Notes on Secondary Consolidation

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The pattern of secondary consolidation over several years has been determined in the laboratory for several peats and clays. Extrapolation of short-time tests is uncertain.

The effects of various loads, precompression and sample thickness have been measured. Time is independent of thickness but higher loads tend to accelerate the process of secondary consolidation.

Tests on desiccated, air dry and wet materials indicate that the seat of secondary consolidation is in the hygroscopic moisture. Sorption of hygroscopic moisture causes considerable swell.

Tests on wood, rosin and cotton indicate that bonding and creep of particles reduce secondary effects, whereas softening due to wetting causes large consolidations.

An interrelation of primary and secondary consolidation is postulated.

• WHEN a soil mass, confined to prevent lateral displacement, is loaded, it becomes denser by rearrangement of the particles. When the rate of densification is controlled by the time required for expulsion of fluids, this volume change is called primary consolidation. Secondary consolidation is the volume change controlled by anything else, such as the sliding of particles over each other or compression of particles. While secondary consolidation occurs throughout the loading period, it is most apparent after primary consolidation is essentially complete.

Secondary consolidation is important wherever primary consolidation is short, as in laboratory tests, organic soils, thin layers, or sand-drained areas. Time-volume change relations, primary and secondary, are important in designing cut slopes and foundations for bridges and embankments, especially when fine-grained soils are involved.

MATERIALS TESTED

The pattern of secondary consolidation for a variety of materials has been observed over several years in the laboratory. The effects of preloading, magnitude of load, sample thickness and limited moisture have been measured. Plasticity test data for several materials used in this study are given in Table 1. Table 2 gives the chemical composition of four peats and one organic silt used in the study.

Ordinary consolidation tests were run by the procedure given in the 1950 edition of ASTM Procedures for Testing Soils (*1*) except that loads were allowed to remain much more than 24 hours. Samples were generally 2 in. in diameter and 0.5 in. thick and were inundated unless otherwise noted.

TYPICAL PATTERNS

A typical time-consolidation curve for a peat is shown in Figure 1. For

TABLE 1

EXPANSION OF KINGSTON LIMESTONE AS A FUNCTION OF SODIUM HYDROXIDE CONCENTRATION

Conc.	Expansion (%)	
	At 15 Days	At 67 Days
0.05 M	0	0
0.1 M	0	0
0.5 M	0.46	1.03
1.0 M	0.68	0.96
1.5 M	0.72	0.98

the 8-16 ksf (kips per square foot) loading, the typical S-shaped primary consolidation pattern is essentially complete at 0.1 day. Linear extension of the secondary consolidation from 0.1 to 1.0 day beyond the one-day record considerably underestimates the consolidation at 100 days. Figures 2 and 3, showing only the secondary consolidation after 0.1 day for two other peats, suggest that secondary consolidation may also produce an S-shaped curve somewhat like primary consolidation but extending over more log-cycles of time.

The magnitude of secondary consolidation for two clays (Fig. 4) is considerably less than for the peats. It is seen that preloading has little effect on the long-time rate of secondary consolidation—one sample of Florida clay had been preloaded to 16 ksf. Tests by Haefeli (*2*) show almost linear consolidation-log time curves up to 3 years. Under high pressures, Chilingar (*3*) found considerable secondary consolidation for montmorillonite but only a short-time effect (few days) for illite and kaolinite.

Peterson (*4*) reported considerable secondary time effect for shale, both in consolidation and swelling. Swelling is basically negative consolidation. For a heavily compacted remolded clay tested by the Bureau

TABLE 2

EXPANSION OF KINGSTON LIMESTONE IN ALKALI HYDROXIDE SOLUTIONS OF EQUAL ACTIVITY

Hydroxide	Conc.	Expansion (%)	
		At 15 Days	At 67 Days
Na	0.71 N	0.68	1.08
K	0.68 N	0.25	0.83
Li	0.87 N	0.17	0.43

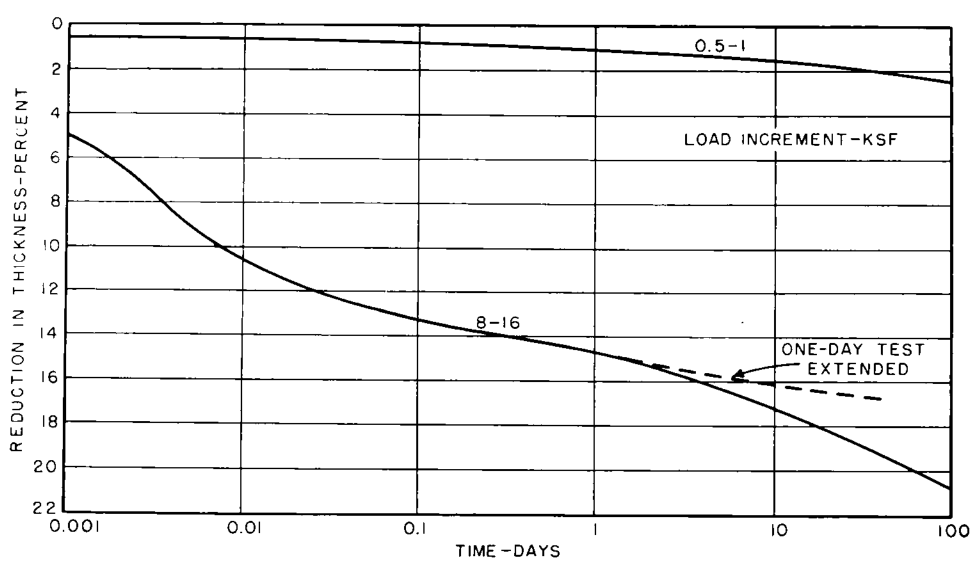


Figure 1. Secondary consolidation of Cambridge, Md., peat.

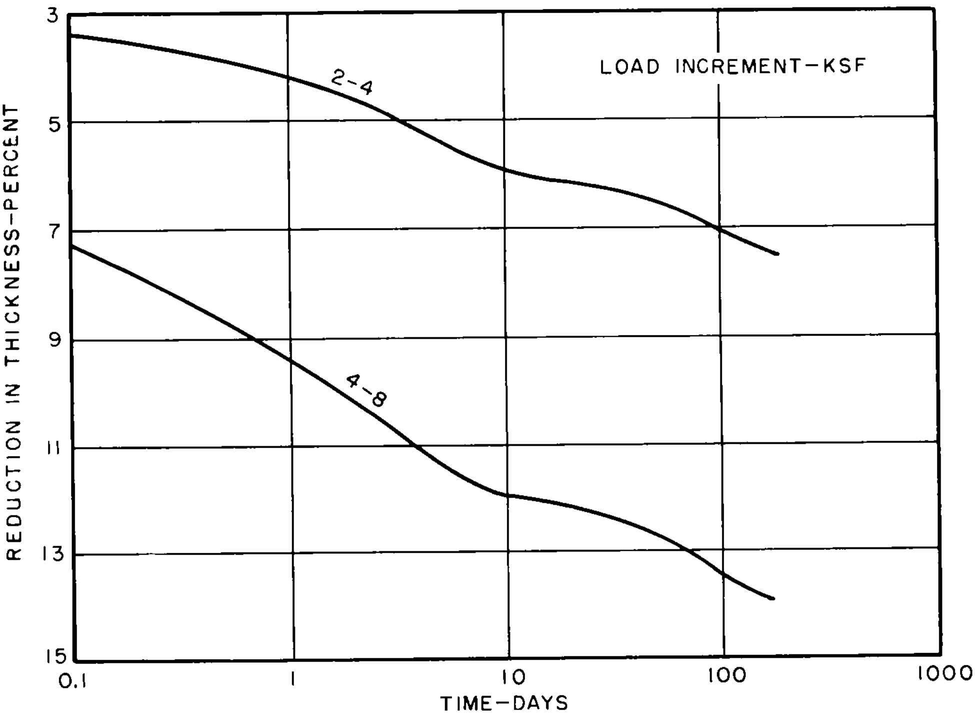


Figure 2. Secondary consolidation of Delaware peat.

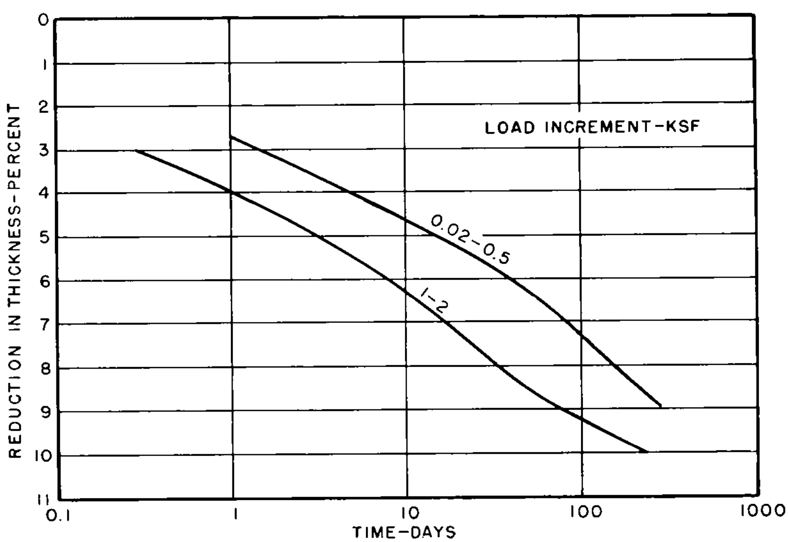


Figure 3. Secondary consolidation of Hyattsville, Md., peat.

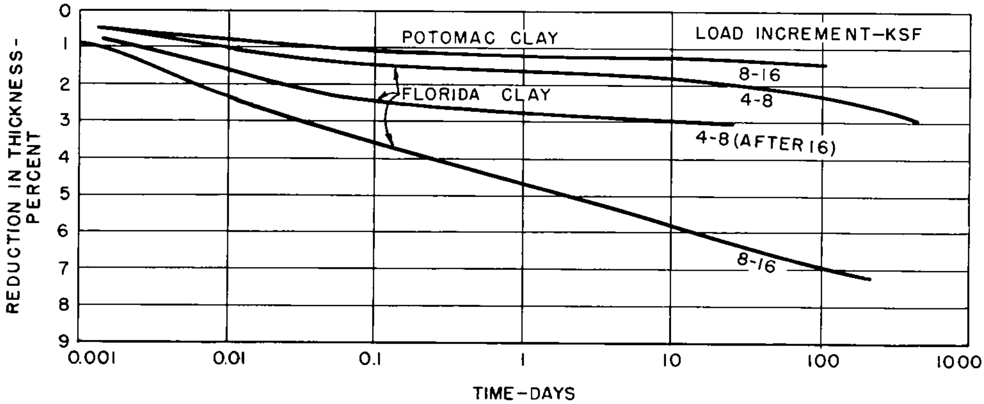


Figure 4. Secondary consolidation of clay soils.

of Public Roads, the observed swelling under a loading of 0.07 ksf follows the calculated primary consolidation (swelling) curve to 270 days (Fig. 5). Fit of a theoretical primary curve to time-consolidation data is assumed to indicate primary consolidation.

Figure 6 shows essentially the same secondary consolidation patterns for two thicknesses of organic silt. The ends of the curves after 6 years may be affected by binding of the consolidometer piston due to accumulation of solids from the tap water used to keep the samples submerged. This problem was later eliminated for other samples by the use of distilled water. Preloading did not greatly affect the long-time secondary consolidation.

Increasing the time between load-

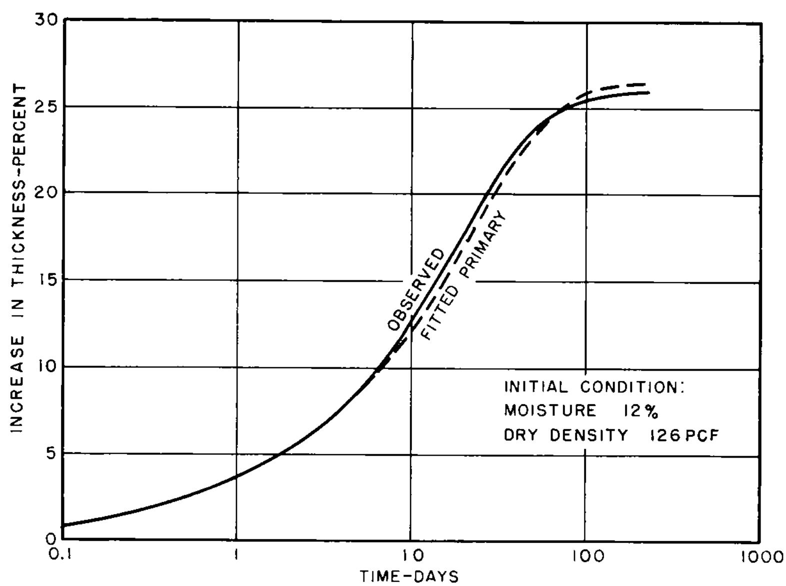


Figure 5. Swelling of compacted Potomac clay.

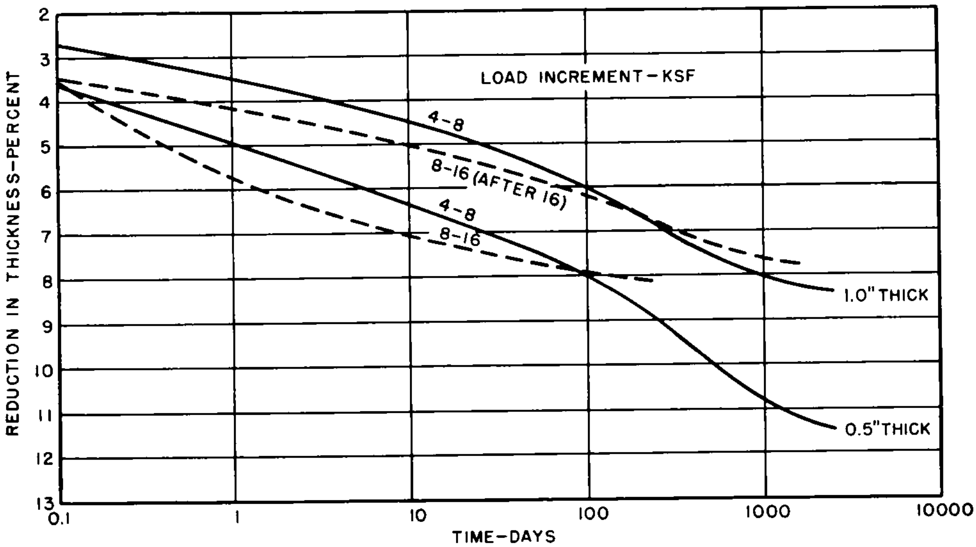


Figure 6. Secondary consolidation of Norfolk organic silt.

ing increments from one day to one week increased the total consolidation considerably (Fig. 7), but increased the slope of the stress-strain curve only a little. The 16-ksf load was left for 1 week in both cases.

Figure 8 shows the tendency for higher loads to accelerate the rate of

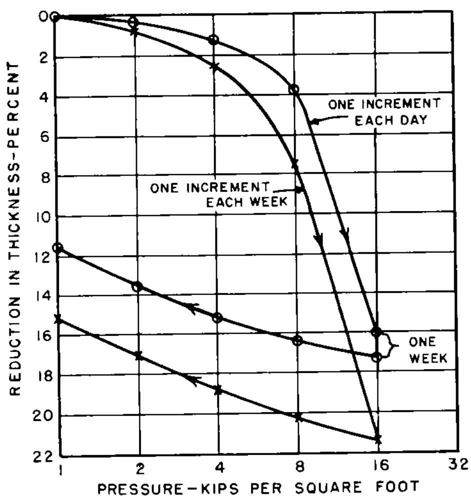


Figure 7. Effect of loading time interval on consolidaton of Norfolk organic silt.

secondary consolidation, and in this case to reduce the amount of additional consolidation occurring after 100 days of laboratory loading.

VARIOUS MATERIALS

To study the causes of secondary consolidation, a number of tests were run on predried and mixed Indiana peat. Figure 9 shows typical patterns for inundated samples. The slope increases greatly after 1 day, and in one case after 100 days.

Reasoning that dry material would have short-lived secondary consolidation, oven-dried samples were tested. However, they swelled in laboratory air under the seating load of 0.5 ksf (Fig. 10) and thereafter consolidated under low humidity in the winter (20-30) and swelled with high humidity in the spring (50-70). The effect of humidity was verified by placing a consolidation device in a vacuum tank which caused rapid consolidation, and by covering another device with a wet cloth which caused rapid swelling. Short-time effects of temperature increase were limited to

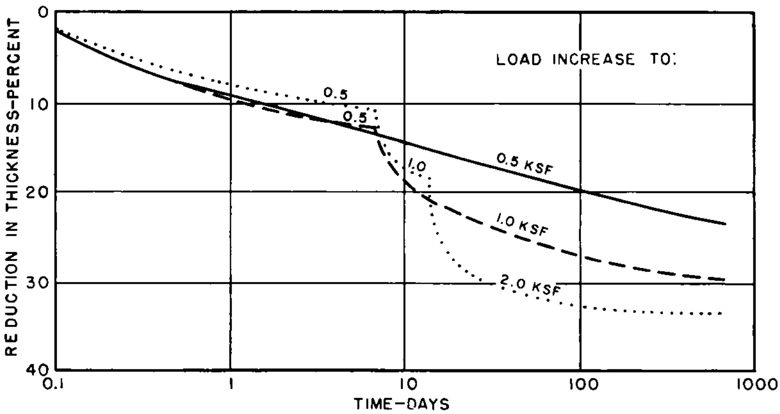


Figure 8. Secondary consolidation of Ohio peat.

the differences in expansion between the brass device and the steel dial stem—an apparent consolidation of 0.06 percent for a rise of temperature from 70 to 90 F. The possibility of decomposition was considered. Observed settlement of 2 in. per year in peat drained to a depth of 3 ft has been partly attributed to decomposition (*5*). However, chemical analyses by the Bureau of Public Roads on soils that had been subjected to 8 years of laboratory consolidation failed to show significant decomposition. A device containing an oven-dried sample was surrounded with desiccant. This almost eliminated secondary consolidation. From

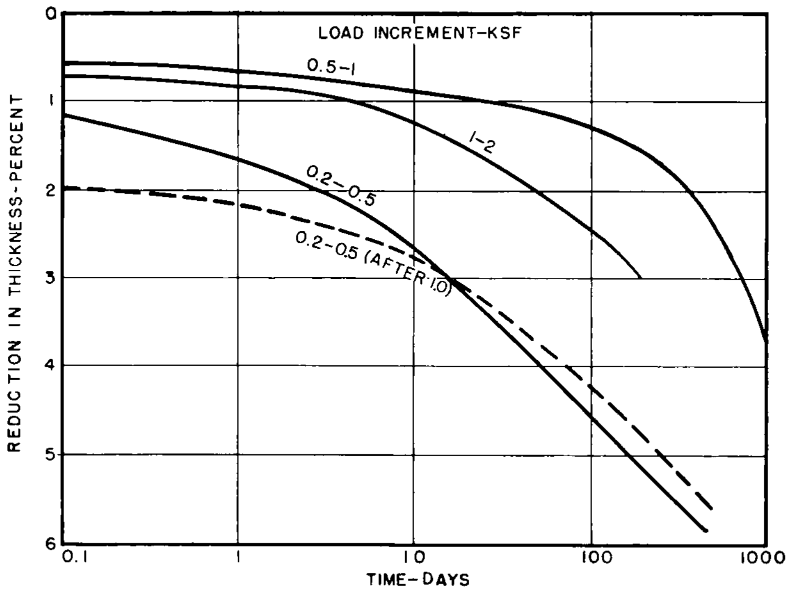
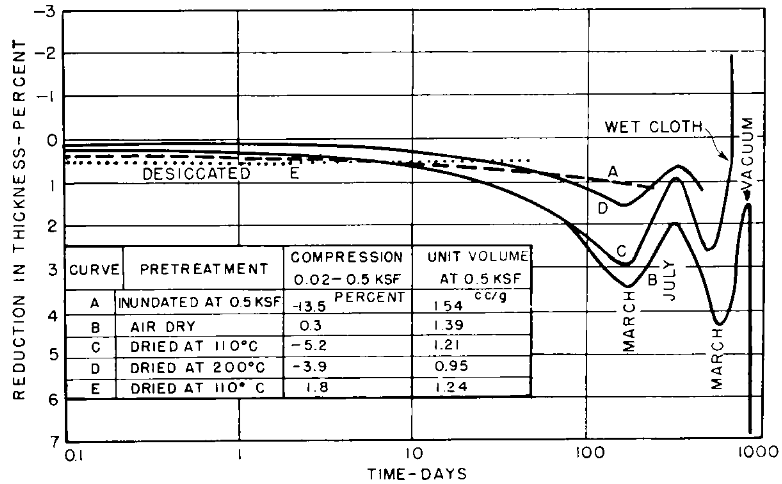


Figure 9. Secondary consolidation of air-dried and soaked Indiana peat.



CURVE	PRETREATMENT	COMPRESSION 0.02–0.5 KSF PERCENT	UNIT VOLUME AT 0.5 KSF cc/g
A	INUNDATED AT 0.5 KSF	-13.5	1.54
B	AIR DRY	0.3	1.39
C	DRIED AT 110°C	−5.2	1.21
D	DRIED AT 200°C	-3.9	0.95
E	DRIED AT 110° C	1.8	1.24

Figure 10. Effect of humidity on secondary consolidation of air-dried Indiana peat loaded from 0.5 to 1.0 ksf.

this evidence, it appears that the seat of secondary consolidation is in the hygroscopic moisture.

Tests were made on several organic materials that have characteristics related to peat. Denham and Dickinson (*6*) have reported 18 percent change in lateral dimensions of silk between the dry and saturated condition. Tests on raw cotton (Fig. 11) show a similar amount of secondary consolidation for air-dry and inundated samples. The desiccated sample consolidated when it absorbed water. Apparently, loss of strength permitted, under load, consolidation

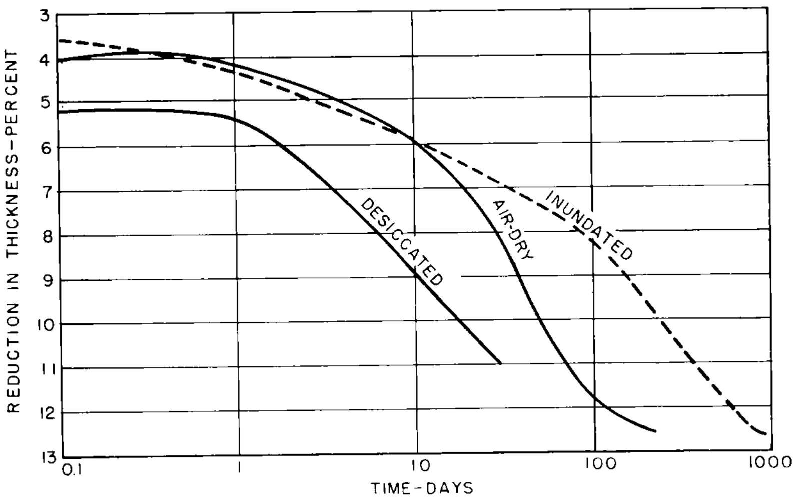


Figure 11. Secondary consolidation of raw cotton loaded from 0.5 to 1.0 ksf.

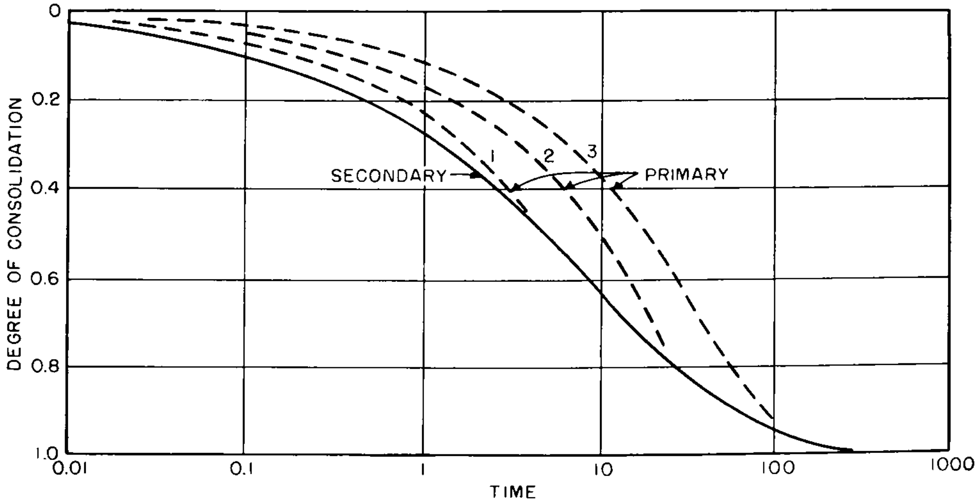


Figure 16. Theoretical combination of primary and secondary consolidation.

sentially the primary down to the point where it meets the secondary and then along the secondary curve. Due to decreased permeability with compaction, curves for increasing load often proceed from primary 1 to primary 2 and 3, resulting in a double-S curve for lighter loads, and progressing to a predominantly primary curve. Increase in sample thickness would cause a similar progression (*8*).

Figure 17 shows one of a number of sets of consolidation curves (*9*) which show this pattern for increasing load. It may be as typical for volcanic ash (*10*) as for peat. Higher loads may also accelerate the secondary consolidation and move the secondary portion of the curve to the left.

Figure 18 indicates a double-S curve for secondary consolidation in the field for a wall resting on piles which only partly penetrate a peaty silty clay.

Because primary consolidation depends on drainage boundaries, field time-consolidation curves depend on boundaries (Fig. 19) where lateral drainage only extends the time for the later portion of primary consolidation. This should not be confused with secondary consolidation.

Field settlement records may also involve lateral displacement. Housel (*11*) has reported rates of settlement

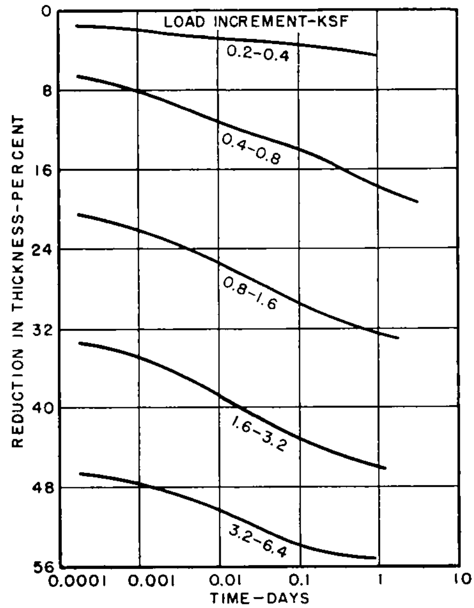


Figure 17. Time-consolidation of Louisiana peat.

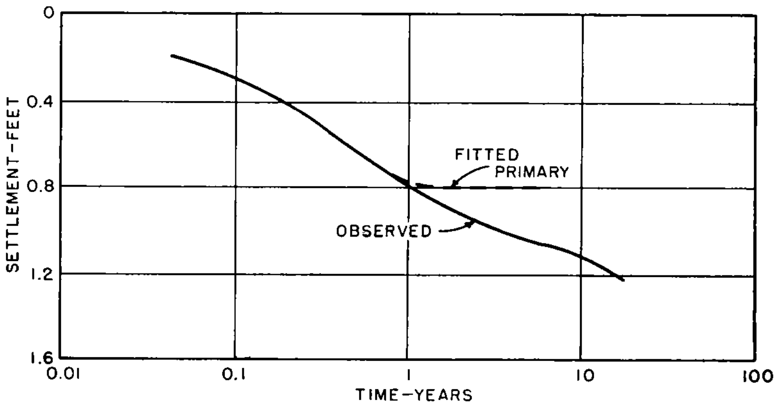


Figure 18. Settlement of northeast wing wall, bridge 8, Pentagon network.

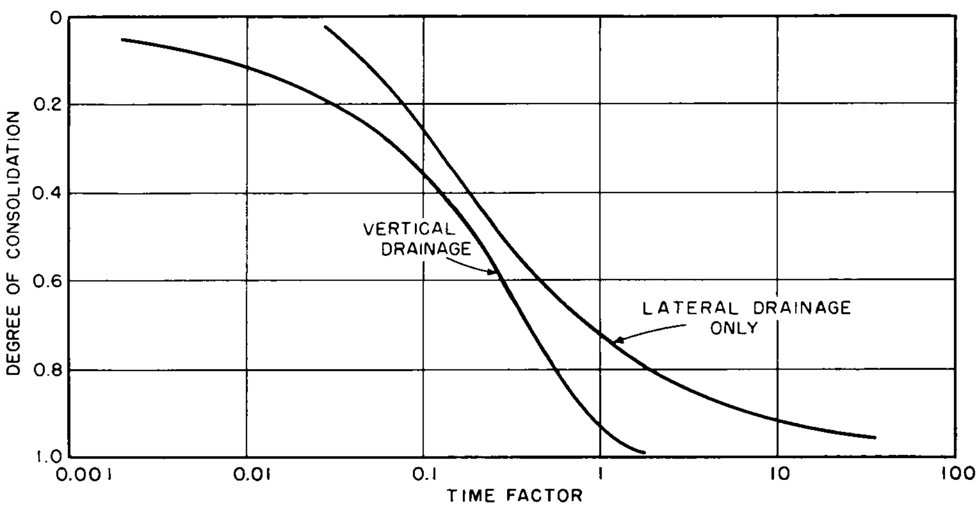


Figure 19. Effect of boundaries on time-consolidation.

directly proportional to the amount by which the shear stress exceeds the yield point.

Various combinations of consolidation and displacement may occur. Helenelund (*12*) reported 20-yr settlement records which are close to primary curves but approach an almost constant rate of settlement with time.

Pier rotation (Fig. 20) indicates that lateral displacement with time in this case is similar to primary consolidation of the fill, apparently because it is controlled by lateral consolidation of soil between the piers. After 30 years, the primary consolidation rate is still greater than the secondary rate measured in a one-day test.

Laboratory tests and field observations will be continued to further investigate the pattern and cause of secondary consolidation.

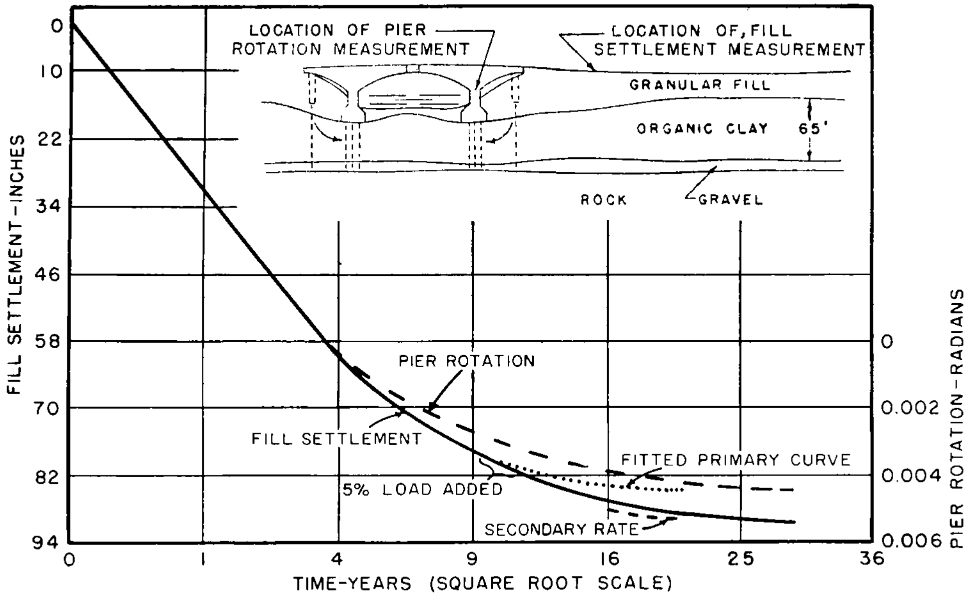


Figure 20. Movement at Boundary Channel bridge.

CONCLUSION

The foregoing observations show the uncertainty of extrapolating short-time laboratory tests but, unfortunately, offer no substitute except tests of long duration and correlation with field observations.

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