ARI The Bulletin of the Istanbul Technical University VOLUME 54, NUMBER 1
Communicated by Derin Orhon

Evaluation of Secondary Compressibility of a Soft Clay

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(Received 11 November 2003)

It is widely accepted that the influence of sustained loading on the rate of secondary compression for all natural soil deposits resembles the effect of preloading. The magnitude of settlement during secondary compression increases with increasing duration of loading. As a result, after longer periods of secondary consolidation, clay samples can sustain relatively larger stress increments before volume changes begin to occur, and display less settlement during next loading stage. The influence of sustained loading has been investigated in this study by long-term consolidation tests. Based on experimental data it has been shown that there is a fairly well defined dependence of C_α on effective stress. Furthermore, the relations between secondary compression parameters and consolidation pressure have also been examined and a correlation between secondary compression index and consolidation pressure has been introduced and discussed in the paper.

Keywords: Soft clay, consolidation, sustained loading, secondary compression and quasi-preconsolidation pressure

1. Introduction

As a result of a series of experimental studies at Purdue University between 1950-1960, normally consolidated clays were found to sustain a small but significant stress increment before volume changes would begin to occur [1]. This "quasi-preconsolidation pressure- σ'_{cq}" can be determined reliably from incremental consolidation tests by using high quality undisturbed samples if stress increments are small enough to define σ'_{cq} closely, and stressing duration does not exceed those corresponding to 100% consolidation [1-3]. After long periods of secondary compression, a quasi-preconsolidation pressure (σ'_{cq}) greater than the consolidation pressure (σ'_c) develops and the ratio of $\sigma'_{cq}/\ \sigma'_c$ is typically in the range of 1.1 $\sim$ 1.4, where larger ratios are related to highly plastic clays [3]. At a stress level σ'_c, where σ'_{v0} is effective overburden pressure, and $\sigma'_{v0} < \sigma'_c < \sigma'_{cq}$, the compressibility is smaller than the normally consolidated clay compressibility. Reliable predictions of consolidation settlements are associated with good estimation of in-situ σ'_{cq}.

There is a general agreement that the rate of secondary compression is affected by the duration of the previous loading. The influence of sustained loading on the rate of secondary compression for all natural soil deposits resembles the effect of preloading. The magnitude of settlement during secondary compression increases with increasing duration of loading. As a result, after longer periods of secondary consolidation, clay samples can sustain relatively larger stress increments before volume changes begin to occur, and display less settlement during next loading stage. This behavior has been clearly shown with data obtained in this experimental study. This paper reports the results of a research program aimed at investigating the secondary compressibility of soft blue clay taken from the runway of Samsun Airport that has been constructed on deltaic deposits of Yesilirmak River, Kizilirmak River and their tributaries.

2. Long-Term Consolidation Tests

2.1. Index Properties and Test Program

Index tests on undisturbed clay samples indicate that natural water contents are in the range of w_n = 60-67%, liquid limit w_L = 63-82%, plastic limit w_p = 28-29% and plasticity index I_P = 35-54%. Samsun Blue Clay, composed of 61-81% silt-sized particles; 18-38% clay-sized particles and 1-1.5% organic matter has high plasticity and activity. The effective overburden pressure (σ'_{v0}) and in-situ preconsolidation pressures (σ'_{vc}) of normally consolidated Samsun Blue Clay are in the ranges of 47-77 kPa and 55-80 kPa, respectively.

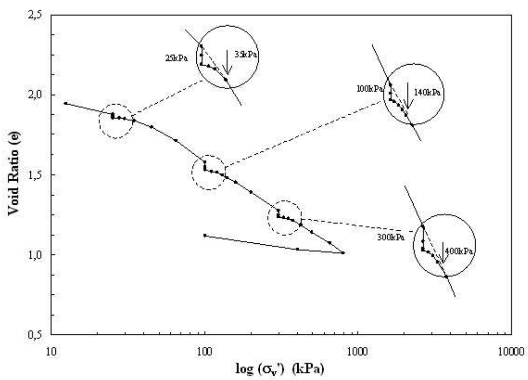

Figure 1. e-log $\sigma_v^{'}$ curve of test no: A1

A series of six conventional one-dimensional consolidation tests were performed on undisturbed samples using a load increment ratio of unity. Primary consolidation was completed in 60-100 minutes for smaller stresses, and 100-150 minutes for greater stresses. 24-hr duration for each load increment encompassed the complete primary compression and some secondary compression phases. Another series of eight long-term consolidation tests on undisturbed samples were performed and secondary compression measurements were made for a period of one week to ten days for sustained loadings. 100-200 minute load duration of other stress levels except the sustained loadings (where secondary compression was allowed) was just sufficient for the completion of primary consolidation (End Of Primary-EOP) as estimated in conventional one-dimensional consolidation tests. Time for the completion of primary consolidation (t_p) was estimated by log (t) (Casagrande) and $\sqrt{t}$ (Taylor) methods for the applied stresses except for the sustained loading for secondary compression. After this, using small load increment ratios as low as LIR= $\Delta\sigma_v^{'} \ / \ \sigma_v^{'} = 0.05 \sim 0.30$ the vertical stress was increased to 1.5 times the sustained loading in order to define apparent preconsolidation pressure closely. After merging EOP e-log$\sigma_v^{'}$ curve, EOP consolidation procedure with load increment ratio of unity was followed.

In some long-term consolidation tests, two or three sustained loadings were applied during one consolidation test in order to collect more data. The second and the third sustained loading were chosen at least three times greater than the first and the second sustained loading respectively, as to prevent the influence of the first sustained loading on the rate of secondary compression [1]. As illustrated in Fig. 1, the secondary compression was allowed for 7 days at first stress level $\sigma_c^{'} = 25$ kPa, then using small load increments (LIR<1), the consolidation pressure was increased beyond 1.5 times the first sustained loading which was 37.5 kPa. During this period, subsequent loading was carried out at 100-200min intervals, which again included all primary consolidation. After merging EOP e-log $\sigma_v^{'}$ curve, the second sustained loading at $\sigma_c^{'} = 100$ kPa was applied and the procedure given above followed.

2.2. Influence of Sustained Loading

As stated previously by the several researchers, when a soil is subjected to sustained loading, an apparent preconsolidation pressure develops. After a long period of secondary compression, an apparent preconsolidation pressures so-called quasi-preconsolidation pressure greater than the sustained loading occurs. The influence of sustained loading has been investigated in this study by laboratory long-term consolidation tests. An example of this phenomenon is illustrated in Fig. 1. For example, in long-term consolidation test A1, the secondary compression was allowed for 7 days at $\sigma_c^{'} = 100$ kPa, resulting in a quasi-preconsolidation pressure of about $\sigma_{cq}^{'} = 140$ kPa.

Results of all long-term consolidation tests are summarized in Table 1. After a long period of secondary compression under a sustained loading ($\sigma_c^{'}$), the soft blue clay behaves as an over consolidated-cohesive soil until the effective stress reaches a value of $\sigma_{cq}^{'} = 1.25 \sim 1.40 \ \sigma_c^{'}$ (where $\sigma_{cq}^{'}$ is the quasi-preconsolidation pressure). Thus, the soft clay has less primary and secondary settlement as compared to normally consolidated clay. After $\sigma_{cq}^{'}$= 1.25 $\sim$ 1.4 $\sigma_c^{'}$, the behavior of the soft clay merges with EOP e-log $\sigma_v^{'}$ curves and the clay samples behave as a normally consolidated clay. The influence of sustained loading on the clay leads to a behavior similar to effect of preloading. Progress of secondary consolidation and the magnitude of secondary compression are related to the duration of sustained loading. Clay samples that have experienced longer periods of secondary compression under a sustained loading exhibit less settlement during the next loading stage.

During the experimental study on which this

Table 1
Quasi-preconsolidation pressure as a result of sustained loading

Test No.	Depth of soil (m)	*Sustained load ($\sigma_c^{'}$) (kPa)	Quasi-preconsolidation pressure ($\sigma_{cq}^{'}$) (kPa)	($\sigma_{cq}^{'}$ / $\sigma_c^{'}$)
		25	35	1.40
$A1$	9.50	100	140	1.40
		300	400	1.33
		50	70	1.40
$A2$	9.50	150	200	1.33
		400	500	1.25
$A3$	9.50	75	100	1.33
		200	250	1.25
$B1$	7.50	25	35	1.40
$B2$	7.50	50	70	1.40
		12.5	17.5	1.40
$C1$	4.50	75	100	1.33
		200	250	1.25
		25	35	1.40
$C2$	4.50	100	140	1.40
		300	400	1.33
		50	70	1.40
$C3$	4.50	150	200	1.33
		400	500	1.25

* Loading duration is seven days

paper is based, long-term consolidation tests showed that after a long period of secondary compression under a sustained loading ($\sigma_c^{'}$), the compressibility of Samsun Blue Clay is smaller than the normally consolidated clay compressibility, until the effective stress reaches a value of $\sigma_{cq}^{'} = 1.25 \sim 1.4\ \sigma_c^{'}$. The behavior of the soft clay merges with EOP e-log $\sigma_v^{'}$ curve at stress levels greater than the ratio of $\sigma_{cq}^{'}$ / $\sigma_c^{'} = 1.25 \sim 1.40$, and the clay sample behaves as a normally consolidated clay. At stress levels, $\sigma_c^{'} < 1.5 \sim 2\ \sigma_{vc}^{'}$, the ratio of $\sigma_{cq}^{'}$ / $\sigma_c^{'}$ is typically in the range of 1.25 to 1.33, whereas for $\sigma_c^{'} > 1.5 \sim 2\ \sigma_{vc}^{'}$ it is about 1.40. Nevertheless, the effect of sustained loading is related to both loading duration and magnitude of secondary compression [4, 5] As a result, longer duration of sustained loading and greater magnitudes of secondary compression lead to higher quasi-preconsolidation pressures.

2.3. Secondary Compression

Secondary compression has been defined in different ways by different investigators. In this paper, secondary compressibility is expressed by the secondary compression index, $C_\alpha = \Delta e\ /\ \Delta\ log\ t$, or coefficient of secondary compression, $C_{\alpha\varepsilon} = C_\alpha\ /\ (1+e_0)$, in which e = void ratio, t = time and e_0 = in-situ void ratio.

It was proposed by Mesri [6] that the coefficient of secondary compression, in terms of $C_{\alpha\varepsilon}$, for a variety of natural soil deposits fall in a range between 0.1% and 10%. Mesri and Godlewski [7] first presented the concept of a unique C_α / C_c ratio during secondary compression for an effective stress level.

The relationship between C_c, C_α and $C_{\alpha\varepsilon}$ and consolidation pressure has been determined by conventional and long-term consolidation tests. At any consolidation pressure, C_c values have been taken from e-log $\sigma_v^{'}$ curve corresponding to the end of primary consolidation whereas C_α values have been obtained from linear slope of the e-log t curve corresponding to the secondary compression. C_c, C_α and $C_{\alpha\varepsilon}$ values versus consolidation pressure have been plotted and shown in Fig. 2(a), Fig. 2(b) and Fig. 2(c). C_α and $C_{\alpha\varepsilon}$ versus C_c values have been also demonstrated in Fig. 3(a) and Fig. 3(b).

C_α gradually increases with the increase in $\sigma_c^{'}$ near the preconsolidation pressure $\sigma_{vc}^{'}$ of Samsun Blue Clay. At values of $\sigma_c^{'}$ greater than 2 $\sigma_{vc}^{'}$, C_α gradually decreases with the increase in $\sigma_c^{'}$. Since

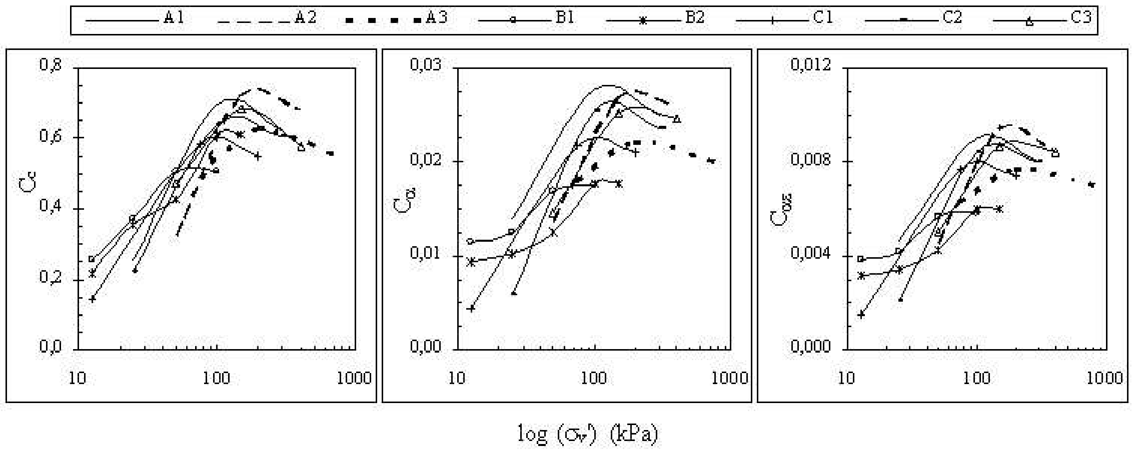

Figure 2. (a) Relationship between C_c and consolidation pressure; (b) relationship between C_α and consolidation pressure; (c) relationship between $C_{\alpha\varepsilon}$ and consolidation pressure

$C_{\alpha\varepsilon}$ is a function of C_α, it is possible to derive the dependence of secondary compressibility on effective stress. Soft Samsun Blue Clay exhibits low secondary compressibility ($C_{\alpha\varepsilon} < 0.005$) for effective stresses less than the preconsolidation pressure ($\sigma_v^{'} < \sigma_{vc}^{'}$) and approaches to its maximum value of $C_{\alpha\varepsilon} = 0.0095$ just beyond the preconsolidation pressure. For effective stresses greater than 2 $\sigma_{vc}^{'}$, the soft clay exhibits medium secondary compressibility ($C_{\alpha\varepsilon}$ = 0.006 - 0.008).

Fig. 3(a) shows the values of C_α / C_c lies within a narrow range of 0.028 ~ 0.045. Similarly, the relationship between $C_{\alpha\varepsilon}$ and C_c, is approximately linear and $C_{\alpha\varepsilon}$ / C_c lie within a narrow range of 0.010 ~ 0.015 (Fig. 3(b)). The relationship between the secondary compression index (C_α) and the compression index (C_c) could be taken as C_α / C_c = 0.035 whereas the relationship between the coefficient of secondary compression ($C_{\alpha\varepsilon}$) and the compression index (C_c) could be taken as $C_{\alpha\varepsilon}$ / C_c = 0.012. A unique relationship exists between secondary compression parameters (C_α and $C_{\alpha\varepsilon}$) and compression index (C_c) as previously stated by Mesri and Godlewski [7]. The relation holds true at any time, effective stress and void ratio during the secondary compression as presented herein [4,5,8,9].

3. Relationship Between Secondary Compression Parameters And Consolidation Pressure

There is no general consensus about the relationship between secondary compression and effective stress. Although some researchers indicate that a well-defined relation between C_α and consolidation pressure exists, others claims that C_α or $C_{\alpha\varepsilon}$ is independent of consolidation pressure. By using load increment ratio of unity for conventional tests, a considerable reliable data reveal that there is a fairly strong dependence of C_α on effective stress. As there is a single relationship between C_α and C_c, depending on the variation of C_r in recompression and C_c in compression stages, C_α is dependent on effective stress. The results show that values of secondary compression index (C_α) are small for an effective stress-$\sigma_v^{'}$ less than the preconsolidation pressure, and increases quickly beyond the preconsolidation pressure. After reaching its maximum value just beyond the preconsolidation pressure, C_α decreases gradually. In this study, based on several conventional and long-term consolidation tests, it has been shown that there is a fairly well defined dependence of C_α on effective stress.

In this paper, the correlation between secondary compression parameters and consolidation pressure has also been examined (Fig. 4). In order to set up the correlation between the secondary compression parameters and consolidation pressure, horizontal axis is taken as $\sigma_v^{'}$ / $\sigma_{vc}^{'}$,

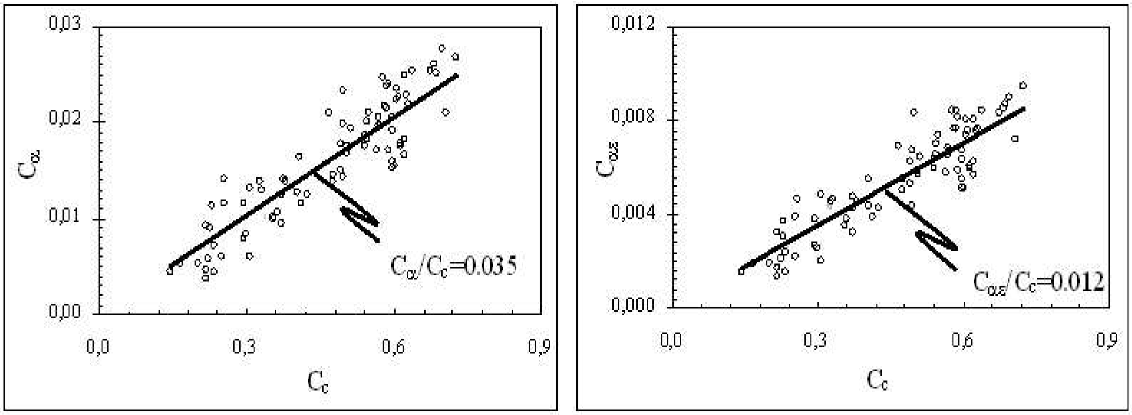

Figure 3. (a) Relationship between C_c and C_α; (b) relationship between C_α and $C_{\alpha\varepsilon}$

to normalize the values on horizontal axis. Vertical axis is the secondary compression index-C_α. Soil layers settling under the same overburden pressure during geological process could have different natural void ratios if they have different organic content. As a matter of fact, the clay samples used in this research had different initial void ratios due to samples that contained different ratio of organic matter taken from different depths of 4.5-9.5 m. Initial void ratios of the samples vary between e_0 = 1.750-2.050. Therefore, data of all consolidation tests have been evaluated considering initial void ratios of the samples.

Based on the conventional and long-term consolidation tests, a correlation shown in Fig. 4 has been found for the soft blue clay between the secondary compression index-C_α , and the effective pressure. As shown in Fig. 4, although there is a less pronounced variation in the secondary compression index for pressures greater than preconsolidation pressure ($\sigma_v^{'}$ / $\sigma_{vc}^{'} > 1$), for pressures less than the preconsolidation pressure ($\sigma_v^{'}$ / $\sigma_{vc}^{'} < 1$), the secondary compression index varies significantly. For increasing initial void ratios, increasing secondary compression index values are obtained. This is an expected result for pressures smaller than the preconsolidation pressure, where the secondary compression index-C_α increases with effective stress along the recompression curve. As the values of C_α is small at effective stress-$\sigma_v^{'}$ less than the preconsolidation pressure and they increases quickly around the preconsolidation pressure. After reaching its maximum value just beyond the preconsolidation pressure, C_α decreases gradually. More to the point, the correlation shows that the secondary compression index increases with increasing initial void ratio of the sample. Consequently, the secondary compression index at any effective stress level or secondary compression after any effective stress increase can be forecast for Samsun Blue Clay by using the correlation given in Fig. 4.

The secondary compression settlement of any type cohesive soil is calculated to follow in terms of the secondary compression index. The value of C_α for the soil can be established either from standard or long-term odometer tests at least at three or four selected consolidation pressure or from any correlation e.g. given in this paper. For any type of natural soils including organic silts, peats, as well as soft clays, the relationship between secondary compression parameters and effective stresses should be determined by several tests with different void ratios, preconsolidation pressures and load increment ratios. However, it is not easy precise prediction of secondary settlement for the design life. Since for thick soil layers in the field where primary settlement stage requires many years and secondary settlement could be relatively unimportant. In contrast, secondary settlement can be considerable part of total settlement where soft clays, peats or organic silts with high secondary compression parameters are under consideration. In this case, it is better to subdivide the compressible profile into sublayers for secondary settlement calculation and then secondary settlement can be predicted by using secondary compression index either calculated in

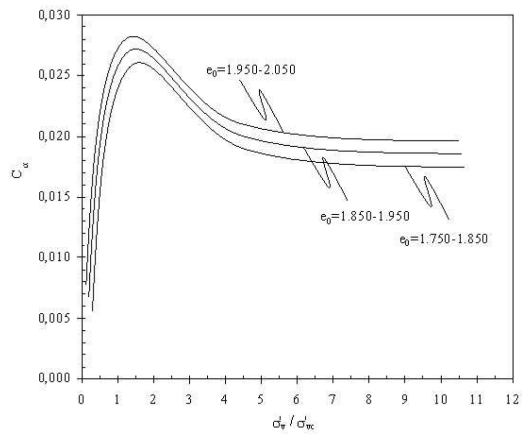

Figure 4. (a) Correlation between C_α and $\sigma_v^{'}$ / $\sigma_{vc}^{'}$

laboratory tests or from any correlation e.g. given in this paper in Fig. 4 for Samsun Blue Clay. Although there is a reasonable relationship between C_α and effective stress found for Samsun Blue Clay, either a concentrated attention or further research on different type of soft soils with different laboratory conditions should be studied.

4. Conclusions

Normally consolidated soft clays that have been consolidating under overburden pressure for a long time can sustain a small but significant stress increment before significant volume changes begin to occur. This phenomenon could not be determined by conventional one-dimensional consolidation tests in a laboratory. By performing long-term consolidation tests, it has been shown that after a long period of secondary compression at certain consolidation pressure levels, when a small load increment ratio is chosen and secondary compression is not permitted, a quasi-preconsolidation pressure ($\sigma_{cq}^{'}$) that is greater than the existing preconsolidation pressure ($\sigma_{vc}^{'}$) develops.

The results of the several conventional and long-term consolidation tests of present study appear to be one of convincing indicator of the relationship between C_α and effective stress. Results of conventional and long-term consolidation tests on high quality undisturbed samples provide considerable practical information about the secondary compressibility of soft blue clay taken from the site of the Samsun Airport. The correlation between secondary compression index and effective stress increase has been introduced and discussed in the paper. The correlation gives a general idea about the secondary compressibility of Samsun Blue Clay. However, it is still difficult to make accurate predictions for the samples having different natural void ratios and consequently different preconsolidation pressures than given in the paper. For practical intentions, the secondary compression index at any effective stress level or secondary compression after any effective stress increase for Samsun Blue Clay can be predicted by using the correlation given in the paper. Nevertheless, the relationship and correlations between secondary compression parameters and effective stresses need to be investigated with further research.

5. Notation

C_c	=	compression index
	=	$\Delta e/\Delta log\sigma_v^{'}$
C_α	=	secondary compression index
	=	$\Delta e/\Delta logt$
$C_{\alpha\varepsilon}$	=	coefficient of secondary compression
	=	$C_\alpha/(1+e_0)$
e	=	void ratio
e_0	=	in-situ void ratio
I_p	=	plasticity index
LIR	=	load increment ratio
$\sigma_v^{'}$	=	effective vertical stress
$\sigma_c^{'}$	=	sustained stress
$\sigma_{cq}^{'}$	=	quasi-preconsolidation pressure
$\sigma_{v0}^{'}$	=	effective overburden pressure
$\sigma_{vc}^{'}$	=	in-situ preconsolidation pressure
t	=	time
t_p	=	time for the completion of primary consolidation
w_L	=	liquid limit
w_n	=	natural water content
w_p	=	plastic limit

References

[1] G. A. Leonards and B. K. Ramiah, ASTM STP **254**, 116 (1959).

[2] G. A. Leonards and P. Girault, Proc. of the 5^{th} ICSMFE **2**, 213 (1961).
[3] G. A. Leonards and R. J. Deschamps, Compression and Consolidation of Clayey Soils (Balkema, Rotterdam, 1995).
[4] E. Yılmaz, Ph.D Thesis, Istanbul Technical University (2000).
[5] E. Yılmaz, A. Sağlamer and G. Çevikbilen, Long-Term Effect of a Sustained Load on a Clay Soil Exhibiting Secondary Consolidation Behaviour, Proc. 8^{th} National SMFE Conf., Istanbul Technical University, Istanbul, Turkey, 2000.
[6] G. Mesri, J. Soil Mech. and Found. Div., ASCE **99**, 123 (1973).
[7] G. Mesri and P. M. Godlewski, J. Geotech. Engrg., ASCE **103**, 417 (1977).
[8] E. Yılmaz and A. Sağlamer, Secondary and Tertiary Compresion Behaviour of Samsun Soft Blue Clay, 15^{th} Int. Conf. on Soil Mech. and Geotech. Engrg., Istanbul Technical University, Istanbul, Turkey, 2001.
[9] E. Yılmaz and A. Sağlamer, Technical Journal of Turkish Chamber of Civil Engineers **14**, 3069 (2003).