratigraphy, and sedimentology, very little work has been published on mass physical properties and even less on consolidation characteristics. Samples from DSDP Leg 10 (Trabant, 1972) and Leg 16 (Keller and Bennett, 1973) had been evaluated for their consolidation characteristics and associated geotechnical properties prior to the work described here.

CONSOLIDATION CHARACTERISTICS

In the fields of soil mechanics and marine geotechnique, consolidation refers to the reduction in volume of a sediment under an imposed load, while the synonymous term "compaction" is employed in geology with reference to the process of hardening or lithification of a sediment.

Twelve 15-cm-long unsliced samples were collected during Leg 31 from the Philippine Sea and Sea of Japan and were consolidated according to standard procedures as set forth in Lambe (1951). The consolidometer apparatuses were Anteus back-pressure units (Lowe et al., 1964) in which a back pressure of 7 atm was maintained on the samples throughout the duration of the tests. This permits the near-total redissolution of any gases due to the removal of hydrostatic pressure, associated with sample retrieval.

The consolidation test, in the very simplest of terms, consists of the application of a normal (vertical) load (pressure) upon a small (4.45 cm or 6.125 cm diameter) free-draining, confined, cylindrical sample of sediment. The loads are increased with time and are usually doubled at 24-hour intervals, while the rate and amount of volume decrease under each load are recorded. The results of the tests are usually displayed as a plot of void ratio (volume of voids divided by the volume of solids) versus the log of normal pressure, commonly referred to as an *e*-log *p* curve. It is this curve that serves as the basis for settlement calculations, as well as determining the preconsolidation pressure (the greatest load to which a sediment has been subjected).

Consolidation tests normally provide a means whereby the depositional history of an accumulation of sediments can be determined. In soil mechanics terminology, a deposit is said to be *normally consolidated* if the effective overburden pressure (P_o) is equal to the preconsolidation pressure (P_c). The effective overburden pressure acting on an in situ sample is equal to the difference between the overburden pressure (P_o) or stress and the pore-water pressure. The total overburden stress is the combined wet-bulk density of the overlying sediments minus the unit weight of the water. Thus, to determine the effective pressure, acting on a sample in place, one needs to know the difference between the expected hydrostatic and in situ pore-water pressure. In spite of the lack of in situ pore-pressure measurements, a good first-order approximation of the in-place effective overburden pressures is obtained as the total stress from the reported wet-bulk-density measurements.

If the computed overburden pressure is greater than the preconsolidation pressure, the sediment is said to be *underconsolidated*, that is, the sediment does not appear to have consolidated (drained its excess pore pressure) under its present load. On the other hand, if the overburden pressure is less than the preconsolidated pressure, the sediments are said to be *overconsolidated*. Underconsolidated sediments commonly occur in areas of rapid sedimentation such as deltas (Fisk and McClelland, 1959) and are expected to be associated with excess pore pressures due to insufficient time for the drainage of pore water (Moore, 1964). Sample disturbance may also produce underconsolidation. Conversely, overconsolidated sediments may be the result of the removal of overlying sediment (reduction in overburden), desiccation of sediments, unusual physicochemical interparticle bonding or cementation, or any externally applied stress.

Although most samples retrieved during Leg 31 are considered highly disturbed, 12 sediment samples, judged sufficiently undisturbed for consolidation testing were selectively collected. The samples tested were obtained from four sites two of which (293 and 298) are located in the West Philippine Sea, while the other two (299 and 302) are located in the Sea of Japan.

SITE 293

This site is located at the western edge of the West Philippine Basin. The *e*-log *p* curves for the three consolidation samples collected at this site are depicted in Figure 1 and the results are tabulated in Table 1.

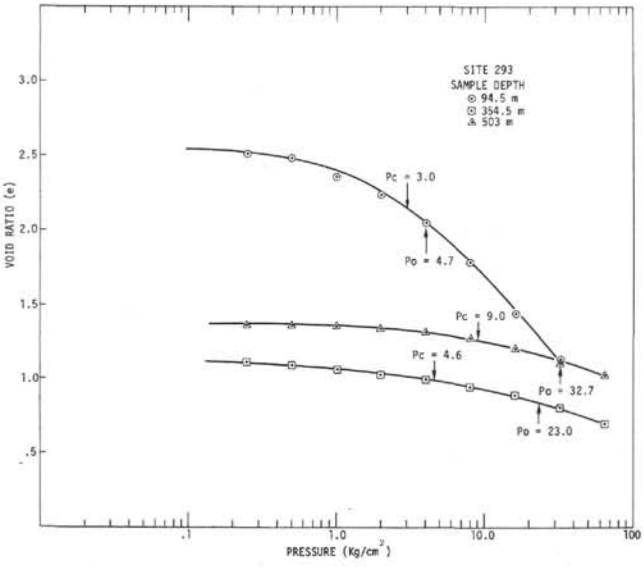

Figure 1. *Void ratio versus log of pressure curves of samples taken at Site 293.*

The estimated sedimentation rates show a minima of 12.5 m/m.y. below a depth of 400 meters, while the younger sediments display considerably larger rates (Site Report Chapter 5, this volume). The results of such high sedimentation rates are apparent in the consolidation test results, which show that all three samples tested are underconsolidated. The very high water content (83%) of the samples obtained from a depth of 503 meters is characteristic of underconsolidated sediments and is attributed to a rapid increase in overburden associated with a decrease in permeability. The degree of underconsolidation is directly proportional to depth at this site and attains a value of 23.7 kg/cm² (P_o-P_c) at 503 meters. As stated previously, this difference may be entirely or at least in part due to excess pore pressure, which, if taken into account in the computation of overburden stress, would give an *effective stress* which would be closer in value to the computed preconsolidation pressure.

The texture of all three samples from this site falls into either the silty-clay or clayey-silt range and contains only a few percent carbonate material. The sediments at this site range from late Pliocene to Recent in age.

SITE 298

This site is located at the base of the Shikoku Slope on the relatively steep wall of the Nankai Trough. The hole was drilled through structures associated with a recently rejuvenated subduction zone (Site Report Chapter 9, this volume).

The data tabulated in Table 1 and the *e*-log *p* curves of Figures 2 and 3 display the results of the four consolidation tests obtained for this site. The high sedimentation rate (428 m/m.y.) for this site, in conjunction with the compressional effects of the subduction zone, has resulted in both a highly underconsolidated sample at a depth of 131 meters and very compact overconsolidated samples at and below a depth of 397 meters. Samples from the three greater depths were early Pleistocene silty shales and displayed slickensides along a variety of plane orientations. The three overconsolidated samples

TABLE 1
Mass Physical Properties and Consolidation Test Results for DSDP Sites 293 and 298

Core-Section	Depth Below Sea Floor (m)	Specific Gravity (Solids) G_s (g/cc)	Bulk Density ρ_g (g/cc)	Porosity n (%)	Void Ratio e	Water Content ω (%)	Overburden Pressure P_o (kg/cm²)	Preconsolidation Pressure P_c (kg/cm²)
Site 293								
2-4	95	2.81	1.82	58	1.36	52	4.7	3.0
12-0	355	2.73	1.94	50	1.12	39	23.0	4.6
17-4	503	2.78	1.58	69	2.24	83	32.7	9.0
Site 298								
2-3	131	2.74	1.55	69	2.25	83	7.9	0.4
11-3	397	2.72	1.96	44	0.79	29	25.8	NA
14-2	519	2.71	1.94	45	0.85	30	33.7	NA
16-2	605	2.76	2.07	40	0.66	25	39.3	NA

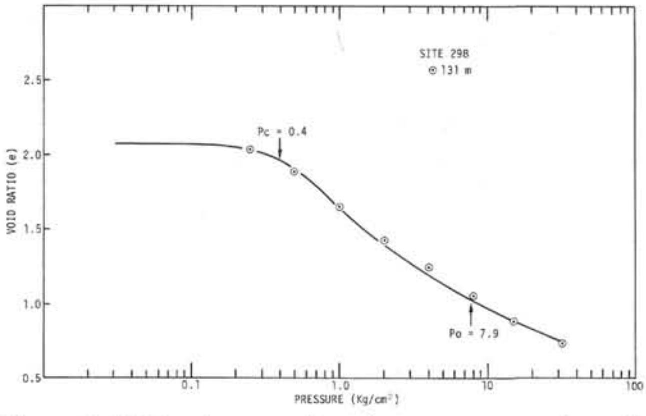

Figure 2. *Void ratio versus log of pressure curve of sample taken at 131 meter depth at Site 298.*

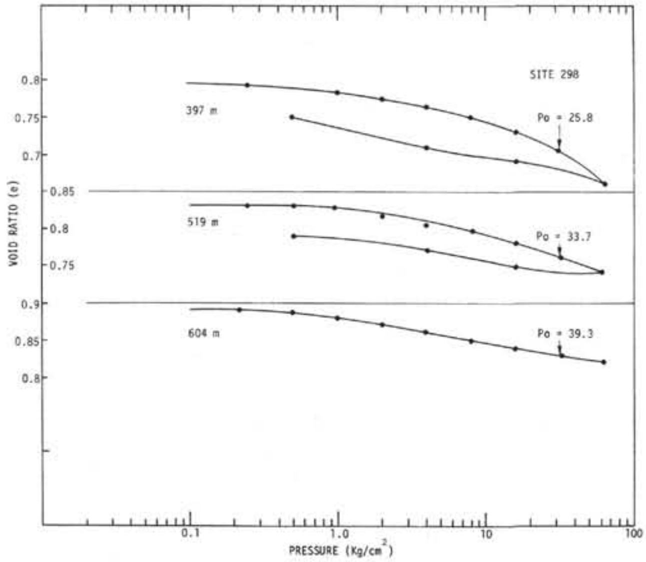

Figure 3. *Void ratio versus log of pressure curves of samples taken at 397, 519, and 604 meter depth at Site 298.*

were cored within an interval of long wavelength folding associated with the subduction zone.

The highly indurated nature of these sediments precluded the computation of a precise value for the preconsolidation pressure.

SITE 299

Drilled in the Yamato Basin of the Sea of Japan, this site penetrated 532 meters of mostly silty clays and claystones, the oldest of which were dated as late Miocene.

Only two samples from depths of 84 and 147 meters were tested. Their *e*-log *p* curves are displayed in Figure 4, while the associated physical properties are listed in Table 2. Both samples are underconsolidated which is most likely attributable to the very high sedimentation rate estimated at 200 m/m.y.

SITE 302

This site was drilled on the northern flank of the Yamato Rise and penetrated 531 meters of sediments

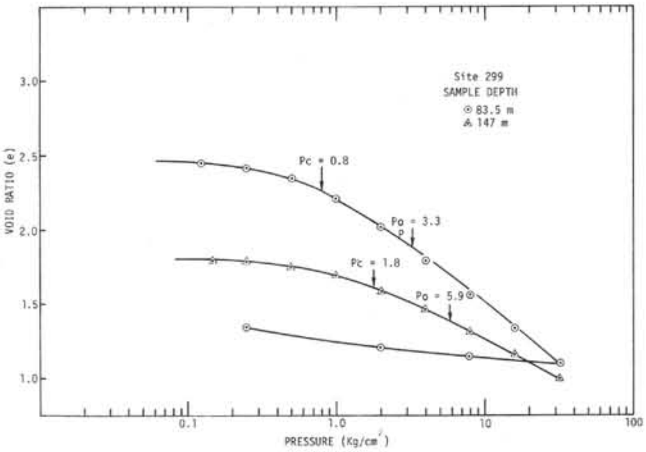

Figure 4. *Void ratio versus log of pressure curves of samples taken at Site 299.*

TABLE 2
Mass Physical Properties and Consolidation Test Results for DSDP Sites 299 and 302

Core-Section	Depth Below Sea Floor (m)	Specific Gravity (Solids) G_s (g/cc)	Bulk Density ρ_g (g/cc)	Porosity n (%)	Void Ratio e	Water Content ω (%)	Overburden Pressure P_o (kg/cm^2)	Preconsolidation Pressure P_c (kg/cm^2)
Site 299								
2-5	27	2.62	1.46	71	2.48	95	3.3	0.8
16-3	147	2.60	1.57	64	1.78	69	5.9	1.8
Site 302								
2-5	27	2.76	1.49	72	2.62	95	0.8	0.6
8-5	141	2.39	1.28	80	3.95	165	4.2	4.0
11-4	196	2.31	1.27	80	3.93	168	5.9	4.5

containing a thick sequence of diatomites and diatom oozes. Samples were obtained for consolidation tests at 27, 141, and 196 meters. The results are tabulated in Table 2, and the *e*-log *p* curves are illustrated in Figure 5.

The uppermost samples at 27 and 141 meters are normally consolidated, while the deepest sample from 196 meters is slightly underconsolidated. The unusually high water content of the two diatomaceous oozes and their odd consolidation characteristics, however, leave some doubt as to the validity of these results. During consolidation the forementioned samples displayed linear log of time versus settlement plots indicating that primary consolidation had never ceased, even after several days of testing. The sedimentation rate at this site was notably lower than those at the previous three sites described, ranging from 41 to 76 m/m.y.

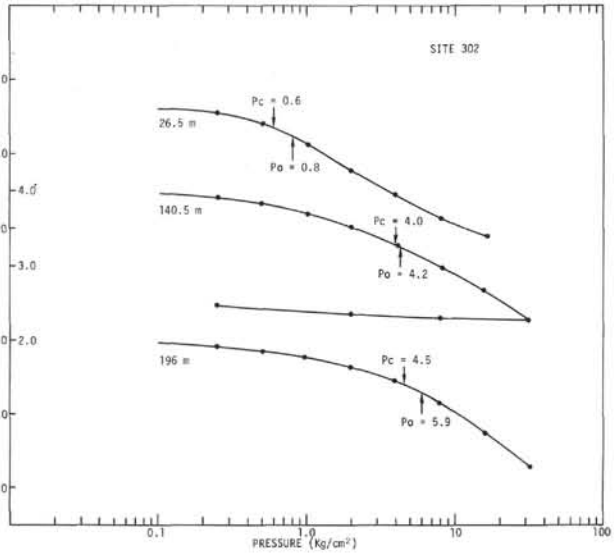

Figure 5. *Void ratio versus log of pressure curves of samples taken at Site 302.*

CONCLUSIONS

The results of previous consolidation test data by Hamilton (1964) and Keller and Bennett (1973) on deep-sea sediments showed predominantly overconsolidated characteristics on samples from depths of 140 meters or less below the sea floor. The conclusions presented by Keller and Bennett (1973) attribute extremely slow rates of deposition and great age of the sediments as the causes of their overconsolidated nature.

Consolidation tests obtained on samples from DSDP Leg 10 (Trabant, 1972) as well as for DSDP Leg 31, show that samples obtained from depths greater than about 200 meters are typically underconsolidated. Exceptions appear due to diastrophism such as the subduction zone described for Site 298, Leg 31, or salt diapirism in the case of samples from Leg 10.

Although the laboratory consolidation test may not necessarily be an ideal standard in the determination of the preconsolidated state of deep-sea marine sediments, it appears from the small amount of data collected to date, that the results are valid. Thus, incongruous or even paradoxical results such as overconsolidated or underconsolidated characteristics associated with marine sediments, which at first glance should only display a normally consolidated state, must be explained on the basis of variations in sedimentation (both lithology and rate).

The slow rates of accumulation and great age of sediments which Keller and Bennett attribute to the overconsolidated nature of marine sediments (less than 200 m burial depth) may equally be the cause for the underconsolidated nature of deeper sediments. The possible development of "rigid bonds" when sediments are initially deposited may also serve to impede the normal consolidation process and produce apparently underconsolidated material. Such an effect, coupled with the rapid reduction in permeability of shallow sediments (less than 200 m), is most probably the cause of excess pore-pressure development and underconsolidation.

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