Geotechnical Testing Journal

doi:10.1520/GTJ20160297 / Vol. 41 / No. 3 / May 2018 / available online at www.astm.org

Mehmet C. Balci,[1] Kamil Kayabali,[2] and Ramin Asadi[2]

Miniature Centrifuge Modeling for Conventional Consolidation Test

Reference

Balci, M. C., Kayabali, K., and Asadi, R., "Miniature Centrifuge Modeling for Conventional Consolidation Test," *Geotechnical Testing Journal*, Vol. 41, No. 3, 2018, pp. 590–600, https://doi.org/10.1520/GTJ20160297. ISSN 0149-6115

Manuscript received November 16, 2016; accepted for publication August 21, 2017; published online February 20, 2018.

1 Department of Civil Engineering, Batman University, Batman 72100, Turkey (Corresponding author), e-mail: mehmetcan.balci@batman.edu.tr, https://orcid.org/0000-0003-3737-2556

2 Department of Geological Engineering, Ankara University, Golbasi, Ankara 06830, Turkey

ABSTRACT

Consolidation parameters are usually determined in the laboratory with oedometer tests in earth gravity conditions (1 *g*). However, performing the test is very time-consuming. Although dynamic approaches in which higher accelerations are applied have been developed as an alternative to the static approaches to reduce the duration of consolidation tests, these methods are expensive and require huge centrifuges. Moreover, the focus for these centrifuges is more on research than on practical applications. This study discusses the applicability of a small-sized centrifuge device in consolidation tests. The particular device developed for this study is a very small centrifuge compared to other examples around the world. The results revealed that employing this device in the tests reduced test duration to a couple of hours. Identical soil samples with a zero disturbance were prepared in the laboratory and used in the experiments. A new parameter, equivalent centrifuge load (W_{ce}), was defined to correlate the results from the proposed approach with the conventional consolidation-test results. An empirical relationship was developed to transform the axial strain (ε)–equivalent centrifuge load (W_{ce}) dataset obtained from the centrifuge tests to ε–effective stress (σ') data pairs. The empirical relationship could predict the virgin compression line with a high level of accuracy while it predicts the preconsolidation stress (σ'_p) with moderate accuracy. These relationships were applied to natural soil samples, and the findings are very promising.

Keywords

consolidation, centrifuge, conventional consolidation test, consolidation parameters

Nomenclature

Symbol = Definition

W_{ce} = equivalent centrifuge load

ε = axial strain (%)

σ' = effective stress (kPa)

σ'_p = preconsolidation stress (kPa)

Copyright © 2018 by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959

a_c = centrifuge acceleration (m/s^2)
ω = angular velocity (rad/s)
T = time (s)
e = void ratio (decimal)
C_r = recompression index
C_c = compression index
$C_{r\varepsilon}$ = modified recompression index
$C_{c\varepsilon}$ = modified compression index
R^2 = coefficient of regression
CM = conventional method
CCM = centrifuge method

Introduction

Consolidation parameters of particularly fine-grained soils are needed for the design purposes of various structures such as buildings, dams, and bridges. The determination of the consolidation characteristics of a fine-grained soil by oedometer test takes up to two weeks in the laboratory. The one-dimentional consolidation test and theory was developed by Terzaghi in the 1920s and is still widely used in geotechnical applications. To overcome the theoretical and practical problems encountered in Terzaghi's conventional one-dimensional consolidation test and theory, a variety of alternative laboratory tests have been developed over the past 40 years. These include the controlled gradient consolidation test (Lowe, Jonas, and Obrcian 1969), the constant rate of loading consolidation test (Aboshi, Yoshikuni, and Maruyama 1970) and the Constant Rate of Strain (CRS) consolidation test (Smith and Wahls 1969; Wissa et al. 1971). Gorman et al. (1978) described the CRS test as being faster and easier to complete than the other tests. Smith and Wahls (1969) and Wissa et al. (1971) proposed the CRS consolidation test as an alternative to conventional consolidation testing, although literature contains many different approaches to the use of the CRS test for determining the constant rate of strain during the test period.

Dynamic as well as static approaches have been developed to reduce the test duration. Centrifuge modeling is a powerful experimental tool for many aspects of geotechnical studies. Phillips (1869) proposed the modeling of high gravitational acceleration by centrifuges. The studies by Bucky (1931) and Pokrovsky and Fedorov (1936) later laid the foundations for the development of present-day geotechnical centrifuges. The fundamental work of the centrifuge is the generation of very high accelerations. Accordingly, conventional laboratory tests that take a long time under static conditions can be performed much more quickly by applying higher gravitational accelerations.

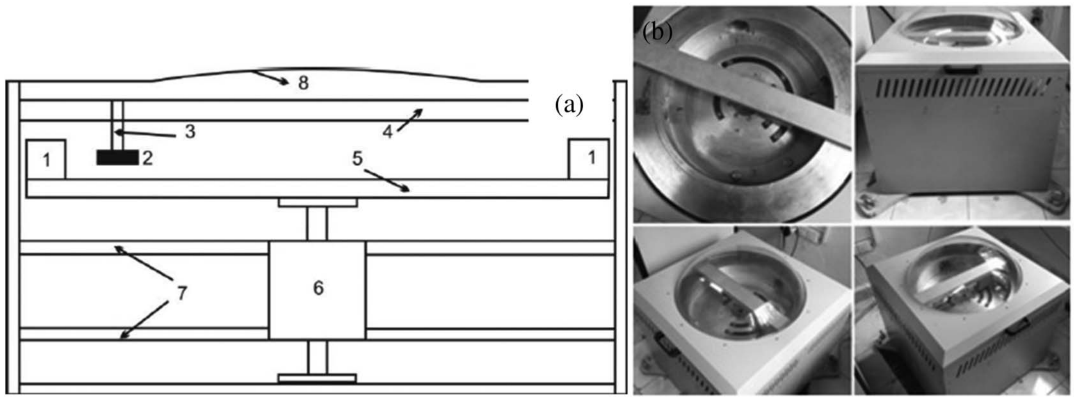
The majority of geotechnical centrifuge studies include the modeling of field conditions and mathematical modeling efforts. In both of these, the high cost of data acquisition systems to collect data and very high-cost centrifuges having an arm length up to a couple of meters are used. Thus, the practical use of these centrifuges is controversial. Examples of such studies using centrifuges can be summarized in the following paragraphs.

Al-Hussaini et al. (1981) studied the modeling of coal-waste fills. Resnick and Znidarčić (1990) reported that pore pressures can be used to define critical slip surfaces by a slope constructed in a geotechnical drum-type centrifuge bucket. Corte et al. (1991) and Bolton, Gui, and Phillips (1993) questioned the use of the centrifuge in cone penetrometer test probe modeling. Liu and Dobry (1999) studied the effects of lateral deformations of piles on liquefaction. White, Randolph, and Thompson (2005) performed a series of experiments to observe the failure behavior in a soil specimen under loading conditions using continuous digital imaging by a camera in a drum centrifuge; they could thereby analyze the deformations induced by the failure.

There are also a few pioneering studies that focus on permeability-related consolidation by centrifuges. The earliest studies were performed on permeability and consolidation behavior in saturated fine-grained soils by Townshend and Bloomquist (1983), Scully et al. (1984), and McClimans (1984). Takada and Mikasa (1986) used a centrifuge to determine the coefficient of volume compressibility and the permeability values for very soft clay. The coefficient of volume compressibility values was determined using the e-log P relationship obtained through the centrifuge consolidation tests, which were carried out without using an extra load such as a surcharge. The permeability values were determined based on the initial settlement figures obtained during the centrifuge consolidation tests, which were carried out according to the same principles and methods. Fahey and Toh (1992) modeled the consolidation behavior of kaolinite and mine tailings using a large-scale centrifuge. Zornberg and McCartney (2010) developed a centrifuge permeameter and reported a novel approach for determining the hydraulic properties of unsaturated soils.

With developments in technology, the size of centrifuges is getting smaller. The use of small, desktop centrifuges is becoming more common in addition to beam- and drum-type centrifuges. However, these centrifuges are employed in scientific research that calls for large geotechnical centrifuges. El-Shall, Moudgil, and Bogan (1996), McDermott and King (1998), and Reid et al. (2012) designed desktop centrifuges to analyze consolidation parameters, void ratios, and permeability profiles of fine-grained slurries based on the disadvantages of large-scale centrifuges. Although these centrifuges are relatively small in scale, their use in engineering applications became questionable because these centrifuges were designed to perform experiments with clayey slurries. Kayabali et al. (2013) developed a practical method to infer the hydraulic conductivity of saturated, fine-grained soils using a centrifuge consolidation apparatus. They used mixtures of clay and sand to assess this technique over a wide spectrum of hydraulic conductivities and reported that the proposed method may be a useful alternative for estimating hydraulic conductivity in a couple of hours.

FIG. 1 Miniature centrifuge device used for investigation. (a) Schematical cross section of the device (not to scale): 1) specimen holder, 2) laser head to measure distance, 3) arm fixing the laser head to rigid beam, 4) rigid beam holding the laser head, 5) revolving table, 6) motor, 7) beams rigidifying the system, 8) lid; (b) Overview.



This study focuses on the design of a small-sized and affordable centrifuge device for practical applications and conventional consolidation tests. It also develops an empirical relationship for the datasets obtained from the tests performed on identical soil samples in the laboratory and investigates the applicability of this relationship to natural soils.

Material

MINIATURE CENTRIFUGE DEVICE

A miniature centrifuge with a radius of 0.35 m and a maximum revolutions per minute of 2,000 was used in this study. A schematic view of the centrifuge is provided in Fig. 1a. It has four arms to hold cylindrical consolidation specimens, as shown in Fig. 1b. The components of the cylindrical module are shown in Fig. 2. To enhance the expelling of water from the pores during the flight, an additional surcharge was used. A laser unit with a 50-mm shooting range was installed horizontally from the upper bound of the surcharge to measure the axial settlements during the test. The resolution of the laser is 1.25 μm, and it can read 100 measurements per second. Special software that allowed the centrifuge to spin at specific velocities and monitored the axial settlements with times for four specimens controlled the centrifuge.

One of the outputs of the centrifuge consolidation tests is a new parameter: equivalent centrifuge load (W_{ce}) is defined for the purpose of this study. W_{ce} is defined to link the axial strains with the centrifuge load and the test duration. The force in the conventional approach is the static force induced by the applied load and the gravitational acceleration. The principle of the centrifuge is to increase static acceleration from 1 g (9.81 m/s^2) up to around 750 g easily under dynamic conditions.

The transformation from static to dynamic conditions was achieved by applying Newton's second law of motion to calculate the equivalent centrifuge load:

$$F = m \cdot a \tag{1}$$

Centrifuge acceleration is defined as the acceleration value that is determined under dynamic conditions with respect to static conditions. It is calculated as follows:

FIG. 2 Components of cylindrical module. (a) Schematical view of the module (not to scale): 1) fixed housing to hold the soil specimen, 2) inner cylindrical module, 3) consolidation ring, 4) centralizer, 5) surcharge, 6) porous stone, 7) soil specimen, 8) laser beam entry hole; (b) Photograph.

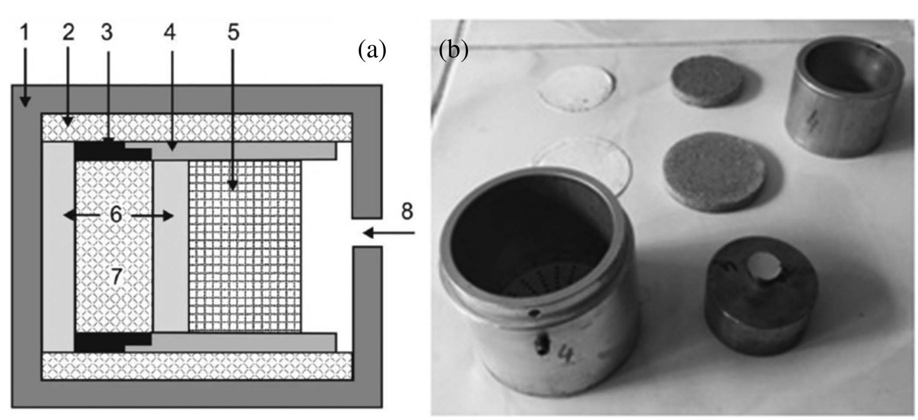
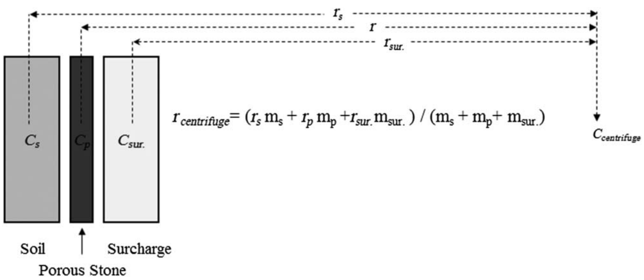


FIG. 3 Details of centrifuge radius calculation for equivalent centrifuge load.



$$a_c = r \cdot \omega^2 \tag{2}$$

The radius used in the calculation of the a_c and the W_{ce} is defined by a weighted average-distance value, which was calculated based on the individual loads in the centrifuge cells and the distance of these loads to the centrifuge's center. The details of the calculation are given in **Fig. 3**. The angular velocity (ω) is calculated by the following equation:

$$\omega = (r/min/60)2\pi \tag{3}$$

Dividing centrifuge acceleration by gravitational acceleration provides an ng value, where n is the multiplication factor:

$$ng = a_c/g \tag{4}$$

The equations given in five stages indicate the transition from static force, which causes the movement of the water through the soil pores in the conventional consolidation test, to the equivalent centrifuge load that defines the work done by the centrifuge during the experiment:

$$W_{ce} = ng \cdot T/3{,}600 \tag{5}$$

where T is time (s).

For instance, when the system runs for an hour at 300 r/min, the equivalent centrifuge load equals 28.1 g/hour. If it is run for 10 min, the equivalent centrifuge load will be only 4.7 g/hour. As a result, it can be understood that this is the additivity of the work done by the centrifuge at various speeds. The details of the calculations are given in **Table 1** for clarification.

SOIL SAMPLES

Laboratory-prepared samples (LPS) and natural soil samples were used in the study. LPS were consolidated in the laboratory using a sample preparation centrifuge by spinning it for each sample at different speeds. Natural soil samples with a different over consolidation ratio were collected from different locations of boreholes at different depths in Turkey.

Methods

SAMPLE PREPARATION

Because this study is parametrical in nature and it is difficult to find enough identical soil samples, the soils were remolded in a large range of plasticity in the laboratory as shown in **Table 2**. Six different soil samples were oven-dried and then sieved using a No. 40 sieve. Water was added to the samples until it reached a gravimetric water content close to the liquid limit. These were consolidated using a sample preparation centrifuge (see **Fig. 4**) by spinning it for each sample at 500, 600, 700, 800, 900, and 1,000 r/min for 6 h. This way, six soil samples with different preconsolidation pressures and zero disturbance were prepared.

TABLE 1 Equivalent centrifuge load (W_{ce}) calculation example for centrifuge method.

Revolutions per Minute (r/min)	Time (min)	Time (s)	Centrifuge Acceleration, $a_c = r\,\omega^2$	ng, a_c/g	Equivalent Centrifuge Load, $W_{ce} = ng \cdot T/3{,}600$	W_{ce} (Cumulative)
100	10.0	600	31	3.1	1	1
200	5.0	300	123	12.5	1	2
300	10.0	600	276	28.1	5	6
400	15.0	900	491	50.0	13	19
500	25.0	1,500	767	78.1	33	51
600	30.0	1,800	1,104	112.5	56	108
700	35.0	2,100	1,502	153.1	89	197
800	45.0	2,700	1,962	200.0	150	347
900	55.0	3,300	2,483	253.2	232	579
1,000	60.0	3,600	3,066	312.5	313	892
1,100	60.0	3,600	3,710	378.2	378	1,270
1,200	60.0	3,600	4,415	450.1	450	1,720
1,300	70.0	4,200	5,182	528.2	616	2,336
1,400	70.0	4,200	6,009	612.6	715	3,051
1,500	70.0	4,200	6,899	703.2	820	3,871

TABLE 2 Index properties of LPS.

Sample Number	Atterberg Limits (LL/PL/PI)	USCS
01	48/30/18	ML
02	53/28/25	CH
03	74/36/39	MH
04	60/22/38	CH
05	64/20/44	CH
06	65/21/44	CH

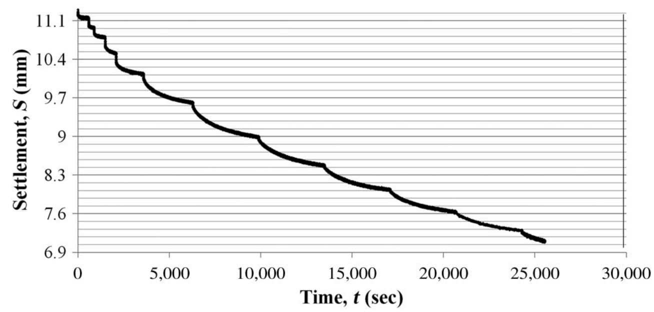
Note: CH, inorganic clay of high plasticity; LL, liquid limit; MH, inorganic silt of high plasticity; ML, inorganic silt of low plasticity; PI, plasticity index; PL, plastic limit; USCS, Unified Soil Classification System.

Thereby, 36 different remolded soil samples were prepared from 6 different soil samples. They were transferred to a consolidation ring with a diameter of 50 mm and a height of 20 mm. Centrifuge consolidation tests and oedometer tests were performed on these samples.

CENTRIFUGE CONSOLIDATION TEST

Centrifuge consolidation tests were performed on LPS with zero disturbance. In each test, two identical soil samples were placed in opposing positions inside the centrifuge device. The lowest rotation speed of the centrifuge device, which was 100 r/min, was selected as the starting speed for the tests. During the tests, the samples were monitored using special software for the centrifuge device, and the centrifuge was operated until the settlement (S)–time (t) curve became horizontal (**Fig. 5**). Once it was determined that the S-t curve was horizontal, the rotation speed was increased to the next level, which was 200 r/min. Using this method, the rotation speed was sequentially increased to 1,500 r/min. However, starting from approximately 1,000 r/min, it was noted that it took very long periods of time (more than an hour) for the S-t curve to reach low slope values. For this reason, starting from this r/min level, the rotation speed was increased to the next level once the slope of the S-t curve decreased to below 45°.

FIG. 5 Settlement-time curve example from centrifuge consolidation test.



Before using S-t data obtained using the aforementioned method, an axial strain and equivalent centrifuge load dataset for each sample was obtained by calculating first the angular velocity and then the equivalent centrifuge load (see **Fig. 6a**).

Conventional consolidation tests were performed according to ASTM D2435, *Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading* (2003), on the LPS and natural soil samples by applying 24-h incremental loading (25, 50, 100, 200, 400, and 800 kPa). Axial strains (ε) associated with the effective stress (σ) and void ratio (e) were measured, and the data were plotted in ε-σ and e-σ spaces as shown in **Fig. 6b**.

The effective stress values that corresponded to each one of the axial strain values obtained during the conventional consolidation tests were determined. In the centrifuge consolidation tests, by contrast, W_{ce} values were determined for each corresponding ε value for the same sample. As a result, σ' values corresponding to the ε values (which was the common parameter between the two methods), the W_{ce} values, and a new dataset consisting of three other parameters such as ε, W_{ce}, and σ' values were obtained. This procedure was performed for 6 different

FIG. 4 Sample preparation centrifuge used for the LPS. (a) Overview, (b) specimen holder to place homogenous water-soil mixture.

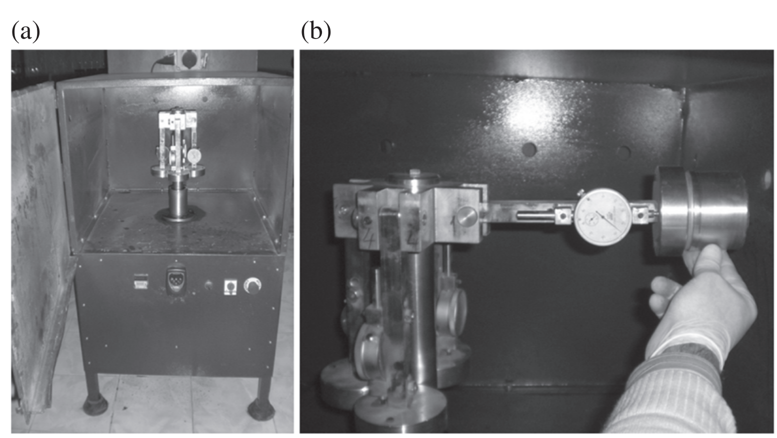
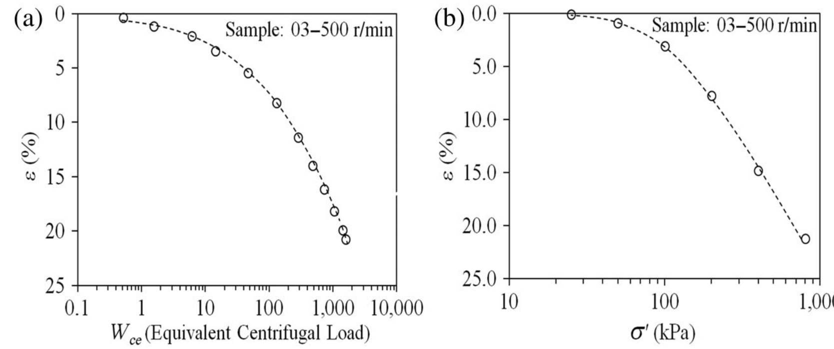


FIG. 6
Sample plots for both consolidation tests. (a) Centrifuge consolidation test, (b) conventional consolidation test (the results belong to the LPS artificially consolidated at 500 rpm).



samples and 36 different varieties of identical soil samples. Thus, a total of 36 "ε (%)-W_{ce}-σ'" datasets were formed. Simple regression was applied to the three obtained parameters, and an empirical relationship was established as follows:

$$\sigma' = 59 \cdot 9(1 \cdot 03)^{\varepsilon} W_{ce}^{0.26} \tag{6}$$

The empirical relationship was identified between the two test methods. The values determined experimentally using the

FIG. 7
Comparison of measured and predicted effective stresses in ε_V-log σ' space.

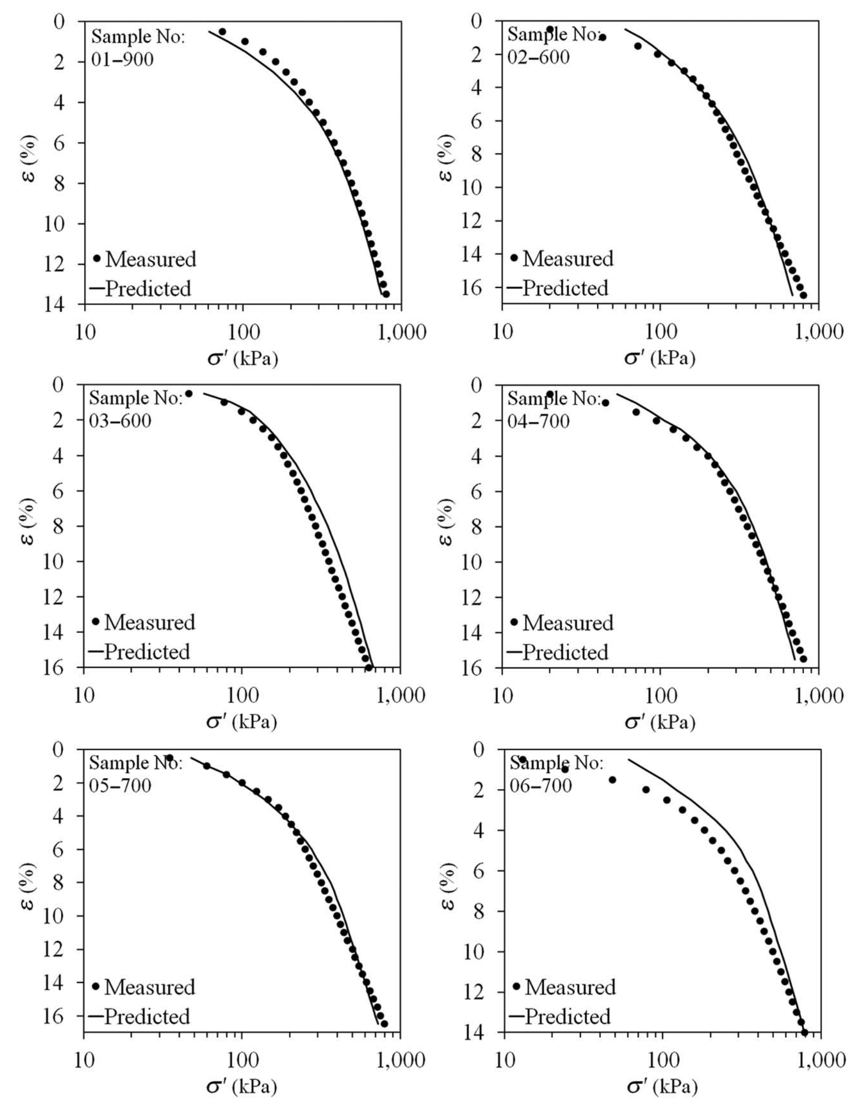


TABLE 3 Preconsolidation stress values of LPS obtained by Casagrande's method from conventional (CM) and centrifuge (CCM) methods.

	σ'_p (kPa)			σ'_p (kPa)	
Sample Number	CM	CCM	Sample Number	CM	CCM
01-500	122	262	04-500	138	178
01-600	170	272	04-600	175	223
01-700	195	295	04-700	205	300
01-800	233	315	04-800	263	305
01-900	265	315	04-900	280	302
01-1000	325	268	04-1000	300	256
02-500	129	275	05-500	122	182
02-600	187	300	05-600	173	238
02-700	210	362	05-700	186	270
02-800	255	340	05-800	250	300
02-900	288	355	05-900	272	252
02-1000	290	386	05-1000	220	248
03-500	132	226	06-500	150	332
03-600	164	250	06-600	242	368
03-700	193	276	06-700	203	347
03-800	310	273	06-800	335	335
03-900	333	280	06-900	315	341
03-1000	330	380	06-1000	337	353

conventional method were then compared with the σ' determined empirically using Eq 6.

Based on the empirical relationships observed, the centrifuge consolidation method results were expressed through the e-σ' and ε (%)-σ' graphs (as in the case with the conventional method). The consolidation parameters were determined using this graph and then compared with the consolidation parameters obtained through the conventional method. The σ'_p were determined from the conventional consolidation tests and the centrifuge consolidation tests using Casagrande's method.

FIG. 8 Comparison of preconsolidation stresses of LPS obtained by Casagrande's method from both approaches. CCM, centrifuge consolidation method; CM, conventional method.

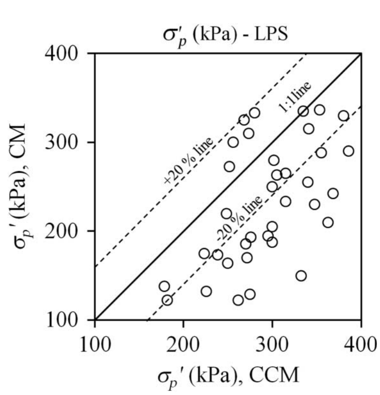
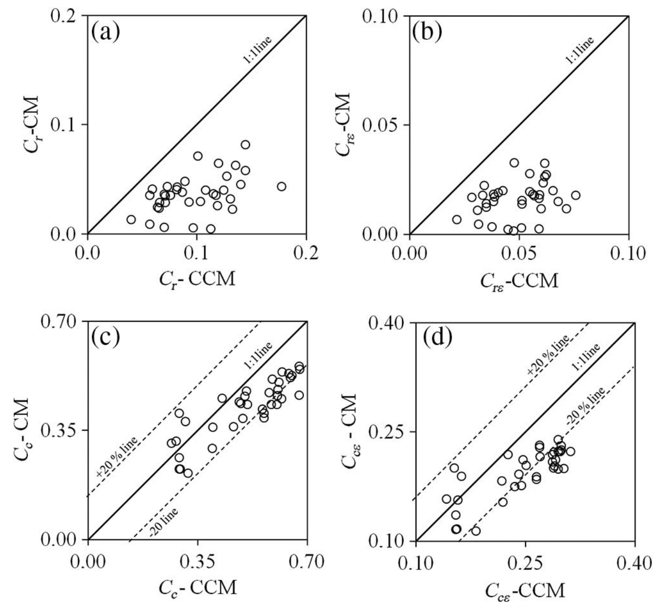


FIG. 9 Comparison of compression indexes of LPS determined by centrifuge (CCM) and conventional (CM) methods.



Experimental Results

The effective stress (σ') from the conventional consolidation test and equivalent centrifuge load (W_{ce}) from the centrifuge consolidation test were evaluated on the basis of associated axial strain (ε). This evaluation led to Eq 6 having a coefficient of regression (R^2) of 0.84.

Eq 6 was used to transform the data from the centrifuge consolidation test to curves that were traditionally obtained from the conventional approach and further analysis of the consolidation parameters. After developing the empirical relationship using the LPS, the reliability of the relationship to the natural soils was investigated. Thus, the consolidation parameters from the centrifuge and conventional approaches were compared. The evaluation of the results of both LPS and natural soil samples from conventional and centrifuge consolidation tests were provided by means of graphical evaluation and regression analysis.

LPS

In conventional consolidation tests, σ' associated with the ε are defined as measured values, whereas effective stresses calculated

TABLE 4 Details of linear regression analysis for LPS.

Parameter	Variables		R^2	Equation
C_c	a	0.594	0.74	$y = 0.594x + 0.121$
	b	0.121		
$C_{c\varepsilon}$	a	0.479	0.66	$y = 0.479x + 0.073$
	b	0.073		

TABLE 5 Details of nonlinear regression analysis for LPS.

Parameter	R^2	Model
C_c	0.79	10th order polynomial
$C_{c\varepsilon}$	0.74	10th order polynomial

from Eq 6 are defined as predicted values. The comparison of measured and predicted effective stresses is given in **Fig. 7**.

Preconsolidation stress (σ'_p) of LPS was determined for both consolidation tests. The results are shown in **Table 3**. They were compared with a variance interval of 20 % in a 1:1 graph as shown in **Fig. 8**. From the standpoint of graphical relationships, it was

TABLE 6 Compression index values of LPS obtained from conventional (CM) and centrifuge (CCM) methods.

	C_r		C_c		$C_{r\varepsilon}$		$C_{c\varepsilon}$	
Sample Number	CM	CCM	CM	CCM	CM	CCM	CM	CCM
01-500	0.063	0.135	0.52	0.64	0.027	0.062	0.22	0.30
01-600	0.041	0.124	0.54	0.62	0.018	0.059	0.24	0.29
01-700	0.033	0.130	0.43	0.58	0.015	0.068	0.20	0.29
01-800	0.039	0.087	0.46	0.60	0.002	0.045	0.22	0.31
01-900	0.049	0.089	0.48	0.50	0.002	0.047	0.23	0.27
01-1000	0.009	0.057	0.36	0.40	0.005	0.031	0.18	0.22
02-500	0.053	0.127	0.45	0.62	0.024	0.061	0.20	0.29
02-600	0.036	0.117	0.43	0.60	0.017	0.059	0.20	0.30
02-700	0.036	0.057	0.43	0.51	0.017	0.028	0.20	0.25
02-800	0.006	0.096	0.40	0.29	0.003	0.051	0.20	0.15
02-900	0.005	0.113	0.38	0.31	0.003	0.059	0.19	0.16
02-1000	0.007	0.070	0.31	0.26	0.004	0.037	0.16	0.14
03-500	0.065	0.119	0.53	0.65	0.028	0.055	0.22	0.30
03-600	0.025	0.064	0.50	0.61	0.011	0.031	0.22	0.29
03-700	0.026	0.118	0.47	0.58	0.012	0.060	0.21	0.29
03-800	0.036	0.075	0.44	0.48	0.017	0.039	0.21	0.25
03-900	0.029	0.066	0.45	0.43	0.014	0.035	0.22	0.23
03-1000	0.014	0.040	0.32	0.28	0.007	0.021	0.16	0.16
04-500	0.082	0.144	0.55	0.67	0.033	0.061	0.22	0.29
04-600	0.044	0.177	0.54	0.67	0.018	0.076	0.22	0.29
04-700	0.044	0.073	0.51	0.59	0.019	0.056	0.22	0.27
04-800	0.046	0.140	0.53	0.64	0.020	0.065	0.23	0.30
04-900	0.043	0.082	0.44	0.49	0.019	0.040	0.19	0.24
04-1000	0.030	0.103	0.39	0.49	0.014	0.051	0.18	0.24
05-500	0.059	0.144	0.46	0.67	0.026	0.061	0.21	0.29
05-600	0.038	0.115	0.48	0.60	0.018	0.057	0.23	0.30
05-700	0.041	0.081	0.42	0.56	0.020	0.042	0.20	0.29
05-800	0.023	0.132	0.46	0.50	0.012	0.071	0.23	0.27
05-900	0.030	0.092	0.29	0.39	0.016	0.051	0.15	0.22
05-1000	0.041	0.059	0.21	0.32	0.022	0.034	0.11	0.18
06-500	0.072	0.101	0.40	0.56	0.033	0.048	0.19	0.26
06-600	0.041	0.108	0.36	0.46	0.020	0.055	0.18	0.23
06-700	0.037	0.070	0.39	0.56	0.018	0.033	0.19	0.26
06-800	0.035	0.071	0.26	0.29	0.018	0.038	0.14	0.15
06-900	0.024	0.065	0.23	0.29	0.012	0.035	0.12	0.16
06-1000	0.029	0.071	0.23	0.29	0.015	0.038	0.12	0.15

TABLE 7 Preconsolidation stress values of natural soils obtained by Casagrande's method from conventional (CM) and centrifuge (CCM) methods.

	σ'_p (kPa)			σ'_p (kPa)	
Sample Number	CM	CCM	Sample Number	CM	CCM
A-1	173	225	B-12	200	180
A-3	186	240	B-14	268	253
A-13	243	230	B-16	151	190
A-15	220	233	B-17	188	145
B-3	254	208	B-18	258	317
B-4	140	145	B-19	240	238
B-11	225	190	C-4	200	206

FIG. 10 Comparison of preconsolidation stresses for natural samples obtained by Casagrande's method from both approaches.

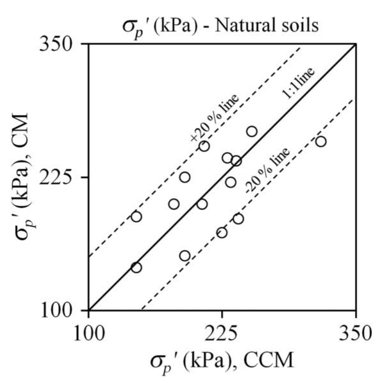
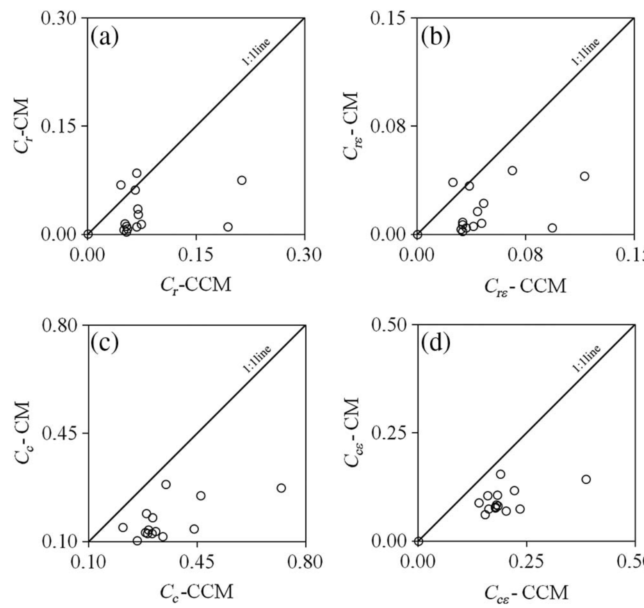


FIG. 11 Comparison of compression indexes of natural samples determined by centrifuge (CCM) and conventional (CM) methods.



observed that the preconsolidation stresses obtained with the centrifuge method gave results that were similar to those of the preconsolidation stresses obtained with the conventional method. Linear and nonlinear regression analyses were performed on preconsolidation (σ'_p) stresses. It was also noted that the regression analyses provided low R^2 values.

Fig. 9 shows the comparison of the compression index values obtained from two different methods. It was observed that the centrifuge method was successful for determining the C_c and $C_{c\varepsilon}$. (In other words, the virgin compression curve could be drawn more accurately with the centrifuge method compared to the traditional method.) The results of the regression analyses performed on these parameters appear to support this observation. However, the centrifuge method failed to provide adequate results for determining C_r and $C_{r\varepsilon}$. It was also noted that the regression analyses provided very low R^2 values for these two parameters. The details of the linear and nonlinear regression analyses regarding the C_c and $C_{c\varepsilon}$ values obtained with both test methods are shown in Tables 4 and 5, whereas the compression index values determined through both test methods are shown in Table 6.

NATURAL SOIL SAMPLES

Preconsolidation stresses of natural soil samples are shown in Table 7. These results are plotted in a 1:1 graph with a difference interval of ±20 % in Fig. 10.

Based on the graphical relationships, it was determined that the centrifuge method was effective for determining the preconsolidation stresses of natural soils.

Fig. 11 shows a comparison of the compression indexes obtained for natural soil samples from both test methods. The compression index values are shown in Table 8. Linear and nonlinear analyses were performed on the preconsolidation stresses and compression index values. It was also observed that the linear regression analysis of these parameters had low R^2 values, whereas nonlinear regression analyses gave R^2 values higher than 0.50. The details of the nonlinear regression analysis performed on the preconsolidation stresses and compression index values are shown in Table 9.

Discussion and Conclusion

The results obtained in this study for the evaluated soil samples can be listed as follows:

The centrifuge method has the potential to be considered as an alternative to the conventional method with regard to the determination of consolidation parameters such as the σ'_p, C_c and $C_{c\varepsilon}$, and the virgin compression curve. In addition to graphical assessments, regression analyses have also indicated that the

TABLE 8 Compression index values of natural soils obtained from conventional (CM) and centrifuge (CCM) methods.

	C_r		C_c		C_{re}		C_{ce}	
Sample Number	CM	CCM	CM	CCM	CM	CCM	CM	CCM
A-1	0.061	0.065	0.19	0.28	0.034	0.036	0.10	0.16
A-3	0.068	0.046	0.14	0.44	0.036	0.024	0.07	0.23
A-13	0.074	0.213	0.28	0.35	0.040	0.115	0.15	0.19
A-15	0.085	0.067	0.27	0.72	0.044	0.065	0.14	0.39
B-3	0.027	0.069	0.18	0.30	0.016	0.041	0.11	0.18
B-4	0.035	0.069	0.14	0.21	0.022	0.046	0.09	0.14
B-11	0.011	0.053	0.13	0.30	0.007	0.031	0.08	0.18
B-12	0.010	0.067	0.13	0.28	0.006	0.039	0.07	0.16
B-14	0.006	0.050	0.10	0.25	0.004	0.030	0.06	0.15
B-16	0.014	0.051	0.14	0.29	0.009	0.031	0.08	0.18
B-17	0.003	0.053	0.13	0.31	0.002	0.031	0.08	0.18
B-18	0.013	0.074	0.12	0.34	0.008	0.044	0.07	0.20
B-19	0.008	0.055	0.13	0.29	0.005	0.034	0.08	0.18
C-4	0.010	0.194	0.25	0.46	0.005	0.093	0.12	0.22

TABLE 9 Details of nonlinear regression analysis for natural soils.

Parameter	R^2	Model
σ'_p	0.59	8th order polynomial
C_r	0.71	9th order polynomial
C_c	0.93	10th order polynomial
C_{re}	0.84	9th order polynomial
C_{ce}	0.88	8th order polynomial

centrifuge method is effective for determining the aforementioned parameters.

By contrast, the centrifuge method was not found to be successful in determining parameters such as C_r and C_{re}. The present study is not sufficient for determining the compression curve and the coefficient of consolidation. Studies aiming to assess and determine these parameters are currently ongoing.

The ε-W_{ce} curve obtained from the centrifuge test was transformed to an ε-σ' (e-σ' with further analysis) curve as in the conventional consolidation test. Then an empirical relationship was proposed to predict the consolidation parameters as follows:

$$\sigma' = 59 \cdot 9(1 \cdot 03)^{\varepsilon} W_{ce}^{0.26} (R^2 = 0.84)$$

The consolidation parameters from centrifuge tests were higher values than those from conventional consolidation tests. This difference might be attributed to the soil fabric. When the centrifuge is on operation, the soil grains and the pores are compressed much more than those in the traditional approach because of the much larger and longer acceleration field. Thus the consolidation parameters that are highly related to the soil fabric are expected to give higher values in the centrifuge consolidation tests.

By using and testing more soil samples with the centrifuge device developed for this investigation, it would be possible to identify and develop better and more empirical relationships. To achieve this, a high plasticity range and more natural soil samples are needed.

ACKNOWLEDGMENTS

This research was funded by Ankara University under the project number 12B4343019. The opinions are those of the authors alone and do not reflect the viewpoint of the sponsor. The authors are grateful to Dr. John S. McCartney for valuable criticsm.

References

Aboshi, H., Yoshikuni, H., and Maruyama, S., 1970, "Constant Loading Rate Consolidation Test," *Soils Found.*, Vol. 10, No. 1, pp. 43–56, https://doi.org/10.3208/sandf1960.10.43

Al-Hussaini, M. M., Goodings, D. J., Schofield, A. N., and Townsend, F. C., 1981, "Centrifuge Modeling of Coal Waste Embankments," *J. Geotech. Geoenviron. Eng.*, Vol. 107, No. GT4, pp. 481–499.

Bolton, M. D., Gui, M. W., and Phillips, R., 1993, "Review of Miniature Soil Probes for Model Tests," presented at the *11th Southeast Asian Geotechnical Conference*, Singapore, Southeast Asian Geotechnical Society, Khlong Luang, Thailand.

Bucky, P. B., 1931, *Use of Models for the Study of Mining Problems*, American Institute of Mining and Metallurgical Engineers, Tech. Pub. No. 425, pp. 3–28.

Corte, J. F., Garnier, J., Cottineau, L. M., and Rault, G., 1991, "Determination of Model Soil Properties in the Centrifuge," presented at the *International Conference on the Centrifuge*, Boulder, CO, International Society of Soil Mechanics and Foundation Engineering, London, England.

ElShall, H., Moudgil, B., and Bogan, M., 1996, "Centrifugal Modeling of the Consolidation of Solid Suspensions," *Miner. Metall. Process*, Vol. 13, No. 3, pp. 98–102.

Fahey, M. and Toh, S. H., 1992, "Physical and Numerical Modelling of Consolidation of Mine Tailings," *Australian Geomechanics*, Vol. 22, pp. 17–25.

Gorman, C. T., Hopkins, T. C., Deen, R., and Drnevich, V. P., 1978, "Constant-Rate-of-Strain and Controlled-Gradient Consolidation Testing," *Geotech. Test. J.*, Vol. 1, No. 1, pp. 3–15, https://doi.org/10.1520/GTJ10363J

Kayabali, K., Baser, T., Balci, M. C., and Kolay, E., 2013, "Evaluation of the Hydraulic Conductivity of Saturated, Fine-Grained Soils Using a Small-Size Centrifuge," *Electron. J. Geotech. Eng.*, Vol. 18, No. K, pp. 2251–2262.

Liu, L. and Dobry, R., 1999, "Effect of liquefaction on lateral response of piles by centrifuge model tests," presented at the *Workshop on New Approaches to Liquefaction Analysis*, Washington, DC, Transportation Research Board, Washington, DC.

Lowe, J., III, Jonas, E., and Obrcian, V., 1969, "Controlled Gradient Consolidation Test," *J. Soil Mech. Found. Div.*, Vol. 95, No. SM1, pp. 77–97.

McClimans, S. A., 1984, "Centrifugal Model Evaluation of the Consolidation Behavior of Sand/Phosphatic Clay Mixes," Doctoral dissertation, University of Florida, Gainesville, FL.

McDermott, I. R. and King, A. D., 1998, "Use of Bench-Top Centrifuge to Assess Consolidation Parameters," presented at *Tailings and Mine Waste '98*, Fort Collins, CO, Colorado State University, Fort Collins, CO.

Phillips, E., 1869, "De l'equilibre des solides elastiques semblables," *Comptes Rendus des Séances de l'Académie des Sciences*, Vol. 68, pp. 75–79.

Pokrovsky, G. Y. and Fedorov, I. S., 1936, "Studies of Soil Pressures and Soil Deformations by Means of a Centrifuge," presented at the *1st International Conference on Soil Mechanics and Foundation Engineering*, Cambridge, MA, International Society for Soil Mechanics and Geotechnical Engineering, London, England.

Reid, D., Fourie, A., Watson, S. and Jewell, R., 2012, "Accelerated consolidation testing of slurries using a desktop centrifuge," presented at the *15th International Seminar on Paste and Thickened Tailings (PASTE 2012)*, Sun City, South Africa, Australian Centre for Geomechanics, Crawley, Australia.

Reid, D. and Fourie, A. B., 2012, "Accelerated Consolidation Testing of Soft Clays and Mine Tailings Using a Desktop Centrifuge," presented at the *Australia New Zealand Conference on Geomechanincs*, Melbourne, Australia, International Society for Rock Mechanics, Lisbon, Portugal.

Resnick, G. S. and Znidarčić, D., 1990, "Centrifugal Modeling of Drains for Slope Stabilization," *J. Geotech. Eng.*, Vol. 116, No. 11, pp. 1607–1624, https://doi.org/10.1061/(ASCE)0733-9410(1990)116:11(1607)

Scully, R. W., Schiffman, R. L., Olsen, H. W., and Ko, H. Y., 1984, "Validation of Consolidation Properties of Phosphatic Clay at Very High Void Ratios," presented at the *Symposium on Sedimentation/Consolidation Models: Predictions and Validation*, San Francisco, CA, American Society of Civil Engineers, Reston, VA.

Smith, R. E. and Wahls, H. E., 1969, "Consolidation Under Constant Rates of Strain," *J. Soil Mech. Found. Div.*, Vol. 95, No. 2, pp. 519–540.

Takada, N. and Mikasa, M., 1986, "Determination of Consolidation Parameters by Selfweight Consolidation Test in Centrifuge," *Consolidation of Soils: Testing and Evaluation, ASTM STP892*, R. N. Yong and F. C. Townsend, Eds., ASTM International, West Conshohocken, PA, pp. 548–566, https://doi.org/10.1520/STP34634S

Townshend, F. C. and Bloomquist, D., 1983, "Centrifugal Model Evaluation of Cap Enhanced Consolidation of Kingsford Waste Clays," *Research Report Prepared for IMC Corporation*, University of Florida, Gainesville, FL.

White, D., Randolph, M. F., and Thompson, B., 2005, "An Image-Based Deformation Measurement System for the Geotechnical Centrifuge," *Int. J. Phys. Model. Geotech.*, Vol. 5, No. 3, pp. 1–12, https://doi.org/10.1680/ijpmg.2005.050301

Wissa, A. E. Z., Christian, J. T., Davis, E. H., and Heiberg, S., 1971, "Consolidation at Constant Rate of Strain," *J. Soil Mech. Found. Div.*, Vol. 97, No. 10, pp. 1393–1413.

Zornberg, J. G. and McCartney, J. S., 2010, "Centrifuge Permeameter for Unsaturated Soils. I: Theoretical Basis and Experimental Developments," *J. Geotech. Geoenviron. Eng.*, Vol. 136, No. 8, pp. 1051–1063, https://doi.org/10.1061/(ASCE)GT.1943-5606.0000319

Copyright by ASTM International (all rights reserved), pursuant to License Agreement. No further reproduction authorized.