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Investigation of the coefficient of consolidation of fine-grained soils using combined apparatus

Ramin ASADI[a], Kamil KAYABALI[a] and Mehmet Can BALCI[b*]

[a]*Ankara University, Faculty of Engineering, Department of Geological Engineering, Ankara, Turkey*
[b]*Batman University, Engineering and Architecture Faculty, Department of Civil Engineering, Batman, Turkey*

Research Article

Keywords:
Coefficient of Consolidation, Coefficient of Permeability, Oedometer Test, Combined Apparatus.

ABSTRACT

The scope of this investigation is to compare the coefficient of consolidation (c_v) values defined by the Taylor's Square Root of Time Fitting Method, which is obtained from the conventional oedometer tests, with the c_v values calculated by Terzaghi's One Dimensional (1D) Consolidation Theory, which is obtained from the permeability-consolidation tests performed with a combined apparatus specifically designed for this study. In addition, an empirical relation is developed to determine c_v using the coefficient of permeability (k) and index properties of the soils. The c_v values obtained from the permeability-consolidation tests using the combined apparatus were found to be larger than the c_v values defined by the Taylor's method, which is one of the oedometer tests. The findings showed that the difference was more prominent in the soil samples with a high plasticity. It was also found that the c_v calculated by the Taylor's method exhibited a distribution in a wide range with the increased load depending on the degree of plasticity of the soil. The c_v obtained from the combined apparatus it decreased with low load values and increased with higher load levels. The c_v obtained by the proposed empirical relationship showed good agreement with the c_v defined by permeability-consolidation relationships.

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1. Introduction

Identification of the characteristics of the soil on which structures are built and estimation of soil behaviour for different load cases are quite important to reveal potential soil problems so that engineering structures can be designed in a sound and economical manner. Settlement is one of the significant issues that may be encountered in essential projects. The acceptable amount of settlement is defined depending on the building's important factor and the type of soil. If the settlement components exceed the permissible limits throughout the design life planned for the structure, some undesirable inconveniences such as fractures, cracks, and splits occur in the superstructure. When this effect reaches an advanced level, the structure is partially damaged or becomes completely unusable.

Consolidation settlement constitutes a large part of the settlement that occurs when soils with a low coefficient of permeability (k) are subjected to load. Consolidation settlement (s_c) is a time-dependent process that can take considerable time with some soil types. In determining the building's design life, it is of great importance to estimate how long it will take for the s_c in the soil to take place under loading conditions. Holtz and Kovacs (1981) reported that the coefficient of consolidation (c_v) is the only parameter that controls the consolidation settlement in terms

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*Corresponding author: Mehmet Can BALCI, mcanbalci@gmail.com

of rate (speed). This parameter is crucial in soil improvement and the use of the preloading technique. The c_v is a term derived from Terzaghi's (1925) 1D Consolidation Theory. Based on Terzaghi's (1925) 1D Consolidation Theory, there is a relationship between soil permeability (k), coefficient of consolidation (c_v), and coefficient of volume compressibility (m_v) as follows:

$$c_v = k / (m_v \gamma_w) \quad (1)$$

where γ_w unit weight of water (kN/m^3).

Numerous methods have been developed for calculating c_v from conventional oedometer tests. These methods generally involve different mathematical approaches and curve-fitting methods. The advanced curve fitting methods for computing c_v are summarized in Table 1.

Casagrande and Fadum (1940), and Taylor (1948) developed empirical methods to approximately adapt observational laboratory test data to Terzaghi's 1D consolidation theory. Feng and Lee (2001) reported that both methods are known to be the most useful methods in routine laboratory tests. However, the c_v defined by Casagrande's logarithm of time fitting method is affected by the primary compression and secondary compression of the axial strain (ε) - time (t) curve. Since 90% of the degree of consolidation is used instead of 100% in Taylor's Square Root of Time Fitting Method, the c_v is affected less from the secondary compression but more from the first compression (Sridharan and Prakash, 1995; Cortellazzo 2002). Sridharan et al. (1995) assert that the c_v should be higher when affected by the primary compression and lower when affected by the secondary compression.

Table 1- Advanced curve fitting methods for computing c_v.

References	**Method**
Casagrande and Fadum (1940)	log t_{50}
Taylor (1948)	$\sqrt{t_{90}}$
Su (1958)	Maximum slope
Sivaram and Swamee (1977)	Computational
Sridharan et al. (1987)	Rectangular hyperbola
Sridharan and Prakash (1993)	δt-t/δt
Robinson and Allam (1996)	Early stage log-t
Mesri et al. (1999)	Inflection point
Feng and Lee (2001)	$\sqrt{t_{60}}$
Al-Zoubi (2010)	SRS

However, the presence of a large number of methods in the literature is an indication that these methods are not applicable under all circumstances. Furthermore, since the c_v values obtained by different methods are very different, it is difficult to make a reasonable decision regarding the c_v merely based on the soil behavior under laboratory test conditions. According to Sridharan and Nagaraj (2004), none of the curve fitting methods applied under different circumstances and using different materials provides an exactly correct result or an approximate result. Al-Zoubi (2004) notes that large-scale variations between c_v defined by curve fitting methods may arise from reasons such as variation of the c_v during a specific load level, the procedure for determining the final sc, loading time including secondary compression, and additional assumptions used in these methods. Lovisa and Sivakugan (2013) compared c_v values, which are determined using curve-fitting methods. Despite many controversial points mentioned above regarding the curve fitting methods, Taylor's Square Root of Time Fitting Method is widely used to determine c_v in current geotechnical engineering applications. Taylor (1948) devised a method based on the square root of the time spent during the consolidation test to calculate c_v. In this method, a curve that depicts the relationship between two dial gauge readings made during the consolidation test and the square root of the applied load's interaction time on the sample, is drawn. The early flat part of this curve is extended until it intersects the vertical axis. Again, a second line is drawn from the start point, which has 1.15 times the value of the obtained intersection point. The projection of the intersection point of the second line and the curve obtained from the consolidation experiments on the horizontal axis shows the time it takes for 90% of the primary consolidation (U=%90) to occur. c_v is calculated using the equation given below, taking the time factor as 0.848, for U = 90%.

$$c_v: T_v\, d^2/t_{90} \quad (2)$$

Where T_v time factor, d drainage path, and t_{90} time when U is 90%. Various researchers conducted different studies due to the problems encountered in c_v calculations by curve fitting methods. Some researchers have tried to calculate c_v using the soil's index properties, independently from the oedometer tests shown in Table 2.

Carrier (1985) developed an equation for the definition of c_v considering the liquidity index, plasticity index, and activity of soils. Narasimha et al. (1995) suggested another empirical equation for the calculation of c_v for normally consolidated clay, taking into account the void ratio in the liquid limit condition and the existing overburden pressure in the field. Solanki and Desai (2008) examined the consolidation parameters of alluvium clays in India's southern Gujarat region, suggesting a relationship between liquid limit and plasticity and c_v. Sridharan and Nagaraj (2004) indicated that the relationship between shrinkage index and c_v was more consistent than the liquid limit or the plasticity index. Al-Ameri et al. (2011) investigated silty clay from 280 different points and defined a new relationship between liquid limit and c_v. Some studies focus on using different methods for the determination of c_v. Olek and Pilecka (2019) used large-scale Rowe cell, Chow et al. (2020), and Vinod and Sridharan (2015) evaluated the measurement of pore water pressure for determination of c_v. Nguyen et al. (2019) predicted c_v values of soft soil using an artificial intelligence approach. In addition to the studies listed above, Olson (1986) suggested that the only rational Method of defining c_v was with Terzaghi's method, taking into account the large variations between the c_v obtained from curve fitting methods.

The present study aims to determine the c_v according to Taylor's square root of time fitting method by performing conventional oedometer tests on identical soil samples prepared from remolded soils with different plasticity characteristics, and determine c_v based on the relationship defined by Terzaghi's equation by carrying out permeability-consolidation tests on the same samples using the combined apparatus specially developed for this study to compare the results of both methods and to question the degree of reliability of c_v obtained from the conventional oedometer tests. Besides, an empirical relationship is provided for the c_v based on the soils' permeability and index properties.

Table 2- Some empirical relationships for calculations of c_v.

Carrier (1985)	$c_v = \frac{9.04(10^{-7})(1.192 + ACT^{-1})^{6.993}(4.135LI + 1)^{4.29}}{PI(2.03LI + 1.192 + ACT^{-1})^{7.993}}$
Narasimha et al. (1995)	$c_v = \left(\frac{1+e_{LL}(1.23-0.276\, log\sigma_v')}{e_{LL}}\right)\left(\frac{1}{\sigma_v'^{(0.353)}}\right)(10^{-3})\ e_{LL} = \left(\frac{LL(\%)}{100}\right)G_s$
Sridharan and Nagaraj (2004)	$c_v = \frac{3}{100(SI)^{3.54}}$
Solanki and Desai (2008)	$c_v = 10^8(LL^{-6.7591}),\ c_v = 7.7525(PI^{-3.1021})$
Al-Ameri et al. (2011)	$c_v = 4258(LL^{-1.75})$

ACT: Activity, eLL: Void Ratio at The Liquid Limit, G_s: Spesific Gravity, LI: Liquidity Index, LL: Liquid Limit, PI: Plasticity Index, SI: Shrinkage Index, σ_v': Vertical Effective Stress

2. Material

2.1. Combined Apparatus

Permeability-consolidation tests were performed on combined cells specifically designed for this study. These cells allow for the flow of water through them during the loading of the samples. Combined cells consist of a base, ahead, and a rigid plexiglass body. The cylindrical rigid plexiglass body has an inner diameter of 50 mm, an outer diameter of 70 mm and a height of 125 mm. A water outlet point was provided for discharging the water accumulating on the base. At the centre of the head lies the inlet of the loading piston. Particular attention was paid to minimizing the friction at the junction between the loading piston and the head. After combining the cell, an O-ring was added to prevent the escape of water through this point. The details of the combined apparatus are given in Figure 1.

2.2. Soil Samples

Tests were carried out on 12 remoulded soil samples. Since the study was a parametric one and plenty of soil samples were needed, the remoulded soil mixtures were prepared in the laboratory environment to meet soil samples' needs. The index properties of the soils used in the study are given in Table 3.

3. Methodology

3.1. Sample Preparation

Each of the soil samples was sifted using a sieve no. 40. The samples were then thoroughly mixed in water content between the values of LL and PL (in a water content closer to LL) until they were homogenized. Subsequently, they were filled into rings of 50 mm

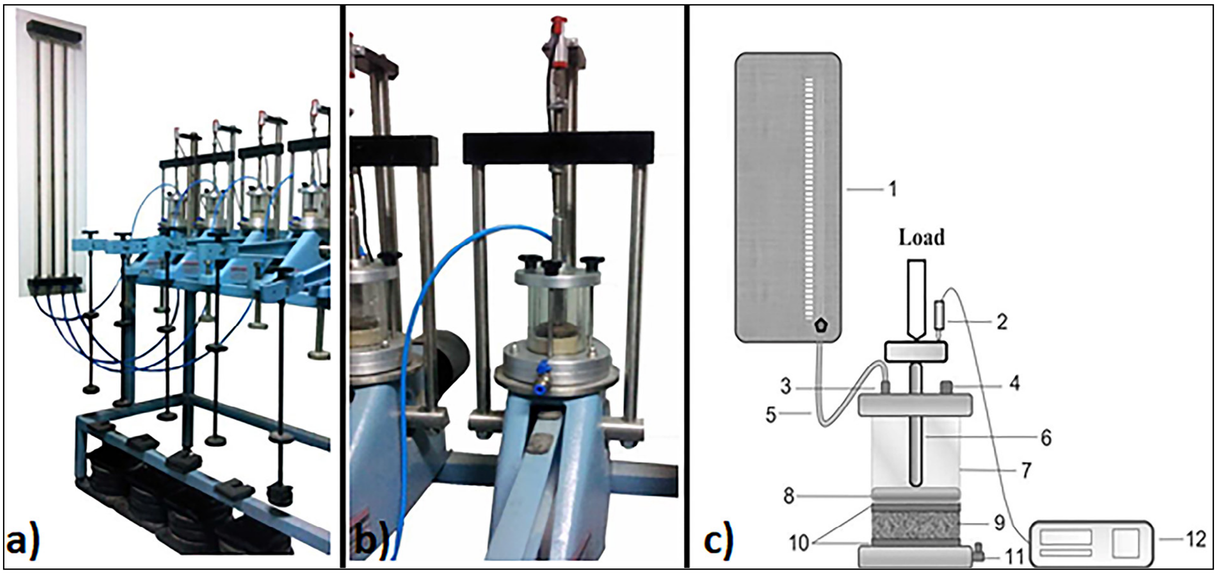

Figure 1- Details of the combined apparatus; a) overview, b) close-up view on the oedometer test set-up, c) schematic cross-section (not to scale): 1) water indicator panel, 2) deformation dial gauge, 3) water inlet valve, 4) air bleed valve, 5) transparent pipe, 6) loading piston, 7) plexiglas cell, 8) loading cap, 9) soil sample, 10) porous stone, 11) water outlet valve, 12) data logger.

Table 3- Index properties of the soil tested.

Sample Number	SL	PL	LL	PI	USCS	G_s
1	17.2	19.6	38.0	18.4	CL	2.69
2	13.6	29.8	48.2	18.4	ML	2.73
3	14.8	28.0	53.2	25.2	CH	2.80
4	26.1	33.0	69.0	36.0	CH	2.78
5	13.8	22.0	59.7	37.7	CH	2.96
6	14.8	35.6	74.1	38.5	MH	2.60
7	18.9	27.5	67.0	39.5	CH	2.84
8	15.1	21.0	64.6	43.6	CH	2.65
9	11.4	20.0	64.4	44.4	CH	2.65
10	22.7	37.0	82.0	45.0	CH	2.77
11	20.9	37.0	87.0	50.0	CH	2.71
12	19.7	37.0	92.0	55.0	CH	2.70

SL: Shrinkage Limit, PL: Plastic Limit, LL: Liquid Limit, PI: Plasticity Index, USCS: Unified Soil Classification System, G_s: Specific Gravity

in diameter and 20 mm in height. The rings were placed in the cells specifically designed for the sample preparation centrifuge device.

The soil samples used in the study were consolidated and prepared in the laboratory according to the soil sample preparation procedures used in Balci et al. (2018). Each soil was subjected to 6 different pre-consolidation stresses for 6 hours in a soil sample preparation centrifuge, resulting in a total of 72 different artificial soil samples. By preparing two samples for each type of soil sample, tests were carried out on a total of 144 soil samples. During the sample preparation, the effect of RPM values applied in incremental values in the soil sample preparation centrifuge on the compaction of the samples is shown in Figure 2 and Table 4. It was observed that the void ratio of the samples decreases with the RPM values increases used for sample preparation. It is determined that the increase in RPM values also causes an increase in the degree of compression.

3.2. Permeability-Consolidation Test

The coefficient of permeability (k) values was obtained in permeability-consolidation tests by applying the falling head permeability test principles. The permeability-consolidation test from the conventional oedometer test is that the permeability

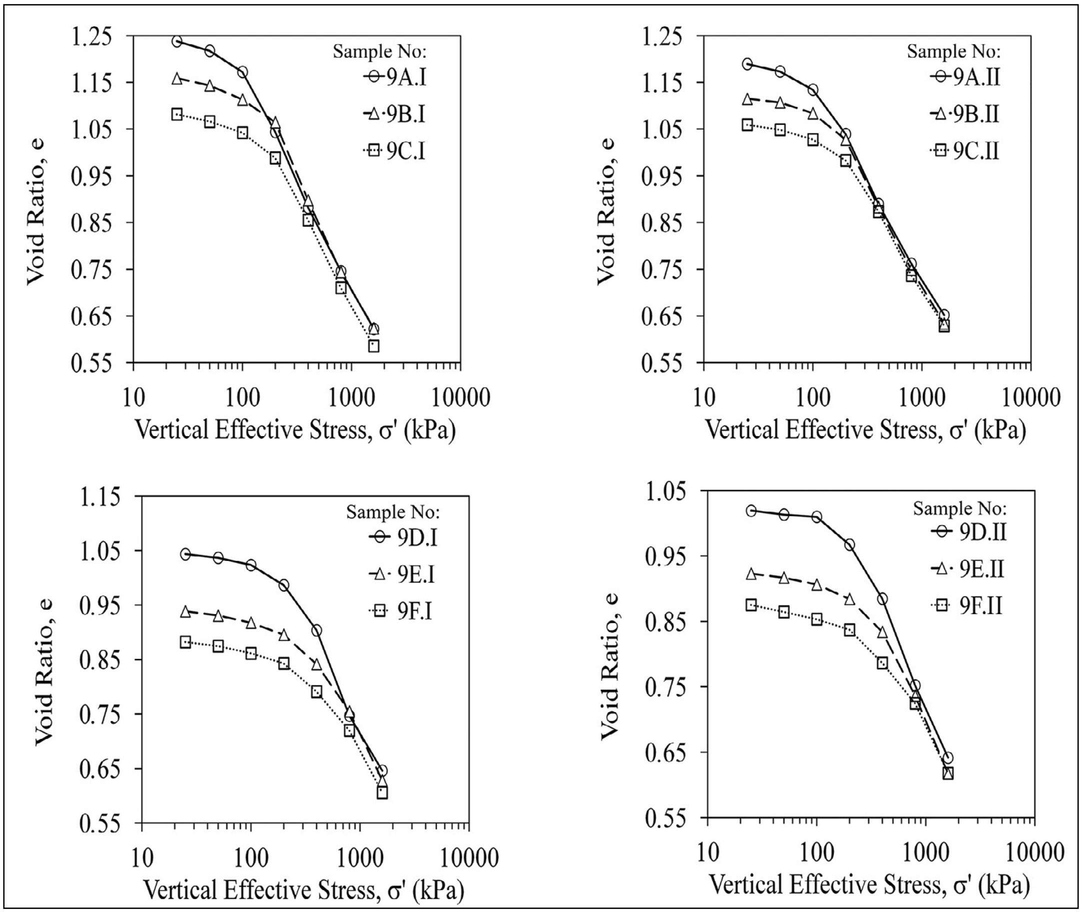

Figure 2- e-σ’ curves obtained from conventional oedometer tests.

Table 4- e-σ’ values obtained from conventional 1D oedometer tests.

		σ’ (kPa)						
		25	50	100	200	400	800	1600
Sample Number	RPM				e			
9A.I	500	1.24	1.22	1.17	1.04	0.88	0.75	0.62
9B.I	600	1.16	1.14	1.11	1.06	0.90	0.74	0.62
9C.I	700	1.08	1.07	1.04	0.99	0.86	0.71	0.59
9D.I	800	1.04	1.04	1.02	0.99	0.90	0.75	0.65
9E.I	900	0.94	0.93	0.92	0.90	0.84	0.75	0.63
9F.I	1000	0.88	0.87	0.86	0.84	0.79	0.72	0.61
9A.II	500	1.19	1.17	1.13	1.04	0.89	0.76	0.65
9B.II	600	1.12	1.11	1.08	1.03	0.88	0.75	0.63
9C.II	700	1.06	1.05	1.03	0.98	0.87	0.74	0.63
9D.II	800	1.02	1.01	1.01	0.97	0.88	0.75	0.64
9E.II	900	0.92	0.92	0.91	0.88	0.83	0.74	0.62
9F.II	1000	0.88	0.86	0.85	0.84	0.79	0.72	0.62

RPM: revolutions per minute. σ’: effective stress. e: void ratio.

and consolidation tests are carried out together and in the same cells. Permeability-consolidation tests were carried out in two phases, namely, the consolidation phase and permeability phase.

In the consolidation phase, after placing the combined apparatus in the loading unit, it was filled with water up to 1 cm above its upper level so that the tested soil sample was utterly saturated, was kept there for one day to check the swelling effect. After the sample was subjected to the swelling effect, it could not swell by increasing the load on it in a controlled manner. The loading process was carried out in the conventional oedometer unit. The applied load was transferred to the soil sample by means of the loading piston, and the amount of deformation that developed was transferred to the data logger using the deformation gauge on the piston and was recorded. According to ASTM D2435 / D2435M-11 (2020) standard test methods for 1D consolidation properties of soils using incremental loading, the loading process was carried out as in conventional oedometer tests.

In the permeability phase, the loading arm was initially fixed with supporting screws to prevent the continuation of loading. Then, the empty section of the combined apparatus was filled with water and was connected to the water indicator panel using a hose. The water-filled hose was connected to the water inlet valve located on the top of the cell to provide water flow. The other end of the hose was connected to the water indicator panel so that the reduction in the hydraulic level of the water could be shown during the permeability test. Before starting the test, air bubbles were removed from the hose and the cell using the air valve on the top of the cell. The permeability process was carried out for one day. Attention was paid to ensure that the hydraulic gradient was within the range of 20 to 30 in this process. In the subsequent loading phases, the loading arm was removed from its fixed state, and the same procedures were repeated. At the beginning and end of each permeability test, the hose's water level was recorded, noting the time, and the coefficient of permeability was calculated. After completing the test, the soil sample was removed from the cell, and saturated/dry unit weights were recorded.

The results obtained from the permeability-consolidation test include the amounts of settlement under different loads, the drop in water level during the permeability process, and the time-dependent deformations obtained under different loads. The c_v values obtained from the conventional oedometer tests conducted using the Taylor's square root of time fitting Method were compared with the c_v values obtained from the permeability-consolidation tests conducted with the Terzaghi's equation by using the combined apparatus.

4. Experimental Findings

The comparison of the ε-σ' graphs and consolidation parameters, obtained from permeability-consolidation tests on the combined apparatus and conventional 1D oedometer tests are given in Figure 3, and Table 5. A high level of consistency is observed between the combined apparatus for different load levels and the results obtained from the experiments performed on conventional oedometers. It is noted that the c_v values are not drastically affected by the differences in the design of the combined apparatus and or by changes in the loading steps. Therefore, it can be suggested that curve fitting methods for the calculation of c_v, such as the Taylor method, can also be used for the time-strain curves obtained from different loading stages of permeability-consolidation experiments.

The change in k and c_v values obtained using the combined apparatus and those obtained from the conventional 1D tests using Taylor's square root of time fitting method (t_{90}) method for each load level is shown in Figure 4 and 5. At low load levels, the difference between the results is more remarkable. It is apparent that the differences between results may be attributed to plasticity, and for samples with high plasticity, this difference is smaller.

Comparing the c_v values obtained from the combined apparatus using the permeability-consolidation relationship and the c_v values obtained from the conventional 1D oedometer tests using Taylor's square root of time fitting method (t_{90}) on a 1:1 graph is given in Figure 6. It is obvious that the c_v values obtained from the combined set-up at high load values are greater than the c_v values determined via the Taylor t_{90} method. It is from this point of view that the following empirical equation was developed between the e, SL, LL and k values of the soil samples with a coefficient of regression (R^2) of 0.66. Details of the regression analysis are given in Table 6.

$$k\ (m/s)=\exp\ (0.113\ SL-0.084\ LL+3.792\ e-23.154) \quad (3)$$

The comparison between the k values defined from the combined apparatus in soil samples and the k values defined from the newly developed empirical equation on a 1:1 graph is shown in Figure 7. When the distribution is evaluated, it is possible to say that the results are compatible with each other.

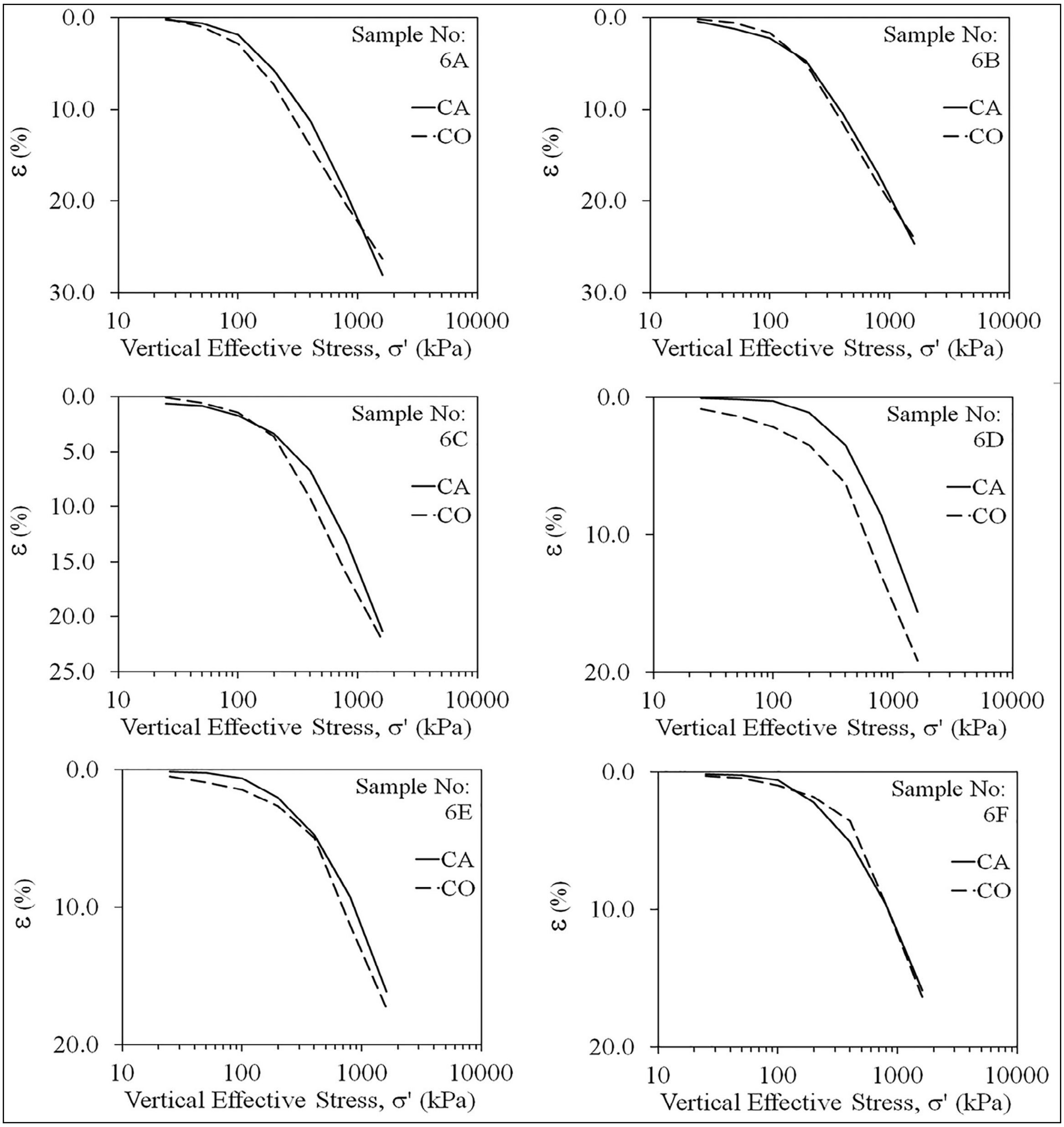

Figure 3- Comparison of the ε-σ' curves obtained from the conventional apparatus and the combined apparatus (CA: combined apparatus, CO: conventional 1D oedometer).

The c_v values calculated from k values obtained from the combined apparatus and the c_v values obtained from k values calculated from the newly developed empirical equation are compared in Figure 8. It is seen that the c_v values obtained from both methods are close to each other. Figure 9 shows that the c_v values calculated from the empirical relationship by using k values and the c_v defined from Taylor's t_{90} Method were compared graphically. High differences were observed between the values determined by both methods. The relationships between c_v values calculated from the empirical equation Equation 3 developed with the combined apparatus and different parameters, including the soils' index properties, were investigated. As a result of the regression analysis, the following empirical equation Equation 4 was proposed between c_v and mv-LL with a coefficient of regression (R^2) of 0.96. Details of the regression analysis are given in Table 7.

$$c_v \,(m^2/s) = (1.5)(10^{-10}) / (LL^{1.053})(m_v^{1.247}) \quad (4)$$

Table 5- Consolidation parameters obtained from conventional 1D oedometer (CO) and combined apparatus (CA) tests.

Sample Number	RPM	CO			CA		
		C_r	C_c	σ'$_p$ (kPa)	C_r	C_c	σ'$_p$ (kPa)
6A.I	500	0.072	0.45	130	0.055	0.40	120
6B.I	600	0.021	0.37	180	0.035	0.41	250
6C.I	700	0.039	0.32	200	0.030	0.35	270
6D.I	800	0.036	0.46	330	0.021	0.34	350
6E.I	900	0.030	0.51	390	0.020	0.29	420
6F.I	1000	0.013	0.44	400	0.013	0.29	400
6A.II	500	0.062	0.50	140	0.044	0.45	140
6B.II	600	0.030	0.48	180	0.052	0.34	200
6C.II	700	0.037	0.49	200	0.035	0.36	290
6D.II	800	0.037	0.44	380	0.029	0.34	350
6E.II	900	0.030	0.49	400	0.028	0.43	440
6F.II	1000	0.015	0.48	420	0.010	0.45	400
9A.I	500	0.066	0.47	100	0.029	0.41	160
9B.I	600	0.050	0.35	180	0.019	0.37	240
9C.I	700	0.050	0.31	190	0.009	0.35	340
9D.I	800	0.023	0.20	240	0.009	0.37	355
9E.I	900	0.025	0.12	400	0.002	0.24	480
9F.I	1000	0.024	0.12	450	0.006	0.23	300
9A.II	500	0.053	0.39	100	0.030	0.39	140
9B.II	600	0.027	0.41	180	0.031	0.38	200
9C.II	700	0.034	0.40	190	0.002	0.34	260
9D.II	800	0.020	0.40	220	0.012	0.34	320
9E.II	900	0.021	0.35	450	0.009	0.28	340
9F.II	1000	0.035	0.28	500	0.012	0.28	300

RPM: Revolution per minute, Cr: Recompression Index, C_c: Compression Index, σ'$_p$: Preconsolidation Index.

The comparison between c_v values calculated from Equation 3 and c_v values calculated Equation 4 is shown in Figure 10. It appears that there is a strong correlation between the c_v values obtained from the two approaches. The comparison of the c_v values, calculated from Equation 4 and defined by Taylor's t_{90} method is given in Figure 11. It was observed that there was not a good correlation between the results. This is thought to be related to the fact that while the samples prepared in the laboratory have high plasticity, those in the field represent a narrower interval in terms of plasticity.

5. Discussion

It was also found that the c_v values obtained from the permeability-consolidation tests using the combined apparatus were greater than the c_v values obtained from the conventional 1D oedometer tests using Taylor's t_{90} method. Furthermore, it can be said that the difference between the c_v values determined through the two testing methods, particularly on the soil samples with a high degree of plasticity, is more significant. It was found that more stable results were obtained from the samples with high plasticity than those with low plasticity when applying Taylor's t_{90} method. It is recommended to evaluate the results of both experimental methods with other curve fitting methods (log t_{50}, maximum slope, computational, rectangular hyperbola, δt-t/δt, early-stage log-t, inflection point, √t60, SRS).

One of the primary reasons for the variation between the consolidation coefficients that are obtained based on the permeability-consolidation relationship when using the combined apparatus, and

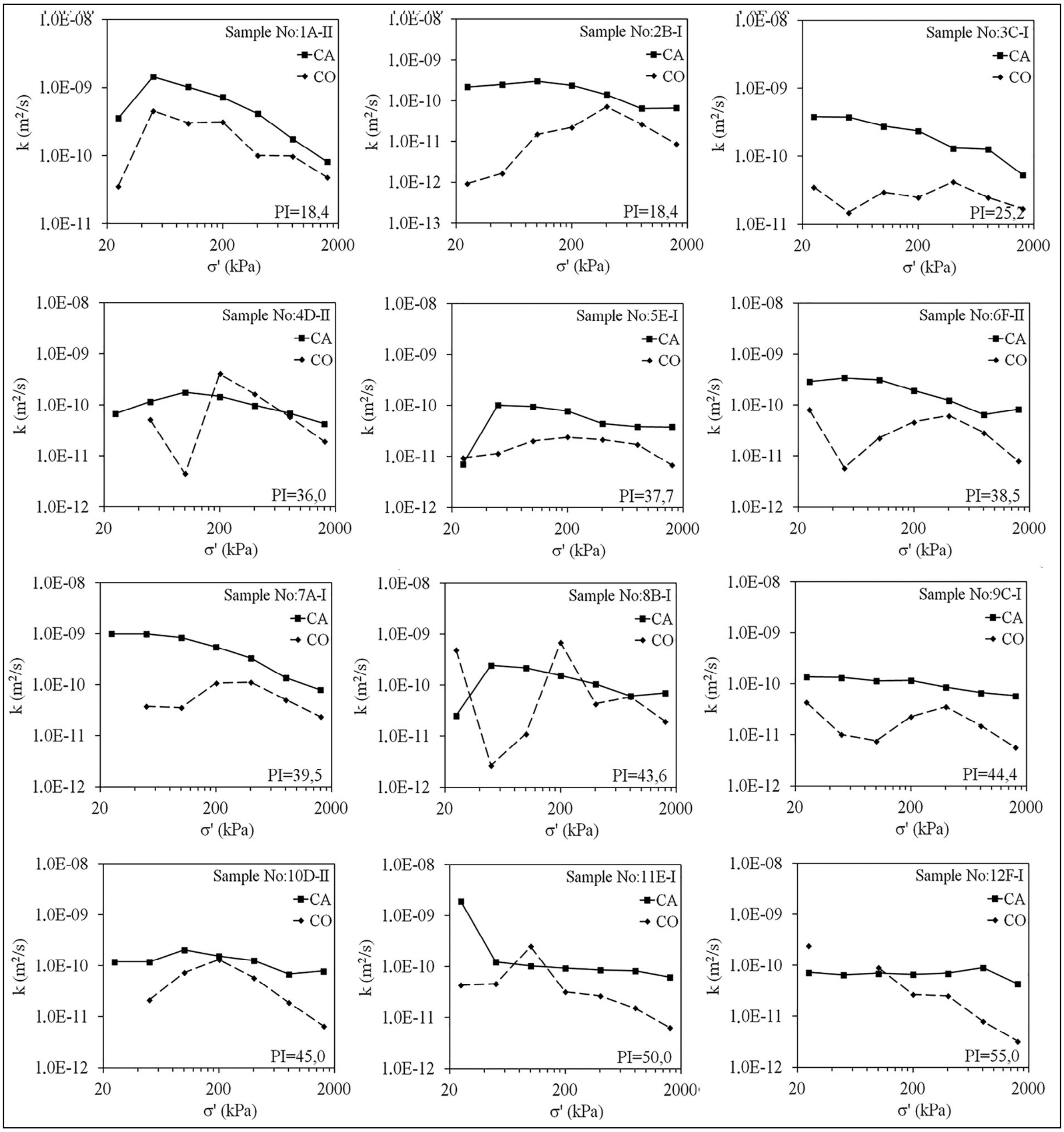

Figure 4- Changes in the k values with increases in load levels (CA: combined apparatus, CO: conventional 1D oedometer).

the c_v obtained from the conventional 1D oedometer tests when using curve fitting methods such as Taylor's t_{90}, must be that Taylor's t_{90} method takes into account only the compression of the sample and the contraction of length, but not the variations in the void ratio of the soil. In this regard, the c_v values calculated using Taylor's t_{90} method at high load levels where secondary compression is observed were lower than the actual c_v values, resulting in a more significant difference between the c_v values obtained from the combined apparatus.

The differences between the c_v values obtained from the permeability-consolidation relation and those obtained from the Taylor t_{90} method at high loads are attributable to the secondary compression. Based on this study results, a comparison of the c_v values obtained from the oedometer tests at high load levels with those obtained from the permeability-consolidation relation and an assessment of the influence of the secondary compression on c_v is suggested.

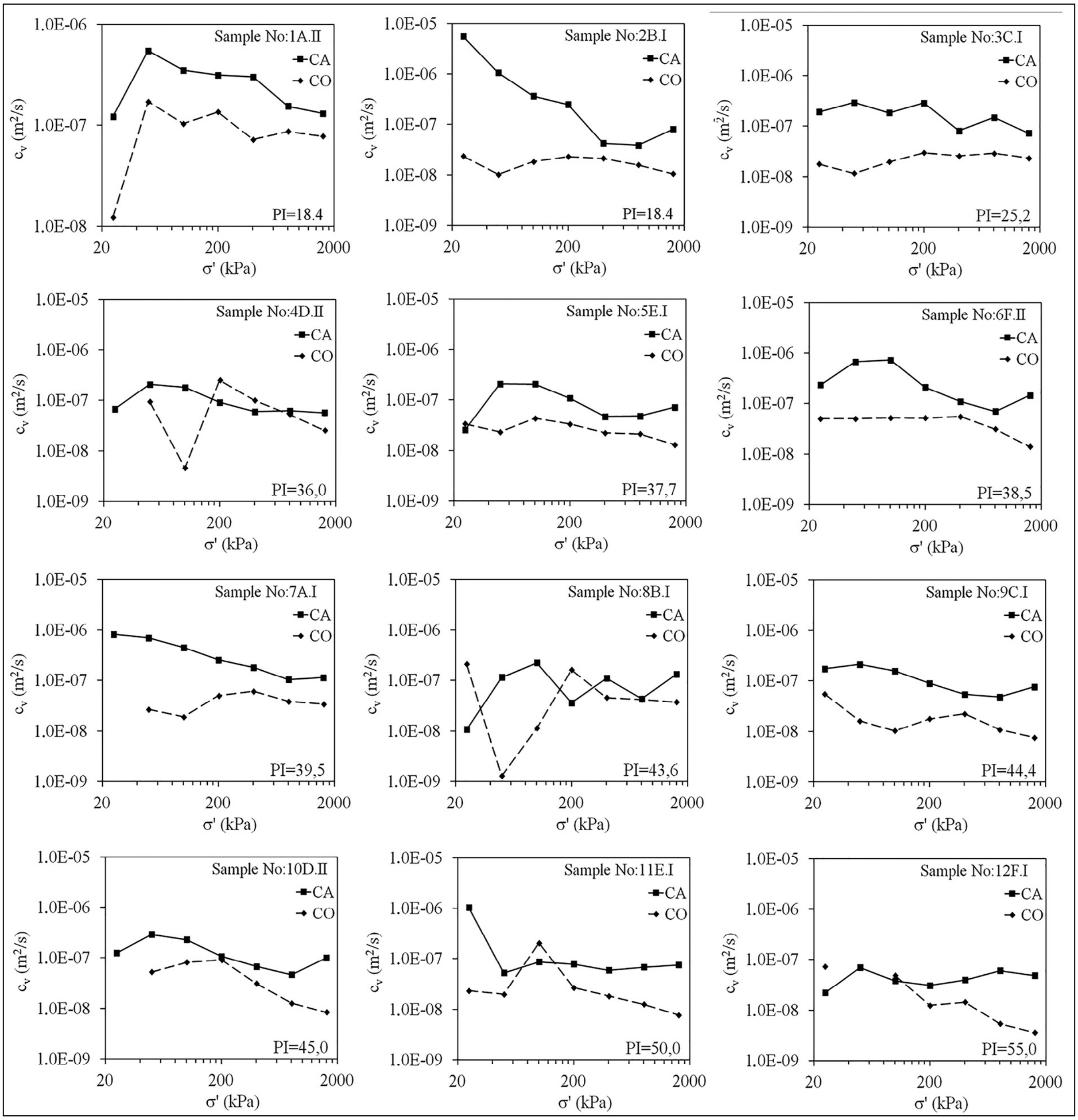

Figure 5- Changes in the c_v values with increases in load levels (CA: combined apparatus, CO: conventional 1D oedometer).

6. Results

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

Considering the relationship between the two testing methods, it was found that the values obtained from the combined apparatus designed specifically for this study were comparable with the c_v values obtained from the conventional 1D oedometer tests. The possibility of determining c_v through the permeability-consolidation relation and curve fitting method, and the compatibility with the results obtained from conventional methods, further increases the advantages offered by this set-up and its application.

By using regression analysis, the relationship between k values and the index properties of the soils, the following correlation between k and SL-LL-e was proposed with R^2=0.66:

$$k\ (m/s)=\exp\ (0.113\ SL–0.084\ LL+3.792\ e–23.154) \quad (3)$$

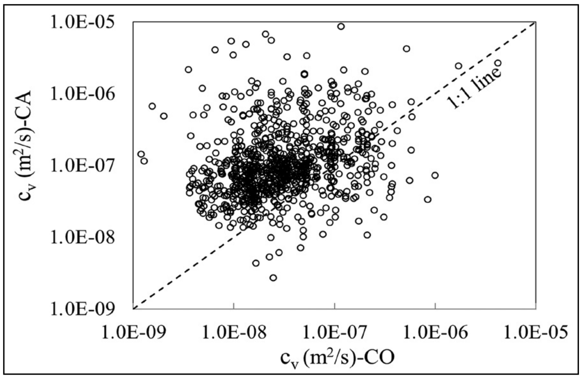

Figure 6- Comparison of c_v values obtained from the combined apparatus and conventional 1D oedometer (CO: conventional oedometer, CA: combined apparatus).

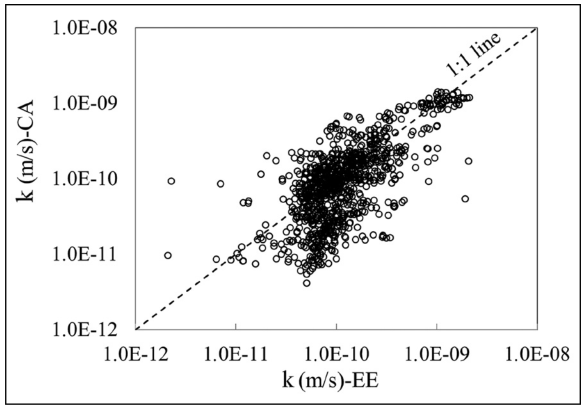

Figure 7- Comparison of the k values obtained from the empirical equation and the combined apparatus (EE: empirical equation, CA: combined apparatus).

Table 6- Regression analysis details of equation (3).

Equation	k (m/s) = exp (0.113 SL – 0.084 LL + 3.792 e – 23.154)
Model Definition	Y = exp(ax+bx2+cx3+d)
Number of Observations	991
Solver Type	Nonlinear
Nonlinear Iteration Limit	250
Number of Nonlinear Iterations Performed	10
Residual Tolerance	1E-10
Sum of Residuals	2.30E+06
Average Residual	2.32E+03
Residual Sum of Squares (Absolute)	2.95E-03
Residual Sum of Squares (Relative)	2.95E-03
Standard Error of the Estimate	1.73E+03
Coefficient of Multiple Determination (R^2)	0.658620984
Durbin-Watson statistic	1.040230
Confidence Interval	99%
F Ratio	634.738

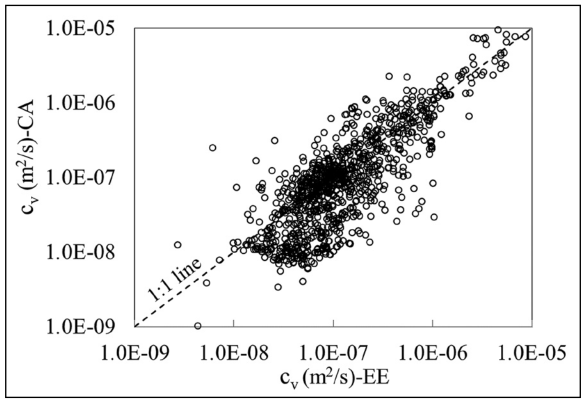

Figure 8- Comparison of the calculated c_v values obtained from the empirical equation and the combined apparatus (EE: empirical equation, CA: combined apparatus).

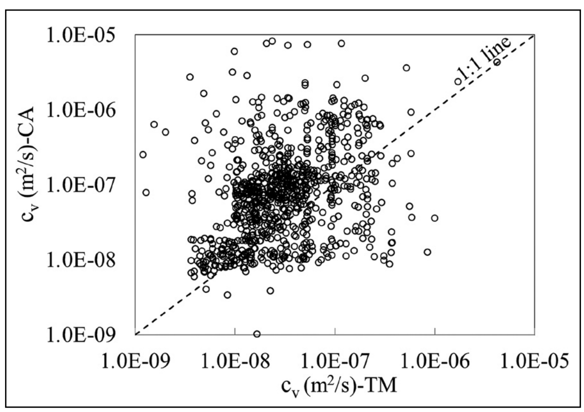

Figure 9- Comparison of the calculated c_v values obtained from the Taylor's t_{90} method and the combined apparatus (TM: Taylor's t_{90} method, CA: combined apparatus).

It is possible to calculate c_v using k (obtained from the proposed empirical equation) and m_v (defined experimentally) together in Terzaghi's permeability-consolidation relationship. The relationship between c_v (calculated from the permeability-consolidation relationship) and different parameters (e and m_v) were evaluated. As a result of the regression analysis, the following empirical relationship between c_v and m_v-LL was proposed with R^2=0.96:

Table 7- Regression analysis details of Equation (4).

Equation	c_v (m²/s) = (1.5) (10^{-10}) / ($LL^{1.053}$) ($m_v^{1.247}$)
Model Definition	$Y = ax1^bx2^c$
Number of Observations	976
Solver Type	Nonlinear
Nonlinear Iteration Limit	250
Number of Nonlinear Iterations Performed	250
Residual Tolerance	1E-10
Sum of Residuals	1.76E+10
Average Residual	1.80E+07
Residual Sum of Squares (Absolute)	3.36E+04
Residual Sum of Squares (Relative)	3.36E+04
Standard Error of the Estimate	5.88E+07
Coefficient of Multiple Determination (R^2)	0.956013
Durbin-Watson statistic	0.968071
Confidence Interval	99%
F Ratio	10.5736

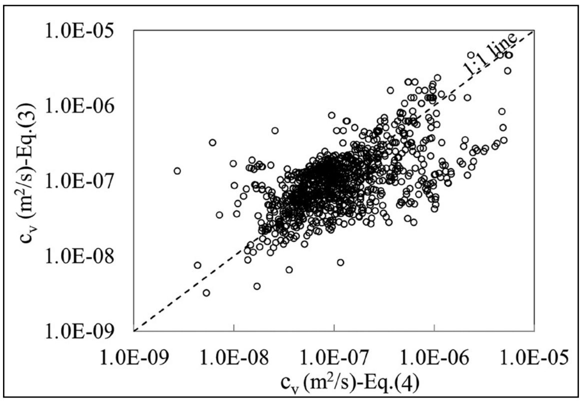

Figure 10- The comparison between c_v values calculated from Equation 3 and 4.

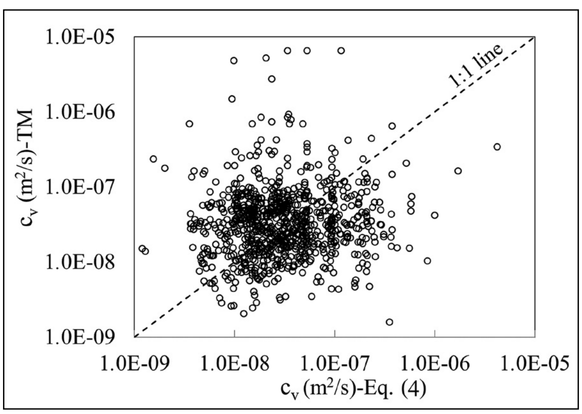

Figure 11- The comparison of the c_v values, calculated from Equation 4 and defined by the Taylor's t_{90} method (Eq. (4): equation 4, TM: Taylor's t_{90} method).

$$c_v\ (m^2/s) = (1.5)(10^{-10}) / (LL^{1.053})(m_v^{1.247}) \quad (4)$$

While a decrease was observed in the c_v values determined using Taylor's t_{90} method, one of the conventional 1D consolidation tests on the soil samples with high plasticity when the load was increased, no stable behaviour was observed in the c_v values on the samples with low plasticity. However, the c_v values obtained from the permeability-consolidation tests using the combined apparatus generally decreased as the load was increased from the initial load levels and then increased as the load was increased to the higher load levels.

It is apparent that the c_v values obtained based on the permeability-consolidation relationship when using the combined apparatus on the soil samples with low plasticity exhibited less scattering than the c_v values obtained when using Taylor's t_{90} method.

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