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Impact of soil composition on maximum depth of wetting in expansive soils

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ABSTRACT

Expansive unsaturated soils present challenges in construction due to their moisture-induced behavior. This study proposes empirical equations to estimate the maximum wetting depth over time. Laboratory experiments and numerical analyses using SEEP/W software investigate wetting depth considering time and sand content in coastal and inland regions. Results reveal the significant influence of sand content on maximum soil moisture depth, emphasizing a recommended content above 30% to mitigate heave. The equations offer practical tools for assessing wetting depth, accounting for temporal and spatial variations. This research highlights the importance of wetting depth in addressing soil-related concerns and provides a foundation for further exploration of related factors.

KEYWORDS

expansive soil, unsaturated soil, depth of wetting, soil suction, soil-water characteristic curve, numerical modeling

1. INTRODUCTION

The depth of wetting is a critical consideration when constructing foundations on expansive soils. It was typical to assume a wetting depth of 2–3 m below the basement slabs, and after recognizing that wetting depths could be deeper, the assumed depth of wetting was increased [1]. Walsh et al. [2] conducted a field study on various sites during different wetting years and found an average wetting depth of 5.1 m with a standard deviation of 2.1 m. However, practitioners would fix the wetting depth assumed without considering the effects of time and soil composition. The sand content present within expansive soil is of paramount importance, as highlighted in [3], and significantly impacts its behavior. As a result, the effect of the expansive soil's initial state on the wetting depths was studied in this research to determine the maximum wetting depth with time.

The depth at which moisture fluctuations occur in the soil is referred to as the active zone depth [4, 5]. Below the active zone depth, there is minimal variation in soil moisture [4, 5]. Many highway slopes constructed on expansive soils have experienced failures, including soil erosion, scarping, and shallow or deep-seated failures due to inadequate site investigation and the insufficient evaluation of wet and dry soil properties within the active zone depth [4–7]. This study focuses on the depth at which moisture spreads over time in expansive soils, an aspect that has been overlooked in previous studies. It is important to note that moisture diffusion in expansive soils takes a considerable amount of time due to their very low permeability. The term "depth of wetting" in this study refers to the depth at which moisture changes occur at a specific time.

Regional climatic conditions usually control the depth of wetting (active zone). Seasonal changes, notably, affect soil suction during successive wet and dry seasons. They affect pressures and the average and differential heave caused by these seasonal changes in suctions [8, 9]. As a result, proper knowledge of the suction distribution within the soil and its region of spread are critical for the geotechnical engineer dealing with expansive soils.

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The swelling or shrinkage behavior of expansive soil can be better understood if the seasonal suction distribution in the expansive soil layer is known. It may also be necessary to determine the actual depth of wetting to enable the correct design and evaluation of light structure foundations to avoid potential damages caused by moisture changes [10, 11]. The range of seasonal moisture fluctuation and the depth of wetting in the soil layer of the studied area are significant in estimating the value of soil heave due to the relationship between volume change and soil moisture content of expansive soil. The estimate of soil heave is dependent on the sum of swelling deformations caused by soil moisture change [2, 12, 13].

A variety of methods can determine the depth of wetting. This study limits itself to numerical simulations due to the complexity and time duration required for other methods. Software packages help to solve this geotechnical engineering issue [14]. Numerous software packages simulating moisture flow in soil include HYDRUS to model soil moisture flow in the unsaturated zone [15], PLAXIS to simulate the soil-rainfall interaction of a slope in Singapore [16–18], VADOSE/W to simulate flow behavior in unsaturated loess while accounting for the influence of environmental factors [19], and other Finite Element Method (FEM) software to conduct an analysis of moisture migration beneath a mat foundation over time [20].

This work discusses a one-of-a-kind assessment into the depth of wetting of expansive soil, with the investigations based on essential unsaturated flow and stress-deformation principles. This paper includes a parametric examination of the effect of the initial degree of saturation, initial dry unit weight, and percentage of sand on the depth of wetting. Climatic data from the southern region and the coastal region of Syria were used.

2. RESEARCH MATERIALS AND METHODOLOGY

To achieve the study objectives, an analytical method was used. The flow analysis in unsaturated soils was studied using the SEEP/W finite element program (formerly VADOSE/W before its merger with SEEP/W) [21], and the deformations under the foundation were studied using the SIGMA/W program [21]. The SEEP/W soil suction results were used as inputs to the SIGMA/W because they are ultimately two branches of the same program.

Atterberg [22] and standard Proctor tests [23] were also performed, on the basis of which suitable initial conditions were determined. Table 1 shows the properties of the expansive soil used for all sand ratios.

Laboratory tests were performed to determine the Soil-Water Characteristic Curve (SWCC) and the saturated hydraulic conductivity coefficient (K_{sat}) for various percentages of sand (0-10-20-30-40-50%), as well as different initial densities and degrees of saturation, and the SWCC results were converted into the Fredlund and Xing equation [24] for all percentages of sand. Tables 2 and 3 demonstrate the parameters of the Fredlund and Xing equation and saturated hydraulic conductivity for various initial dry unit weights and initial degrees of saturation, respectively.

Validating the problem correctly is a crucial issue that warrants careful consideration. To achieve this, numerical predictions generated by the model are compared with the outcomes of engineering software's, which rely on independent solutions or field measurements [25, 26]. In line with prior studies, the model validation process and dimensions employed in this research are identical to those presented in [27], with the exception that soil replacement was not taken into account. The study employed a uniform expansive soil profile and incorporated time-varying boundary conditions on the ground surface, including changes in climate over time. Initial suction conditions were assigned to the other boundaries, which changed over time due to alterations in suction on the ground surface.

The calculation of wetting depths in this study utilized the climatic data from two distinct regions in Syria, namely the coastal region, characterized by high humidity, and the southern region, characterized by a dry climate. According to meteorological data, the average annual precipitation over the last thirty years has been around 18.5 and 58.6 cm for the southern and coastal regions, respectively (Fig. 1) [28]. The analysis in this study lasted 50 years.

3. RESULTS AND DISCUSSION

3.1. Study the effect of initial dry unit weight

To investigate the impact of initial dry unit weight on the maximum depth of soil moisture, the present study

Table 1. Atterberg and standard Proctor results for various percentages of added sand

Sand Percentage *Fs* (%)	Liquid Limit *LL* (%)	Plastic Limit *PL* (%)	Plastic Index *PI*(%)	Shrinkage Limit *SL* (%)	Optimum moisture w_{opt} (%)	Maximum dry unit weight γ_{dmax} (kN m^{-3})
0	78.8	34.6	44.2	12.0	31.6	13.95
10	72.1	32.2	39.9	13.8	28.4	14.66
20	63.3	27.7	35.6	14.9	25.4	15.30
30	55.8	24.5	31.3	15.7	22.4	15.95
40	48.6	21.4	27.2	16.4	19.7	16.73
50	41.1	17.9	23.2	17.1	17.5	17.40

Table 2. The fitting parameters of Fredlund and Xing model for various percentages of added sand at various initial dry densities

Initial state parameters			The fitting parameters of Fredlund and Xing model				
Fs(%)	Y_d (g cm^{-3})	*SR* (%)	*m*	*n*	α (kPa)	*Θs*	K_{sat} (m day^{-1})
0	1.328	75	1.15	0.49	3034.3	0.611	2.57E-05
0	1.395	75	1.12	0.47	2308.4	0.655	7.98E-06
0	1.463	75	1.11	0.45	1674.0	0.707	3.06E-06
0	1.530	75	1.10	0.45	1260.0	0.765	2.63E-06
10	1.400	75	1.10	0.44	1916.9	0.608	1.32E-05
10	1.466	75	1.09	0.43	1592.1	0.646	8.21E-06
10	1.530	75	1.07	0.42	1242.6	0.711	6.75E-06
10	1.600	75	1.06	0.40	975.9	0.753	3.61E-06
20	1.430	75	1.00	0.48	1600.0	0.546	2.96E-05
20	1.480	75	0.99	0.43	1490.0	0.585	1.55E-05
20	1.530	75	0.98	0.43	1150.0	0.623	1.12E-05
20	1.600	75	0.97	0.39	700.0	0.679	2.66E-06
30	1.530	75	0.90	0.46	484.9	0.590	6.61E-06
30	1.595	75	0.88	0.47	445.4	0.617	5.41E-06
30	1.660	75	0.85	0.47	348.7	0.649	3.42E-06
30	1.725	75	0.82	0.47	334.0	0.669	2.06E-06
40	1.530	75	0.77	0.51	470.7	0.467	9.60E-06
40	1.602	75	0.75	0.53	450.0	0.491	8.88E-06
40	1.673	75	0.73	0.54	373.0	0.523	5.92E-06
40	1.744	75	0.70	0.55	299.0	0.554	5.32E-06
50	1.53	75	0.63	0.70	232.7	0.411	1.61E-05
50	1.635	75	0.60	0.71	300.0	0.430	1.04E-05
50	1.74	75	0.59	0.79	288.4	0.457	5.40E-06
50	1.845	75	0.53	0.94	216.2	0.509	3.59E-06

Table 3. The fitting parameters of Fredlund and Xing model for various percentages of added sand at various initial degrees of saturation

Initial state parameters			The fitting parameters of Fredlund and Xing model				
Fs(%)	Y_d (g cm^{-3})	*SR* (%)	*m*	*n*	α (kPa)	*Θs*	K_{sat} (m day^{-1})
0	1.395	72	1.10	0.49	2200.0	0.683	7.98E-06
0	1.395	81	1.11	0.52	2727.9	0.644	4.28E-06
0	1.395	91	1.15	0.55	4482.2	0.619	9.49E-07
0	1.395	100	1.17	0.56	5119.7	0.613	4.12E-07
10	1.466	64	1.05	0.47	1087.7	0.675	1.62E-05
10	1.466	80	1.10	0.49	2200.0	0.629	8.21E-06
10	1.466	91	1.12	0.54	4237.9	0.595	2.48E-06
10	1.466	100	1.13	0.56	4744.2	0.590	9.70E-07
20	1.530	53.0	1.05	0.42	819.5	0.705	3.13E-05
20	1.530	71.0	1.05	0.43	1235.5	0.631	1.12E-05
20	1.530	88.0	1.11	0.54	3799.0	0.558	5.93E-06
20	1.530	100.0	1.13	0.56	4202.8	0.561	1.06E-06
30	1.595	59.0	0.85	0.46	183.6	0.668	1.42E-05
30	1.595	74.6	0.88	0.46	477.2	0.570	5.41E-06
30	1.595	88.0	1.09	0.53	3500.0	0.501	3.14E-06
30	1.595	100.0	1.10	0.54	4000.0	0.499	7.63E-07
40	1.673	44.5	0.59	0.85	150.7	0.628	1.50E-05
40	1.673	74.8	0.72	0.54	372.4	0.525	5.92E-06
40	1.673	87.7	0.98	0.52	1150.7	0.493	3.45E-06
40	1.673	100.0	1.00	0.52	1877.2	0.470	1.15E-06
50	1.740	49.8	0.49	1.07	130.0	0.532	9.44E-06
50	1.740	74.7	0.59	0.79	288.4	0.457	5.40E-06
50	1.740	85.0	0.95	0.50	753.6	0.454	4.00E-06
50	1.740	100.0	0.97	0.50	992.1	0.438	1.16E-06

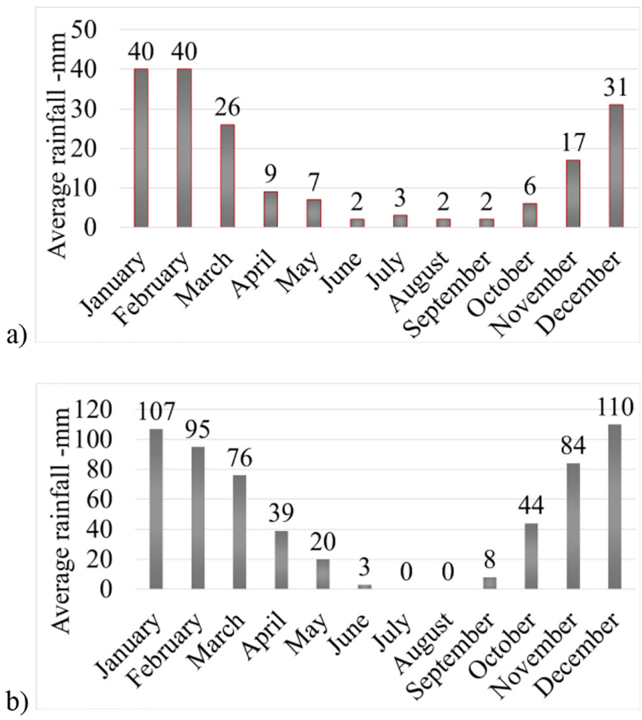


Fig. 1. The average monthly rainfall in a) southern region of Syria and b) coastal region of Syria for the past 30 years, (*Source*: compiled by the Authors based on [28])

employed numerical simulations using established methodology and dimensions. The study adopted a constant initial suction of 1800 kPa and a sand content of 30%, while varying the initial dry unit weight. The obtained results of the depth of wetting over time for various initial dry unit weights are depicted in Fig. 2.

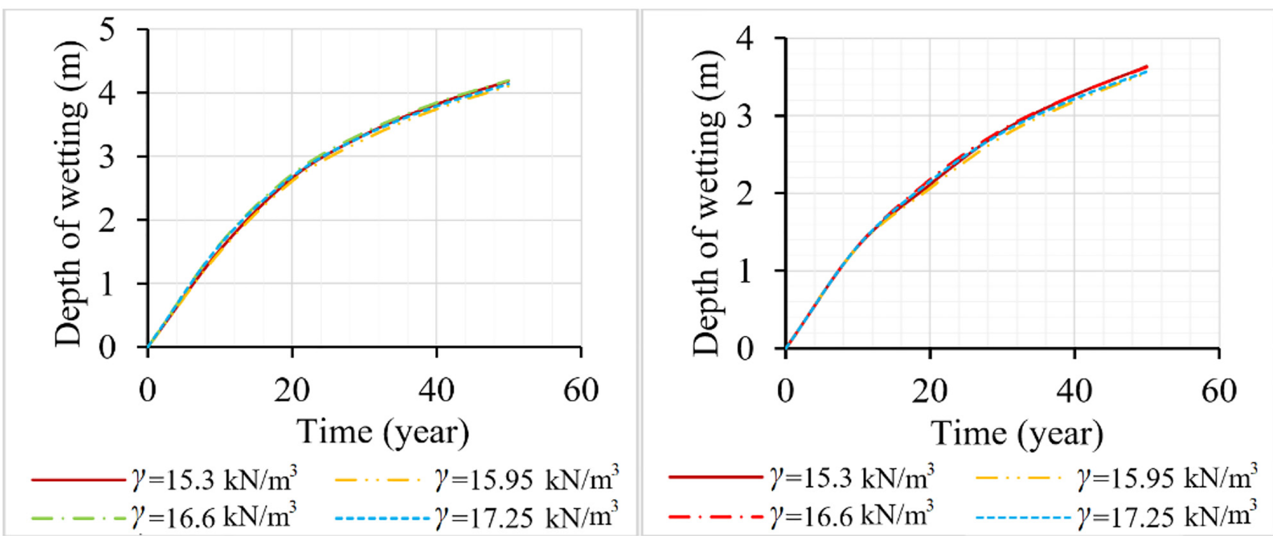
As it is shown in Fig. 2 it is observed that the effect of initial dry unit weight on the depth of wetting is minimal over time.

3.2. Study on the effect of initial suction on depth of wetting

Wetting penetration depths were investigated for samples prepared with a standard Proctor unit weight under different initial suction conditions (various degrees of initial saturation (SR)). The wetting penetration depth was determined after one year, and Fig. 3 illustrates the depth of wettings after one year for both Latakia and Daraa climates as a function of sand content.

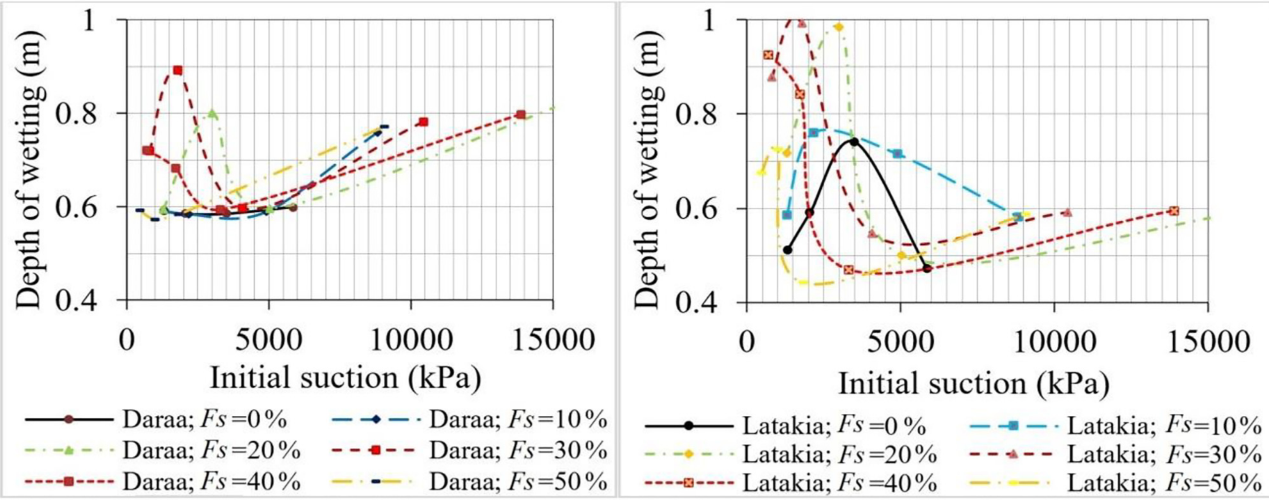
Figure 3 indicates that the maximum depths of wetting for the Latakia climate exceeded those for the Daraa climate for the same initial suction value. This is due to the higher amount of rainfall in Latakia, allowing for greater water penetration into the soil and deeper depths of wetting, as opposed to Daraa, where limited rainfall results in less water infiltration and shallower depths of wetting. With increasing initial suction, the depth of wetting also increases as the suction force pulls water deeper into the soil, but eventually, the soil becomes too dry, and the suction force becomes too strong, limiting water infiltration and reducing the depth of wetting. The maximum depth of wetting occurs at an initial suction of 1800 kPa and a sand content of 30%. Furthermore, it should be noted that the critical initial suction value, which yields the maximum depth of wetting, decreases as the sand content increases.

Moreover, Fig. 4 illustrates the heave values as a function of initial suction after one year. It is observed that the heave values increase with increasing initial suction until reaching the critical suction value that corresponds to the maximum



a) b)

Fig. 2. Results of depth of wetting over time for different initial dry unit weight, a) Coastal Region climate (Latakia), b) Inland Region climate (Daraa)



a) b)

Fig. 3. The wetting of depths after one year for both Latakia and Daraa climates, a) Daraa climate and b) Latakia climate

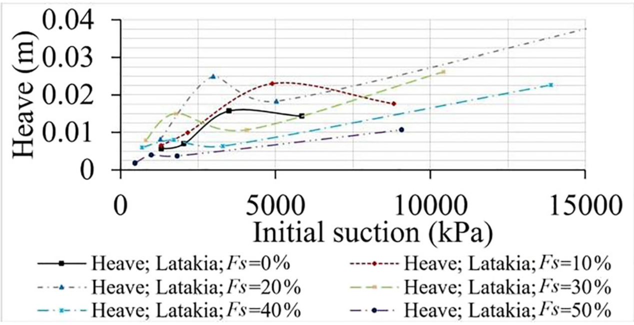


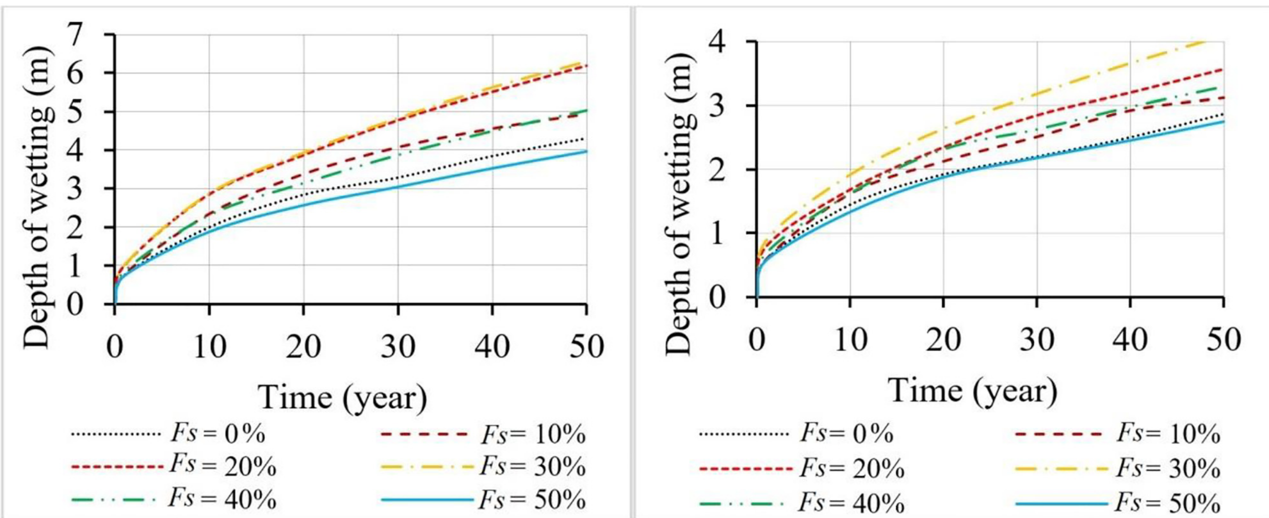
Fig. 4. Heave values after one year as a function of initial suction for Latakia climate

depth of wetting. After that, the heave values decrease and then increase again with further increases in initial suction.

3.3. Maximum depth of wetting

To determine the maximum expected depth of wetting, the critical suction value was adopted for each sand ratio, and the maximum depth of wetting was found during the age of the structure, which was adopted as 50 years according to the Syrian Arab Standard Code [29].

Figure 5 shows the maximum expected depth of wetting for each sand ratio over time. These depths are largely consistent with the field study by Walsh et al. [2] and Dye et al. [30].



a) b)

Fig. 5. Maximum expected depth of wetting for each sand ratio over time, a) Latakia climate, b) Daraa climate

Figure 6 illustrates the heave values at the base and surrounding of the structure (heave basin) corresponding to the Latakia climate after 50 years for different sand ratios.

Figure 6 shows an increase in uplift with increasing sand content up to 20%, followed by a significant decrease. This result confirms that the sand content in expansive soils should not be less than 30%.

3.3.1. Proposed equation of maximum depth of wetting. Based on numerical analysis of wetting depth, two equations were developed to describe the relationship between maximum soil moisture depth and time in both coastal and southern climates. The study considered the influence of sand content by subjecting the independent variables, *Fs* and *t*, to a thorough parametric study. Time intervals of 0, 1, 5, 10, 20, 30, 40, and 50 years were chosen for *t*, while *Fs* varied at levels of 0, 10, 20, 30, 40, and 50%.

To establish the mathematical connections between the dependent and independent variables, the EUREQA Version 1.2 software [31] was employed. By analyzing the available dataset, the software aided in formulating the proposed equations these equations provide a concise representation of the relationship between maximum soil moisture depth, time, and sand content.

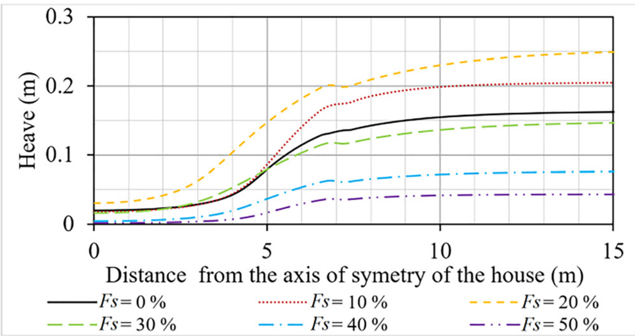


Fig. 6. Heave values beneath and around the building corresponding to Latakia climate after 50 years for different sand percentages

Coastal region:

$$W_d = \left(0.608 + 0.02264 \cdot F_s - 0.000473 \cdot F_s^2\right) \cdot \sqrt{t}, \quad R^2 = 0.991, \tag{1}$$

Southern region:

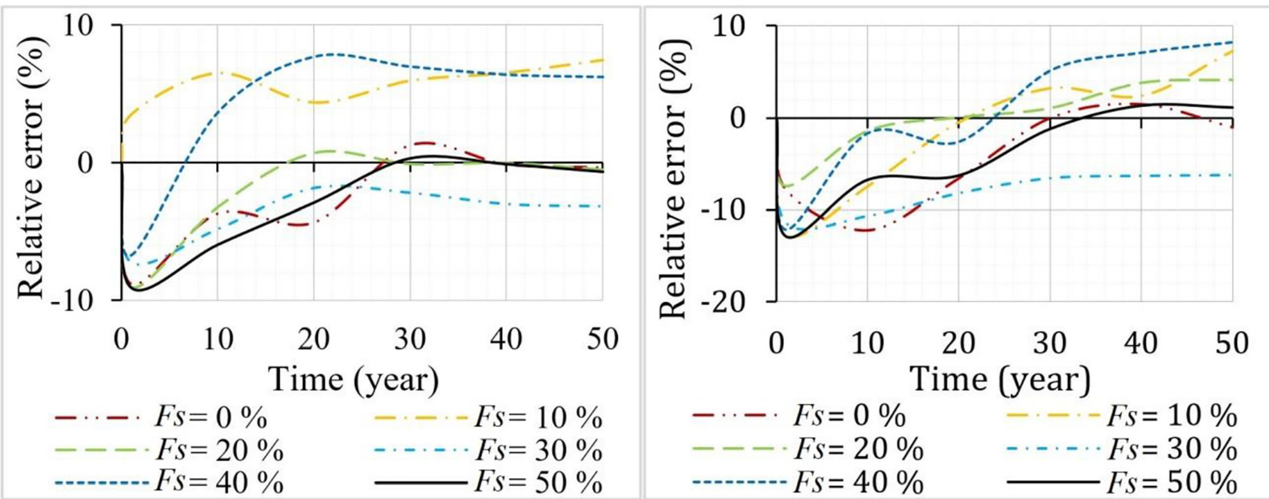
$$W_d = \left(0.401 + 0.00746 \cdot F_s - 3.052 \cdot 10^{-6} \cdot F_s^3\right) \cdot \sqrt{t}, \quad R^2 = 0.988, \tag{2}$$

where W_d is the maximum expected moisture depth (m); F_s is the percentage of sand (%); t is the time in years.

Equations (1) and (2) is used to find the largest expected depth of wetting for the coastal inland regions respectively, regardless of the initial suction rate, provided that the sand content does not exceed 50% and the clay fraction ranges between 35 and 75% under which the relative error rate does not exceed 10%, as it is shown in Fig. 7.

4. CONCLUSION

The study's findings highlight the significant importance of the maximum depth of wetting in geotechnical engineering applications. The developed relationships provide a valuable method for estimating the maximum moisture depth in coastal and inland regions of Syria, taking into account the effects of sand content and time. These relationships were derived from laboratory experiments and numerical analyses, using the SEEP/W software to simulate soil moisture movement.



a) b)

Fig. 7. Relative error percentage in predicting the maximum depth of wetting using the derived equation for the coastal and southern regions of Syria, a) Relative error percentage using Eq. (1), b) Relative error percentage using Eq. (2)

The results highlight the substantial impact of sand content on the maximum depth of soil moisture over time, emphasizing the need for sand content to exceed 30% to achieve desirable outcomes in terms of heave. To ensure accuracy, it is recommended to maintain sand content below 50% and clay content within the range of 35–75%, as these criteria yield a relative error of less than 10% for the proposed equations.

The proposed equations provide valuable insights for designing foundations on unsaturated expansive soils, allowing for proactive measures against potential damages caused by variations in soil moisture content. However, it is important to note that these equations are primarily recommended for elementary analyses of wetting depth. Further verification and validation through additional research and field studies are essential to fully assess their applicability in practical engineering scenarios.

Future studies should aim to explore other factors such as soil structure, vegetation, and slope, which can also influence the behavior of unsaturated expansive soils. Investigating these factors will contribute to a more comprehensive understanding of the complex interactions involved. The applicability of the proposed equations should also be examined in different regions with similar climate conditions, broadening their scope of usefulness in geotechnical engineering practice.

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