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Water Characteristic Curve for Soils in Kazakhstan

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ABSTRACT: Flux boundary conditions must always be taken into account when analyzing soil behavior under climatic conditions. Since environmental conditions are constantly changing, it is difficult to predict the expansive behavior of the soil and work with it. The soil-water characteristic curve (SWCC) of soils is one of the most important indicators that carries information on the interaction of the air, liquid, and solid phases of soils. Even though large databases of various soil characteristics have now been created in Kazakhstan, many territories remain unexplored with the construction of the main soil-water characteristics curve since the study and construction of these functions can take a long time. The main objective of this study is to construct the SWCC for various soil types throughout Kazakhstan. To achieve it, soil data were collected from the available geotechnical investigations to draw up the soil profile and its properties in the studied regions. The results of the analyses indicate that soils in Kazakhstan can be divided into three main regions. The typical SWCC for different soil classifications at different regions is generated as a result from this study.

KEYWORDS: Soil-water characteristic curve, Unsaturated soil mechanics, Soil properties, Soil profile.

1. INTRODUCTION

Being able to predict the movement of moisture in the soil is crucial for engineers to formulate an idea of what the soil surface and structure boundary will be like. Soil-structure interaction must always be taken into account when designing foundations, pavements, and slopes (Rahardjo et al., 2012). Since environmental conditions and water tables are constantly changing (Morris et al., 1992), it is difficult to predict the expansive behavior of the soil and work with it.

The soil-water characteristic curve (SWCC) of soils, also called the water retention curve, is one of the most important indicators that carries information on the interaction of the liquid and solid phases of soils (Rahardjo et al., 2016a). SWCC is widely used both in scientific soil-physical studies and in practical tasks, such as predictive modeling of ecosystems and optimization of sustainable agricultural production management (Fredlund et al., 2011). The quality of determining this dependence will affect the adequacy of the model, the quality of the forecast, its accuracy, and, accordingly, the decision-making and management of soil processes (Kim et al., 2021).

Even though large databases of various soil characteristics have now been created in Kazakhstan (Zhussupbekov et al., 2018), many territories remain unexplored with the construction of the main SWCC since the study and construction of these functions can take a long time. It is necessary to understand the characteristics of unsaturated soil for this region, especially the relationship between water content and suction, so-called the soil-water characteristic curve.

The main objective of this study is to determine the SWCC for various soil types in certain regions in Kazakhstan. To achieve it, soil data were collected from the available geotechnical investigations to draw up the soil profile and its properties in the studied regions.

2. LITERATURE REVIEW

The soil cover on the territory of Kazakhstan is very diverse. This is due to differences in climate, topography, underlying rocks, and vegetation. Steppe and desert soils predominate here: chernozems, chestnut soils, and brown and gray-brown soils (Pachikin et al., 2013). On the vast plains of the republic, soils have a zonal distribution, and in mountainous areas, they change in a vertical direction (Figure 1) (Pachikin et al., 2013). Meadow soils are common in river valleys in all zones and swamp soils in highly humid places (Pachikin et al., 2013).

Soils that experience volume change associated with changes in water contents are known as expansive soils. Such soils are common in Kazakhstan, Egypt, the USA, South Africa, Georgia, Azerbaijan, Ukraine, Russia, etc. (Pachikin et al., 2013). Expansive soils are widespread in the plains, less often in the foothill areas, and confined to zones of dry steppes and semi-deserts. Since vast areas (more than 80%) are occupied in Kazakhstan by landscapes of clay deserts and plains, the damage of expansive soils causes a range of risks and impacts on the structures, particularly pavements and foundations of buildings (Pachikin et al., 2013)

Figure 1 Soil map of Kazakhstan

Currently, it is believed that the movement of moisture in the soil occurs under the action of a gradient of soil suction (Kristo et al., 2019). It is one of the most important variables in unsaturated soil mechanics. Soil suction is based on the concept of soil water potential, which indicates the potential energy of soil water per unit volume, mass, or weight relative to pure water (Rahardjo et al., 2016). A more conservative definition of soil suction is the difference between pore-air pressure and pore-water pressure ($ua - uw$) in the soil.

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The main algorithm for describing the movement of moisture, based on the use of the thermodynamic apparatus of soil moisture, is associated with the SWCC of soils - the dependence of the soil suction on soil moisture (Fredlund and Rahardjo, 1993). According to modern concepts, SWCC is a quantitative characteristic of the water-retaining capacity of soils (Zhai et al., 2019). Water retention can be defined as the ability of soil to retain moisture by soil suction; this is expressed as the amount of soil moisture at a certain pressure (Zhai et al., 2017). The higher the soil moisture at the same pressure, the higher the water-holding capacity of the soil (Zhai et al., 2021).

3. METHODOLOGY

Prior to the determination of SWCC, the classification of soil using USCS classification was performed on soil data from Kazakhstan. Based on the Unified Soil Classification System and Casagrande's plasticity chart, it is possible to identify which group soils belong to. Due to the significant diversity of soils in terms of mechanical components, as well as the complexity of the experimental determination of the complete SWCC, a large number of formulas have been proposed to determine the potential of soil moisture. Drawing on the work of previous scientists, the joint work of Fredlund and Xing (1994) on learning the best method for fitting SWCC led to the improvement of the equation by introducing independent parameters - a, n, m, θ_s (Fredlund and Xing, 1994).zz

$$\theta = \left[1 - \frac{ln\left(1+\frac{\psi}{C_r}\right)}{ln\left(1+\frac{10^6}{C_r}\right)}\right]\left\{\frac{\theta_s}{\left\{ln\left[e+\frac{\psi}{a}\right]^n\right\}^m}\right\} \quad (1)$$

Where ψ = matric suction; e = base of natural logarithm; a = fitting parameter related to the air entry value of the soil; n = fitting parameter related to the maximum slope of the curve; m = fitting parameter related to the curvature of the slope; Cr = correction factor

It should be noted that the empirical equation proposed by Fredlund and Xing (1994) is applicable only for well-graded and poorly-graded soils. For gap-graded soil, Satyanaga et al. (2022) proposed an equation that is subsequently used to match a curve called bimodal SWCC (Mercer et al., 2019).

$$\theta_w = C_r\left[\theta_r + (\theta_{s1} - \theta_{s2})\left(1 - (\beta_1) erfc\frac{ln\left(\frac{\psi_{a1}-\psi}{\psi_{a1}-\psi_{m1}}\right)}{s_1}\right) + (\theta_{s2} - \theta_r)\left(1 - (\beta_2) erfc\frac{ln\left(\frac{\psi_{a2}-\psi}{\psi_{a2}-\psi_{m2}}\right)}{s_2}\right)\right] \quad (2)$$

where: θ_{s1} = saturated volumetric water content; θ_{s2} = volumetric water content related to air-entry value 2; $\beta_1 = 0$ when $\psi \le \psi_{a1}$; $\beta_1 = 1$ when $\psi > \psi_{a1}$; $\beta_2 = 0$ when $\psi \le \psi_{a2}$; $\beta_2 = 1$ when $\psi > \psi_{a2}$; ψ_{a1} = parameter related to air-entry value 1 (AEV1) (kPa); ψ_{a2} = parameter related to air-entry value 2 (AEV2) (kPa); Cr = input parameter according to Fredlund and Xing (1994) (kPa); erfc = the complementary error function; ψ_{m1} = parameter related to suction at the inflection point 1; ψ_{m2} = parameter related to suction at the inflection point 2; θ_r = parameter related to volumetric water content at residual condition; s_1 = parameter related to standard deviation 1; s_2 = parameter related to standard deviation 2

4. GEOTECHNICAL DATABASE

4.1 Development of a Geotechnical Database for Nur-Sultan City

Because Nur-Sultan has extensive studies on engineering-geological mapping based on field and laboratory studies, this city was analyzed first. According to the research by Zhussupbekov et al. (2021), the mechanical and physical properties of soil were determined based on the locations of existing boreholes Buranbayeva et al. (2021). According to Shaldykova et al. (2020), the territory of Nur-Sultan city is split into three zones that were constructed based on soil profile. Since the goal of this research is to construct a soil-water characteristic curve for various soil types, it is necessary to separately summarize the mechanical and physical properties of coarse-grained and fine-grained soils, which are presented in Table 1 to Table 3 (Zhussupbekov et al., 2017; Seidmarova, 2008).

Table 1 Engineering properties of coarse-grained soil for Nur-Sultan city [15]

Zone	Soil Type	Cohesion, ***c***, kPa	Friction angle, ϕ (°)	Elastic Modulus, E MPa
2	Silty medium gravel	1.0	35	29.0
2	Sandstone	2.0	38	32.0
3	Medium dense sand	2.0	35	17.0
3	Gravelly sand	1.0	38	21.0
3	Sandy gravel	2.0	35	25.5

Table 2 Index properties of fine-grained soil for Nur-Sultan city

Zone	Soil Type	Moisture content, w (%)	Liquid limit, LL (%)	Plastic Limit, PL (%)
1	Loam	16.1	26.0	15.0
1	Clay	31.1	60.0	35.0
1	Clay	33.0	60.0	41.0
1	Clay	31.4	70.0	44.0
2	Sandy loam	20.9	24.0	15.0
2	Clay	28.7	63.0	36.0
2	Clay	28.0	68.0	36.0
2	Clay	31.1	60.0	35.0
2	Clay	33.6	71.0	41.0

Table 3 Engineering properties of fine-grained soil for Nur-Sultan city

Zone	Soil Type	Elastic Modulus, E MPa	Cohesion, ***c***, kPa	Friction angle, ϕ (°)
1	Loam	7.9	-	-
1	Clay	9.3	-	-
1	Clay	11.9	53.3	17.5
1	Clay	9.1	45.3	20.6
2	Sandy loam	7.2	18.2	-
2	Clay	6.9	45.0	10.8
2	Clay	7.2	45.0	10.8
2	Clay	8.8	37.3	20.6
2	Clay	-	50.0	14.0

4.2 Development of a Geotechnical Database for Southeast Kazakhstan

The Southeast region includes the mountainous territory, namely the Northern Tien Shan (NTS) and Almaty (A) city itself. The soil profile of this area mainly consists of clayey loam Khomyakov et al., (2013). The mechanical and physical properties of coarse-grained and fine-grained soils are summarized separately, which are presented in Table 4 and Table 5 (Seinassinova et al., 2020; Baymahan et al., 2015).

Table 4 Engineering properties of fine-grained soil for Southeast Kazakhstan

Soil type	Region	Elastic Modulus, E MPa	Cohesion, ***c***, kPa	Friction angle, ϕ (°)
Clayey loam	A	12.0	33.0	19
Soft clay	NTS	8.0	80.0	16
Firm sandy loam	NTS	9.0	12.0	20
Loam	NTS	12.0	20.0	22
Sandy loam	NTS	18.0	20.0	26
Firm clay	NTS	30	45.0	25

Table 5 Engineering properties of coarse-grained soil for Southeast Kazakhstan

Soil type	Region	Elastic Modulus, E MPa	Cohesion, ***c***, kPa	Friction angle, ϕ (°)
Clayey gravel	A	30.0	27.0	24
Sandy gravel	A	75.0	36.0	37
Sand	A	28.0	0	35
Silty Sand	A	19.6	0	30

4.3 Development of a Geotechnical Database for Western Kazakhstan

The third region of Kazakhstan – Western (specifically the Caspian Sea Coastal Area) – is analyzed to identify the soil water characteristics curve near the coastal area. 22 geotechnical boreholes and 7 reports of cone penetration tests were compiled and presented in the Geotechnical Interpretation Report (2018) (Zhussupbekov et al., 2018). As a result, it allows summarizing of the mechanical and physical properties of coarse-grained and fine-grained soils, which are presented in Table 6 and Table 7.

Table 6 Engineering properties of coarse-grained soil for Western Kazakhstan

Soil Type	Elastic Modulus, E MPa	Cohesion, ***c***, kPa	Friction angle, ϕ (°)
Fill sand	2.8	1	29.4
Silty sand	30	2.7	31.5
Silty sand	40	2.4	31.8

Table 7 Engineering properties of fine-grained soil for Western Kazakhstan

Soil Type	Elastic Modulus, E MPa	Cohesion, ***c***, kPa	Friction angle, ϕ (°)
Silt	2.75	1	29.4
Clay	2.0	20.8	24.7
Clay	4.0	22.7	25.8
Clay	2.5	25.0	24.7

5. REGRESSION ANALYSIS OF SOIL PROPERTIES

Because of the deep analysis of soil in Nur-Sultan city, it is possible to see the relationship between liquid limit and cohesion, which will prove the measure of cohesiveness. So, a high value of the liquid limit indicates a high degree of cohesion. As can be seen from Figure 2, the R-square (R^2) approaches 1, indicating a direct relationship between cohesion and liquid limit. There is no data on the liquid limit for coarse-grained soil, so a graph cannot be constructed. The next step is to find the relationship between friction angle and elastic modulus.

According to Figure 3, R^2 is less than even 0.5, indicating a weak relationship between cohesion and liquid limit for fine-grained soil. The same procedure is done for coarse-grained soil, for which the following graph has been drawn (R^2 is less than 0.5) (Figure 4).

The same procedure is done for southeast and western Kazakhstan (Figures 5 to 8). Due to the lack of soil data in geotechnical reports, the correlation between cohesion and Liquid limit was not done.

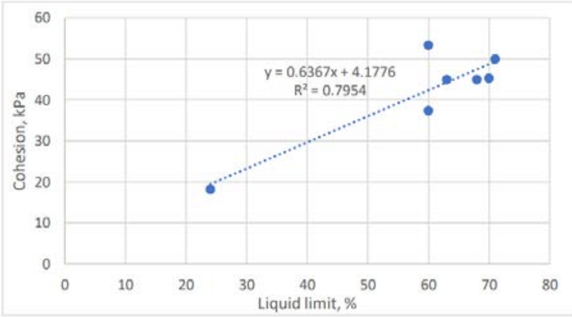

Figure 2 Cohesion vs. Liquid limit for fine-grained soils of Nur-Sultan

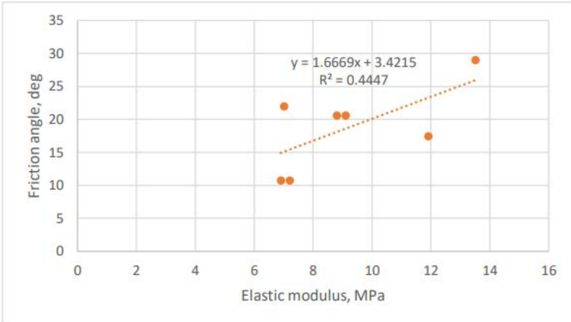

Figure 3 Friction angle vs. Elastic modulus for fine-grained soils of Nur-Sultan

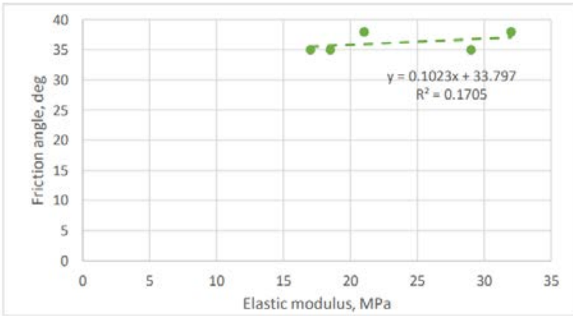

Figure 4 Friction angle vs. Elastic modulus for coarse-grained soils of Nur-Sultan

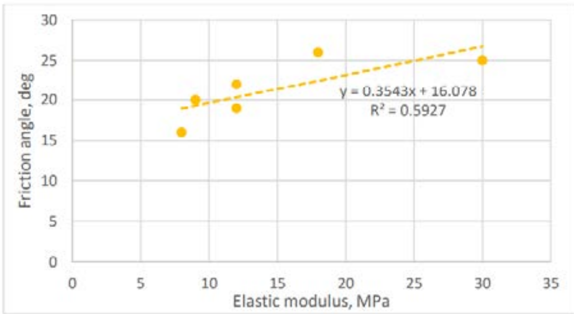

Figure 5 Friction angle vs. Elastic modulus for fine-grained soils of Southeast Kazakhstan

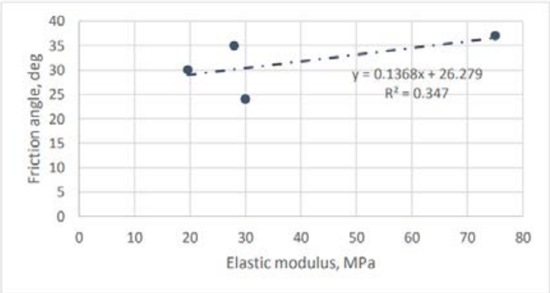

Figure 6 Friction angle vs. Elastic modulus for coarse-grained soils of Southeast Kazakhstan

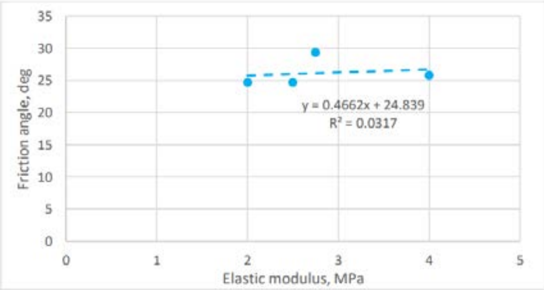

Figure 7 Friction angle vs. Elastic modulus for fine-grained soils of western Kazakhstan

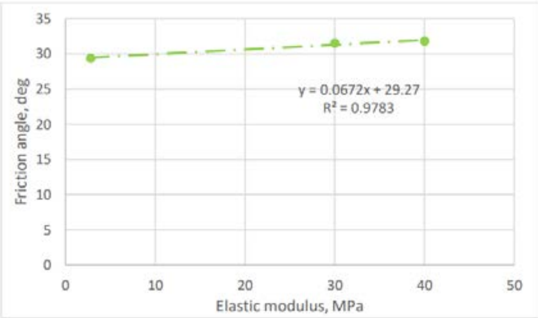

Figure 8 Friction angle vs. Elastic modulus for coarse-grained soils of western Kazakhstan

6. CONSTRUCTION OF SWCC

6.1 Soil Classification

Having defined the soil profile presented in Section 5, it is now necessary to designate the soil groups for plotting the soil-water characteristic curve. Using the Unified Soil Classification System and Casagrande's plasticity chart, soil classification for the study regions was developed and presented in Tables 8 - 12.

Since only the Atterberg limits are available for soils in Nur-Sultan, the classification of soils for other regions was conducted based on the analysis of the available soil properties and soil types that were presented in the previous sections.

It is not possible to classify fine-grained soils into soil groups for Western Kazakhstan due to the lack of soil data. Therefore, this part will be omitted.

Table 8 Soil classification of coarse-grained soil for Nur-Sultan city

Zone	Soil classification (Symbol)	Soil classification (Group name)	Elastic Modulus, E MPa	Friction angle, ϕ (°)
2	GM	Silty gravel	29.0	35
2	GW	Well-graded gravel	32.0	38
3	SW	Well-graded sand	17.0	35
3	SP	Poorly-graded sand	21.0	38
3	GP	Poorly-graded gravel	18.5	35

Table 9 Soil classification of fine-grained soil for Nur-Sultan city

Zone	Soil classification (Symbol)	Soil classification (Group name)	Liquid limit, LL (%)	Plastic Limit, PL (%)
1	CL	Silty clay	26.0	15.0
1	MH	Silt with high plasticity	60.0	35.0
1	MH	Elastic silt	60.0	41.0
1	MH	Elastic silt	70.0	44.0
2	CL	Clay with low plasticity	24.0	15.0
2	MH	Elastic silt	63.0	36.0
2	MH	Elastic silt	68.0	36.0
2	MH	Elastic silt	60.0	35.0
2	MH	Elastic silt	71.0	41.0

Table 10 Soil classification of fine-grained soil for Southeast Kazakhstan

Region	Soil classification (Symbol)	Soil classification (Group name)	Elastic Modulus, E MPa	Friction angle, ϕ (°)
Almaty	CL	Clay with low plasticity	12.0	19
Northern Tien Shan	CH	Fat clay	8.0	16
Northern Tien Shan	CL	Clay with low plasticity	9.0	20
Northern Tien Shan	CL	Clay with low plasticity	12.0	22
Northern Tien Shan	CH	Fat clay	18.0	26
Northern Tien Shan	CL	Clay with low plasticity	30	25

Table 11 Soil classification of coarse-grained soil for Western Kazakhstan

Region	Soil classification (Symbol)	Soil classification (Group name)	Elastic Modulus, E MPa	Friction angle, ϕ (°)
Almaty	GC	Clayey gravel	30.0	24
Almaty	GP	Poorly-graded gravel	75.0	37
Almaty	SW	Well-graded sand	28.0	35
Almaty	SP	Poorly-graded sand	19.6	30

Table 12 Soil classification of coarse-grained soil for Southeast Kazakhstan

Soil classification (Symbol)	Soil classification (Group name)	Elastic Modulus, E MPa	Friction angle, ϕ (°)
SP	Poorly-graded sand	30	31.5
SP	Poorly-graded sand	40	31.8

6.2 Construction of SWCC Based on the Selected Methods

The empirical equation of Fredlund and Xing (1994) for well-graded and poorly-graded soils (so-called unimodal grain-size distribution) and the empirical expression of Satyanaga et al. (2013) for gap-graded soils were used to construct the soil-water characteristic curve for soils in Kazakhstan. The procedure of the construction of SWCC follows the method proposed by Mercer et al. (2019). To best fit, the SWCC for well-graded and poorly-graded soils, Fredlund and Xing (1994) identified constant values that are used in their formula. These numbers are presented in Table 13.

Table 13 Best fitting parameters for unimodal SWCC

USCS Classification	Fredlund and Xing (1994) parameters based on Mercer et al. (2019) method			
	$\boldsymbol{\theta_s}$	a	n	m
GW	0.111	8.91	4.68	1.37
GP	0.101	31	1.81	3.33
GM	0.313	66	2.49	15.0
GC	0.313	66	2.49	15.0
SW	0.260	8829	1.09	441
SP	0.402	6.98	1.16	1.75
SM	0.495	2616	0.57	6.00
SC	0.489	1486	0.73	6.20
ML	0.418	94	0.62	1.55
CL	0.450	108	0.83	0.77
CH	0.432	391	0.75	0.92
MH	0.620	851	1.20	3.50
PT	2.501	190	0.72	1.81

Based on soil classification from different regions in Kazakhstan (Tables 8-12), it is selected appropriate fitting parameters in the analysis. Starting with fine-grained soils, it was determined that the investigated soils are more related to the CL, CH, and MH groups. Then Equation 3 is used to construct the SWCC incorporating the fitting parameters from Table 13. SWCCs for CL, CH, and MH groups for soils in Kazakhstan are presented in Figures 9 – 11.

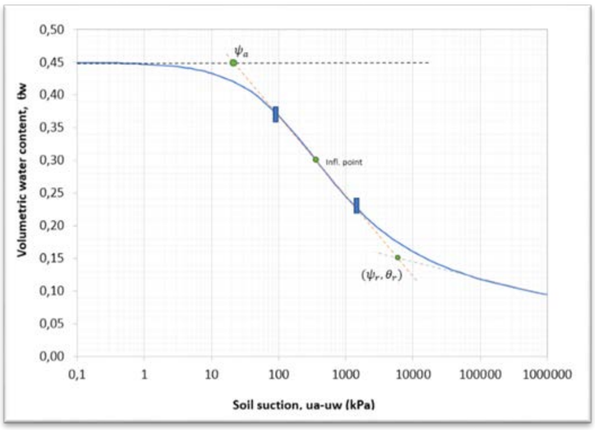

Figure 9 Unimodal SWCC for CL soil

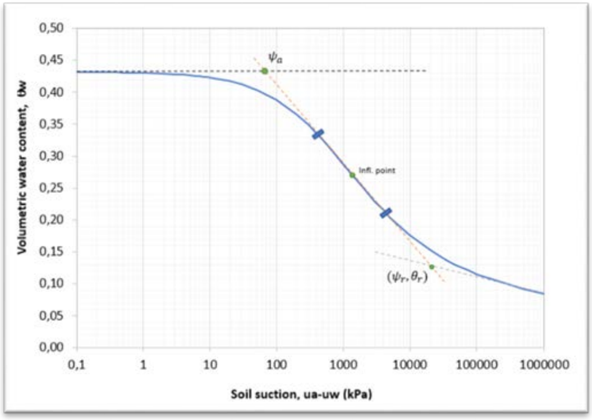

Figure 10 Unimodal SWCC for CH soil

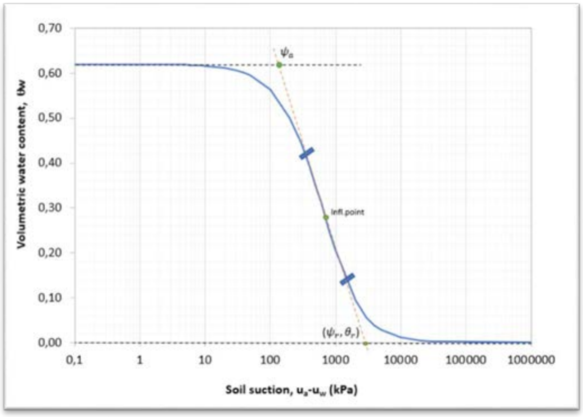

Figure 11 Unimodal SWCC for MH soil

To check the reliability of constructed SWCCs, it is necessary to compare the computed data with the theoretical values as suggested by Satyanaga et al. (2013). Table 14 summarized the comparisons between the fitting parameter from the constructed SWCC with the theoretical values from Satyanaga et al. (2013). As can be seen from Table 14, the fitting parameters from the constructed SWCC are within the range of the theoretical values from Satyanaga et al. (2013), which shows the reliability of the constructed SWCC. The same procedure is carried out for coarse-grained soil. The following Figures 12 - 17 show the results of the constructed SWCC for coarse-grained soils in Kazakhstan. Table 15 shows the comparison between the fitting parameters of the constructed SWCC with the theoretical values from Satyanaga et al. (2013).

Table 14 Comparisons of measured and theoretical values of parameters for unimodal SWCC

Fitting parameters	Soil classification		
	CL	MH	CH
Measured from constructed SWCC			
Air-entry value, ψa, kPa	20	140	60
Inflection point, kPa	350	700	1500
Residual suction, ψr, kPa	6 000	3 000	20 000
Residual water content, θr	0.15	0	0.13
Theoretical values from Satyanaga et al. (2013)			
Air-entry value, ψa, kPa	9 - 70	80 – 200	50 - 100
Inflection point, kPa	200 – 5 000	500 – 900	800 - 9000
Residual suction, ψr, kPa	3 000 – 60 000	5000 – 10000	8000 - 200 000
Residual water content, θr	0.09 – 0.17	0 – 0.08	0.01 – 0.1

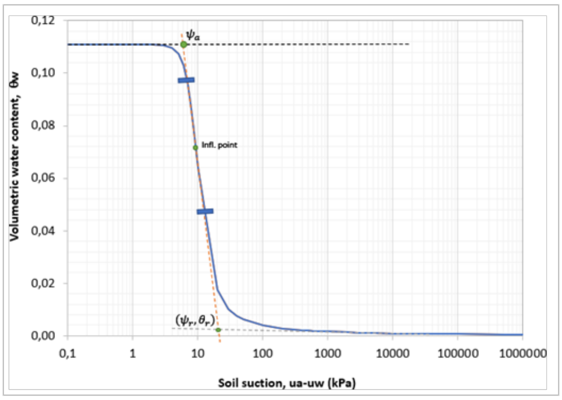

Figure 12 Unimodal SWCC for GW soil

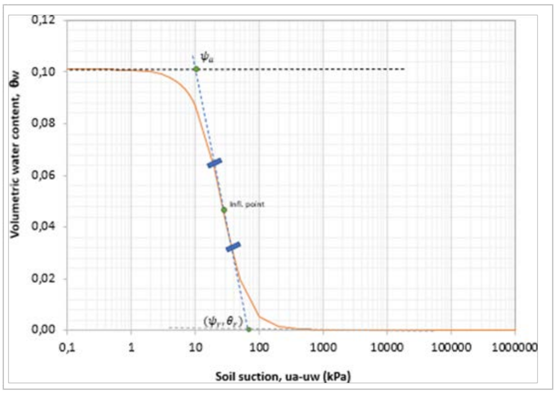

Figure 13 Unimodal SWCC for GP soil

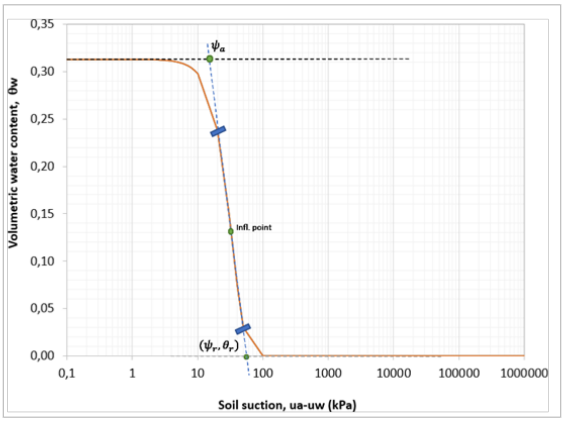

Figure 14 Unimodal SWCC for GM soil

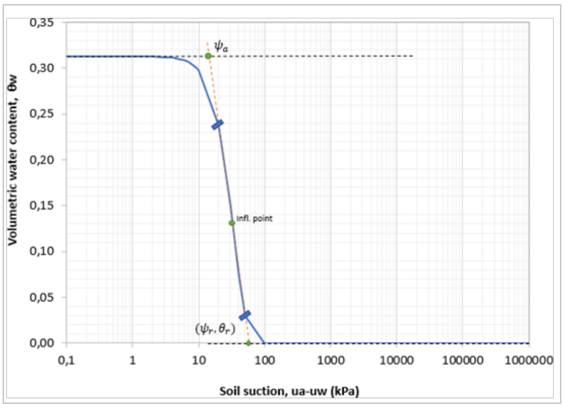

Figure 15 Unimodal SWCC for GC soil

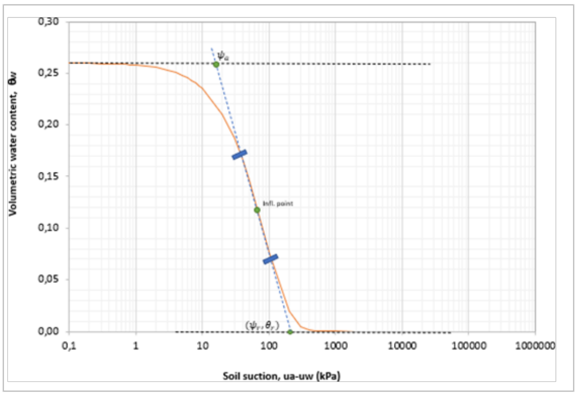

Figure 16 Unimodal SWCC for SW soil

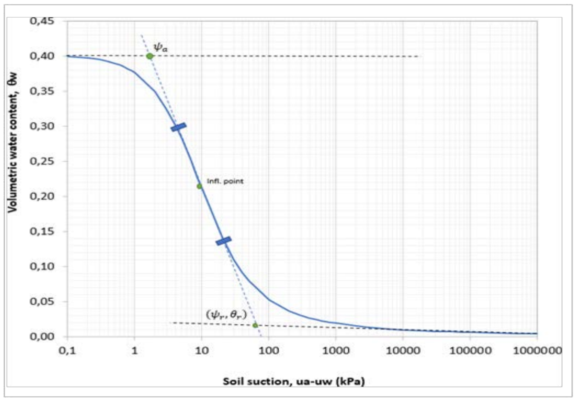

Figure 17 Unimodal SWCC for SP soil

Table 15 Comparisons of measured and theoretical values of parameters for unimodal SWCC

Fitting parameters	Soil classification			
	GW	GP	GM	GC
Measured from constructed SWCC				
Air-entry value, ψa, kPa	6	10	17	15
Inflection point, kPa	13	30	32	30
Residual suction, ψr, kPa	20	65	65	58
Residual water content, θr	0.004	0.001	0	0
Theoretical values from Satyanaga et al. (2013)				
Air-entry value, ψa, kPa	5 - 9	8 - 12	10 - 19	9 - 15
Inflection point, kPa	10 - 20	20 - 30	20 - 37	25 - 40
Residual suction, ψr, kPa	12 - 30	60 - 80	50 - 70	50 - 90
Residual water content, θr	0 - 0.04	0 - 0.04	0	0

Table 16 Comparisons of measured and theoretical values of parameters for unimodal SWCC

Fitting parameters	Soil classification	
	SW	SP
Measured from constructed SWCC		
Air-entry value, ψa, kPa	18	2
Inflection point, kPa	65	10
Residual suction, ψr, kPa	200	60
Residual water content, θr	0	0.018
Theoretical values from Satyanaga et al. (2013)		
Air-entry value, ψa, kPa	10 - 80	0.08 - 18
Inflection point, kPa	35 - 200	2.5 - 50
Residual suction, ψr, kPa	90 - 400	8 - 200
Residual water content, θr	0	0.01 – 0.04

As can be seen from Tables 15 and 16, the computed values are in the range of generally accepted data. This means that the classification of soil groups was carried out with minimum errors. To fit the SWCC for gap-graded soils, Satyanaga et al. (2022) identified constant values that are used in derived Equation 4. These numbers are presented in Table 17. To construct bimodal SWCC (Figures 18 and 19) for soils in Kazakhstan, Equation 4 and parameters from Table 17 are used.

Table 17 Best fitting parameters for bimodal SWCC (Satyanaga et al., 2022)

Fitting Parameter	Soil Classification for gap-graded soils			
	SC	ML	CL	MH
$\boldsymbol{\theta s}$	0.300	0.600	0.320	0.445
$\boldsymbol{\psi a1}$	0.95	10	1.0	1.0
$\boldsymbol{\psi m1}$	12	12	18	15
$\boldsymbol{s1}$	1.77	0.20	0.50	2.95
$\boldsymbol{\theta s}2$	0.25	0.37	0.25	0.20
$\boldsymbol{\psi a}2$	51	25	51	47
$\boldsymbol{\psi m}2$	511	150	300	512
$\boldsymbol{s}2$	1.5	1.5	2.0	2.4
$\boldsymbol{\psi}$r	1000	500	2000	1000
$\boldsymbol{\theta}$r	0.165	0.030	0.100	0.311

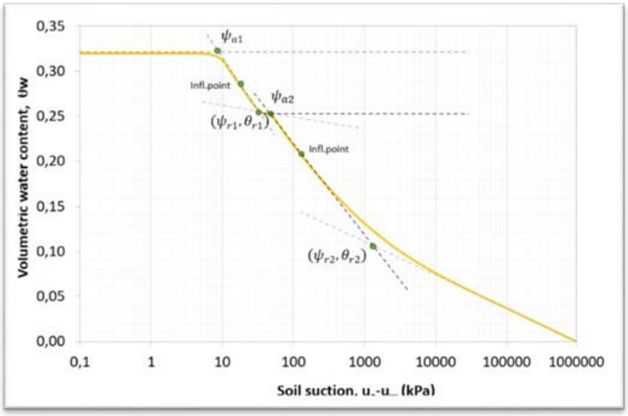

Figure 18 Bimodal SWCC for CL soil

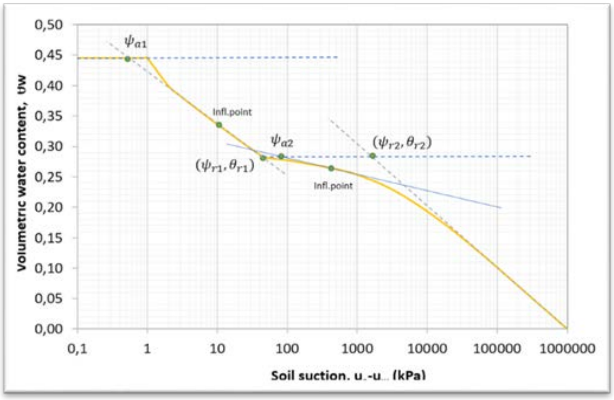

Figure 19 Bimodal SWCC for MH soil

Having plotted the bimodal SWCCs, it is now possible to compare theoretical and computed values. Theoretical values are taken from Satyanaga et al.'s (2013) recommendation. Table 18 shows that the values of some variables are within the range of generally accepted data. This means that the classification of soil groups was carried out with minimum errors.

Table 18 Comparisons of measured and theoretical values of parameters for bimodal SWCC

Fitting Parameters	Type of values	Soil Classification	
		CL	MH
Air-entry value, $\psi a1$, kPa	Measured	9	0.75
Air-entry value, $\psi a2$, kPa		54	90
Inflection point 1, kPa		20	10
Inflection point 2, kPa		120	420
Residual suction, $\psi r1$, kPa		30	45
Residual suction, $\psi r2$, kPa		1300	1800
Residual water content, $\theta r1$		0.25	0.28
Residual water content, $\theta r2$		0.15	0.285
Air-entry value, $\psi a1$, kPa	Theoretical	2 - 20	0.5 - 2
Air-entry value, $\psi a2$, kPa		30 - 200	20 - 110
Inflection point 1, kPa		7 - 80	50 - 100
Inflection point 2, kPa		100 - 700	100 - 700
Residual suction, $\psi r1$, kPa		20 - 100	20 - 80
Residual suction, $\psi r2$, kPa		9	0.75
Residual water content, $\theta r1$		54	90
Residual water content, $\theta r2$		20	10

7. CONCLUSIONS

Overall, the following outcomes can be drawn from the results of the study:

- A complete analysis of mechanical and physical soil properties was made for the selected regions;
- The envelope of the relationship between soil properties and soil type was constructed and examined;
- A statistical analysis of index and shear strength properties was carried out;
- The soil-water characteristic curve (SWCC) was built for a specific soil group;

- ➢ It was achieved that the results of the experimental part are in agreement with the theoretical values of the SWCC variables.

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