Vacuum Consolidation on Highly Compressible Soil

고 압축성 토질에서의 진공압밀

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요 지

5가지의 토질을 대상으로 하여 심지배수가 존재하는 경우와 그렇지 않은 경우에 있어서 진공압밀 실험을 실시하여 진공압밀에서의 시간에 따른 침하량을 측정하였다. 이에 앞서 기초실험을 통하여 토질의 특성을 파악하고 아울러 일차원 압밀실험을 행하여 심지배수가 존재하지 않은 경우의 진공압밀이 진행되는 동안 기존의 압밀 실험이 토질의 거동을 예측할 수 있는지를 검토하여 보았다. 본 연구결과 기존의 일차원 압밀실험은 심지배수가 존재하지 않는 경우의 진공압밀 실험과정을 예측하는데 부적절하였으나 최종침하량은 적절하게 예측하였음이 밝혀졌다. 진공압밀의 실험결과에서는, 실트질토에 있어서 심지배수의 존재가 압밀의 속도에는 커다란 영향을 미쳤으나 최종 침하량은 심지배수의 존재에 상관없이 동일하였음이 밝혀졌으며 심지배수의 존재는 시료의 깊이에 대해 함수비와 밀도를 일정하게 한다는 것은 규명되었으나 점토질토에서의 심지배수의 존재는 압밀의 속도 뿐만 아니라 최종침하량도 증가시킴이 밝혀졌다.

Abstract

Laboratory testings, consisting of soil properties testing and vacuum consolidation testing with and without vertical wick drain, were carried out on five different types of soil to determine soil properties and relationship between settlement and time. One dimensional consolidation test was performed to determine if this test could be used for predicting the behavior of soils during vacuum consolidation. From the results of this study, the one dimensional consolidation test does not appear to be suitable for predicting the rate of vacuum consolidation without wick drain. However, one dimensional consolidation test reasonably predicts the total settlement of vacuum consolidation without wick drain. In vacuum consolidation, the amount of the settlement for silty soils were more or less the same for both cases, with wick drain and without wick drain, even if the time required for consolidation was considerably different. And, strategic placement of wick drain ensures moisture content and the value of the density are similar throughout the soil sample. However, the presence of wick drain for clay soils increased the amount of settlement and also shortened the time required for consolidation.

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1. Introduction

Consolidation of compressible soils has been one of the most important aspects of geotechnical engineering practice. Predicting and controlling the time rate of settlement continue to be a major challenge for geotechnical engineers. Typically, cohesive compressible soils consolidate too slowly for most constructional needs. By Terzaghi's theory of one dimensional consolidation, the dissipation of excess pore pressure with respect to time is related to the magnitude of applied external load, soil properties and the length of the minimum drainage path within the soil. Therefore, effective ways to accelerate the consolidation of compressible soils were to increase the magnitude of applied external loading and/or shorten the length of the minimum drainage path within the soil.

2. Vacuum Consolidation

In 1952, Walter Kjellman[11] proposed a new method for using atmospheric pressure to apply temporary surcharge loadings for precompressing soft clay. In the method, a plastic or rubber membrane is placed over a sand or gravel filter layer and sealed to the clay below the ground surface. Then a vacuum is applied as the air is pumped out of the porous filter(Fig. 1). Then vacuum is maintained at the desired preload pressure, and a pressure difference of 0.6 or 0.7 atm (60 to 70 Kpa), which is equivalent to about 16ft(5m) of sand fill. The method, although theoretically sound, was impractical in 1952 because the plastic sheets that covered the sand filter deteriorated rapidly in field use, and consequently the vacuum could not be easily maintained. Today, durable plastic sheets are available. In addition, prefabricated wick drains have been developed that promise to make the vacuum preloading method practical.

In any precompressing techniques, following surcharge application, total normal pressure remains constant. The total stress equation is

$$\sigma = \sigma' + u \tag{1}$$

where σ = total stress

σ' = effective stress

u = pore water pressure

assuming saturated condition with $u>0$.

Differentiation of equation(1) yields

$$d\sigma' = -du \tag{2}$$

Thus, the decrease in pore water pressure is equal to the increase in effective stress. In the case of conventional earth-fill technique to preload the soil, when the load is applied, the shear stresses in the soil increase immediately, while effective stresses, hence strength, increase only as pore water pressure dissipates. Therefore, the step-by-step filling system must be adopted to avoid base shear failure. In the case of vacuum preloading technique, however, when the vacuum is applied, shearing failure does not occur because the total stress does not increase, hence shear stresses in the ground do not increase, Therefore the greatest advantage is that the loading is not restricted by the shearing strength of the soil in situ.

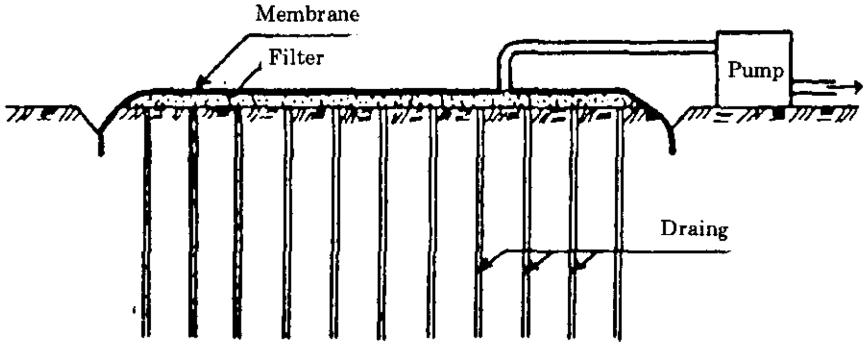

Fig. 1 Principle of vacuum method (after Kjellman, 11)

There are several advantages to vacuum preloading over the conventional earth−fill techniques such as

1) no fill materials for precompression are needed;

2) the soil does not undergo a shear failure from the loads introduced by atmospheric pressure as a results of vacuum because no change in total stress in the soil occurs. Therefore, loading is not restricted by the shearing strength of the soil in situ;

3) the softer the soil, the more evident the effectiveness of this method:

4) it is possible to greatly decrease the time required for preloading;

5) the time required for removal of surcharge is negligible in comparison with the time required to remove and dispose of large masses of preload fill:

6) the operating cost of the vacuum with wick drain method is relatively small;

7) a surcharge preloading cannot be used at all for stabilizing an existing slope or shaft because it would likely cause a slide. Vacuum, on the contrary, can well be applied in such cases, since no additional shear stresses are induced;

3. Laboratory Testing

3.1 General

Laboratory testing was carried out on five different types of soil to determine soil properties and relationship between settlement and time. Laboratory testing consisted of two parts, soil properties testing and consolidation testing. Soil property testing included specific gravity determination, Atterberg limits, grain size analysis, and the relationship between permeability and void ratio. One dimensional consolidation test was performed to determine if this test could be used for predicting the behavior of soils during vacuum consolidation.

3.2 Classificaiton Testing

Soils were classified after laboratory testing in accordance with ASTM D-2487 "Classification of Soils for Engineering Purpose". These classifications are based on laboratory results on the actual samples tested and visual classification. Using ASTM D-2487 method with Atterberg Limits and the minus 200 sieve fraction(%), the five different types of soil were classified as follows;

Table 1 Classification of soil sample

Soil	Classification	Description of soil
soil #1	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.
soil #2	MH	As above
soil #3	MH	As above
soil #4	CL	Lean clay with sand
soil #5	CL	As above

A summary of generalized soil properties was prepared from the laboratory test data. This summary is presented on Table 2. The minimum, maximum, and average values are shown for the various soil classification.

Table 2 Summary of generalized soil properties

Soil Type	Material Class		Specific Gravity	Atterberg Limit			Minus No. 200 Sieve(%)
				(LL)	(PL)	(PI)	
Soil #1	MH	MIN	2.635	48.90	42.61	4.38	70.47
		MAX	2.654	51.24	46.86	6.42	70.47
		AVE	2.650	49.78	44.74	5.7	70.47*
Soil #2	MH	MIN	2.673	56.92	51.84	4.47	61.19
		MAX	2.703	57.35	52.45	5.51	61.19
		AVE	2.692	57.14	52.15	4.99	61.19*
Soil #3	MH	MIN	2.34	72.0	67.0	5.0	65.39
		MAX	2.36	72.0	67.0	5.0	65.39
		AVE	2.35	72.0*	67.0*	5.0*	65.39*
Soil #4	CL	MIN	2.748	27.07	19.13	6.87	82.26
		MAX	2.772	27.26	20.26	8.13	82.26
		AVE	2.76	27.15	19.60	7.56	82.26*
Soil #5	CL	MIN	2.656	45.10	15.12	26.54	72.16
		MAX	2.713	48.25	18.89	29.98	72.16
		AVE	2.67	46.38	16.99	28.63	72.16*

*only one test performed

3.3 Permeability and Void Ratio Determination

Because of the low permeability measured with the constant head test on the unconsolidated sample[1], the falling head test was used to determine permeability at various levels of loading.

Before the permeability testing, consolidation at various levels of loading was necessary in order to obtain permeabilities at different void ratios. Parts from the permeability test setup were used to vacuum consolidate the 6.35cm diameter and approximate 2.6cm height soil specimen. After assembled the permeability setup, vacuum was applied at the base of the permeability setup and the specimen was consolidated for 30 minutes. Six different specimen were consolidated at 0, 16.90, 33.80, 50.70, 67.60, and 74.35KN/m². After the specimen was consolidated, falling head permeability tests were performed using the ASTM D−2424 test designation method. The volume and dry weight of each specimen was found to determine void ratios at various load increments. The results of the testing are shown in Table3.

Table 3 The results of permeability test at various load increments

Effective Stress (KN/m²)	Soil #1		Soil #2		Soil #3		Soil #4		Soil #5	
	Permeability (m/day)	Void Ratio	Permeability (m/day)	Void Ratio	Permeability (m/day)	Void Ratio	Permeability (m/day)	Void Ratio	Permeability (m/day)	Void Ratio
0.0	0.02462	2.460	2.541×10^{-2}	2.835	6.309×10^{-2}	2.364	2.748×10^{-3}	1.115	7.810×10^{-4}	1.2316
16.90	9.118×10^{-3}	1.950	1.325×10^{-2}	2.757	2.191×10^{-2}	1.798	8.597×10^{-4}	0.9079	7.733×10^{-4}	1.1998
33.80	8.482×10^{-3}	1.848	1.061×10^{-2}	2.695	1.622×10^{-2}	1.738	7.230×10^{-4}	0.8672	7.555×10^{-4}	1.1925
50.70	8.248×10^{-3}	1.806	1.035×10^{-2}	2.566	1.179×10^{-2}	1.510	6.805×10^{-4}	0.8345	6.749×10^{-4}	1.1719
67.60	7.762×10^{-3}	1.693	8.485×10^{-3}	2.389	−	−	6.394×10^{-4}	0.8011	5.468×10^{-4}	1.1583
77.73	7.440×10^{-3}	1.511	6.031×10^{-3}	2.166	3.751×10^{-3}	1.286	5.518×10^{-4}	0.8006	4.535×10^{-4}	1.1467

From the experimental results, the relationship between permeability and void ratio can be expressed as a function of the best fit curve for the data. This function was found to be cubic equation for five different types of soil. This function. with coefficient for the different soil types, is expressed as followings.

$$K = 0.02762e^3 - 0.1359e^2 + 0.2248e - 0.1173 \quad \text{for soil\#1} \quad (3)$$

$$K = 0.02166e^3 - 1.573e^2 + 3.807e - 3.062 \quad \text{for soil\#2} \quad (4)$$

$$K = 0.04832e^3 - 0.2232e^2 + 0.3728e - 0.2092 \quad \text{for soil\#3} \quad (5)$$

$$K = 0.05959e^3 - 0.1468e^2 + 0.1226e - 0.0340 \quad \text{for soil\#4} \quad (6)$$

$$K = -0.02465e^3 + 0.1002e^2 - 0.1298e + 0.05479 \quad \text{for soil\#5} \quad (7)$$

where K = permeability

e = void ratio

This function, with appropriate coefficients, is only valid between initial void ratio and final void ratio.

3.4 Consolidation Testing

3.4.1 Consolidation Apparatus

A testing apparatus was designed for large scale laboratory consolidation testing. The apparatus consisted of a five gallon plastic bucket, steel reinforced bellow, liquid catch, specially fabricated rulers, geotextile, and a vacuum source. The geotextile was Texel 375 PE 50 G, which was found to be a compatible geotextile for the slurry[1]. Special wick drains were fabricated for the experimental testing to limit scale effects. The full scale (cross section) wick drains would have a relatively large flexural rigidity in the 26.7cm test specimen length and would bias the consclidation results. Wick drains of smaller cross section, consisting of the same material as the full-size wick drains, were fabricated for use in the tests. The testing apparatus is shown schematically in Fig. 2.

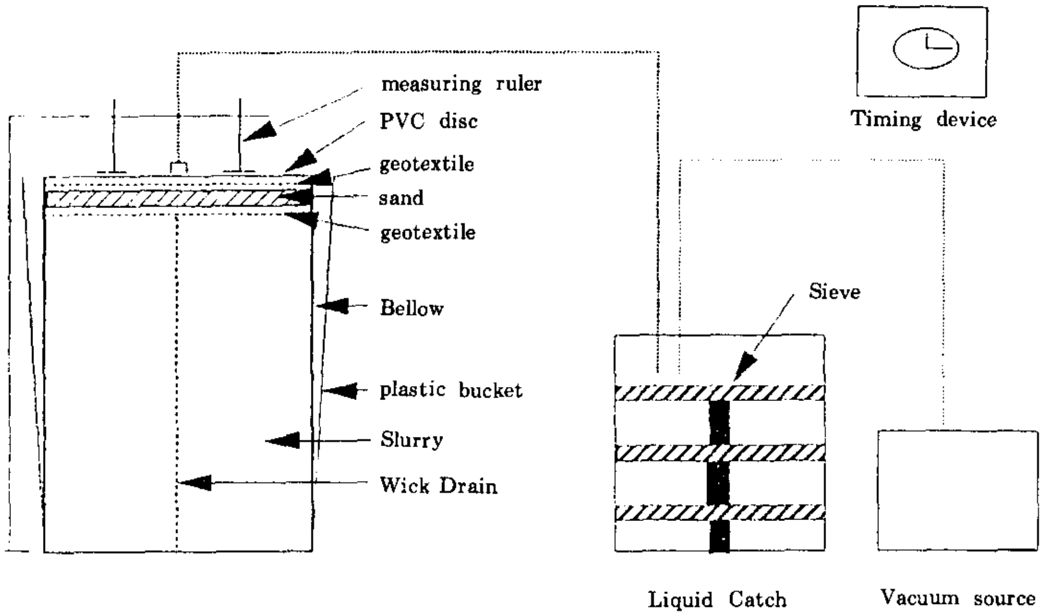

Fig. 2 Vacuum consolidation apparatus schematic

To alleviate any side resistance, a bellow was design to move with the consolidation process. The bellow consisted of a 25.4cm diameter flexible heating duct trimmed to an adequate length to allow for consolidation of the soil The bellow was placed over the bottom of the bucket and was sealed with duct tape and silicons.

3.4.2 Vacuum Consolidation

The vacuum consolidation testing included obtaining data on settlement with respect to time, initial void ratio and moisture content before vauum consolidation. Final void ratio, final moisture content, and final density of th soil were measured after vacuum consolidation. Vacuum consolidation was performed for two cases, with wick drain and without wick drain, such as to determine the efficiency of the wick drain.

After the soil was placed in the experimental apparatus, duct tape was applied to provide a seal. The size of soil sample for this test was 26.7cm depth and 25.4cm diameter. After sealing was finished, the three fabricared rulers were put on the PVC disk, one in the middle, the other two at the edges. One meter long wooden sticks fixed during the test were put across each fabricated ruler. Initial reading were measured by three people. After the vacuum pump was started, settlements were read by each person at 0.25, 1.0, 2.25, 4, 6.25, 9, 12.25, 16, 20.25, 25, 40, 60 minutes from the beginning of the test. The interval of time to read the settlements was the same as those commonly used for one−dimensional consolidation test up to 1 hour. After 1 hour, settlements were read every twenty minutes for 2 more hours. After 3 hours from the beginning of the test, a thirty minute interval was adopted for three more hours. The settlements were read every hour after six hours from the beginning of the test. If one hour was not a sufficient time interval to achieve perceptible settlement, then time interval to read settlement was changed to between 2 and 3 hours. The vacuum pressure for this test was held $78KN/m^2$ until the test was finished.

The height change during vacuum consolidation was determined by taking the arithmetic average of the three readings at the center and edges of the PVC disc. It was assumed that vacuum consolidation was complete if three consecutive readings showed no additional settlement. The length of the vacuum consolidation test were dependant on the presence of wick drain and type of soil. The lengths of the test ranged from 3.5 to 27 hours with wick drain, and from 7.5 to 38 hours without wick drain.

After the vacuum consolidation was finished, the three sets of data with respect to the same time were averaged. The averaged settlement for each time interval was substracted from the initial height of the soil sample consecutively. Primary settlement of the sand layer shown in Fig. 2. was neglected because of its small thickness, and because it would take place within seconds of the application of the load.

3.4.3 Sampling

Before the vacuum consolidation was set up, a sample of the soils was taken and its volume and dry weight were measured to determine the initial void ratio. The moisture content was also measured to represent the initial condition of the soil sample.

After the vacuum consolidation test was finished, soil specimens were takn at five levels within the sample, 0, 1/4H, 1/2H, 3/4H, and H from top of samples, where H is the height of sample. At each level, soil specimens were taken near the wick drain and half way between the edge of bellows and wick drain. Soil specimens were taken at the middle of the bellow if a wick drain was not installed. The soil specimens were taken such as to limit disturbance.

The weight and the volume of the soil specimens were measured to determine the final density. The dry weight of the soil specimens was also measured to determine the final moisture content and void ratio.

4. Results

The results of vacuum consolidation with and without wick drain for five different types of soil are represented by curves on Fig. 3 and Fig. 4. The summaries of vacuum consolidation with and without wick drain for five different types of soil are shown on Table 4 through Table 7.

The amount of ultimate settlement for silty soils were more or less the same for both cases. However, the presence of wick drain for clay soils increased the amount of ultimate settlement. This may indicated that the ultimate settlement was not achieved during the test without wick drain. This is mainly due to that the densification close to drainage surface disturbs the water flow from the soil sample near the bottom part of the sample near the end of test.

The time required for consolidation without wick as compared to with wick drain was approximately 2.0 times longer for clay type soils and approximately 3.0 times longer for silty type soils. The time required for consolidation of clay type soils was also 8.0 times longer with wick drain and 4.0 times longer without wick drain than that of silty soils.

Soil samples were uniform in terms of moisture content and density for silty and clay type soils after vacuum consolidation test with wick drain. Soil samples were essentially uniform for silty type soils without wick drain. However, soil samples were not uniform for clay type soils without wick drain. The deeper portion of the sample(further from the

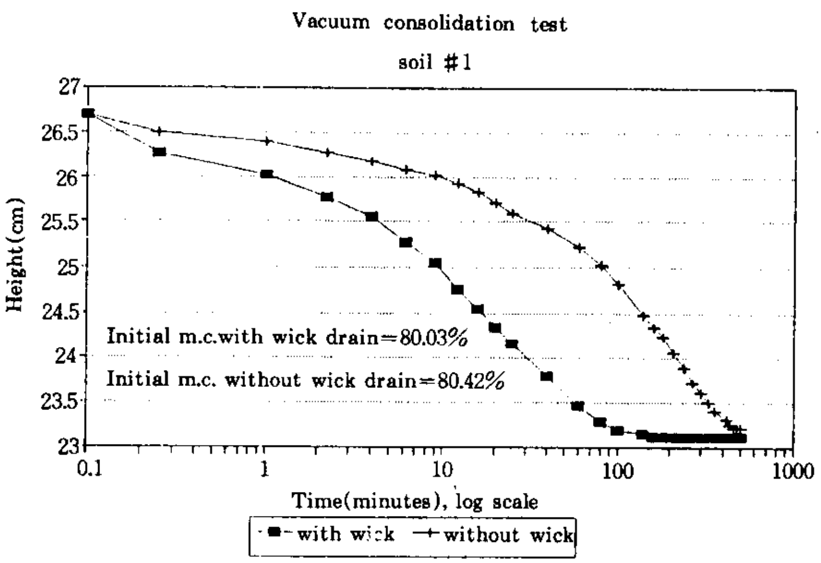

Fig. 3 Vacuum consolidation test on soil #1

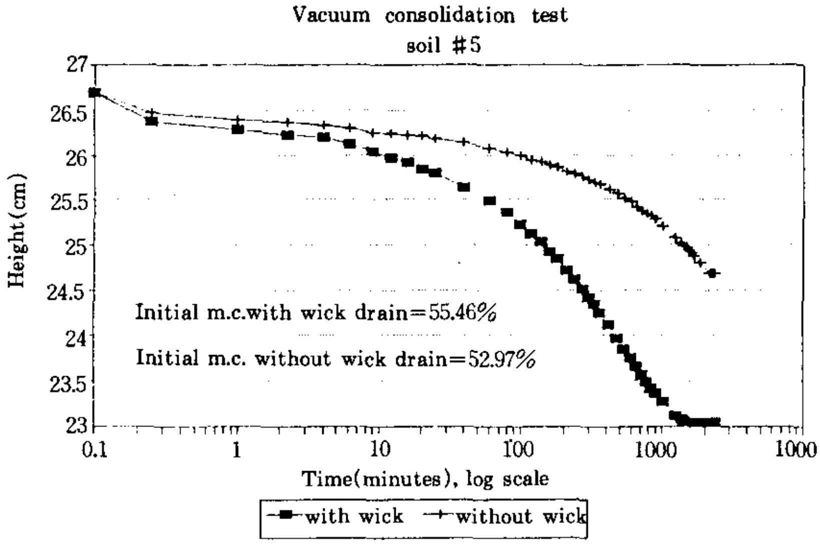

Fig. 4 Vacuum consolidation test on soil #5

Table 4 Summary of vacuum consolidation with wick on soil #1

Levels	Final Density (g/cm²)	Initial Moisture Content(%)	Final Moisture Content(%)	Initial Void Ratio	Final Void Ratio
0	1.6299	80.03	54.79	2.1207	1.5167
(1/4)H	1.6356	–	55.37	–	1.5173
(1/2)H	1.6325	–	57.19	–	1.5517
(3/4)H	1.6420	–	57.69	–	1.5450
H	1.6312	–	59.74	–	1.5933

Table 5 Summary of vacuum consolidation without wick on soil #1

Levels	Final Density (g/cm²)	Initial Moisture Content(%)	Final Moisture Content(%)	Initial Void Ratio	Final Void Ratio
0	1.6466	80.42	53.65	2.1312	1.4726
(1/4)H	1.6211	–	57.87	–	1.5807
(1/2)H	1.6349	–	59.91	–	1.5920
(3/4)H	1.6156	–	61.96	–	1.6566
H	1.6396	–	62.41	–	1.6249

Table 6 Summary of vacuum consolidation with wick on soil #5

Levels	Final Density (g/cm²)	Initial Moisture Content(%)	Final Moisture Content(%)	Initial Void Ratio	Final Void Ratio
0	1.8410	55.46	36.90	1.4803	0.9855
(1/4)H	1.8410	–	39.48	–	1.0521
(1/2)H	1.7999	–	41.44	–	1.0974
(3/4)H	1.8294	–	38.73	–	1.0385
H	1.8366	–	38.04	–	1.0059

Table 7 Summary of vacuum consolidation without wick on soil #5

Levels	Final Density (g/cm²)	Initial Moisture Content (%)	Final Moisture Content (%)	Initial Void Ratio	Final Void Ratio
0	1.8439	52.97	36.38	1.4137	0.9742
(1/4)H	1.8052	–	39.54	–	1.0632
(1/2)H	1.7608	–	44.93	–	1.1968
(3/4)H	1.7570	–	48.13	–	1.2654
H	1.7869	–	45.67	–	1.2056

vacuum source) was much softer than the shallower portion after the test. This is also mainly due to that the densification close to drainage surface disturbs the water flow from the soil sample near the bottom part of the sample near the end of test

By the comparison between the results of vacuum consolidation without wick drain and those of one dimensional consoliation, the one dimensional consolidation test does not appear to be suitable for predicting the rate of vacuum consolidation without wick drain. However, one dimensional consolidation reasonably predicts the total settlement of vacuum consolidation without wick drain. The results of this comparison are shownin Fig. 5, Fig. 6, and Table 8.

Plots of detailed settlement with respect to time on vacuum consolidation with other types of soil have also been generated but not all are included in this paper.

5. Conclusions

Based on the results of vacuum consolidation, following conclusion can be drawn;

1. The time for completion of vacuum consolidation was dependant on the presence of

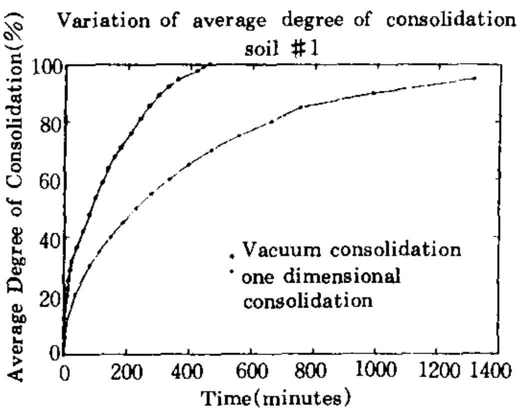

Fig. 5 Comparison of variation of average degree of consolidation for soil #1

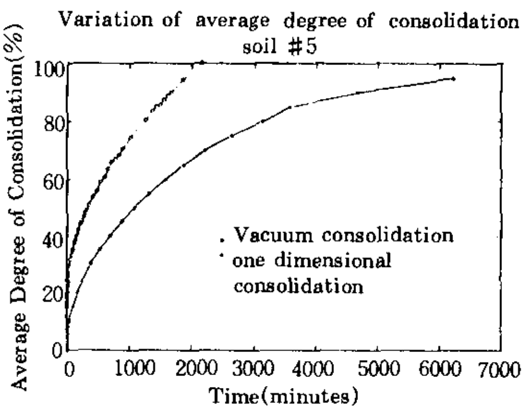

Fig. 6 Comparison of variation of average degree of consolidation for soil #5

Table 8 Comparison of one-dimensional consolidation test with vacuum consolidation test without wick drain

	Settlement by One-Dimensional Consolidation Test(cn)	Settlement by Vacuum Consolidation Test Without Wick Drain(cm)
Soil #1	3.262	3.476
Soil #2	3.046	2.017
Soil #3	2.130	2.780
Soil #4	3.980	3.561
Soil #5	3.040	2.009

wick drain, the value of permeability, and the type of soil.

2. The amount of settlement for silty soils were more or less the same for both cases, with wick and without wick drain, even if the time required for consolidation was considerably different. The presence of wick drain for clay soils increased the amount of settlement and also shortened the time required for consolidation.

3. Soil samples were uniform in terms of moisture content and density for silty and clay type soils after vacuum consolidation test with wick drain. Soil samples were essentially uniform for silty type soils without wick drain. However, soil samples were not uniform for clay type soils without wick drain.

4. The rate of settlement is mainly due to the values of permeability. The densification close to drainage surface and/or wick drain also effects the rate of settlement.

5. The one dimensional consolidation test is not suitable for predicting the rate of vacuum consolidation without wick drain. But, one dimensional consolidation test reasonably predicts the total settlement of vacuum consolidation without wick drain.

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