3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering,
28-30 June 2012, Near East University, Nicosia, North Cyprus

Preliminary results from a small geotechnical centrifuge for consolidation tests

Kamil Kayabalı
Ankara University Geological Engineering Department, Ankara, Türkiye

Mehmet Can Balcı
Batman University Geological Engineering Department, Batman, Türkiye

Tuğçe Başer
Bozok University Geological Engineering Department, Yozgat, Türkiye

KEYWORDS: Geotechnical centrifuge, centrifuge consolidation, conventional consolidation, consolidation parameters

ABSTRACT: Laboratory tests of consolidation and permeability take many days. Although geotechnical centrifuges developed to model geotechnical problems include those two tests, they have been used only for research purposes owing to the constraints of size and cost. A small-size centrifuge was designed to perform consolidation and permeability tests. Because the present investigation is parametrical in nature, the study material requires a number of identical samples, which were prepared through artificial consolidation. As for the testing methods, the conventional consolidation and centrifuge consolidation methods were employed. The results of the former were in the form of effective stress versus the axial strain whereas the results of latter were in the form of the equivalent centrifuge load versus the axial strain, from which an empirical form was derived relating the equivalent centrifuge load to the effective stress based upon the common parameter of axial strain. The empirical relationship yield a reasonable correlation between the predicted and experimentally determined consolidation parameters excluding the coefficient of consolidation. An alternative way was chosen to determine this parameter. The coefficient of permeability determined through the falling-head tests were correlated with the ultimate axial strains from the centrifuge tests, which provided a reasonably good relationship allowing computation of the coefficient of consolidation using the coefficient of permeability. The present investigation revealed that the small centrifuges have the potential to be routine laboratory testing tools.

1 INTRODUCTION

Geotechnical centrifuges are used to model many soil mechanics and foundation problems. Due to cost considerations, there are a limited number of geotechnical centrifuges worldwide, which have been used solely for research purposes. In spite of this fact, they are still more economical than performing some tests in situ. The presently available geotechnical centrifuges are huge in size; radius of such an instrument is usually around a few meters.

Some of the investigations employing geotechnical centrifuges are as follows. Cooke and Mitchell (1991) studied physical modeling of dissolved contaminant movements in partially saturated soils using a geotechnical centrifuge and concluded that centrifuge modeling may be a viable approach for this purpose. Probaha and Goodings (1996) studied the centrifuge modeling of geotextile-reinforced cohesive soil retaining walls and showed that, using the simplified two-dimensional limit equilibrium approach, the simplified Bishop method incorporating reinforcement was found to be a good predictor of the models based on calculated factors of safety at failure. Zornberg et al. (1997) analyzed behavior of reinforced slopes using a geotechnical centrifuge. They presented a description of the experimental testing procedures implemented as part of a centrifuge testing program and used an example dataset from their investigation to illustrate typical results which included the g-level at failure, visual observation of failure development, and post-failure analysis of reinforcement breakage. Liu and Dobry (1999) investigated the effect of liquefaction on lateral pile response by employing a 100 g-ton geotechnical centrifuge. Following that, they proposed a guideline for seismic analysis of piles in liquefying sand. McDowell and Bolton (2000) examined the specific boundary problem associated with the penetration of a model pile into two different gradings of sand in a geotechnical centrifuge and found that insignificant crushing had occurred in the sand retrieved from depths less than the depth of peak resistance but that significant crushing had occurred in the sand retrieved from greater depths. They also proposed a micro mechanical model for their observation. White et al. (2005) combined digital still photography technique with a drum centrifuge. They intended to make precise measurements to picture the moment of failure in soil under loading. Harris et al. (2008) utilized a geotechnical centrifuge to investigate mass movement processes on thawing ice-rich slopes. They employed scaling laws to simulate correct prototype self-weight stresses during thaw and they used the measured pore pressures in slope stability analyses based on a simple planar infinite slope model. Gong et al. (2011) studied the deformation characteristics, reinforcement effect of soil nailing and the stability in the excavation unloading course of loess slopes. Their model study concluded that soil nailing can greatly increases the stability of loess slopes.

All investigations cited above employed geotechnical centrifuges enormous in size. Different from those, Allersma (1994) developed a small centrifuge of 1 m in radius and showed that a number of various geotechnical experiments can be carried out in a shorter time. More recently, Kayabali and Ozdemir (2012) investigated the feasibility of using the centrifuge consolidation test as a practical tool to estimate consolidation behavior of natural soils by employing a miniature centrifuge apparatus. They developed a crude but practical means allowing the centrifuge consolidation results to be converted to the standard consolidation format. They employed a beam centrifuge of 0.35 m in radius; the measurements were taken using mechanical dial gages. The instrument did not allow continuous measurement of deformations which were recorded by stopping the system. By doing so, a systematical error owing to the rebound of soil specimens was introduced.

The scope of this investigation is to examine the usability of a “mini” geotechnical centrifuge for consolidation testing by employing an instrument allowing continuous and more accurate measurement of deformation.

2 MATERIALS AND METHODS

The material used for this investigation is a clayey soil (CH) with the liquid and plastic limits of 76 and 34, respectively. Because the study is parametric in nature and it is very difficult, if not impossible, to find sufficient number of identical natural samples, the study material was artificially consolidated soil samples. For this, the dry soil sieved through a #40 mesh was wetted around its liquid limit for a homogeneous mixture. It was then subjected to centrifuge at varying revolution speeds ranged from 300 RPM to 1000 RPM with the increments of 100 RPM. Four specimens were subjected to centrifuge at every revolution speeds for 6 hours duration. This way, 32 artificially consolidated soil specimens were constituted. The artificially consolidated specimens were transferred into consolidation rings of 50 mm in diameter and 20 mm in height, Two of the four specimens consolidated at each revolution level were reserved for the conventional oedometer test and the remaining two were for the centrifuge consolidation test.

The conventional oedometer test involved application of effective stresses of 50, 100, 200, 400, 800, and 1600 kPa. A sample plot is presented in Figure 1a as the axial strain versus the effective stress.

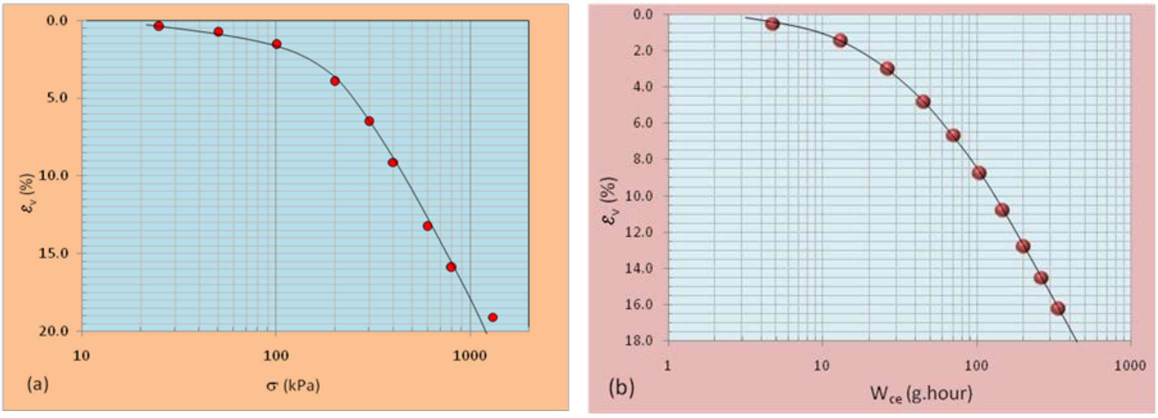

Figure 1. Sample plots for consolidation tests. (a) Conventional oedometer; (b) centrifuge consolidation (the results belong to the specimens artificially consolidated at 600 RPM).

The centrifuge consolidation tests were carried out using the instrument shown in Figure 2a. The instrument hosts 4 cells, which were actually positioned as shown in Figure 2b. The soil specimen inside the consolidation ring is sandwiched between two porous stones. A surcharge of 4N was applied to facilitate rapid drainage. As the table revolves, on which the centrifuge consolidation cells are anchored, a laser beam continuously measures the distance from top of the surcharge to the source of laser beam, which is the contraction for the consolidation specimen. The axial strain is obtained by dividing this entity to the original height of specimen. A data acquisition unit collected the deformation versus time data for further analyses.

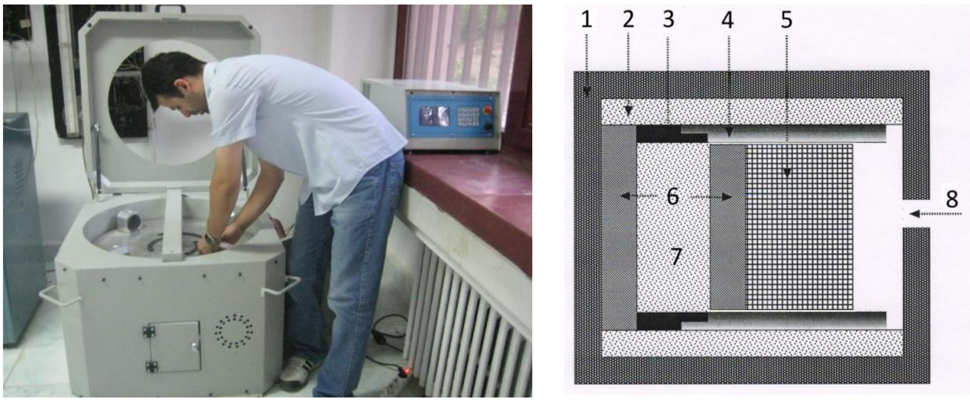

Figure 2. The small geotechnical centrifuge employed for the present investigation (left) and the schematical cross section of the centrifuge consolidation cell (right): 1) Fixed housing to hold the test specimen, 2) inner cylindrical module, 3) consolidation ring (D=50 mm, h=20 mm), 4) centralizer, 5) surcharge, 6) porous stone, 7) soil specimen, 8) laser beam entry hole (dimensions are proportional to consolidation ring).

Application of centrifuge load was carried out such that the initial revolution speed was 300 RPM. Centrifuge loads were applied at 100 RPM increments, each of which lasted 10 minutes. This way, each centrifuge consolidation test involved revolution speeds of 300, 400, 500, 600, 700, 800, 900, and 1000 RPM and lasted 80 minutes in total. The results were plotted as shown in Figure 1b as the axial strain versus the equivalent centrifuge load, W_{ce} (in units of g.hours), which is determined as follows.
The concept of equivalent centrifuge work was introduced to relate the axial strain with the centrifuge work and test duration. Presenting a numerical example would be helpful. Let the revolution speed be 300 RPM. A soil specimen of 75 grams in mass and 20 mm in thickness, whose center is 300 mm from the center of the centrifuge, a porous stone of 30 grams in mass and 9 mm in thickness and a surcharge of 400 grams in mass and 26 mm in thickness yield a total mass

of 0.505 kg with an average centrifuge radius of 0.274 m. The centrifuge acceleration (a_c) equals to the centrifuge radius times the square of angular velocity ($a_c = r\omega^2$), which turns out to equal to 280 m/s^2. Division of this entity by the gravitational acceleration yields an ng value of 28.6, where n is the multiplication factor. That is, running the system at 300 RPM with a mass radius of 0.274 m would yield an acceleration equaling to 28.6 times the gravitational acceleration. If the system revolves at the 300 RPM for one hour duration, the equivalent centrifuge work would be equal to 28.6 g.hours. Should the small centrifuge run only for 10 minutes, the yielding W_{ce} would be only (28.6/6=) 4.8 g.hours. It appears that this entity is an addable one and the work done by the small centrifuge can be summed up for various revolution speeds along with their respective durations. Ten minutes of loading durations are to simulate supposedly the loadings in conventional oedometer test. Concerning this duration of loading for centrifuge consolidation, a number of trials were done on soil samples of different characters. Because the soil specimen in a centrifuge is loaded at accelerations many times higher than the gravitational acceleration, deformations did not appear to stop so that the specimen comes to equilibrium. However, trials showed that a greater part of the deformation in a specimen under centrifuge loading takes place usually in 10 minutes or so. The equivalent centrifuge loads were computed as 5, 8, 13, 19, 26, 34, 43, 53, 64 and 76 g.hours for the centrifuge loading levels of 300, 400, 500, 600, 700, 800, 900, and 1000 RPM, respectively, each lasting ten minutes. When plotted as in Figure 1b, the W_{ce} values were taken as cumulative figures.

3 EXPERIMENTAL WORK

Conventional oedometer and centrifuge consolidation tests involved 8 sets of artificially consolidated soil specimens. Each set had four identical soil specimens; the sample plots given in Figure 1 include the averages of axial strains (ε_v) of two specimens for both methods. The most crucial part of this investigation involves transformation of ε_v versus W_{ce} data from a centrifuge consolidation test to a more manageable form of ε_v versus σ' data, with which geotechnical engineers are all familiar. The transformation was carried out by determining the W_{ce} from the centrifuge consolidation tests and σ' from the conventional consolidation tests corresponding to the same axial strain. Figure 3a was constituted by determining W_{ce} and σ' values corresponding to axial strains of 1%, 2%, 3%, and so on. It reveals that there is a significantly good relationship between those two parameters. This fact is verified by complete set of data for all artificially consolidated soils as shown in Figure 3b.

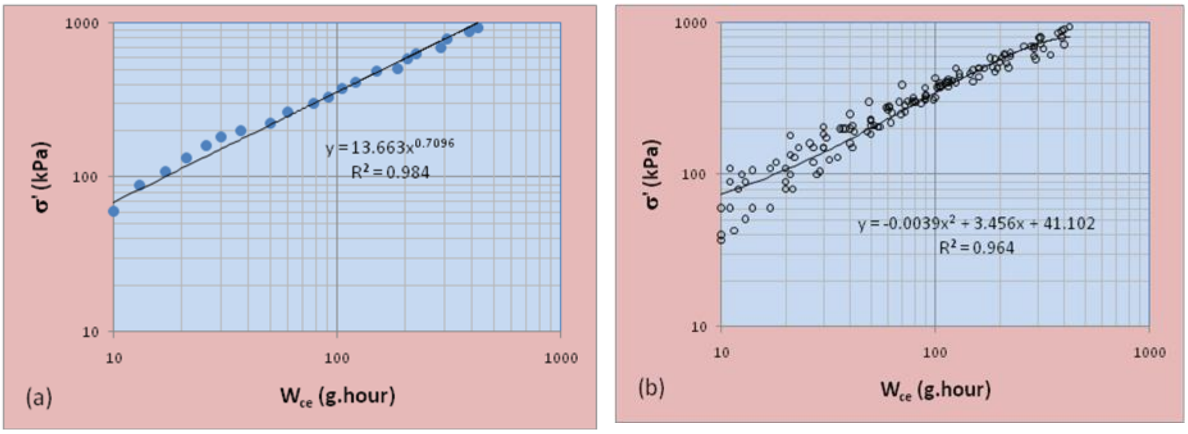

Figure 3. Plot of the effective stress versus the equivalent centrifuge load data: (a) from Figure 1; (b) for 8 artificially consolidated soils. Each point on graphs corresponds to certain axial strain.

The next step involves developing an empirical form to predict the effective stress using the axial strain and equivalent centrifuge load data from a centrifuge test. For this, axial strains (common to the conventional and centrifuge consolidation tests) along with the equivalent centrifuge loads and effective stresses were subjected to a multiple regression tests and the following relationship was derived:

$$\sigma' = 17.96\varepsilon_v^{0.0145}W_{ce}^{0.64} \qquad (1)$$

The coefficient of regression (R^2) for this equation is 0.97. This empirical form allows one to obtain a series of σ'- ε_v data pairs by which a plot can be constructed to determine the consolidation parameters such as the pre-consolidation pressure (σ'_p), the modified recompression index ($C_{r\varepsilon}$) and modified compression index ($C_{c\varepsilon}$), which are the slopes of the gentler and steeper part of the typical σ'- ε_v curve, respectively. By knowing the initial void ratio (e_o) of the soil specimen, the compression index (C_c) and the recompression index (C_r) values, which are determined from a void ratio (e) versus the effective stress (σ') curve of a conventional consolidation curve, can be easily computed using the following equations (Holtz and Kovacs, 1981):

$$C_c = C_{c\varepsilon}\,(1 + e_o) \qquad (2)$$

$$C_r = C_{r\varepsilon}\,(1 + e_o) \qquad (3)$$

To see if the empirical form established to convert the centrifuge consolidation data into the conventional consolidation data (Eqn. 1) works properly, Figure 4 was constructed, where circles are for the consolidation data obtained from the conventional method and diamonds represent the converted data from Equation (1). Examination of Figure 4 reveals that the agreement between the predicted σ'- ε_v curve (diamonds) from the centrifuge consolidation test data and the experimental σ'- ε_v curve (circles) from the conventional consolidation tests is promising.

A comparison between the consolidation parameters obtained from conventional method and the predicted parameters are presented in Table 1. The level of agreement between the predicted- and the experimentally-determined pre-consolidation stresses, which were determined using the Silva method (Silva, 1970), is remarkably good. The similar level of agreement can be also observed for the modified compression indices. Nevertheless, the agreement between the modified recompression indices is not as good.

One of the significant parameters in the general area of consolidation is the coefficient of consolidation (c_v), which is determined through methods commonly known as t_{90} (Taylor's square root of time method) or t_{50} (Casagrande method). Neither of those methods is applicable to the time versus deformation data acquired through a centrifuge consolidation test. An alternative way of determining this parameter is the equation given through Terzaghi's consolidation theory:

$$c_v = k / (m_v\gamma_w) \qquad (4)$$

where k is the coefficient of permeability, m_v is the coefficient of volumetric compressibility and γ_w is the unit weight of water. Because m_v is an easily definable coefficient for any consolidation test, c_v can be easily derived if the permeability of the soil is known.

Başer (2012) conducted a series of centrifuge permeability tests on artificially compacted 15 soil samples using the same setup given in Figure 2. She also performed falling-head permeability tests on the same samples. The centrifuge consolidation tests conducted by Başer (2012) involved revolution speeds of 300 RPM through 1200 RPM with the increments of 100 RPM, each lasting 10 minutes. Başer (2012) produced Figure 5(a) to correlate the coefficient of permeabilities obtained from those tests with the ultimate axial strains obtained from the centrifuge consolidation tests. The empirical form relating the ultimate axial strain (ε) to the coefficient of permeability (k) is given as:

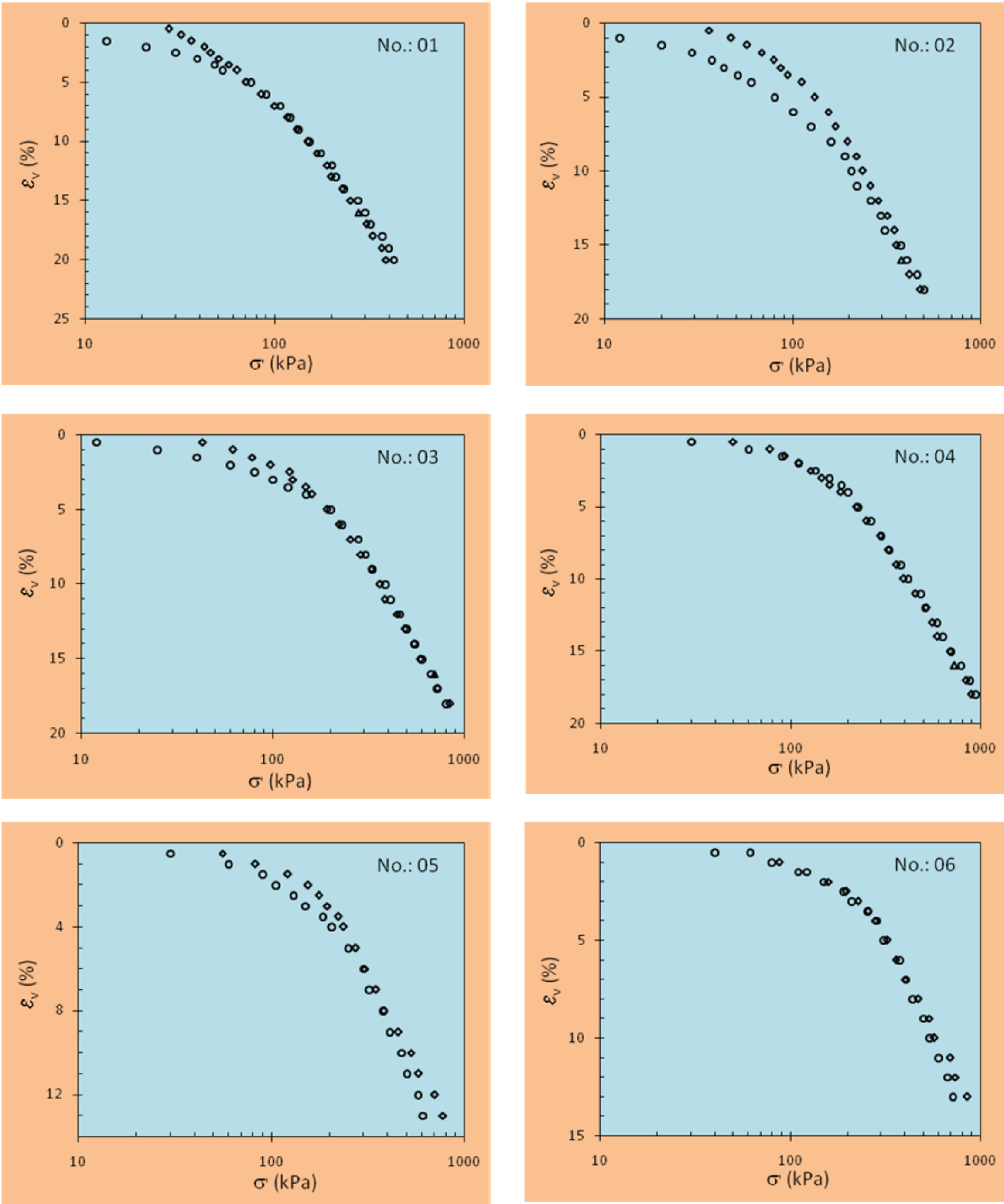

Figure 4. Comparison between the results from conventional consolidation tests (circles) and the predicted effective stresses (diamonds) from the centrifuge consolidation data using the conversion equation.

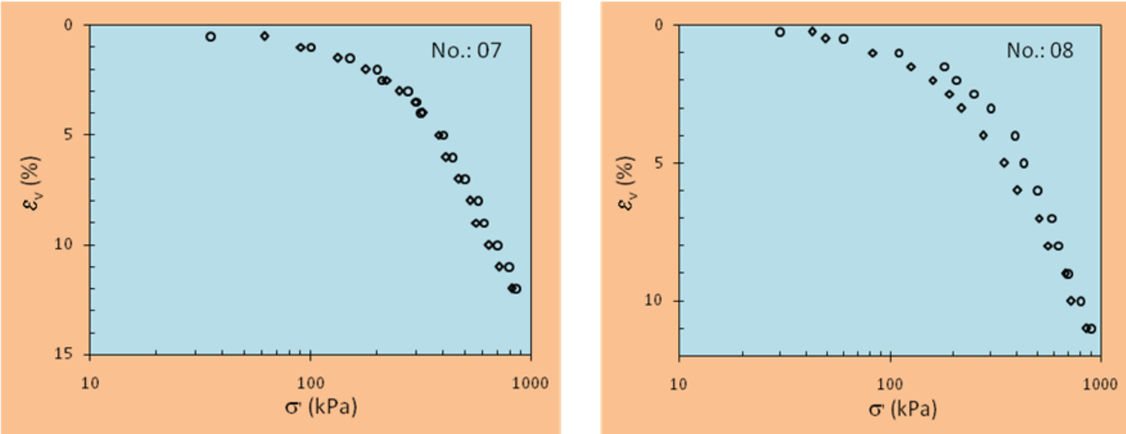

Figure 4. Continued

Table 1. Comparison between the consolidation parameters obtained from conventional consolidation method (CCM) and the predicted consolidation parameters from the centrifuge consolidation method (SCM).

	σ'_p (kPa)		$C_{r\varepsilon}$		$C_{c\varepsilon}$	
No.	CCM	SCM	CCM	SCM	CCM	SCM
1	82	76	0.035	0.090	0.21	0.23
2	102	106	0.040	0.053	0.20	0.23
3	200	135	0.030	0.055	0.23	0.20
4	190	190	0.024	0.048	0.23	0.21
5	195	170	0.030	0.036	0.19	0.16
6	250	210	0.032	0.037	0.23	0.17
7	270	235	0.018	0.032	0.19	0.18
8	315	210	0.014	0.026	0.19	0.16

$$\log(k) = -15.84 + 0.91\varepsilon \quad (5)$$

Figure 5(b) was plotted using Equation (5) to show that the coefficient of permeability can be predicted with a reasonable degree of success using the centrifuge consolidation technique.

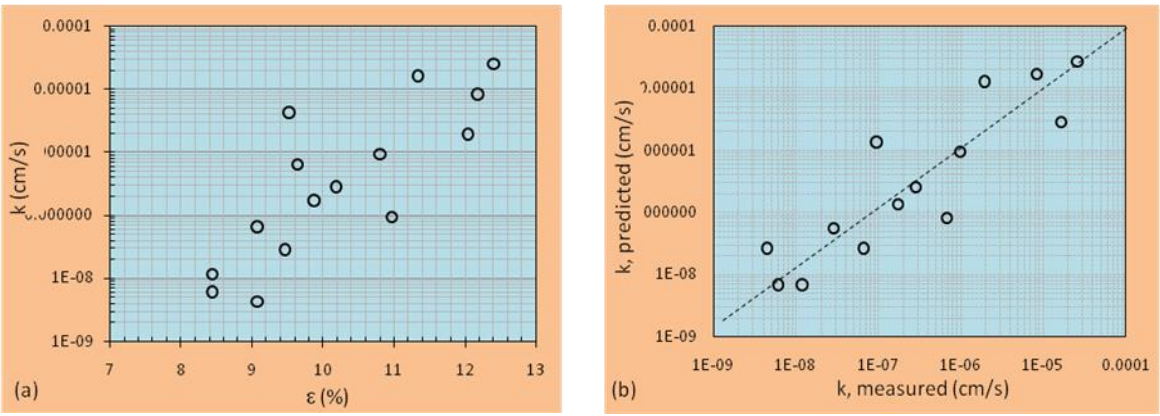

Figure 5. Correlation between the coefficient of permeability from falling-head test methods and axial strains from the centrifuge consolidation tests (a) and correlation between predicted and measured permeabilities (b).

4 CONCLUSIONS

The conclusions derived from the present investigation are as follows:
A small-size centrifuge provides reasonably good estimates of pre-consolidation stress, coefficient of compression index, and the recompression index to a lesser extent. These finding are based upon only one type of soil. Therefore, the validity and the reliability of results presented herein need to be checked using more soils, both artificial and natural.
The time versus deformation data obtained from the centrifuge consolidation method are not suitable to determine such parameters as t_{90} or t_{50} to predict the coefficient of consolidations as in the conventional consolidation method. The coefficient of consolidation can be predicted alternatively should the permeability of soil is known. The instrument developed for this investigation also helps to establish a relationship between the ultimate axial strain and the coefficient of permeability allowing computation of the coefficient of consolidation.
The instrument developed herein has a great potential to be a routine geotechnical testing tool for both the consolidation and permeability.

REFERENCES

Allersma, H.G.B. (1994), Development of miniature equipment for a small geotechnical centrifuge. Transportation Research Record No.1432, National Academic Press Washington, D.C.: 99-105.

Başer, T. (2012), İnce taneli zeminlerde geçirgenliğin santrifüj yöntemiyle tayini. Bozok Üniversitesi Fen Bilimleri Enstitüsü: 40 s (yayınlanmamış).

Cooke, B. & Mitchell, R.J. (1991), Physical modeling of a dissolved contaminant in an unsaturated sand. Canadian Geotechnical Journal: 28(6), 829-833.

Gong, C.M., Cheng, Q.G. & Liu, Z.P. (2011), Centrifuge model tests on excavation and reinforcement effect of loess slope. Rock and Soil Mechanics, DOI: CNKI:SUN:YTLX.0.2010-11-02.

Harris, C., Smith, C.S., Davies, M.C.R. & Rea. B. (2008), An investigation of periglacial slope stability in relation to soil properties based on physical modeling in the geotechnical centrifuge. Geomorphology, 93(3-4), 437-459.

Holtz, R.D. & Kovacs, W.D. (1981), Introduction to geotechnical engineering. Prentice Hall: 733pp.

Kayabali, K. & Ozdemir, A. (2012), Assessing the practicality of the centrifuge method in 1-D consolidation. Bulletin of Engineering Geology and the Environment: DOI : 10.1007/s10064-012-0426-7.

Liu, L. & Dobry, R. (1999), Effect of liquefaction on lateral response of piles by centrifuge model tests. Federal Highway Administration, Report No. FHWA-RD-99-165. 5 pp.

McDowell, G.R. & Bolton, M.D. (2000), Effect of particle size distribution on pile tip resistance in calcareous sand in the geotechnical centrifuge. Granular Matter: 2, 179-187.

Probaha, A. & Goodings, D.J. (1996), Centrifuge modeling of geotextile-reinforced cohesive soil retaining walls. Journal of Geotechnical Engineering: 122(10), 840-848.

Silva, P.F. (1970), A new graphical construction for determination of pre-consolidation stress of a soil sample. In: Proceedings of the 4th Brazilian Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil: 2(1), 225-232.

White, D., Randolph, M.F. & Thompson, B. (2005), An image-based deformation measurement system for the geotechnical centrifuge. International Journal of Physical Modeling in Geotechnique, 5(3): 1-12.

Zornberg, J.G., Mitchell, J.K. & Sitar, N. (1999), Testing of reinforced slopes in a geotechnical centrifuge. Geotechnical Testing Journal, 20(4): 470-480.