GRAIN DIFFUSION AND DISPERSION OF CLAYEY SOILS IN A CONSOLIDATION PHENOMENON

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ABSTRACT: In this study, the phenomena of grain diffusion and dispersion were considered and the effects of time rates of settlement on consolidation were discussed. It was shown that time rates of settlement can be considered throughout the consolidation process of a soil in terms of grain diffusion and dispersion. For this reason, consolidation tests were performed on soil samples taken from a specific region in Adana Turkey in order to investigate and evaluate diffusive and dispersive characteristic of the region. By comparing the obtained experimental results to theoretical counterparts, it was seen that the results were in a very close aggreement to each other. These results were also compared to each other in order to observe the effect of plasticity of a clayey soil in grain diffusion and dispersion.

Keywords: grain diffusion, dispersion, consolidation, plasticity, clayey soil.

INTRODUCTION

In soil mechanics, as well as stress-strain relationships, deformation-time relationships are also important. For this reason, deformation-time relationship is explained by the theory of consolidation. The first theory on consolidation was given by Terzaghi and the change in pore water pressures as a result of the variations in hydraulic gradient was defined by the following equations given below as Equation 1.a and Equation 1.b (Özaydın 2005):

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \qquad (1.a)$$

$$c_v = \frac{K}{m_v \gamma_w} \qquad (1.b)$$

The independent variables in this differential equation are the coordinate z and time t. c_v and u represent the coefficient of consolidation and pore water pressure, respectively (Battaglio et al. 2003). Terzaghi's theory of consolidation is a linear theory which considers compaction and settlement of saturated and homogeneous soils. In this theory, the coefficient of consolidation was accepted to be a parameter as a result of small deformation amounts, compatible soil water permeability and compressibility values (Geng et al 2006). In addition, compressibility and permeability of a soil were considered to stay constant for a soil layer whereas aforementioned soil parameters differ according to the type and history of a soil (Battaglio et al 2005). On the other hand, the non-linear nature of a consolidation phenomenon and viscous property of soils cause a creep effect at the upper layers of a soil. Therefore, viscous effect is related to the continuous and slow deformations of a soil subjected to an external loading (Asch et al 1989). The aforementioned creep phenomenon is taken into consideration as a diffusion movement throughout a soil mass (Culling 1963). In all of the consolidation equations, the occurrence of laminar and transient flows and the validity of Darcy's Law have been accepted. It is also known that time rate of settlement and drainage decrease as a result of consolidation. Low time rates of settlement which occur under these conditions bring out the phenomena of hydrodynamic dispersion along with the viscous nature of fine grained soils. The term hydrodynamic dispersion stands as a process in which both grain diffusion and dispersion of a soil are considered. Consolidation process has also a profound effect on the transportation of contaminating particles throughout a compressed porous medium. It was observed that drainage of pore water is highly effective in the transportation of soluble particles inside of a soil mass by means of diffusion. Eventually, the random nature of pore structure of a soil mass and the transportation and spreading of contaminating particles in a soil brings out the diffusion problem. In addition, since courses and directions and so time rates of pore water differ vastly during the application of a loading as a result of random pore geometries, the phenomenon of dispersion also comes into question. Hydrodynamic dispersion, in general, defines the combined effect of orientation of particles to form a more disperse structure and grain diffusion occurring as a result of very low time rates of settlement. On the other hand, hydrodynamic dispersion is a phenomenon which occurs in micro pores and at the outside of a solid-liquid intersection as a result of low flow velocities (Tekinsoy 2013). Also, according to performed studies, dispersion is a physical phenomenon that occurs between solid and liquid phases as a result of low time rates of settlement. Variations in time rates of settlement occur in relation to the changes in pore water pressures (Nielsen et al. 1972). However, dispersion and grain diffusion were only studied by the writers of this study in an aspect of soil mechanics. Besides of soil mechanics point of view, the only study about the subject was in the transportation of melted particles in homogeneous soils as a result of a concentration gradient (Nielsen et al. 1972). In this study, the phenomena of dispersion and grain diffusion in the consolidation of clayey soils are studied and effects of time rates of settlement in a consolidation phenomenon are discussed. Obtained data are given in an aspect of hydrodynamic dispersion and some contributions are presented.

METHODS

Consolidation tests are generally performed on fine grained and plastic soils. Therefore, soil samples taken from different regions of Adana with various dry unit weights and plasticity properties are used in this study. Results of these experiments are both compared to theoretical counterparts and to each other. Physical properties of the soil samples are given in Table 1.

Table 1. Index Properties of Soil Samples (Mahmutluoğlu ve Tekinsoy, 2015)

Sample No.	Samp.1	Samp.2
Drilling Depth (m)	1.6	8.4
Liquid Limit (w_L) (%)	45	82
Plastic Limit (w_p) (%)	19	24
Finer than No.200 Sieve (%)	96	96
Activity	0.271	0.604
Natural Water Content (w_n) (%)	26	28
Dry Unit Weight (γ_k) (gr/cm^3)	1.319	1.284
Unit weight of Grains (γ_s) (gr/cm^3)	2.520	2.520
Natural Unit Weight (γ_n) (gr/cm^3)	1.662	1.644
Plasticity İndex (I_p) (%)	26	58

Note: Samp.1 and Samp.2 represent the soil samples which were taken from Adana Kayışlı District from depths of 1.6 m and 8.4 m, respectively.

Initially, the phenomenon was studied statistically and it was realized that dry unit weight is the primary variable in dispersion (Mahmutluoğlu 2014). As a result of the performed regression analyses, the most compatible equations to the phenomena were constructed and eventually Equation 2 was given as the dispersion differential equation (Mahmutluoğlu 2014):

$$\frac{\partial u}{\partial t} = v_z \frac{\partial u}{\partial z} + c_v \frac{\partial^2 u}{\partial z^2} \qquad (2)$$

The equation of dispersion given as Equation 2 is an equation which includes convective flow relative to time rates of settlement along with the conventional consolidation term. Since dry unit weight is the primary parameter in hydrodynamic dispersion, based on the equation given in Equation 2, the following differential equation can be derived as the dispersion differential equation with respect to dry unit weight (Mahmutluoğlu 2014):

$$\frac{\partial \gamma_k}{\partial t} = v_z \frac{\partial \gamma_k}{\partial z} + D_s \frac{\partial^2 \gamma_k}{\partial z^2} \qquad (3)$$

where, γ_k is dry unit weight, v_z is time rate of settlement and D_s is diffusivity coefficient.

Diffusivity coefficient and the other hydrodynamic dispersion parameters were obtained by solving the differential equation given as Equation 3 (Mahmutluoğlu 2014). These solutions were used in this study to obtain diffusion and dispersion parameters of a specific region in Adana Turkey and to show the effect of plasticity on the phenomena by comparing clayey soils of low and high plasticity properties. The equations for diffusion and dispersion parameters which were found by solving dispersion differential equation are given by Equation 4, Equation 5, Equation 6, Equation 7, Equation 8 and Equation 9 in the following pages of the study (Tekinsoy 2013; Mahmutluoğlu 2014).

RESULTS AND FINDINGS

Results of the performed consolidation tests on CL group soil samples can be seen in Table 2. Based on the results given in Table 2, diffusive and dispersive parameters are obtained and presented in Table 3.

Table 2. Effective Stress Variations relative to Dry Unit Weights for the CL group Sample taken from Kayışlı District (Mahmutluoğlu ve Tekinsoy, 2015)

Total Press. p (kg/cm^2)	Samp. Height H (mm)	Void Ratio e (%)	Pressure Increment Δp (kg/cm^2)	Dry Unit Weight γ_k (gr/cm^3)	Coeff. Of Volume Comp. m_v (cm^2/kg)	Efective Stress Increment σ' (kg/cm^2)
0.00	20.000	91.10	-	1.319	-	-
0.13	19.898	90.10	0.13	1.326	0.041	0.129
0.25	19.858	89.80	0.13	1.328	0.016	0.094
0.51	19.756	88.80	0.25	1.335	0.021	0.250
1.02	19.510	86.40	0.51	1.352	0.025	0.506
2.04	19.047	82.00	1.02	1.385	0.024	1.005
4.07	18.392	75.70	2.04	1.434	0.018	1.932
8.15	17.568	67.90	4.07	1.501	0.011	4.151
4.07	17.688	69.00	-4.07	1.491	0.002	-3.342
2.04	17.850	70.60	-2.04	1.477	0.004	-2.359
1.02	18.029	72.30	-1.02	1.463	0.010	-0.952

Table 3. Dispersion Results of CL Group Soil Sample taken from Kayışlı District (Mahmutluoğlu ve Tekinsoy, 2015)

Total Press. p (kg/cm^2)	Dry Unit Weight γ_k (gr/cm^3)	Dif. Coeff. $D_s \times 10^{-4}$ (cm^2/dk)	Disp. Vrb. x -	Disp. Flux J_s (gr/cm^2dk)	Dispers. Amount ΔW_s (gr)	Soil	Total Comp. Soil ΔW_t (gr)
0.00	1.319	-	-	-	-		-

0.13	1.326	0.03515	13.984	2.307×10^{-92}	6.525×10^{-88}	0.0014
0.25	1.328	0.04878	11.847	3.287×10^{-68}	9.296×10^{-64}	0.0025
0.51	1.335	0.08318	9.026	2.851×10^{-42}	8.063×10^{-38}	0.0077
1.02	1.352	0.16392	6.349	6.191×10^{-24}	1.751×10^{-19}	0.0318
2.04	1.385	0.30751	4.526	6.908×10^{-15}	1.954×10^{-10}	0.1235
4.07	1.434	0.49223	3.454	7.904×10^{-11}	2.235×10^{-6}	0.3632
8.15	1.501	0.69471	2.777	1.009×10^{-8}	2.854×10^{-4}	0.8693
4.07	1.491	0.66726	2.853	0.609×10^{-8}	1.722×10^{-4}	0.7810
2.04	1.477	0.62911	2.965	0.283×10^{-8}	8.004×10^{-5}	0.6672
1.02	1.463	0.58548	3.105	0.107×10^{-8}	3.026×10^{-5}	0.5574

Note: Since consolidation stops at the end of each pressure increment, the time rate of settlement v_z was taken as $v_z=0$.

Table 4. Effective Stress Variations relative to Dry Unit Weights for the CH group Sample taken from Kayışlı District (Mahmutluoğlu ve Tekinsoy, 2015)

Total Press. p (kg/cm²)	Samp. Height H (mm)	Void Ratio e (%)	Pressure Increment Δp (kg/cm²)	Dry Unit Weight γ_k (gr/cm³)	Coeff. Of Volume Comp. m_v (cm²/kg)	Efective Stress Increment σ′ (kg/cm²)
0.00	20.000	96.2	-	1.284	-	-
0.13	19.970	95.9	0.13	1.286	0.012	0.130
0.25	19.801	94.3	0.13	1.297	0.067	0.127
0.51	19.578	92.1	0.25	1.312	0.046	0.250
1.02	19.278	89.1	0.51	1.333	0.030	0.529
2.04	18.825	84.7	1.02	1.364	0.023	1.000
4.07	18.197	78.5	2.04	1.412	0.017	2.034
8.15	17.448	71.2	4.07	1.472	0.010	4.162
4.07	17.536	72.0	-4.07	1.465	0.001	-4.767
2.04	17.592	72.6	-2.04	1.460	0.002	-1.709
1.02	17.700	73.6	-1.02	1.452	0.006	-0.916

Table 5. Dispersion Results of CH Group Soil Sample taken from Kayışlı District (Mahmutluoğlu ve Tekinsoy, 2015)

Total Pressure p (kg/cm²)	Dry Unit Weight γ_k (gr/cm³)	Dif. Coeff. $D_s \times 10^{-4}$ (cm²/dk)	Disp. Vrb. x -	Disp. Flux J_s (gr/cm²dk)	Dispersive Soil Amount ΔW_s (gr)	Total Compacted Soil ΔW_t (gr)
0.00	1.284	-	-	-	-	-
0.13	1.286	0.1039	25.814	0	-	0.0001
0.25	1.297	0.6807	10.000	1.88×10^{-50}	5.32×10^{-46}	0.0051
0.51	1.312	1.4191	6.848	6.75×10^{-27}	1.91×10^{-22}	0.0232
1.02	1.333	2.3723	5.215	5.48×10^{-18}	1.55×10^{-13}	0.0695

2.04	1.364	3.7251	4.064	4.88×10^{-13}	1.38×10^{-8}	0.1846
4.07	1.412	5.4312	3.253	3.56×10^{-10}	1.01×10^{-5}	0.4533
8.15	1.472	7.2148	2.707	1.56×10^{-8}	4.41×10^{-4}	0.9423
4.07	1.465	7.0192	2.758	1.12×10^{-8}	3.17×10^{-4}	0.8759
2.04	1.460	6.8928	2.792	0.89×10^{-8}	2.52×10^{-4}	0.8324
1.02	1.452	6.6448	2.861	0.57×10^{-8}	1.61×10^{-4}	0.7589

Note: Since consolidation stops at the end of each pressure increment, the time rate of settlement v_z was taken as v_z=0.

The same calculations were performed in order to obtain both the consolidation and dispersion parameters of the CH group samples. On the other hand, dispersive and diffusive properties of CL and CH group samples and their comparisons were discussed by graphics and comments. As can be seen from Table 2 and Table 4, the effective stress increment values in the final columns which were found theoretically (σ′) are very close to the experimental counterparts (p) in the first columns both for CL and CH group soil samples. These theoretical values were reached by using Equation 4 below which is given for effective stresses and this equation, as mentioned previously, was obtained by solving the differential equation in Equation 3 (Tekinsoy 2013; Mahmutluoğlu 2014).

$$\sigma' = \frac{1}{m_v} \ln \frac{\gamma_{k2}}{\gamma_{k1}} \quad \text{((Mahmutluoğlu ve Tekinsoy, 2015))} \qquad (4)$$

where, m_v is the coefficient of volume compressibility, γ_{k1} and γ_{k2} are the initial and final dry unit weights for any pressure increment, respectively. The obtained values and graphics show the effectiveness of dry unit weight on effective stress variations in a soil. Comparison of effective stress variations obtained both theoretically and experimentally can be seen in the graphics given in Figure 1 and Figure 2 for CL and CH group soil samples, respectively.

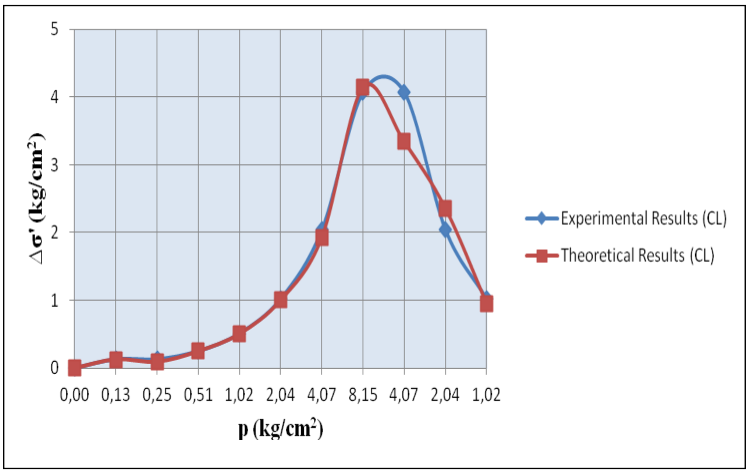

Figure 1. The Relationship between Theoretical (Δσ') and Experimental (p) Effective Stress Increments for CL Group Soil (Mahmutluoğlu ve Tekinsoy, 2015)

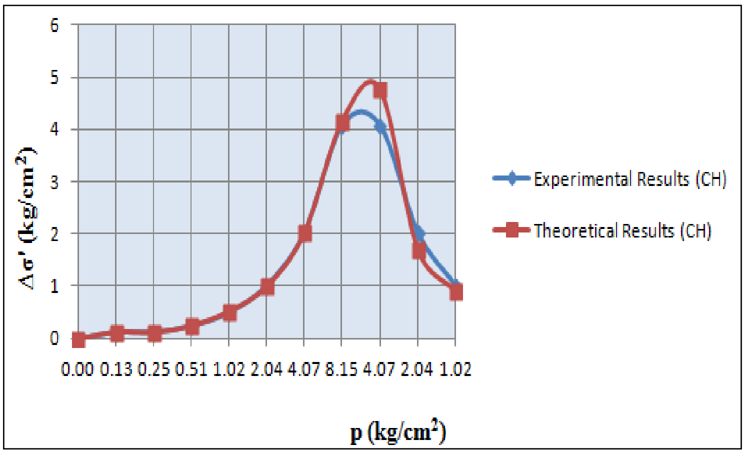

Figure 2. The Relationship between Theoretical (Δσ') and Experimental (p) Effective Stress Increments for CH Group Soil (Mahmutluoğlu ve Tekinsoy, 2015)

A similar relationship can be observed between theoretical and experimental effective stress increments for CH group soil sample, as well. Additionally, if Table 3 and Table 5 are considered, it can be seen that the values for diffusivity coefficients in column 3 for CL group sample are lower than that for CH group except for the first pressure increment value on which pre-consolidation pressure has an effect. These values were obtained by using the equation given below as Equation 5:

$$D_s = \frac{z^2}{4t} \ln \frac{z_i}{z} \qquad (5)$$

where, z_i ve z are the initial and any sample heights, respectively, $z^2/4$ is the squared power of the drainage path (z/2) and t is time.

The relationship between diffusivity coefficients of CL and CH group samples can be clearly seen from the graphic given in Figure 3 below:

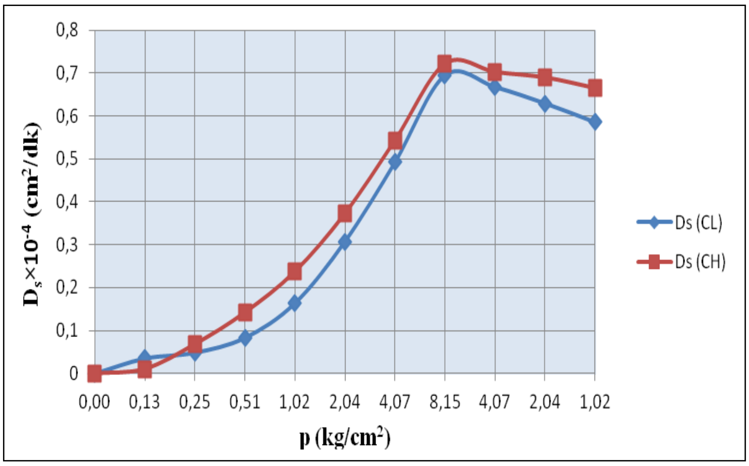

Figure 3. The Relationship of Diffusivity Coefficients ($Ds \times 10^{-4}$) of CL and CH Group Samples relative to Pressure Increments (p) (Mahmutluoğlu ve Tekinsoy, 2015)

The values for flux (J_s) and dispersive variable (x) were found by using the equations below as Equation 6.a and Equation 6.b, respectively:

$$J_s = \sqrt{\frac{D_s}{\pi t}} \cdot \left(\gamma_{kf} - \gamma_{ki}\right) e^{-x^2}$$

(6.a)

$$x = \frac{z + v_z t}{2\sqrt{D_s t}} \tag{6.b}$$

where, D_s is the diffusivity coefficient, γ_{ki} and γ_{kf} are the initial and final values for dry unit weights, respectively, v_z is the time rate of settlement, z is sample height at any instant and t is time.

The occurrence of v_z in the equations includes the effects of time rates of settlement to the phenomena. The values for time rates of settlement can be obtained by using the equation below, theoretically:

$$v_z = \frac{z}{2t} \ln \frac{z}{z_i} \tag{7}$$

where, z_i and z are the initial and any sample deformation heights, respectively and t is time.

The amount of soil which fills into macro pores and diffuses inside the soil matrix were found by using Equation 8 below:

$$\Delta W_s = J_s A \Delta t \tag{8}$$

where, J_s is flux, A is the cross sectional area of the sample and t is time. Since variables of both time and location exist in Equation 8, the amount of dispersive soil can be obtained at any pressure increment or for any instant throughout a consolidation process.

In the last columns of Table 3 and Table 5, total compacted soil amounts (ΔW_t) are given for CL and CH group samples, respectively. These values were obtained by using Equation 9 below:

$$\Delta W_t = A \Delta z \Delta \gamma_k \tag{9}$$

where, A is the cross sectional area, z is the deformational height, γ_k is dry unit weight and this equation represents total compaction. If the total compacted amounts of the CL and CH group soil samples are compared, it can be seen that all of the values are larger in CH group except for the first value on which pre-consolidation pressure is effective. This relationship can be observed in the graphic given in Figure 4.

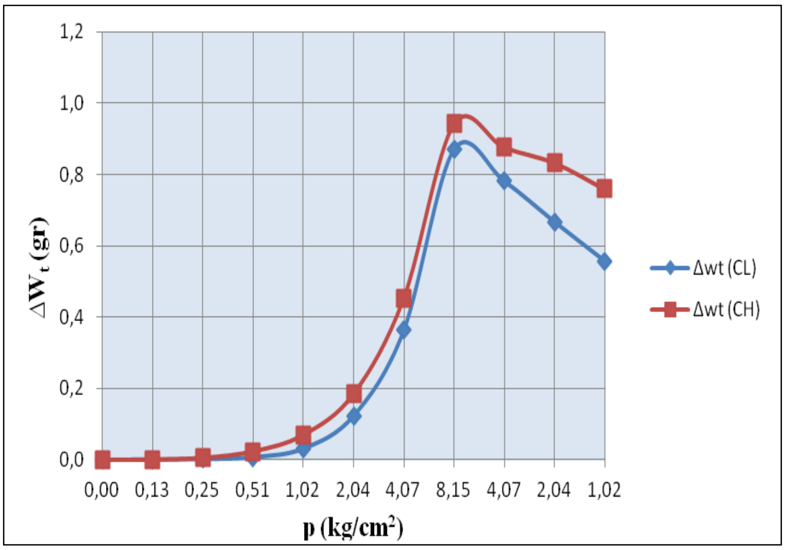

Figure 4. Total Compacted Soil Amounts (ΔW_t) for CL and CH Group Soil Samples with respect to Pressure Increments (p) (Mahmutluoğlu ve Tekinsoy, 2015)

As can be seen from the graphical relationship given in Figure 4, the total amount of compacted soil for CH group soil sample is greater than that for CL group throughout the consolidation process. Therefore, CH group soil sample is compacted more than CL group sample and more soil particles are transported, oriented and compacted in terms of grain diffusion and dispersion.

CONCLUSION

In this study, an approach is presented in which time rates of settlement and their effect on consolidation are studied in terms of dispersion and grain diffusion along with the effects of pore water pressure. A result of this study is that it enables to acknowledge information on the subjects of grain diffusion and dispersion in a consolidation phenomenon. In this aspect, values for variations in effective stresses, diffusivity coefficients, dispersive flux, dispersive and total compacted soil amounts were obtained by solving the differential equation given as Equation (3) being related to dispersion in terms of dry unit weight variations. This equation which was obtained theoretically gives results that are in a very close agreement to the experimental counterparts.

On the other hand, diffusive and dispersive characteristic of a specific region in Adana Turkey is studied and the effects of dry unit weight and plasticity are discussed to shed some light to the phenomena for the first time. By considering the phenomenon of consolidation in an aspect of hydrodynamic dispersion, a great deal of information can be obtained about time rates of settlement. Consequently, viscous properties of a soil could be considered as a result of using the presented theory. Viscous properties of soils are of great importance in the examination and solution of slope stability problems. Eventually, it can be pointed out that the presented theory enables a more clear understanding and perspective in the subject.

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REFERENCES

Özaydin, K. (2005). Zemin Mekaniği., Birsen Yayınevi, 165-167.

Battaglio, M., Bellomo, N., Bonzani, I., Lancellotta, R. (2003). Non-Linear Consolidation Models of Clay Which Change Type. Int. J. of Non-Linear Mechanics, 30, 493-500.

Geng, X., Xu, C., Cai, Y. (2006). Non-Linear Consolidation Analysis of Soil with Variable Compressibility and Permeability under Cyclic Loading. International Journal of Numerical Analysis Methods in Geomechanics, 30, 803-821.

Battaglio, M., Bonzani, I., Campolo, D. (2005). Non-Linear Consolidation Models of Clay with Time Dependent Drainage Properties. Mathematical and Computer Modelling. 42, 613-620.

Asch, W. J. V., Deimel, M. S., Haak, W. J. C. (1989). The Viscous Creep Component in Shallow Clayey Soil and the Influence of Tree Load on Creep Rates. Special Issue: Proceedings of the Fourth Benelux Colloquium on Geomorphological Processes IGU-COMTAG Meeting, 14, 557-564.

Culling, W. E. H. (1963). Soil Creep and the Development of Hillside Slopes. The Journal of Geology, 71-2, 127-161.

Tekinsoy, M. A. (2013). Theoretical Soil Mechanics, Soil Behavior in K_0 Condition. DaisyScience International Publishing House, 125-126; 334-340.

Nielsen, D. R., Jackson, R .D., Cary, J. W., Evans, D. D. (1972). Soil Water. American Society of Agronomy, Soil Science Society of America, 31-39.

Mahmutluoğlu, B., (2014). Hidrodinamik Dispersiyonun Konsolidasyona Olan Etkisi. PhD Thesis, Çukurova University Institution of Natural and Applied Sciences, Adana, 268.

Mahmutluoğlu, B. Tekinsoy, M. A. (2015), Hidrodinamik Dispersiyon' un Konsolidasyona Olan Etkisi, Çukurova Üniversitesi Fen ve Mühendislik Bilimleri Dergisi, Cilt:32/3.