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A LITERATURE REVIEW

BY

I. C. MACFARLANE

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An important factor in the over-all stability of any structure is the amount of compression of the subsoil that will occur when the weight of the structure is applied. For clays, a rational system has been developed for estimating the magnitude of the total and differential settlements as well as for the time required for a given amount of settlement to occur; this system is based on the Terzaghi theory of consolidation (Taylor, 1942).

A characteristic feature of highly organic soils (or peats) is their extremely compressible nature; large settlements can be produced even under small loads. Consequently, peat is not a desirable soil type on which to build roads or other structures. Until recently, construction on peat has been limited and the chief interest in peat bogs or muskeg areas has been with regard to their potential for reclamation for agricultural or forestry purposes, or in the mining of the peat for fuel or as "peat moss." Within the past 10 years or so, however, interest in peat as an engineering material has been substantially increased as a result of two major factors:

(1) The rapidly accelerated pace of northern development in Canada has required an increasing amount of construction in regions

of almost continuous muskeg cover. In the construction of roads in such regions it is seldom possible to avoid muskeg, and economic considerations often militate against excavation of the peat and back-filling with a more suitable material. The road, therefore, must be "floated" on top of the organic terrain. Consequently, the compression characteristics of the underlying peat become a matter of some importance.

(2) The second factor is related to more southerly regions where urban expansion requires the extensive utilization of formerly marginal land (such as peat bogs) for airfields, shopping centres, factories, or warehouses. Here also the question of the compression characteristics of peat becomes a matter of great importance.

Although the classical consolidation test has proven useful in analysing settlement characteristics of clays, the wide variation between the fundamental nature of clays and peats is sufficient to require an independent evaluation of its use in assessing the compression characteristics of peats. Several investigators in various countries have compared settlement predictions based on laboratory consolidation tests on peats with observed behaviour in the field. In view of the unusual nature of the material it is not surprising that the conclusions of some investigators have been at rather marked variance with the conclusions of others. One obstacle to the validity of comparing results of various investigators has been the lack of a rational (and international) system of classifying peats. All systems of classification in current use (including the Radforth system, which is used almost exclusively in Canada*) are qualitative rather than quantitative, and this is a serious limitation to investigations involving engineering characteristics of peat.

A particular area of controversy in the early literature was centred around the relative contribution to the total settlement of that phase of consolidation known as "primary consolidation" (associated with dissipation of excess pore water pressure) and that known as "secondary compression" (the plastic deformation phase). This controversy developed largely as a result of the difficulty in estimating when the primary phase was completed and when the secondary phase began. The relevant literature on laboratory compression tests and field settlement observations of peat extends over the past 25 years. About two thirds of the papers examined that refer to consolidation and settlement characteristics of peat, however, have been written in the past 5 years. A trend towards some unanimity of opinion is only now being established.

One of the earliest investigators to study the compression characteristics of peat, Buisman (1936) considered consolidation of peat to include a large "secondary" or "secular" effect. He observed that for laboratory peat samples of 2 cm (0.75 in.) thickness the settlement -- log time curve became a straight line about one minute

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* "Guide to a Field Description of Muskeg (based on the Radforth Classification System)". National Research Council, Assoc. Comm. on Soil and Snow Mechanics, Tech. Memo. 44, Ottawa, 1958.

or a few minutes after loading and remained a straight line throughout the test. The slope of this line increased for higher temperatures. Buisman also noted that the settlement -- log time diagram for a road embankment (observed over a 2-year period) was a straight line. He concluded that laboratory consolidation is composed of a combination of "direct load effects" and "secular time effects," the magnitude of the latter depending upon the test procedure.

Another early investigator, Ringeling (1936) investigated the settlement characteristics of a peat layer 2 to 3 metres (6-$\frac{1}{2}$ to 10 ft) thick beneath a projected road. He determined both the rate of compression under the fill load and the time at which consolidation would be complete. Laboratory consolidation tests were carried out on several peat samples and an experimental road section was constructed to check actual settlement against that predicted from test results. Settlements of the test fill did not agree with computed settlements, being less for the lower loads and greater for the higher loads than those predicted. Ringeling also measured pore water pressures beneath the test fill and noted that immediately following loading of the peat, about 75 per cent of the load is taken by the pore water. He pointed out that despite the low permeability of the peat, pore water pressures decreased practically immediately.

Van Mierlo and Den Breeje (1948) also indicated that the so-called "secular" effect is responsible for an appreciable part of the total settlement of peat. This secular effect had to be taken into account in calculating the rate of settlement of a sand fill on peat and clay in the Spangen Polder. Laboratory compression tests on the peat showed a straight line relationship between settlement and log time. The average coefficient of permeability of the peat tested was 1×10^{-5} cm/sec.

Ward (1948) reported on an investigation into an embankment slip failure on peat. The water content of the peat varied from 800 to 1000 per cent, the specific gravity, 1.2 to 1.5. Laboratory consolidation tests on 2-in.(5.08 cm) thick samples were carried out; the samples never fully consolidated although all loads were left on for a week. The predicted settlement -- log time curve assumed a straight line, but the values were on the low side. Actual settlement of the peat under the embankment was 4 ft (1.22 m) in 2 years, about double the predicted value.

Colley (1950) carried out one-dimensional (4.25 in. (10.8 cm) diameter sample) as well as triaxial consolidation tests on peat, which had an average moisture content of 728 per cent, an average organic content of 83 per cent, and an initial void ratio range of 4.6 to 10.3. The triaxial apparatus was arranged with a scale-size sand drain installed in the centre to observe its effect on the rate of consolidation. Colley reported that the sand drain increased the rate of consolidation by 12 times, in contrast to the observations of various other investigators who found that vertical sand drains do not increase the rate of consolidation in peat. Colley measured the permeability of the peat, which averaged 0.3 ft/day (1.059 x 10^{-4} cm/sec), in the vertical direction and in the horizontal direction it ranged from 0.2 to 1.3 ft/day (7.06 x 10^{-5} to 4.59 x 10^{-4} cm/sec).

Thompson and Palmer (1951) reported on a fairly comprehensive series of consolidation tests on a black fibrous peat ranging in natural moisture content from 239 to 341 per cent, dry weight range of 14.5 to 20.8 lb/cu ft (232.3 to 332.2 kg/cu m), specific gravity range of 1.80 to 2.04, and initial void ratio range of 5.1 to 6.7. Consolidation specimens were 2 in. (5.08 cm) in diameter and 1/2 and 1 in. (1.27 and 2.54 cm) thick. It was not possible to draw an e-log p curve for these specimens to determine the preconsolidation load. The authors could see no line of demarcation between primary and secondary consolidation in laboratory tests and postulated that the primary phase, if it exists, is apparently completed in less than one minute. When observed settlements were plotted against log time, an approximately straight line was produced. Laboratory specimens also showed no tendency to deviate from a straight line. This line extended from one minute to approximately one day, changing to another and steeper straight line from one day until the end of the test. Thompson and Palmer observed that the rate of consolidation of peat is independent of the distance of flow of the pore water and consequently concluded that it is futile to attempt to stabilize peat with vertical sand drains.

In his pioneer work on the engineering properties of peat, Hanrahan (1952, 1954) carried out various physical and mechanical tests on peat with the following general characteristics: water content range - 280 to 1450 per cent, specific gravity - 1.2 to 1.7, dry density - 4.0 to 7.5 lb/cu ft (64.1 to 120.1 kg/cu m) and initial void ratio - 9 to 25. Hanrahan performed a number of small- and large-scale consolidation tests and observed that the curve of settlement plotted against time bore little resemblance to the theoretical curve. He attributed the discrepancy to various phenomena, including the abnormally large decrease in permeability that accompanied the application of load, the decreasing coefficient of compressibility, and thixotropy. High surface activity and adsorption properties of peat also contributed to appreciable secondary consolidation. The compressibility of peat was observed to be temperature sensitive, agreeing with Buisman's (1936) observations. As a result of comparative small- and large-scale consolidation tests, Hanrahan concluded that accurate forecasts for settlement can be made by assuming that the magnitude of settlement is directly proportional to thickness and that the time of settlement varies as the square of the thickness, for a considerable period after the completion of the excess pore water pressure phase.

Shea (1955) reported that the use of consolidation tests for the prediction of settlement of levees constructed on peat had been only partially successful. The amount of settlement could be determined with fair accuracy, but the predicted length of time required for it to take place was not even approximately correct. Consolidation tests indicated 15 to 20 years for 90 per cent settlement, whereas the actual settlement took place in a few days or weeks. From settlement plates installed beneath the levees on peat, Shea observed that the total settlement came very close to the predicted 50 per cent of peat thickness, but that practically 100 per cent of this settlement occurred during construction. This latter observation is at variance with the findings of most other investigators.

Cook (1956) presented a compilation of test data to show that a relationship exists between the moisture content and the "coefficient of compressibility" of a wide range of soils from pure peat to organic clay silts in the Vancouver area. He also shows that there is a relationship between the moisture content and the specific gravity, initial void ratio, and submerged weight of these soils. He suggests that these simple relationships permit the calculation of expected settlements without the trouble of lengthy consolidation tests.

Lewis (1956) concluded from his consolidation tests on peat (1 in. (2.54 cm) thick samples, average water content 580 per cent) that 100 per cent primary consolidation was about complete within the first 10 minutes. Much of the consolidation was observed to be of a secondary nature, a fact that was attributed to plastic deformation, or creep, with the rate of movement a function of many factors such as the nature of the material, the magnitude of the applied stress and the temperature.

Although it was not possible to calculate rates of settlement, from results of long-term consolidation tests Lewis estimated the ultimate value of settlement to be expected in the field. This agreed closely with subsequent observations.

Brawner (1958) noted that for field observations of a fill on muskeg, graphs of settlement versus log time (in days) were essentially straight lines for the period following construction. He concluded that the settlement was principally secondary over this period. The rate was very uniform, ranging from 1.2 to 1.4 ft per log cycle of time. The rate and magnitude of settlement were observed to be almost identical for sections of the road with and without sand drains, so that the sand drains did not accelerate the rate of the settlement to any great extent. It was concluded from this that the rate of consolidation of the peat was independent of the length of the drainage path. Inlater reports, however, Brawner (1959, 1961) suggested that the consolidation of peat may be largely primary rather than secondary. Piezometers installed beneath a roadway fill on DEI muskeg (average water content of the peat = 1396 per cent, specific gravity = 1.61, initial void ratio = 24.8) indicated that primary consolidation of peat extends well into what is normally considered to be the secondary phase of consolidation, with the transition taking place at about 25 days. Brawner considered that the magnitude of the settlement varies as the thickness of the peat layer, and that the rate of settlement varies as the square of the thickness. Subsequent investigations, however, necessitated a revision of these conclusions.

Hillis and Brawner (1961) pointed out that some of the misunderstanding regarding the process of settlement within a peat layer had been caused by the fact that significant pore pressures had been observed in peat for a long time after settlement had become directly proportional to log time. They expressed doubt as to the validity of these pore pressure measurements because of inadequacies of the piezometers used; and noted that for both field and laboratory observations the settlement of most peats continues as a straight line on a semi-log plot after a relatively short time. The initial process is compared to the usual primary consolidation associated with inorganic clays where the rate of settlement is a function of the decrease in pore water pressure. For peat this is qualified, however, by heterogeneity, the presence of gas in the peat, and the remarkable decrease in permeability with increase in stress. After the pore pressures have dissipated, and probably for some time before, the secondary compression phase of settlement occurs, The rate is independent of drainage conditions and thus theoretically independent of the thickness of the peat layer. Hillis and Brawner suggested that the primary phase of consolidation in the field can be calculated from the laboratory void ratio-log pressure curve, and recommended that each load increment be permitted to remain in the sample for only about 30 minutes. Long-term tests can be run to define the secondary stage. The secondary consolidation is determined from the formula: $S_{sec} = C_{sec} . H. \log t_2/t_1$ where C_{sec} is the coefficient of secondary compression and is the slope of the straight line portion of the e-log t plot, H is the thickness of the layer (after primary settlement is completed), t_1 the time of primary settlement, and $t_2 - t_1$ the time over which it is desired to calculate secondary settlement. The total settlement at a given time can be obtained by adding the settlements for the primary and secondary phases. Hillis and Brawner stated that sand drains do not have a beneficial effect in peats.

Lea (1958) pointed out that for peat soils, where the coefficient of consolidation is not a constant but may vary as much as 100 times in the common range of pressures, some modification must be made to the theoretical analysis of the non-steady flow condition. He suggested that the basic principles of laminar flow would be applicable and that studies of primary consolidation of peat should be based on these general principles rather than on the mathematics of the Terzaghi theory. Lea considered that primary consolidation is a much more important factor in peat consolidation than is generally believed. The rate of volume change of peat under load is affected by a variation of strength with time and a gradual crushing of cells and slipping of fibres. Lea and Brawner (1959) carried this thinking a step further and advocated a fresh approach to the analysis of peat consolidation: to assume that consolidation is primary and that Darcy's Law applies. They suggested that calculations of settlement in peat can be determined by direct proportionality between laboratory tests and field predictions. They used the square rule to estimate the time rate of settlement and reported reasonable agreement between the rates of settlement in a test section and laboratory tests.

In a more recent paper Lea and Brawner (1963) report, however, that additional information does not support the view that the time to 100 per cent primary consolidation is proportional to the square of the thickness; rather than the exponential "i" is closer to the power 1.5 than it is to 2 as for the classical theory. They report that both laboratory and field time curves usually show the characteristic "S" shape on semi-log paper and indicate that it is usually not difficult to establish 100 per cent primary consolidation. Secondary settlement follows a straight line on a semi-log plot of time settlement. Records are assembled to show that laboratory tests give a reliable estimate of magnitude of settlement. The magnitude of secondary compression (S_{sec}) was computed from the formula already referred to (Hillis and Brawner, 1961): $S_{sec} = C_{sec} \cdot H \cdot \log t_2/t_1$. The rate of secondary compression was found to be much greater in the field than in the laboratory by a factor of up to 5. Values of C_{sec} were observed by the authors to depend to a substantial extent upon the load history of the deposit and the magnitude of the load. Lea and Brawner also point out that rebound can be quite a significant matter in the removal of surcharge - from 15 to 35 per cent of the settlement upon full removal of load. They found also that, in general, the field rebound is about double the laboratory rebound. They suggest that this may be a result of elastic rebound plus gas expanding and coming out of solution.

In their comprehensive report on a study of vertical sand drains, Moran et al. (1958) considered in some detail the consolidation characteristics of organic soils, including peat. They indicated that the effects on consolidation of gas in the pore spaces (caused by decomposition of organic matter) are quite significant: (1) when load is applied, compression of the gas may cause a delay in the response of pore pressures to a change in boundary water pressures; (2) when loading has been completed, expansion of the gas will decrease the rate of consolidation. The effect of gas on time-settlement curves is similar, therefore, to the effect of secondary compression, and care must be exercised to distinguish between these two effects. In the authors' view, almost all of the primary consolidation under a particular load is completed before an appreciable amount of secondary compression takes place, so that practically no excess pore pressures exist during secondary compression. The magnitude of secondary compression, compared to the magnitude of primary consolidation, varies with soil type, state of stress and temperature and is maximum for highly organic soils. Relative proportions of the two phases of settlement are said by the authors to be approximately independent of the magnitude of effective stress for stresses in excess of the preconsolidation value. The magnitude of settlements resulting from secondary compression was calculated from the formula: $\Delta H_{sec} = C_\alpha \cdot H_t \cdot \log t_{sec}/t_p$, which is essentially the same as that used by Hillis and Brawner (1961) and Lea and Brawner (1963). C_α is the coefficient of secondary compression and is equal to the amount of secondary compression per unit thickness of soil occurring in one cycle increment of time. The rate of secondary compression is independent of the permeability of the soil and of the coefficient of consolidation as is the rate per unit thickness at which secondary compression occurs also independent of thickness. Laboratory consolidation tests to determine the effect of preloading on secondary compression indicated that although preloading may not completely eliminate settlements due to secondary compression, they reduce them to very small values.

Root (1958) considered that settlement analyses of peat by the conventional methods developed for clays are not always reliable. He questioned whether primary consolidation can be identified in the consolidation tests of peats. If there is primary consolidation he believed that it takes place during the very early stage of the test and is completed in 1 to 10 minutes. The initial permeability of peat before loading is relatively high but diminishes rapidly as the peat is compressed. Root suggested that at some time subsequent to completion of the initial "primary consolidation" the permeability of peat may decrease to a point where the rate of consolidation is influenced or controlled by the dissipation of pore pressure. In the field, the rate of settlement greatly diminishes a short time after loading of the fill is discontinued, thereafter following a straight line on a semi-log plot. Root reports that the slope of the line varies markedly even between points where fill loads are comparable and the moisture content and thickness of the peat layer appear to be the same. Root also pointed out that the rate of settlement is not proportional to the thickness of the peat layer. Long-term consolidation, which is proportional to log time, he considered due to possible plastic deformation or slow structural failure of peat fibres. It was found that sand drains did not accelerate settlement in peat, but did effect an increase in its shear strength during construction.

Tressider (1958) pointed out that the first phase in the consolidation process in peat is governed by the rate at which the water can escape from and through it. This is predominantly a hydrodynamic phase and the time of consolidation varies as the square of the length of the drainage path. The time involved for this first stage varies, but he noted that it is often very lengthy and may continue for many years in deep peats. Tressider stated that the second phase continues at a rate independent of the drainage process and thickness of the peat layer. This occurs simultaneously with primary consolidation, but continues long after primary consolidation has ceased. Laboratory samples were observed to compress slowly for years under load. He pointed out that the permeability of peat decreases significantly during the consolidation process; and also stated that there is very little rebound in peat when consolidation is complete and the load removed.

Anderson and Hemstock (1959) observed that for a test fill on FI muskeg (with peat ranging from non-woody fine fibrous to amorphous-granular) initial or primary consolidation takes place within a matter of days. This was indicated by the observed excess pressures being dissipated at an 8-ft depth in 3 to 4 days under a load of 0.2 ton/sq ft (0.195 kg/sq cm). Settlement, in addition to this initial amount, continued at a rate proportional to log time, as was confirmed by laboratory consolidation tests. Anderson and Hemstock considered that this secondary compression is independent of drainage, but influenced by the soil type and by the state of stress. Settlement for the first several weeks under the loading conditions noted above was 0.11 ft per ft of depth per log cycle of time. On the other hand, field observations of settlement gauges under oil tanks on ABI muskeg indicated a rate of secondary consolidation of 0.017 ft per ft of depth per log cycle of time, for a load of 0.15 tons/ft^2 (0.15 kg/cm^2).

Zegarra (1959) reported on consolidation tests carried out on a very fibrous tropical peat (water content range 719 - 795 per cent, specific gravity 2.1, organic matter 27.8 per cent). He pointed out that unless the vegetal fibres were broken during loading, the peat would regain its original volume after removal of compressive load if no restraint were placed on the rebound. This was not too evident from the e - log P curves; the discrepancy was attributed to side friction. Settlement -- log time curves did not produce the usual straight-line portion (for times up to 1000 min) but all the curves are slightly convex down for all load increments except the final one of 3.5 tons/ft^2 (3.42 kg/cm^2)

when the curve has a slight tendency to flatten.

Keene (1960) found that for Connecticut upland and tidal peats settlement estimates based on consolidation tests agreed quite well with field observations. Preconsolidation load obtained by the Casagrande method gave close agreement with the calculated overburden load for normally consolidated peat, and settlement calculations from the virgin compression portion of the e-log P curve were confirmed by observed settlements. Rates of consolidation presented a more difficult problem. Keene noted from laboratory and field observations that when primary consolidation is almost complete, secondary consolidation proceeds as a straight line on a settlement -- log time graph. The slope of the secondary line gives a settlement in one cycle of time of about 10 to 20 per cent of the primary settlement. Keene pointed out that it is often difficult to determine from the data at what point the primary settlement is about completed and the secondary settlement has begun.

Carrying out field and laboratory tests on Scottish peats (average water content = 800 per cent), Lake (1960, 1961) found that vertical sand drains did not effect a significant increase in rate of settlement, although they did increase the rate of excess pore water pressure dissipation. Laboratory tests also indicated that the rate of dissipation of excess pore water pressure was affected by the length of the drainage path, conforming to the Terzaghi square law. He noted that except for the first increment of load, the rates of settlement of the laboratory samples one minute after loading were largely independent of the length of the drainage path. Lake observed that for both small-scale field tests and laboratory tests the settlement -- log time curves were not linear - contrary to the observations of most other investigators. For a 3-in. (7.62 cm) diameter sample, 0.5 in. (1.27 cm) thick, settlements that took place after pore water pressures returned to normal varied from 39 per cent of the total after the first load increment to 81 per cent of the total after the final load increment.

From his research on Japanese peats (water content range 300 to 1000 per cent; organic matter content range 50 to 95 per cent; dry density range 5.0 to 15.5 lbs/cu ft (80.1 to 248.3 kg/cu cm)), Miyakawa (1960) found that from a fairly early stage settlement became a straight line with relation to log time, both in laboratory tests and in the field. He suggested that the amount of primary settlement could be predicted from the ordinary consolidation test with a 24 hour loading period, which contrasts with the 30 minute loading period recommended by Hillis and Brawner (1961). Mayakawa calculated the magnitude of total settlement from the equation: $\delta = a + b \log (t/t_o)$, where "a" is the settlement of the primary phase, "b" is the rate of settlement of the secondary phase for one cycle of log time, "t" is the elapsed time, and "t_o" is the time for the primary phase. The coefficient of secondary consolidation, C_s, is equal to b/H, where "H" is the thickness of the compressible layer. He found that C_s increased with stress for loads less than the preconsolidation load, after which it showed no direct relationship. Miyakawa also indicated that C_s can be shown to vary directly with the moisture content of the peat. He doubted that sand drains would be effective in accelerating settlement in peats except in the primary stage of consolidation.

Adams (1961) concluded from early tests on woody, fine fibrous peats (water content range from 375 to 430 per cent; specific gravity range from 1.62 to 1.70; ash content range from 12.2 to 22.5 per cent) that the consolidation of peat is predominantly due to the expulsion of water under excess hydrostatic pressure. A large proportion of the settlement takes place very rapidly when the material is relatively pervious. With time the permeability is reduced with a corresponding reduction in the rate of settlement. He reported that an increase in load resulted in a significant reduction in voids volume and in permeability, changing from approximately 1×10^{-1} ft/min (5.1×10^{-2} cm/sec) at zero load to 1×10^{-6} ft/min (5.1×10^{-7} cm/sec) at 2.89 kg/cm^2. Adams considered that the consolidation occurring under excess pore pressure was extended to relatively long-term compression by this large reduction in permeability. He estimated that approximately 90 per cent of the consolidation was due to expulsion of water under excess hydrostatic pressure. In a more recent paper, however, Adams (1963) reported that for peat samples 8 in. (20.32 cm) in diameter and 3.8 in. (9.65 cm) thick there was an initial settlement of relatively large magnitude which occurred in a very short period of time (5 min). The long-term settlement occurred relatively slowly and was linear with log time. Excess pore pressures were dissipated during the initial consolidation period, although a residual excess pressure of low magnitude remained and showed only a slight reduction with time. On the basis of these laboratory tests and the results of field instrumentation, Adams has concluded that the consolidation of peat occurs in two separate stages: an initial or immediate stage and a long-term stage, which continues indefinitely at a slow rate. Available data indicate that the magnitude of the initial settlement and the rate of long-term consolidation bear a predictable relationship to the applied load and the thickness of the peat. Adams suggests further that the initial consolidation is due to the expulsion of the pore water in the peat mass, and that the long-term consolidation is due to the expulsion of the water in the solid matter. This is essentially the same conclusion as that reached by Evgen'ev (1961).

Barber (1961), in an effort to determine the cause of secondary consolidation, carried out a rather extensive series of laboratory tests on various organic materials, including peat, using 2-in. (5.08 cm) diameter, 0.5-in. (1.27 cm) thick samples. Tests on desiccated, air dry and wet materials indicated that the seat of secondary consolidation is in the hygroscopic moisture. Barber noted that for a specified loading increment for a peat sample, the typical S-shaped primary consolidation phase was essentially complete in 0.1 day. Linear extension of the secondary consolidation beyond the 1-day record considerably under-estimated the consolidation at 100 days. Barber suggested that secondary consolidation may also produce an S-shaped curve somewhat like that of primary consolidation, but extending over more log cycles of time. He showed that an increase in load tends to accelerate the rate of secondary consolidation and to reduce the magnitude of the long-term settlement.

Evgen'ev (1961) concluded from an analysis of numerous consolidation tests that deformation of peat under load consists basically of two phases: (1) deformation due to squeezing out of water from the open macropores and (2) deformation resulting from the squeezing out of water from the closed pores. In the first phase, the movement of water follows Darcy's Law and compression proceeds very quickly even under small loads. The amount of consolidation varies considerably, depending upon the loading history of the peat and the disturbance of the sample. Evgen'ev found that deformation in this phase amounted to 75 to 90 per cent of the total settlement. The amount of deformation in the second phase is believed to depend basically upon the degree of decomposition of the peat and varies within rather narrow limits for a given type. Evgen'ev presented tabulated data for the amount of deformation to be expected in the second phase for various peat types and loads. He suggested that for calculations not requiring great accuracy the second phase can be ignored and the settlement of the first determined by a relatively rapid method involving application of load increments every

24 hours rather than at the end of consolidation. Evgen'ev observed that when the load was removed from peat samples they rebounded almost exactly to the deformation stage of the beginning of the second phase, from which he concluded that the second phase is completely elastic deformation.

Mickleborough (1961), in describing the performance of embankments constructed on muskeg, stated that the magnitudes of primary settlement were found to be somewhat less than had been predicted on the basis of laboratory consolidation tests. He reported that the trend on the time-settlement curve for field conditions indicated that for the muskeg under consideration (depths up to 8 ft (2.44 m)) the major portion of the secondary compression would take place in the first 3 or 4 years after completion of the embankment.

Ripley and Leonoff (1961) reported significant differences between the observed behaviour of peat and the predicted behaviour computed by conventional theoretical analyses based on field and laboratory test results (amorphous granular peat with woody fine fibres; average water content = 1000 per cent). The data from long-term laboratory consolidation tests (both one dimensional and triaxial) indicated that long-term settlements occurring during the period normally attributed to secondary compression may amount to 50 per cent of the total settlement. Their field settlement measurements revealed a high rate of continuing long-term settlements. Settlements of raft sections of an embankment where no fill load had been placed for 3-1/2 years were observed to be continuing on a straight line relationship at a relatively steep slope.

Goodman and Lee (1962) considered that the classical consolidation theory predicts the magnitude of expected settlements of peat rather well, although the rate of consolidation in theory and practice do not agree. Their conclusions were based on experience with peaty soils in the Syracuse, New York area (water content range 282 to 403 per cent; initial void ratio range 5.23 to 5.48; specific gravity 1.51 to 1.62; organic content 42.5 to 75.2 per cent). In contrast with most other investigators, Goodman and Lee believed that relatively minor effects would result from secondary compression, since their observations indicated that most of the settlement of structures on peat appeared to have taken place shortly after construction.

Schroeder and Wilson (1962) carried out an extensive series of consolidation tests on partly disturbed peat samples with initial void ratios varying from 40 to 10. The initial heights of the specimens ranged from 0.5 in. to 25 in. (1.27 to 63.5 cm), and were consolidated under loads of 0.5 to 20 psi (0.035 to 1.406 kg/cm^2). They observed that the settlement -- log time curves for peat had characteristics similar to clay consolidation curves for the first increment only. For succeeding load increments the time graphs were either straight lines or slightly curved downwards at the beginning. Points of zero pore pressure occurred at various positions on the straight-line portion of the time-settlement curves owing to differences in drainage paths, but were observed to have no effect on the curves themselves. Schroeder and Wilson concluded from their test results that secondary consolidation and, consequently, plastic or viscous time relationships are more important for peats than for clays, at least for a load increment ratio of unity. A second series of tests was carried out using samples taken from one large undisturbed specimen and all samples having the same drainage path. These samples were examined and analysed on the basis of rheological principles. From this they concluded that consolidation characteristics of peat are governed by: (1) variation in the material; (2) drainage conditions; (3) load increment ratios; (4) range of void ratios; (5) stress and strain history; and (6) viscous or plastic resistance to flow. In a more recent report, Wilson (1963) described a series of large-scale consolidation tests (25 cm (9.8 in.) diameter by 75 cm (29.5 in.) high) carried out on disturbed amorphous granular peat to measure the pore water pressures during consolidation. These tests showed that the pore water pressure, immediately after loading was considerably less than the theoretical value, and that it then increased to a value slightly less than the theoretical value during the early part of the test. Wilson compared the theoretical and experimental U/T curve and reported that the plastic structural deformations took place at a rapid rate in the early stages of consolidation as a result of a decrease in pore water pressure with consequent increase in effective stress.

Tests conducted with identical loads on samples of different heights showed that the timesfor the dissipation of excess pore water pressures conformed to the Terzaghi theory relating length of drainage path to time. Due to structural deformations, however, the rate of settlement or change in void ratio did not conform to the theory.

Wahls (1962) reported on an experimental study of the primary and secondary consolidation characteristics of a calcareous organic silt, the results of which may be applied generally to some peats. Both undisturbed and remoulded samples were used. From his experimental results he concluded that the coefficient of secondary compression C_α, is dependent on the void ratio (and, consequently, on the total pressure) and independent of the magnitude of the pressure increment and pressure-increment ratio. The coefficient of secondary compression, C_α, represents the maximum rate, with respect to log time, at which secondary compression occurs during a pressure increment. During primary consolidation, secondary compression is occurring at a rate that is not linear with respect to the logarithm of time. The time required for the rate of secondary compression to approach C_α is directly related to the time required for completion of primary consolidation.

As the pressure-increment ratio is reduced, the shape of the compression-logarithm of time curve differs more radically from the theoretical curve for primary consolidation.

For sufficiently small pressure-increment ratios ($\Delta p/p_o < 1/3$) the time at which primary consolidation is completed cannot be found by the conventional Casagrande method. In such instances, the maximum slope of the curve during primary consolidation is less than the final secondary slope, and thus there is no inflection point on the curve. As the pressure-increment ratio is reduced, the time required for the completion of primary consolidation, as measured by the coefficient of consolidation C_v, increases. Wahls concluded, therefore, that:

(a) investigations of secondary compression effects are simplified if small pressure-increment ratios are used, and

(b) the use of laboratory tests with $\Delta p/p_o = 1.0$ in the analysis of practical problems for which the field pressure-increment ratio is much less than one may lead to unconservative conclusions. In such cases the secondary effects will have greater significance in the field than in the laboratory.

As the observed behaviour of a soil exhibiting considerable secondary compression cannot be explained by classical consolidation theory, Wahls proposed a new mathematical model for the consolidation process. This model is used to explain the effect of pressure-increment ratio and to analyse time-compression curves when secondary compression predominates.

SUMMARY

From this study of the literature, certain conclusions may be drawn on which there is fairly general (although not necessarily universal) agreement. These are as follows:

(1) In general, field and laboratory time-settlement curves for peat on a semi-log plot show initially the characteristic "S" shaped curve, although it is not as clearly pronounced as for inorganic soils. It is usually difficult to define any clear demarcation between the end of the primary consolidation phase and the beginning of the secondary compression phase.

(2) In the laboratory primary consolidation occurs very rapidly, generally within a few minutes, and may constitute as little as 50 per cent of the total settlement.

(3) The magnitude of settlement in the primary consolidation phase varies directly as the thickness of the peat; consequently, this phase of field settlement can be predicted from laboratory tests.

(4) The time rate of the primary consolidation phase of peat compression is also proportional to the thickness. It is variously reported to be directly proportional to the thickness, proportional to the thickness to a power of 1.5, and proportional to the thickness to a power of 2. This variation may be a function of the peat type; further investigation of this possibility is required.

(5) Complete consolidation of peat is reached only after a long period of time - several months even for small specimens -

due to secondary effects.

(6) Secondary compression is considered to be of a viscous or plastic nature, its magnitude affected by temperature, the nature of the peat and the state of stress. It is independent of drainage conditions. Secondary compression is unusually high for peats and may account for as much as one half of the total settlement. The order of magnitude of field settlements due to secondary compression can be calculated from long-term consolidation tests.

(7) Secondary compression follows a straight line on a semi-log plot of time-settlement for both laboratory and field curves. The slope of this line, the coefficient of secondary compression, depends upon the load history of the peat and is influenced by the magnitude of the applied load.

(8) The coefficient of permeability of normally consolidated peat is initially very high, but it diminishes rapidly as the peat is compressed and is dependent upon the magnitude and duration of the load. The coefficient of permeability is greater in the horizontal plane than in the vertical plane, with an anisotropy ratio of about 3 to 6.

(9) If the load is fully removed during or following the secondary compression phase, the rebound may be a very significant factor to consider.

(10) Gas (caused by decomposition of organic matter) in the pores may be a factor contributing to the difficulty in interpreting time-settlement characteristics for peat.

(11) Vertical sand drains do not accelerate settlement of peat; they may effect an increase in the shear strength, however, during construction.

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