The Rates of Consolidation for Peat

Vitesse de consolidation de la tourbe

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SUMMARY

This investigation is concerned with the behaviour under load of a characteristic peat type. An examination is made of the mechanics of consolidation to determine whether the dynamics involved constitute a simple process or a multiple one with events which can be isolated. The complex botanical structure is investigated with respect to: (*a*) the way water is held within the peat and (*b*) the arrangement and size of constituents, and the influence these factors have on the rates of consolidation. In establishing a fundamental approach, tests involved only amorphous granular peat, although it is recognized that other structural types of peat might have been chosen.

When the peat samples are loaded, there is a significant change in the rates of consolidation after some time has elapsed. The fundamental e–log t graph is used as a basis for analysis, and when converted to a log (de/dt)–log t graph, the data produce curves in the form of two tangents to a short arc. These curves are parallel for variations of sample height, stress, or initial void ratio. Three series of tests were conducted where the sample height, stress, and initial void ratio were individually varied. For these tests, straight-line envelopes can be drawn tangentially to the derived curves, and can be described by three equations. This graphic representation makes it possible to construct a nomograph which can be used to predict the behaviour of this peat under load. It is indicated that consolidation is not entirely a function of the rate at which free water can be expelled from the peat but that other relationships within the peat, evidently structural, exert considerable influence.

SOMMAIRE

Cette étude se rapporte au comportement sous charge d'un type caractéristique de tourbe. On y examine la mécanique de consolidation pour déterminer si la dynamique en jeu constitue un procédé simple ou un procédé multiple composé d'évènements qui peuvent être isolés. Nous avons étudié la structure botanique complexe par rapport (*a*) à la façon dont l'eau est retenue dans la tourbe et (*b*) à l'arrangement et aux dimensions des éléments, et l'influence que ces facteurs ont sur les vitesses de consolidation. Pour établir une approche fondamentale du problème, les essais ont été faits sur de la tourbe granulaire amorphe bien qu'on reconnaisse que d'autres types structuraux de tourbe aient pu être choisis.

Quand les échantillons de tourbe sont chargés, il se produit un changement significatif dans les vitesses de consolidation après quelque temps. On emploie le graphique fondamental e–log t comme base pour l'analyse, et une fois converties en un graphique log (de/dt)–log t, les données produisent des courbes en forme de deux tangentes à un arc court. Ces courbes sont parallèles pour des variations de hauteurs des échantillons, de contraintes, et de rapports des vides initiaux. On a fait trois séries d'essais où on a fait varier individuellement la hauteur de l'échantillon, l'effort, et le rapport des vides initiaux. Pour ces essais, on peut tracer des droites enveloppes tangentes aux courbes théoriques, qui peuvent être décrites par trois équations. Cette représentation graphique rend possible la construction d'un nomogramme qui peut être employé pour prédire le comportement de cette tourbe chargée. Il semble que la consolidation ne soit pas uniquement en fonction de la vitesse à laquelle l'eau libre peut être rejetée de la tourbe, mais que d'autres relations évidemment structurales à l'intérieur de la tourbe exercent une influence marquée.

AN EXAMINATION is made of the mechanics of consolidation for a selected peat to determine the dynamics involved. The possibility of complexity arises because of the characteristic stucture of the peat which consists of macroscopic, microsopic, and submicroscopic elements, together with the interrelationship of these various elements with themselves and with the water inherent in the peat. The structure of peat, as contrasted to that of mineral soil, suggests that an approach to consolidation other than the classical should be made. This proposition is the objective of the work.

All peat is an accumulation of partially decomposed and disintegrated plant remains which have been fossilized under conditions of incomplete aeration and high water content. Physicochemical and biochemical processes cause this organic material to remain in a state of preservation over a long period of time.

The peat for this investigation was procured from a confined muskeg, as contrasted with continuous or blanket terrain, near Parry Sound, Ontario. It has an FI cover and is classified as an "amorphous granular" peat (Radforth, 1952, 1955). The letter symbols refer to a sedge-grass–moss cover common on several continents. In North America, this cover is found as far north as fifty feet from the permanent ice cap and south to the Gulf of Mexico. Unless secondary disturbance has occurred it signifies beneath it the presence of a non-woody peat, highly colloidal in its organic constitution. Predominantly the peat particles though granular lack special form, hence the amorphous granular designation.

The peat deposit was 4 feet deep and the homogeneous sample was obtained from approximately the 3-foot depth and adjacent to open water. In order to achieve reproducibility of results, the peat was remoulded by mixing. It has a natural water content in excess of 600 per cent of dry

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FIG. 1. Amorphous granular peat (magnification, 200 ×).

weight and a specific gravity of 2.0. Although the loss on ignition is only 25 per cent by weight, by volume the soil is primarily organic. Due to an infusion of mineral matter in the form of silt and fine sand, it approaches an organic silt. Under microscopic examination, the organic constituent is a mixture of commonly occurring rod-shaped diatoms (microscopic unicellular algae with silicified cell walls—see Fig. 1) together with pollen grains, spores, and microparticles in an organic colloidal matrix. The diatoms, with silicified cell walls contributing to the mineral content in the loss on ignition test, partly account for the low organic content. A small quantity of minute non-woody axes (fibres) also was observed. The constitution of the peat indicates that it accumulated within a body of water by the deposition over many centuries of enormous quantities of diatoms, airborne pollen and spores, and the somatic remains of aquatic and emergent plants and aquatic invertebrates. Concurrent with this deposition, the inwashing of mineral matter from erosion of the surrounding soil occurred. As the lake filled up, submerged anchored aquatic vegetation (e.g., water lilies and subsequent plants) obtained a footing and contributed their remains to the peat mass. Eventually the lake was filled and covered by a mat such as the present moss and sedge-grass vegetation.

In establishing a fundamental approach and an experimental technique, tests involved only remoulded amorphous granular peat although it is recognized that other structural types of peat might have been chosen.

CONSOLIDATION TESTS

The three parameters, sample height (*H*), stress (σ), and initial void ratio (e_0), are the most important factors affecting the characteristics of peat consolidation. Other factors such as temperature and atmospheric pressure have an effect but a lesser one. In order to evaluate the individual influence of sample height (*H*), stress (σ), and initial void ratio (e_0) on the consolidation characteristics, three series of tests were conducted with each of these three parameters individually varied. In these test series the sample height (*H*) was varied from 0.27 to 6.45 inches (0.69 to 16.38 cm), the applied stress (σ) from 0.45 to 7.03 lb/sq.in. (0.03 to 0.49 kg/sq.cm.), and the initial void ratio (e_0) from 8.6 to 12.4.

Consolidation tests were conducted in a 6-inch (15.24-cm) diameter cylinder, 12 inches (30.48 cm) high, with drainage to the top only; provision was made for the measurement of pore water pressures at the base. A porous stone (Norton # P2120) was fitted into the piston which was sealed to the cylinder walls by two O-rings. Loads were applied by dead weights. In all the tests, only one load was applied to each sample.

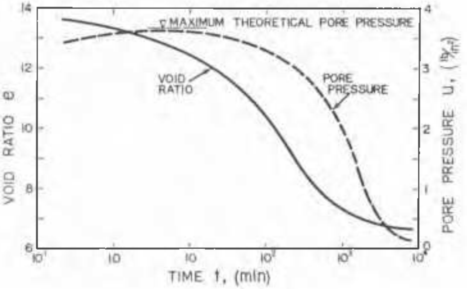

FIG. 2. Typical *e*–log *t* graph.

The data, plotted on the regular *e*–log *t* graph, are shown on Fig. 2. It indicates that the peat exhibits considerable "secondary" settlement; this is believed to be due to structural modification. On this typical *e*–log *t* graph, it is noted that the pore water pressures had unusual characteristics. The maximum pressure does not occur until some time has elapsed and does not reach the full theoretical value. This phenomenon also was observed by others (Taylor, 1942) who attributed it to the plastic resistance associated with "secondary" settlement. A further indication of "secondary" settlement is that the peat continues to settle after the dissipation of excess pore water pressures. These pore water

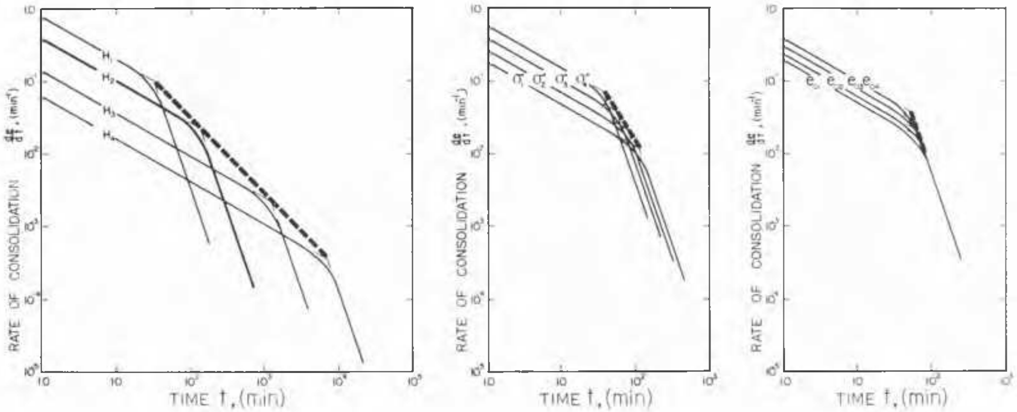

FIG. 3. Log (de/dt)–log t graphs for individual variations of H, σ, and e_0.

pressures do not reduce to zero but have a very low value as volume changes continue and, consequently, a small hydraulic gradient exists.

ANALYSIS OF RATES

The fundamental e-log t graph is used as a basis for analysis; the data are converted to rates of consolidation (de/dt) and plotted as a log (de/dt)–log t graph. Two tangents to a short arc are produced (Fig. 3). This shows that, after some time (t_t) has elapsed following loading, a significant change in the rates of consolidation occurs. The initial tangent, or "early" stage of consolidation, is analogous to "primary" consolidation; the final tangent, or "late" stage of consolidation, is analogous to "secondary" consolidation. The time at maximum curvature (t_t) is analagus to $U =$ 100 per cent, although it occurs slightly earlier than the comparable time as found by the Casagrande construction and much earlier than the time when the pore water pressure approaches zero. The rates of consolidation (de/dt) and the elapsed times (t_t) are dependent upon three parameters: sample height (H), stress (σ), and initial void ratio (e_0). On the log (de/dt)–log t graph, the curves are parallel for variations of H, σ, or e_0 (Fig. 3).

Fig. 3 shows that the sample height (H) and the stress (σ) affect the rates of consolidation in both the "early" and the "late" stages, whereas the initial void ratio (e_0) affects the rates of consolidation to some extent in the "early" stage but has no effect on the "late" stage.

The tangent portions of the curves are described by two equations, one for the "early" stage of consolidation and one for the "late" stage of consolidation. These equations have the general form:

$$\log (de/dt) = \log t^k + \log C$$

or

$$de/dt = C.t^k.$$

The two stages are expressed by:

$$\log (de/dt) = \log t^{k_1} + \log C_1 \text{ — "early" stage}$$

$$\log (de/dt) = \log t^{k_2} + \log C_2 \text{ — "late" stage,}$$

where k_1 and k_2 are the negative slopes of the lines in the "early" and "late" stages respectively; C_1 and C_2 are the intercepts on the (de/dt) axis, when $t = 1$, for the "early" and "late" stages respectively.

For variations in sample height (H) the slopes of the tangents, k_1 and k_2, are fixed for a particular sample of peat, when stress (σ) and initial void ratio (e_0) are kept constant. The initial rate of consolidation (C_1) is a function of $(H, \sigma$, and $e_0)$. As k_1 and k_2 are obtainable from consolidation tests, $C_1 = f_1\ (H, \sigma, e_0)$, and $t_t = F\ (H, \sigma, e_0)$, it is possible to determine the void ratio of peat under load at any time during the test.

To investigate the influence of the varied parameter $(H, \sigma$, or $e_0)$ on the log (de/dt)–log t graph, the tangents

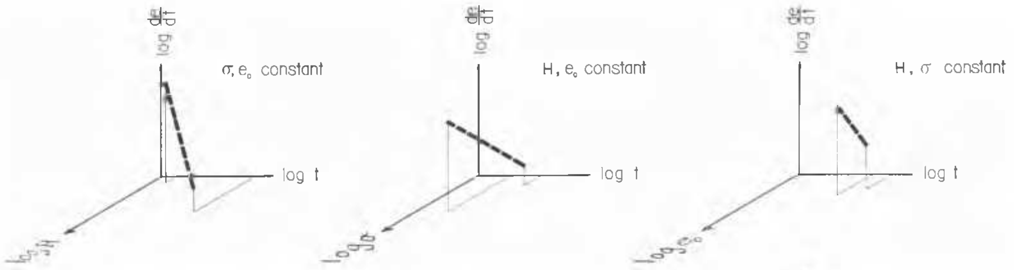

FIG. 4. Three-dimensional log-log-log graphs for individual variations of H, σ, and e_0.

for the "early" and "late" stages are produced to the intersection point (t_t). A straight line is drawn through these intersection points for each test series. This line relates the elapsed time (t_t) to the significant change in rate of consolidation both to the rate of consolidation and to the varied parameter (H, σ, or e_0). For each varied parameter, this line can be plotted on a three-dimensional log-log-log graph and again a straight line relationship exists (Fig. 4). The data for the three tests series, with individual variations of H, σ, and e_0, were checked graphically and were within the range of experimental error.

Using these graphs which indicate that the consolidation characteristics can be described in analytical terms or by graphic means, it is possible to construct a nomograph to determine the void ratio of the peat during the tests.

The void ratio at any time (t_1) during "early" stage of consolidation is determined from the equation $de/dt = C_1 t^{k_1}$. The change in void ratio is obtained:

$$\Delta e_1 = \int_1^{t_1} \frac{de}{dt}\, dt$$

$$= \int_1^{t_1} C_1 \cdot t^{k_1}\, dt$$

$$= \left[\frac{C_1}{k_1 + 1} t_1^{k_1+1} - 1 \right].$$

As $(t_t) = F\ (H, \sigma, e_0)$, the end of "early" stage consolidation and the beginning of "late" stage consolidation can be obtained. The void ratio at any time during the "late" stage can be obtained from the equation

$$de/dt = C_2 . t^{k_2}$$

where $C_2 = f_2\ (H, \sigma, e_0)$. The change in void ratio at any time (t_2) during the "late" stage from the void ratio at the end of the "early" stage is:

$$\Delta e_2 = \int_{t_t}^{t_2} \frac{de}{dt}\, dt = \frac{C_2}{k_2 + 1} [t_2^{k_2+1} - t_t^{k_2+1}]$$

when $t_t < t_2 < \infty$.

If the tangent for the "late" stage is a straight line for an infinite time, the maximum value of Δe_2 is found by letting $t_2 \to \infty$. For this peat $(k_2 + 1)$ is negative. Thus

$$\Delta e_{2(t_2 \to \infty)} = \frac{C_2}{k_2 + 1} [-t_t^{k_2+1}].$$

The total change in void ratio for any time interval is the sum of the void ratio changes in both the "early" and "late" stages; thus

$$\Delta e_{\text{total}} = \Delta e_1 + \Delta e_2 + \Delta\delta,$$

where $\Delta\delta$ is the change in void ratio during the first unit of time.

GRAPHICAL PRESENTATION

A nomograph (Fig. 5) is constructed on the log (de/dt)–log t axes in a manner similar to Fig. 3. As the slopes of the tangents for the "early" and "late" stages (k_1 and k_2) are fixed for variations of one of the parameters (H, σ, or e_0), two series of lines are drawn to represent these tangents.

For a sample of a particular height, the values of C_1 (the rate when t = 1) and t_t (the time to the significant change in the rates of consolidation) can be obtained. Entering these values into the nomograph, it is possible to plot the line relating the rates of consolidation to the elapsed time from loading. The dotted line shown on the nomograph is an example of this procedure and corresponds to line H_2 on Fig. 3a. This typical nomograph has been drawn to show the influence of sample height (H) on rates of consolidation (de/dt) with values of stress (σ) and initial void ratio (e_0) held constant. It is possible to draw three nomographs similar to the development of Fig. 3.

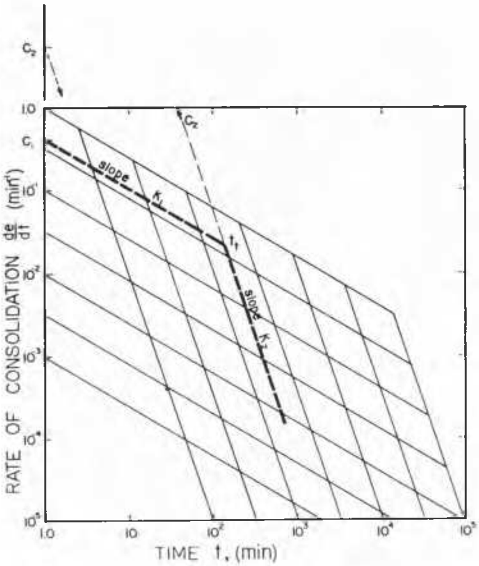

FIG. 5. Nomograph for settlement predictions.

Consequently, the change in void ratios, for any elapsed time during the consolidation process, can be calculated from the values of rates of consolidation (de/dt) and time (t).

CONCLUSIONS

A microscopic examination assists in the interpretation of the unusual consolidation characteristics of the peat, both in terms of rates of settlement and pore-water-pressure dissipation. This examination also may explain the occurrence of plastic resistance as found by Taylor. The physical structure and arrangement of the particles greatly affect the size and continuity of the pores, and hence affect the permeability. The wide range of microstructure found in different peat types is exhibited by Figs. 1 and 6. They represent the amorphous granular peat under discussion and a non-woody fine fibrous peat, respectively.

When a comparison is made of the characteristics of the curves on the log (de/dt)–log t graph, for samples under identical test conditions, the initial rate of consolidation of an amorphous granular peat is lower than that of a fine fibrous peat due to the lower permeability of the former. Furthermore, the differences in permeability result in a greater elapsed time to the significant change in the rates of consolidation for amorphous granular peat. Based on this comparison, a hypothesis can be made of the behaviour

FIG. 6. Fine fibrous peat (magnification, 200 ×).

of these peats under load. In the "early" stage of consolidation, the slope of the line for the fine fibrous peat is steeper than that for the amorphous granular due to the more rapid change in permeability.

The amorphous granular peat is a highly complex structure of descending particle size from fine sand and silt through diatoms, spores, microparticles, to colloids. The fibrous peat is an intricate and complicated cellular structure, with the cells of the hydrophilic plants of which it consists capable of holding immense quantities of water. Consequently, peat under compression may exhibit not only "primary" and "secondary" consolidation characteristics but also tertiary, quaternary, etc., characteristics. Investigation of these phenomena is continuing.

Colloidal phenomena relative to compression characteristics are not yet fully understood. It has been demonstrated previously, however, that amorphous granular peat under compression acts as a quasi-plastic material (Schroeder and Wilson, 1962). Concurrent with the expulsion of water under excess hydrostatic pressure, the particles rearrange their positions and deform. In particlar, floccules of colloids tend to plug the pores and interstices. Although the initial permeability may be high, it rapidly becomes greatly reduced, even under constant load. The "secondary" effects predominate when the rate of plastic deformation of the organic matrix becomes slower than the rate of expulsion of water from the decreasing volume of voids within the matrix. A subsequent effect is the collapse of cell walls of the constituents of the organic matrix.

The complex behaviour of the peat can be explained by the complexity of its structure which varies widely for different peat types (MacFarlane, 1957; Adams, 1963). Nevertheless, it has been demonstrated that one peat type can be analysed mathematically and graphically to permit the prediction of the rates of consolidation at any time during the loading process. On the results obtained herewith, it is proposed that this approach may be valid for other peat types. Research is continuing to verify this and enable the field conditions to be predicted.

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