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INTEGRATION OF UNSATURATED SOIL ANALYSIS AND GIS BASED MAPPING OF COLLAPSIBLE SOIL HAZARDS IN ARID REGIONS (ALGERIA)

Purpose. This paper aims to synthesize experimental investigations conducted on unsaturated soils from the Djemaa–El Oued region (Souf Valley), located in an arid zone of southeastern Algeria. The research focuses on understanding the geotechnical behavior of these particular and evolving soils, especially the influence of suction on their mechanical response and collapse potential. In addition, the study integrates Geographic Information Systems (GIS) analysis to better characterize the topographic and hydrological features of the region.

Methodology. A comprehensive experimental program was carried out, including physical and geotechnical characterization tests to identify the soil properties. Special attention was given to the unsaturated state of the soil throughout all stages of the investigation. An experimental protocol was developed to evaluate the effect of suction on selected geotechnical parameters and soil behavior. Furthermore, advanced GIS-based spatial analyses were performed, including slope, aspect, hillshade, and contour mapping, to simulate and interpret the topographic characteristics of the study area.

Findings. The soils of the El Oued region are characterized by the absence of well-developed structure, heterogeneous texture, high porosity, and good surface aeration. Their mode of deposition has led to the formation of an open and metastable structure susceptible to collapse. The continuous rise of the groundwater table has significantly influenced the urban landscape of the Souf Valley. Experimental results demonstrate that suction plays a crucial role in controlling the mechanical behavior of these unsaturated soils. GIS-based analyses proved effective in identifying topographic and hydrological patterns influencing soil distribution and stability.

Originality. The originality of this work lies in combining unsaturated soil mechanics with advanced GIS spatial analysis to provide an integrated understanding of soil behavior in arid environments. The study offers new insights into the relationship between geomorphological setting, groundwater evolution, suction effects, and collapse susceptibility of soils in the Souf region.

Practical value. The findings provide a relevant geotechnical database for the Souf Valley and contribute to improved risk assessment and urban planning strategies. The integration of experimental soil mechanics and GIS tools supports more accurate decision-making in construction, land-use planning, and infrastructure development in arid regions.

Keywords: *collapsible soil, arid region, unsaturated soil, GIS, remote sensing, suction, lineaments*

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Introduction. Collapsible soil is a type of soil that is prone to losing its structural integrity and becoming denser when subjected to pressure, and is typically found in areas with high clay content that are susceptible to changes in moisture levels [1]. The resulting collapse can cause significant damage to structures and infrastructure, including roads, bridges, and buildings [2]. To classify and analyze information related to geographic data, experts use geographic information systems (GIS) that enable them to store data in databases. GIS technology enables professionals such as geographers and engineers to obtain data from any location on earth, even those that are challenging to access using traditional methods. Digital elevation models (DEM) provide a 3D representation of the earth's surface and are a simple way to represent the topography of a study area [3]. DEMs can be utilized to determine various topographical studies, including slope, aspect, contour map, and hill shade, lineaments map as well as for hydrological studies. Several methods can be employed to create digital elevation models, such as satellite images, aerial photos, laser scanning, and field surveys, each differing in terms of accuracy, time, and cost.

Algeria is classified as a semi-arid to arid zone due to the significant evapotranspiration compared to precipitation. This study presents a synthesis of experimental results on an unsaturated soil from the Djemaa El Oued region, classified as an arid zone. The behavior of soils in these regions is more or less specific and evolving. El Oued's soils are distinguished by their geomorphological position and origin, as well as their water regime. They share particular characteristics, such as the absence of structure, a variable heterogeneous texture from one point to another, high porosity, and good superficial aeration [4]. It should be noted that the rising of groundwater has continually shaped the urban landscape of the Souf Valley. The mode of accumulation of soil deposits seems to be mainly responsible for the formation of an open and metastable structure, which is likely to collapse [5].

To understand the effect of suction on the selected parameters and the behavior of the tested soil samples, and following the necessary physical and geotechnical characterization tests to identify the soil under study, an experimental protocol is proposed. The concept of unsaturated is considered in all stages of this study. The experimental results obtained provide a relevant database for the soils of the Souf region [6].

Material and methods. ***Materials. Study area.***

Oued Souf region is located between latitudes 05°30' and 07°00' Est, and longitudes 35°30' and 37°00' North. The Souf region is located in the eastern part of the Grand Erg Oriental, it is bordered by:

1) to the East by the Tunisian Republic;
2) to the Northeast by Tebessa;
3) to the North by Khenchela and Biskra;
4) to the Northwest by Biskra;
5) to the West by Djelfa;
6) to the Southwest and South by Ouargla.

The research site lies in the arid northern temperate region where the climate is characterized by desert conditions. During summer, temperatures can soar up to 50 degrees Celsius, while in winter, they plunge to below zero degrees Celsius. The topography comprises sandy hills, valleys, and water systems that are fed by rainwater. Fig. 1 illustrates the map indicating the location of the study area.

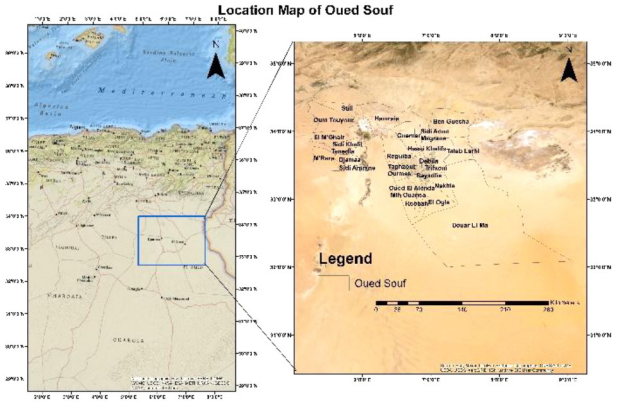


Fig. 1. Geographical location of the study area

Data used. To carry out the geomorphological and spatial analysis, various primary datasets were gathered from recognized international institutions. The topographic features and slope gradients of the study area were extracted from a Digital Elevation Model (DEM) with a 30-meter spatial resolution, sourced from the United States Geological Survey (USGS) [7]. Surface monitoring and structural lineament extractions were performed using Landsat 8 Operational Land Imager (OLI) satellite imagery, also retrieved from the USGS database. The regional lithological (Fig. 2) and geological background was evaluated using the Geologic Map of Africa obtained from the USGS world mapping applications. Finally, the baseline soil distribution and pedological attributes were integrated into the spatial models using the global soil map from the Food and Agriculture Organization (FAO) via the SWAT framework [8].

Methods. The study area's digital elevation model (DEM) was generated using ArcGIS software 10.8, and the data collected during the field survey. The spatial interpolation technique was employed to condense the points and obtain a DEM that closely approximates the actual surface. The Inverse distance weighted (IDW) method was used, which is dependent on the distance between known and unknown points. The accuracy of the DEM is less than ten meters, making it more precise than the resolution of free DEMs available from satellites. Fig. 3 depicts the resulting DEM for the study area. The research relied on the field survey technique to generate the DEM and perform the required analyses and represent the study area's topography. Previous studies have demonstrated that DEMs created using the field survey method are more accurate than those generated using free DEMs from satellites and provide a better visualization of the study area.

The identification tests show that the material used for this study is a low plasticity clay loam, sourced from the El Oued valley in the Djamaa region. The geomorphology of the Souf region is characterized by its low, sometimes very dry and irregular rainfall climate, and by three relief forms: sandy regions, rocky plateaus, and chotts zones to the north. Samples of soil with a brownish color are collected at a depth of

Table 1

Geotechnical characterization results

Designation	Value	Observation
% elements <80 µm	14.62	
% elements <2 µm	4.93	
D 50	0.67	Gravelly soil
Cu	22.1	Spread granulometry
Cc	10.55	Well graded
WL, %	18.47	
Wp, %	5.28	
Ip, %	13.19	Moderately clayey
WL, Ip	18.47 13.19	Low plasticity clay
Ic	0.79	Very firm clay
Ac	2.67	Highly active clay
Sp	34.74	Between Kaolinite and Illite not very sensitive)
VBS	2.47	Loamy soil of medium plasticity
γs, g/cm^3	2.60	
W (caco^3), %	37.5	Marl
Wopt, % normal	13.88	NF P 94-093
Wopt, % modified	12.82	NF P 94-093
CBR immediate	40.61	Very high bearing capacity
CBR after immersion	6.55	Medium bearing capacity

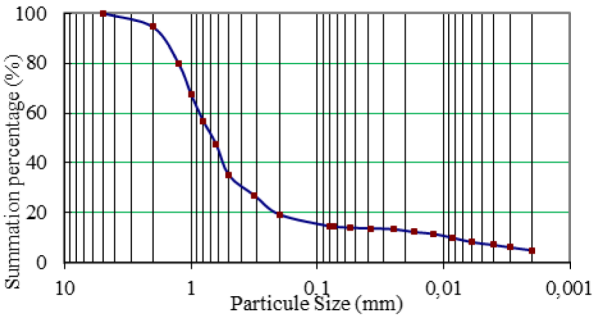


Fig. 2. The grain size distribution curve

approximately one to two meters. It is important to note various geotechnical degradations recorded in this study area. Following these degradations and incidents, several monitoring, maintenance, and restoration projects have been planned and are currently in progress [8–10].

Results and discussion identification tests. The identification of physical characteristics and bearing capacity tests of the tested soil led to the results presented in Table 1. As for chemical results, they were determined by X-ray fluorescence spectrometry, as shown in Table 2. The test for carbonate content was performed because calcite is a swelling mineral that can often be significant in clay, causing the sediment to swell.

The geotechnical characterization results indicate that the studied soil is predominantly sandy with a limited clay fraction and a wide particle-size distribution. According to the Atterberg limits, the material is classified as a low-plasticity clay, while the methylene blue value confirms a loamy soil with moderate plasticity. The relatively high carbonate content (37.5 %) reflects the marly nature of the soil and may contribute to its metastable structure under unsaturated conditions.

Compaction tests reveal relatively low optimum water contents, consistent with the granular nature of the material. The immediate CBR value (40.61 %) indicates excellent bearing capacity in its natural unsaturated state. However, the significant decrease in CBR after immersion (6.55 %) highlights the strong sensitivity of the soil to wetting and the loss of mechanical strength upon saturation. According to the GTR classification [11–14], the soil belongs to class A2 and can be described as a fine sandy soil with moderate clay content and low plasticity. The combination of high porosity, carbonate content, and the marked reduction in bearing capacity after soaking suggests a significant susceptibility to collapse when subjected to water infiltration.

Tests of suction. The interpretation of the experimental data was based on the Van Genuchten model, which is one of the most widely used analytical models for describing the hydraulic behavior of unsaturated soils and the soil-water retention curve. The model establishes a continuous relationship between volumetric water content and matric suction, allowing an accurate characterization of the hydraulic properties of the investigated soil.

Soil-Water retention curve modeling. Modeling the soil-water retention curve (SWRC) provides a continuous representation of the hydraulic behavior of the material over the entire moisture range, from residual water content to full saturation. This approach also enables the estimation of suction values corresponding to intermediate water contents that were not directly measured during the experimental program [15].

The Van Genuchten (1980) model was selected due to its proven reliability and widespread application in the characterization of unsaturated soils. The model parameters were calibrated using the SWRC Fit software, which is specifically designed for fitting soil-water retention curves to experimental data.

The effective degree of saturation is expressed by the Van Genuchten equation

$$\theta e(h) = \frac{1}{[1+(ah)^n]^m},$$

where θe is the effective degree of saturation; h is the matric suction; a, n, m are empirical fitting parameters controlling the air-entry value and pore-size distribution of the soil [16–18].

Table 2

Chemical composition by X-ray fluorescence spectrometry

Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	MnO	Fe_2O_3	SrO
0.0407 %	0.531 %	2.08 %	13.5 %	0.0961 %	0.114 %	0.203 %	82.0 %	0.0599 %	1.04%	0.374 %

Table 3

Experimental suction–water content data for soil

Soil	
S (kPa)	w
1.21	0.35
5.53	0.32
9.84	0.25
13.9	0.2
24.6	0.12
31.4	0.1
54.7	0.05
161.2	0.02

Table 4

Parameters of the Van Genuchten (1980) soil-water retention model for soil

The air-entry value (1/α)	10.4580632
The saturated water content θs	0.32
Residual water content θr	0.007
n	2.12
m	0.54751131
α	0.09562
R^2	0.9992

The experimental suction-water content data obtained for Soil 1 were used to calibrate the model. The resulting parameters are summarized in Table 3.

These parameters have a clear physical significance. The parameter α is inversely related to the air-entry suction, whereas *n* controls the pore-size distribution and the steepness of the retention curve. The parameter *m* defines the asymmetry of the desaturation process and is commonly related to n through the expression $m = 1-1/n$ [19].

The obtained results demonstrate that the Van Genuchten model adequately reproduces the hydraulic behavior of the investigated soil and provides a reliable framework for analyzing suction-related phenomena, particularly those associated with collapse susceptibility and hydro-mechanical behavior under varying moisture conditions [20].

Using the DEM that was created, the topographic and hydrologic analyses for the study area were carried out using ArcGIS in the following manner.

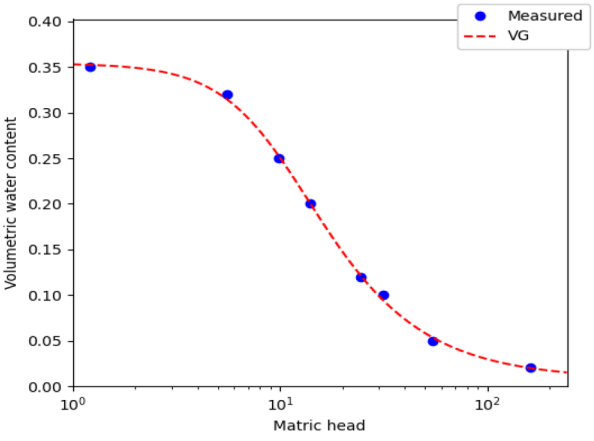


Fig. 3. Measured and predicted soil-water retention curve using the Van Genuchten model for soil

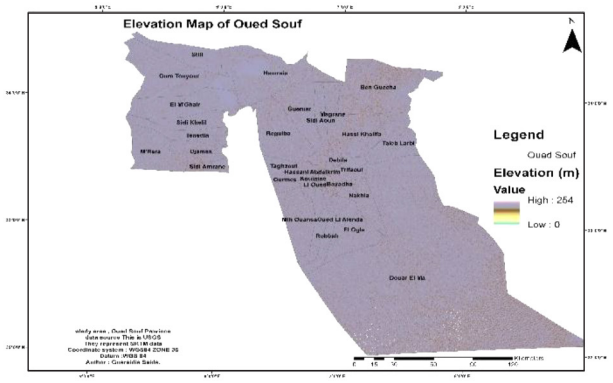


Fig. 4. Elevation map of Oued Souf

Digital elevation model. A digital elevation model (DEM) is a file that displays the earth's surface elevation in 3D. The data is collected from specific points on the earth's surface, with the distance between each point calculated using latitude-longitude or the Universal Transverse Mercator (UTM) coordinate system [21]. The production model depicts the height differences of an area, and closer point intervals provide more detailed information. DEM files can be created in ASCII or binary format, and the file format must be known to read it. A reference location is typically provided in the file name, but it only includes the height value and not the geographical location. DEM files may contain information about roads and buildings. These results are shown in Fig. 4.

Geology. The geological structures have shown that the studied region presents a very heterogeneous geology (Fig. 5).

Topographic map lines. Topographic Contour lines are commonly used to describe the surface of a landscape, which not only represents its geometry but also implicitly preserves the topology of the earth's surface. Elevation values are frequently provided as text descriptions on topographic maps to illustrate the height of the contour lines. In addition to contour lines, spot altitudes are available, which are represented by a dot or a cross and used to indicate notable natural features on a prominent region, such as hilltops, knolls, isolated summits,

Table 5

Representation of the stratigraphic scale

Age			Dominant lithology
Quaternary	Higher		Sand
	Lower		Clays
Tertiary	Neogene (Mio-Pliocene)		Sands Gypsum clays Coarse sands; Gravels
	Paleogene		Lagoon clays; marls. cracked limestone
Secondary (Mesozoic)	Cretaceous	Higher	cracked limestone Evaporites, clays
		Middle	Dolomite, passage of slightly Dolomitic limestone Clays, marl
		Lower	Dolomite, limestone, marl Sandstone, dolomite, limestone, sand, flint

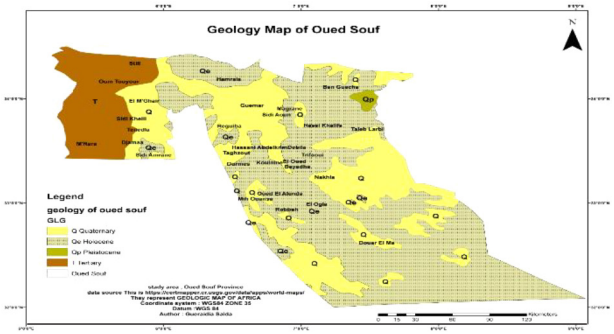


Fig. 5. Geology map of Oued Souf

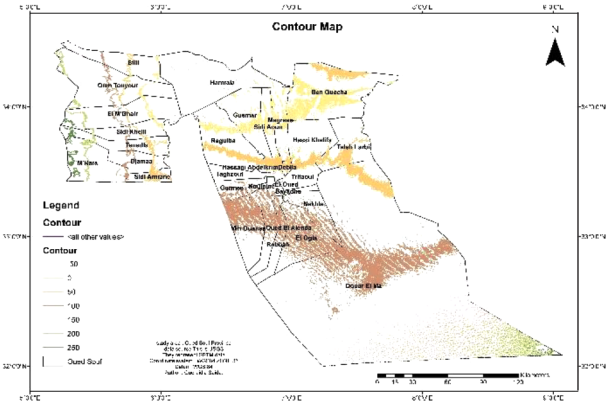


Fig. 6. contour map Oued Souf

mountaintops, mountain passes, saddles, and other high points. The watershed contour map is displayed in Fig. 6, with contour lines ranging from –50 to 250 meters due to the mountainous terrain of the small watershed. The water divisions of the watershed are mostly mountainous.

Aspects. The aspect map depicts the general direction of the slope of a mountain, while an elevation map is a significant tool in comprehending the impact of sunlight on the microclimate of a particular location. The aspect map plays a vital role in determining the distribution of vegetation types in a given area. The display map generated from the DEM represents the compass direction of the slope. In the case of the Oued Souf watershed, the east-facing slopes have more moisture content and vegetation compared to the west-facing slopes (Fig. 7).

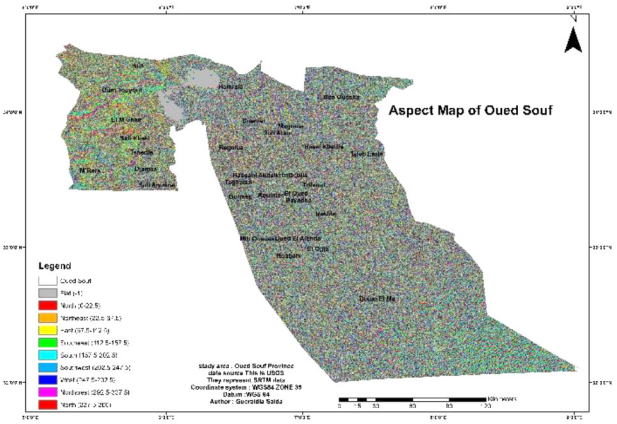


Fig. 7. Aspect map of Oued Souf

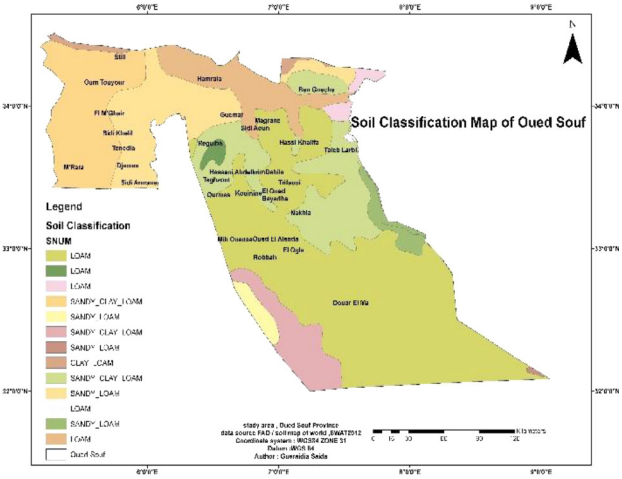


Fig. 8. Soil map of Oued Souf

The results obtained represent a very important database. They are essential for any geotechnical investigation or rheological behavior modeling work.

The soil in question has been identified as a SANDY_CLAY_LOAM prone to collapse (Fig. 8).

Slope map. The projection of the digital elevation model for the study area was converted from its original units in degrees to units of length to create a slope map for the study area. The slope of the map was measured in degrees using ArcGIS software 10.8, as displayed in Fig. 9. The map indicates that the low slope is 0 degrees, and the high slope is 3.16 degrees, with the study area's average slope being approximately 3.61 degrees.

Drainage map. A map illustrating all river and stream systems within a drainage basin is referred to as a drainage map. When conducting a drainage analysis, one examines the drainage patterns, texture, and stream patterns in detail. with a few locations featuring the trellis type. Moreover, new drainages have emerged in nearly all watersheds, and a stream has altered its course in the southern portion of the study area. Stream orders are based on their origin, with the main stream having the highest order from river-mouth to stream-head and the largest tributary possessing a lower stream order by one. As a general rule, stream numbers and mean gradient decrease while the mean length of streams and the mean area of drainage basins increase in an inverse geometric ratio as stream order

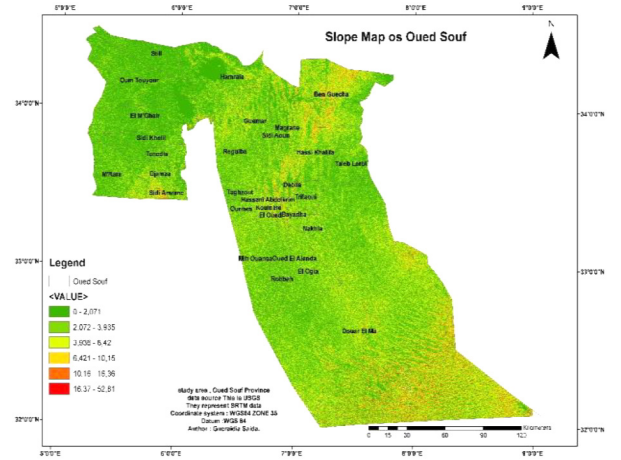


Fig. 9. Slope map of Oued Souf

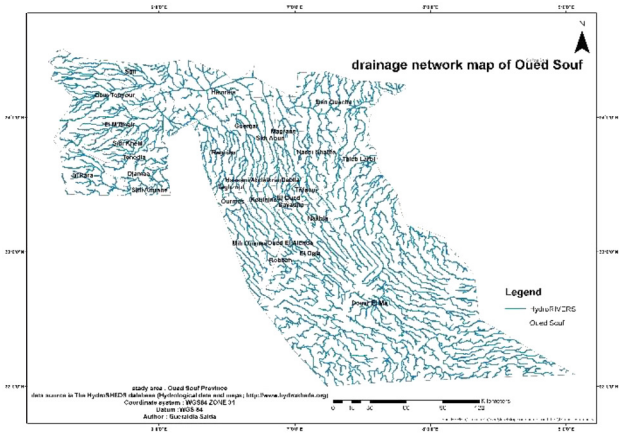


Fig. 10. Drainage network map of Oued Souf

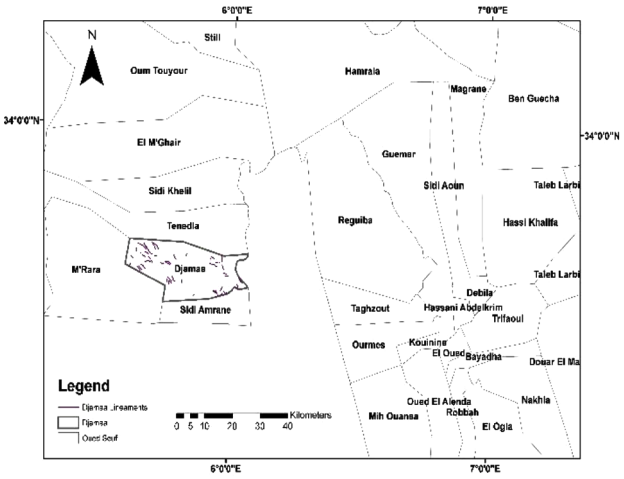
increases. The study area streams are characterized by having the shortest lengths, and the steepest streams have the smallest drainage basins. In most of the area, a first-order stream network was observed (Fig. 10).

Lineaments map. A lineament refers to a sizable and elongated characteristic that can be observed in satellite images based on the topographical features and straight tonal alignments of the underlying structure. By visually interpreting Landsat image data, lineaments can be identified, and they are often viewed as promising areas for soil collapse. Typically, lineaments are found in regions with soil collapse hazards, with those oriented towards the NNE-SSW, NE-SW, NW-SE, and NS directions being the most prevalent in the study area (Fig. 11).

Conclusion. This study investigated the hydro-mechanical behavior of an unsaturated collapsible soil from the Djemaa region (Oued Souf, southeastern Algeria) through a combination of laboratory testing, soil-water retention modeling, and GIS-based spatial analysis. The geotechnical characterization identified the material as an A2 sandy clay loam with low plasticity, a significant carbonate content (37.5 %), and a metastable structure typical of collapsible soils. Although the soil exhibited a high immediate bearing capacity (CBR = 40.61 %), the soaked CBR decreased markedly to 6.55 %, demonstrating its pronounced sensitivity to water and confirming the detrimental effect of saturation on its mechanical performance.

The soil-water retention behavior was successfully described using the Van Genuchten model. The excellent agreement between the experimental data and the fitted curve ($R^2 = 0.9992$) confirms the suitability of this model for representing the hydraulic behavior of the investigated soil. The estimated air-entry value (10.46 kPa), together with the saturated and residual water contents, provides valuable insight into the desaturation process and the influence of pore structure on water retention. These findings demonstrate the fundamental role of matric suction in maintaining the apparent cohesion and stability of the soil under unsaturated conditions.

The GIS analysis complemented the experimental investigation by identifying geomorphological factors influencing collapse susceptibility. The predominance of low slopes, the presence of dense drainage networks, and the distribution of structural lineaments promote



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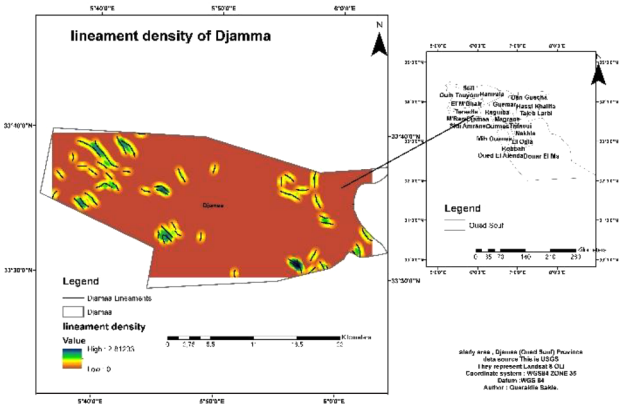

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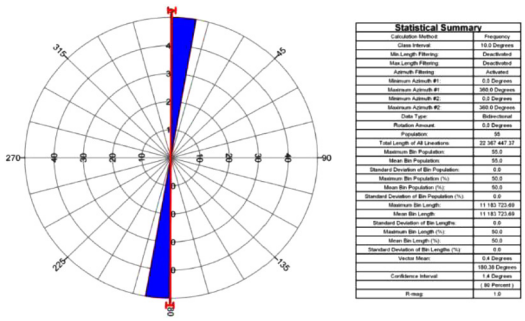

c

Fig. 11. Structural lineament analysis of the Djamaa (Oued Souf) area showing:

a – extracted lineament map, lineaments map of Djamaa (Oued Souf); b – lineament density map, lineaments density map of Djamaa (Oued Souf); c – rose diagram illustrating the dominant lineament orientations, rose diagram lineaments of Djamaa

water infiltration and groundwater circulation, leading to a reduction in soil suction and an increased risk of collapse. The integration of laboratory data with spatial analysis therefore provides a comprehensive framework for understanding the occurrence of collapse phenomena in the study area.

Overall, the proposed methodology demonstrates that coupling unsaturated soil mechanics, soil-water retention modeling, and GIS techniques constitutes an effective approach for evaluating collapse-prone soils in

arid and semi-arid environments. The generated geotechnical database provides valuable information for foundation design, land-use planning, and hazard assessment in the Oued Souf region. Future work should focus on in-situ validation, long-term monitoring of groundwater fluctuations, and the development of predictive susceptibility models integrating hydro-mechanical and environmental parameters.

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Інтеграція аналізу ненасичених ґрунтів і ГІС-картографування небезпек просадних ґрунтів у посушливих регіонах (Алжир)

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Мета. Ця робота спрямована на узагальнення експериментальних досліджень, проведених на ненасичених ґрунтах регіону Джемаа–Ель-Уед (долина Суф), розташованого в посушливій зоні південно-східного Алжиру. Робота зосереджена на розумінні геотехнічної поведінки цих специфічних і динамічних ґрунтів, зокрема впливу сукції на їхню механічну реакцію й потенціал просідання. Крім того, дослідження інтегрує аналіз із використанням геоінформаційних систем (ГІС) для детальнішої характеристики топографічних і гідрологічних особливостей регіону.

Методика. Була реалізована комплексна експериментальна програма, що включала фізичні й геотехнічні випробування для визначення властивостей ґрунту. Особливу увагу приділено ненасиченому стану ґрунту на всіх етапах дослідження. Розроблено експериментальний протокол для оцінки впливу сукції на вибрані геотехнічні параметри й поведінку ґрунту. Додатково виконано просторовий аналіз на основі ГІС, зокрема побудову карт ухилів, експозиції, тіньового рельєфу (hillshade) та ізоліній, для моделювання й інтерпретації топографічних характеристик території дослідження.

Результати. Ґрунти регіону Ель-Уед характеризуються відсутністю чітко сформованої структури, неоднорідною текстурою, високою пористістю й гарною поверхневою аерацією. Умови їхнього формування спричинили утворення відкритої й метастабільної структури, схильної до просідання. Постійне підвищення рівня ґрунтових вод суттєво вплинуло на міський ландшафт

долини Суф. Експериментальні результати показують, що сукція відіграє ключову роль у контролі механічної поведінки цих ненасичених ґрунтів. Аналіз на основі ГІС виявився ефективним для визначення топографічних і гідрологічних закономірностей, що впливають на розподіл і стійкість ґрунтів.

Наукова новизна. Полягає у поєднанні механіки ненасичених ґрунтів із розширеним просторовим аналізом ГІС для забезпечення інтегрованого розуміння поведінки ґрунтів у посушливих умовах. Дослідження пропонує нові підходи до встановлення взаємозв'язку між геоморфологічними умовами, еволюцією рівня ґрунтових вод, впливом сукції та схильністю ґрунтів регіону Суф до просідання.

Практична значимість. Отримані результати формують релевантну геотехнічну базу даних для долини Суф і сприяють удосконаленню оцінки ризиків і стратегій містобудівного планування. Інтеграція експериментальної механіки ґрунтів і ГІС-інструментів підтримує більш обґрунтоване прийняття рішень у сфері будівництва, землекористування й розвитку інфраструктури в посушливих регіонах.

Ключові слова: *просадні ґрунти, посушливий регіон, ненасичені ґрунти, ГІС, дистанційне зондування, сукція, лінеаменти*