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The Collapsible Soil Definition and Mitigation Strategies: A Review Study

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ABSTRACT

One category of challenging soils is collapsible soils, which show a significant quantity of strength when dried but undergo a sufficient solidity reduction while soaking, leading to illegal settlement. One of the most collapsing soils is gypseous soil, which is affected by geotechnical components such as loading, hydration, soil density, and immersion conditions. In Iraq and many other regions, collapsible soils like gypsum frequently dry and get hard. This soil collapses noticeably when it becomes moist. The work attempts to provide an overview of the meaning of collapsed soil, categorization, footing construction, perfection, and collapse attenuation. Collapse occurs quicker by increasing the void ratio or gypsum content, although it is negligible at a pressure less than the pre-consolidation stress of saturated soil. Several types of soil enhancement procedures exist, including densification, reinforcement, removal and replacement, and physicochemical changes. Every category has a unique application whereby it outperforms the others. The most popular approach is often densification as it is generally less expensive than alternative methods, particularly when a sizable portion of a structure needs to be upgraded. Ultimately, by achieving all requirements, the goal is to reach an ideal design criterion resulting from the presence of gypsum. Also, can enhance the stabilizing qualities of gypseous soil by adding materials such as kaolin, lime, and calcium chloride, which are best suited for treating them in the subgrade layer. This knowledge is essential for the geotechnical characterization of soils to construct cost-effective, safe infrastructure that also considers long-term serviceability.

Keywords: Gypsum content, Problematic soil, Collapse potential, Dry density, Soil improvement.

1. INTRODUCTION

This review frames techniques for recognizing collapsible soils and proposes different foundation planning systems to counterbalance their negative effects. Such soils are

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regularly labeled as "collapsible" due to their sensibility for soaking, with an increased value of water content and a decrease in volume. Recognizing these non-collapsible soils involves using various research centers and field tests, as they usually exhibit low dry densities. **(Delage et al., 2008; Kalantari, 2013; Abd-Alhameed and Albusoda, 2022).** Due to their limited carrying capacity when submerged, these soils are inadequate for several kinds of substructures in their unique condition. Steps like installing stable footings can make differential settlements or transmitted structural loads more adaptable and deeper across deep foundations **(Aiban, 1994; Hassan and Al-Busoda, 2022).**

Furthermore, preloading strategies may be utilized to stiffen problematic sand soil increment capacity to sustain effective loads, or this soil may be stabilized with stabilizers such as Portland cement **(Albusoda et al., 2013; Albusoda and Hussein, 2013; Hammad et al., 2023)**.

2. THE DESCRIPTION OF COLLAPSIBLE SOIL

Some unsaturated soils may withstand minimal settlement at low site water content even at large applied loads. If wetness occurs without increasing the applied stress, these soils show a drop in volume and accompanying settlement **(Hassan and Albusoda, 2022).** Through reviewing and studying the reported studies on collapsible soils, different definitions have been found for defining such types of soils. Some of the important definitions are shown in **Table 1** below.

Table 1. Different meanings of soil that sever collapse

Author name	Descriptions
(Holtz and Hilf, 1961)	Loess soil is more likely to collapse if it has a large enough proportion of voids t permit its humidity to pass the liquid level when it is submerged.
(Tsytovich and Chetyrkin, 1973)	A soil that experiences a significant change in volume when changing in the applied load or in the moisture content will occur, or both of them
(Barden et al., 1973)	An expansion in pore-water pressure will cause any metastable structured soil to lose volume, but an unsaturated stable structured soil may swell as a result of increased pore-water pressure.
(Dudley, 1970)	Any unsaturated soil that, when wet, undergoes a drastic particle rearranging and has a significant volume reduction with or with no extra loading.
(Handy, 1973)	The visible cohesion strength of soil that is unsaturated is associated with a condition of under-consolidation.
(Jennings and Knight, 1975)	More settling as a result of soaking partially saturated soil, often without applying more pressure
(Booth, 1977)	Settling in soil that is only partially moist as a result of increased solidification
(Houston and Houston, 1989)	Investigated collapsed soil, taking note of the presence of rounded, and the structure of the honeycomb involved minimal density in the dry form.
(Lawton et al., 1992)	Gypseous soils are addressed as one variation of collapsible soils. Density and cohesion are characterized as moderately low degrees when wet; while dry, it exhibits remarkable rigidity and strength.
(Houston et al., 2001a)	Classified soils that collapse as moisture-sensitive. According to their reviewed study, there were more deformations or settlements as the moisture content rose.
(Lommler and Bandini, 2015)	Excavations of the soil showed a reduction in the lab-anticipated collapsing amount in situ soils while increasing the probability of compressed layers.

3. IDENTIFICATION OF THE COLLAPSING SOIL

The determination of the collapse potential can be made through the use of the doubling Oedometer method (DOT) and the singular Oedometer method (SOT) is used to determine collapse potential (CP). Jennings and Knight developed a (DOT) technique, which prepared twin similar specimens and analyzed them independently using an Oedometer. The primary sample was evaluated under its original amount of water, while the second sample was tested under immersion. The two specimens received an equal load. The growing magnitude of stress in the stress-strain diagram can be used to calculate the quantity of collapses. In accordance with **(ASTM D5333, 2003)**, (SOT) was performed and evaluated for all of the specimens in that beneath unsaturated condition. This approach was updated by **(Houston and Houston, 1989)**. A round 200 kPa force was utilized. At B, the sample was flooded to saturation and left for a day. Point B-1 is the collapse quantity which indicates the variations in stresses prior to and following the flooding illustrated in **Fig. 1**.

The equation below is used to calculate the collapse potential (CP):

$$CP = \frac{e_B - e_I}{1+e_o} = \frac{\Delta e}{1+e_o} \quad (1)$$

Where:
e_B : Proportion of voids prior to saturation at a certain stress threshold.
e_I : Void ratio with a certain amount of moisture stress.
e_o : The original proportion of voids.
CP: The possibility of collapse potential.
The degree of difficulty as determined by CP obtained using Oedometer collapse experiments **(Jennings and Knight, 1975; ASTM D5333, 2003)** is displayed in **Table 2**.

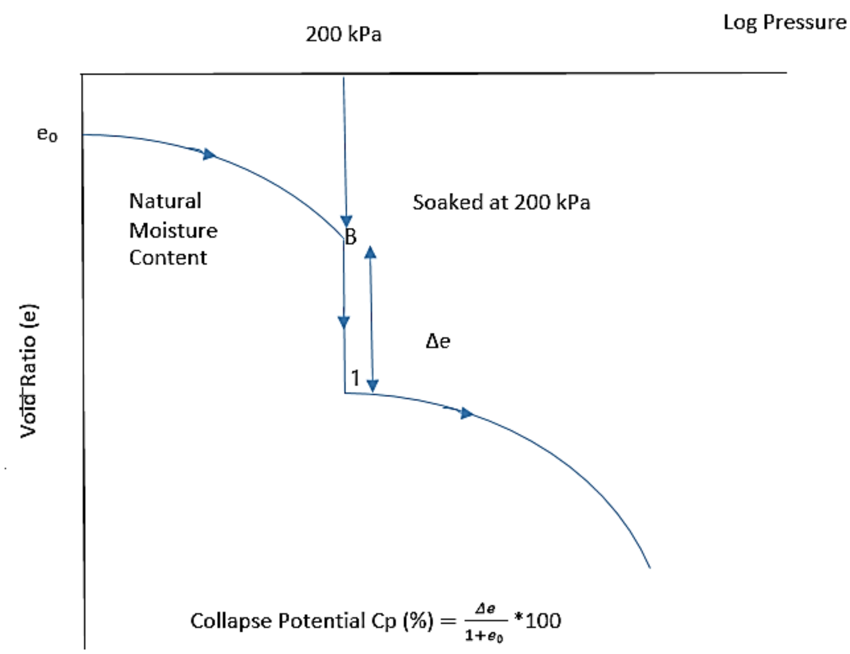

Figure 1. The procedure for Oedometer collapsing **(Das and Sivakugan, 2018)**.

Table 2. The intensity of the issue according to CP.

Jennings and Knight		Standard ASTM	
CP (%) σv=200 kPa	Degree of trouble Severity	CP (%) σv=200 kPa	Degree of collapse
From 0 to1	Without problem	0	None
From 1 to 5	Moderate difficulty	From 0.1 to 2.0	lightly
From 5 to 10	Some trouble	From 2.1 to 6	mild lightly
From 10 to 20	Severe problem	From 6.1to 10	Moderate severe
>20	Very severe problem	>10	Severe

4. COLLAPSE-RELATING ASPECTS

Most of the variables influencing CP include the nature of the soil, the degree of stress, the starting amount of water, and the degree of compaction **(Houston and Houston, 1989; Ayadat and Hanna, 2007; Al-Taie and Al-Shakarchi, 2017; Altameemi and Al-Taie, 2022)**.

At a particular immersion pressure, CP may arrive at a maximum amount. Numerous studies indicate that the movement of soil results from collapse will grow when the load from floods rises. The collapse potential (CP) is determined by several objects; the original hydration level and the dried unit weight are two of the most crucial variables **(Lawton et al., 1992; Al-Busoda, 2009)**.

The percentage of collapse decreases before soaking as an increase in dry mass and moisture level of the soil **(Tadepalli and Fredlund, 1991)**. Any disturbance to the in situ specimen may result in a decrease in CP **(Lommler and Bandini, 2015)**.

(Al-Obaidi, 2014) examined three collapsible specimens of soil as illustrated below:

1. An Iraq specimen of gypseous soil (GI).
2. A German loess specimen (LG).
3. A combination of 30% Silber sand and 70% made-up gypsum for the soil sample.

- It was discovered that: The starting proportion of voids, saturated intensity, and suction applications influence the deformation processes of collapse.
- At a low suction, the final soil collapse is reached.

There are three phases to the collapse potential: major collapse, preliminary collapse, and final collapse **(Burland et al., 2012)**.

5. COLLAPSIBLE SOIL: METHODS FOR FOUNDATION DESIGNING AND IMPROVING

Throughout construction and beyond, as well as throughout the project, the engineer is free to investigate various foundation types to be sure that the loads supporting the structures are safe and do not experience excessive settlement or shear failure. The rapid volume reduction and fast settling of the subsurface that supports the foundation without any signal make designing a foundation in collapsible soil a challenging undertaking. A major role in selecting a certain foundation design depends on the depth of the collapsing layers, the size of the collapse, and the design process. When the collapsible layer locates at a shallow depth around 1.5 to 2 meters, continuous strip footings can offer a cost-effective stable foundation than isolated type. A mat foundation is the most suitable type when the footing area is more than 50% of the building´s total area. Before the construction of the foundation, the soil layer can be wet and re-compacted by heavy rollers. Applying additional loads and overburden stress may eliminate settlement.

Deep footings can be used to support the weight of the structure to more reliable supporting layers below the collapsing layer, such as piles and piers **(Al-Rawas, 2000; Albusoda et al., 2013; Zbar and Hussein, 2013; Abd-Alhameed and Albusoda, 2022; Mohsen and Albusoda, 2022; Mohsen and Albusoda, 2023).** A few techniques to lessen the possibility of collapsing are presented in **Table 3**. While the positive aspects and drawbacks of various treatment regimens are mentioned in **(Rollins and Rogers, 1994)** and are shown in **Table 4**.

Table 3. Numerous techniques to reduce collapsing risk.

Authors	Techniques
(Clemence and Finbarr, 1981)	A collapsible soil at Continuous strip footings, as opposed to isolated footings, may provide a more affordable and secure foundation at a shallow depth of 1.5–2 m. This approach takes into account a more equal distribution of stresses while eliminating unequal settings among parts.
(Bally and Culitza, 1987)	In Russe, an adequate layer of loess soil can be balanced out by compacting dynamically prior to building a foundation.
(Bowles, 1997)	Three comprehensive and useful methods to minimize CP of soil consist of: -Compaction of the soil with removal and substitution in order to reach an approximate dry density of 15.5 kN/m^3. - Adding different mixtures similar to Portland cement in the process of the compactor. - Using deep foundations to penetrate the unstable grounds and access a stabling layer underneath.
(Houston and Houston, 1989)	Extract water with injection carbon dioxide. Grouting made of silicate sodium. Insert carbon dioxide to eliminate the alkaline solutions.
(Day, 1995)	Some parts of the United States make extensive use of deep dynamic compaction.
(Pengelly et al., 1997)	In some parts of the US and other nations, grouting is a widespread technique for improving soil.
(Herrmann and Bucksch, 2014)	Conventional impacting or vibrating wheels are commonly used for compacted and hydrating procedures up to around 1.5 m in deep. If a certain level is exceeded, stone columns or vibro-flotation may be used, additionally being investigated is chemical stabilization using sodium silicate and carbon dioxide infusion.
(Parto and Kalantari, 2011; Altameemi and Al-Taie, 2022; Altameemi et al., 2023)	Windblown sand was one of the collapsed soils that scientists had improved significantly in strength by stabilizing using different additives including CKD, cement, polypropylene fibers, etc. Based on their studies, an important decrease in the quantity of cemented material needed was achieved by adding polypropylene fibers to the mix.

Table 4. The benefits and disadvantages of certain modification techniques **(Rollins and Rogers, 1994)**.

Benefits	**Disadvantages**
(a)pre-wet with water	
-Minimal price -Easily applied	Overcrowding without prior preloading during excavation Inability to solidify the topmost layers Differential settlement most probable
(b) Using sodium silicate to pre-wet	
-Significant decrease in collapsing settlements. -Permanent Creation of cementation. -Hydraulic conductivity is decreased. -Important for creep settling. -Possibility of using as a corrective action	-Increased price -A little background in experience -Treatment distance is restricted to under two meters
(c) Excavation in part, replaced with fill	
-Reasonably inexpensive. -Application simplicity. -Extensive knowledge of the technique among contractors. -Reduction of the tension that is created in collapsible soil. -Minimal settling for little water volumes. reduction of the disparity in settlement	-Just the surface zones are treated. -Over-settlement when deep zones are flooded.
(d) At natural moisture, dynamic compaction	
-Significant decrease in collapsing settlement Hydraulic conductivity decline Enhancement up to noteworthy depths (>5 m)	-The cost is high - Vibration-related harm might occur. - Inconsistent treatment. -Reduced contractor experience using the technique
(e) Following pre-wetting, dynamic compaction	
-Notable decline in collapse settlement. - More compacting effectiveness before liquefaction. - Decrease in the vibrational intensity. - Increased densification homogeneity. - Hydraulic conductivity decline Enhancement up to noteworthy depths (>5 m)	-More expensive. -Rise in long-term, creep settlement Liquefaction risk in situations with significant moisture content. -Having trouble removing weight after a drop might take too long for the area to dry after treatment. -Reduced contractor experience using the technique difficulty in quantifying progress

6. THE CONCEPT OF SOIL COLLAPSING

Geotechnical scientists must consider a number of important challenges, including the significant decrease in quantity observed in natural, unsaturated soil deposits or compressed fill upon soaking according to total stresses known as "collapse" **(Houston et al., 2001b; Albusoda et al., 2013)**.Collapsing soils commonly include loess and gypseous soil, as identified by **(Lawton et al.,1992)**.In an arid condition, loess has fairly low densities and cohesiveness, but it has sufficient strength and rigidity **(Al-Taie and Al-Shakarchi, 2017; Altameemi and Al-Taie, 2022)**. Research by **(Tadepalli and Fredlund, 1991)** and

(Ng and Menzies, 2007) has shown various oxides, salts, soil suction, and dried clay contribute to the natural production of collapsible soils, with levels varying from high to low. These soils are often found in loose, poorly organized states that have little unit weight and moisture level.

Furthermore, collapsible soil can be intentionally created from waste materials by compaction performed without technical specifications and with a lower moisture content **(Madhyannapu et al., 2006; Burland et al., 2012)**. In dry form, the collapsible layer can support high weights and little settlement; however, it may undergo a significant drop in volume during soaking **(Al-Naje et al., 2020)**. **(Dudley, 1970; Clemence and Finbarr, 1981; Das, 2013)**, in addition to **(Burland et al., 2012)**, illustrate some of the important problems that collapsed sites face as a result of volume changes and the degree of moisture that they will experience. **(Dudley, 1970; Clemence and Finbarr, 1981**; **Das, 2013)**, in addition to **(Burland et al., 2012)**, highlighting considerable issues as a result of changes in quantity and wetness.

7. COLLAPSED SOIL TYPES

Collapsed soil, as previously mentioned, is defined as soil undergoes a rapid and notable reduction in volume, when subjected to additional water content. The main types of collapsed soil are as follows:

7.1 Gypsum Soil

The gypsum layer of the collapsible soil is found in extremely salinized regions that are semi-arid and desert. The main issues with gypsum soil are gypsum dissolving and leaching of the fine soil (if at inundation). Gypsum soil becomes less strong when wet and becomes more compact **(Karim, 2010; Al-Taie et al., 2019)**.

Gypsum hydrated calcium sulfate, or $CaCO_4.2H_2O$, is present in significant amounts in gypseous soils, also known as gypsiferous soils. These soils are classified as collapsible soils because, when soaked either with or with no extra stresses, all unsaturated soil undergoes a dramatic reorganization of particles in addition to a notable alteration in volume **(Al-Yasir and Al-Taie, 2022)**.

Geotechnical problems with most soils rely on a number of variables, including the type, composition, soil physics and mechanical characteristics, and mineral content **(Al-Naje, et al., 2020)**. Furthermore, deformation may happen under loads that alternate between both wet and dry states **(Al-busoda and Salman, 2023)**.

Most construction efforts applying to gypsum experienced fractures, inclinations, and collapse. CP of gypseous can be decreased by using a variety of treatment techniques.

7.1.1 Definition of gypsum

(Alphen, 1971) stated that a certain type of gypsum has a weight greater than 2%. While; **(Al-Barazanji, 1973)** classified gypsum soils into groups based on gypsum values, as illustrated in **Table 5**.

Table 5. Categorization of gypseous sites subsequent to **(Al-Barazanji, 1973)**.

Gypseous composition (%)	Grouping
From 0.0 to 0.3	No gypsum
From 0.3 to 3.0	Very light gypsum
From 3.0 to10	lightly gypsum
From 10 to 25	Moderate gypsum
From 25 to 50	High gypsum

7.1.2 Gypsum Difficulties

Several problems appear when dissolving gypsum in moist soil. These issues can cause failure, fracture, and collapse **(Nashat, 1990).**
Numerous construction projects in Iraq experienced collapse and failure as illustrated:

- Hotel in Samarra.
- Reservoir of water in Karbala.
- Tikrit instructional facility.
- Habbaniya resort town.
- Communication center in Dujail.
- Baiji Refinery.
- Water reservoirs in the northern part of Iraq **(Karim, 2010)**.

Replacing soil at low elevations or maintaining a steady state of moisture may reduce the problems. **(Al-Naje et al., 2020; Al-Taie and Al-Shakarchi, 2017)**.

7.1.3 Gypsum Soil Enhancement

Table 6. illustrates several chemical and physical treatment procedures that have been implemented in Iraq to modify the behavior of gypseous soil.

Table 6. Past research to enhance gypsum soil by **(Hassan and Albusoda, 2022).**

Authors	Gypseous soil	Treatment strategies	Projected improvements
(Al-Busoda, 2008)	Gypsum with Poorly graded sand	Four admixtures are chosen to decrease the collapse stress of soil: cement, bentonite, calcium chloride and silica gel	Particularly when using cement, an adequate reduction in compressibility and collapsibility was achieved.
(Albusoda and Khdeir, 2018)	Gypsum sand with low grading	Combining Nano-fly ash and nan silica fume with gypseous soil	The collapsibility is sufficiently reduced at about 83% and improves CP at typically 2% fly ash and 4% silica fume.
(Al-Busoda, 1999)	Gypsum sand	Treatment with ($CaCl_2{\bullet}2H_2O$)	When 2.5% $CaCl_2{\bullet}2H_2O$ by weight was applied, the collapse potential dramatically decreased. Additionally, un-leached treated samples showed a reduction in compressibility characteristics.

(Al-Gharbawi et al., 2021)	Organic gypsum soil (SP) with (35-75) % relative densities	Combining carbonated and natural gypsum with MgO	100% reduction in coefficient of permeability after adding 10% carbonated magnesium oxide for three hours.
(Hayal et al., 2020)	Gypsum sand with low grading	Two different kinds of nanomaterial—Nano-silica and Nano-clay—were combined with gypsum.	There was a 91% reduction in CP when nano-silica was raised to 1%, and a 73.75% reduction in CP when nano-clay was added.
(Al-Obaidi et al., 2020)	Gypsum sand that is poorly graded without fines.	Silica and Nano-silica fumes gypsum soil.	Improving the CP of gypseous soil by utilizing nano-silica fume to enhance the CP of gypsum soils.
(Safa et al., 2012)	Gypseous soil with elastic silts	Combining the Portland cement plus gypseous soil	It was demonstrated that a considerable decrease in collapsibility occurred when gypsum soil was treated with cement and compression. The collapsibility of the cured specimen decreased by 95% when 10% cement was injected and the density of the resultant soil was raised.
(Abood, 1994)	Two types of soil: gypsum with clay and gypsum with sand	Two primary kinds of gypsum with various gypsum percentages and sodium silicate solution	Adding sodium silicate increased gypsum strength and reduced its tendency to collapse.
(Al-Busoda and Al-Rubaye, 2015)	SP SM	A simulated pile constructed on the ground contained 42% gypsum.	Compression axial model pile load testing was performed on model piles placed in gypseous soil both before and after saturation of the soil at an early degree of 7%. The Shen method produces satisfactory results for almost all load tests of typical piles. When the typical piles were loaded after being wet for 24 hours, a significant decrease in capacity was observed due to the loss of gypsum cement activity resulting from the wetness.
(AL-Busoda and Alahmar, 2023)	SP	The dynamic reaction of moist and drier states utilizing foundation rest on collapsible soil	Based on the results, the wet state has a greater resonance frequency than the dry state, and the amplitude of displacement is greater in the submerged state. Moreover, at a given frequency, the displacement amplitude and resonant frequency increase with an increase in eccentric mass
(Al-Busoda and Hussein, 2013)	SP	Compressed dune sand over gypsum has a shallow bearing capability.	The best thickness of the sandy dune layer at the interface with geotextile was approximately equal to the width of footing at the level; collapsible settling reducing factor (CSRF) increased to 7%.

			Additionally, under concentric loads, the capacity improves approximately two times, and in the case of eccentric forces, it increases more than 2 times.
(Al-Busoda and Hussein, 2013)	SP	The research uses a new technique to investigate the performance of replacement and geo-synthetic reinforcement materials for the improvement of gypsum soil behavior	When replacing and reinforcing gypsum layers. The bearing capacity was improved to (1.5-2.0) times under a centric load and (2.5-3.0) times under an eccentric load.

7.2 Loess Soil

A windborne, Aeolian, or periglacial sedimentation known as loess soil is composed of about equal amounts of sand and silt and 20% or less clay. Several researchers have examined the attributes of collapsible soil as explained in **Table 7 (Mohsen and Albusoda, 2022).**

Table 7. Loess soil is interpreted in different ways **(Mohsen and Albusoda, 2022).**

Authors	**Identifications**
(Barden et al., 1973)	Loess soils are described as quaternary Aeolian deposits consisting mostly of silt-sized particles (20 to 60mm) having capillary water, and carbonates, with clays serving as binding agents at the particle interfaces.
(Rauch et al., 2003)	The most often used chemical additions are conventional stabilizers like Portland cement and lime.
(Terzaghi et al., 1996)	A uniform, compacted soil with light brown sediments that range in size from 0.01 to 0.05 mm is known as loess soil.
(Delage et al., 2008)	Investigated the structure and collapse mechanism of extensive Aeolian loess strata in northern France. The clay aggregates that filled the pores between the grains were diverse and dispersed due to their porous structure, which, in certain cases, acted as a bonding agent between the grains, as shown by Micro scan SEM examinations. In areas devoid of clay, silt grains with sharp edges measuring (15 to 30 mm) in diameter show significant intergranular porosity. Mercury porosimetry's incursion revealed that the small holes within the clay grains that occur in the interfacial void spaces upon collapse were unaffected by the alteration. By the well-graded pore size distribution curve, a collapsed structure was more regular.
(Munoz-Casteblanco et al., 2011)	The densification of the area where the clean, large-pored soil grains are located is what causes collapse by wetness. These zones become less vulnerable to local collapse and more resistant to collapse as a result of clay aggregation filling the porosity in them.

(Li et al., 2016)	Drafted a review paper on the process by which moisture causes collapsible soils to collapse. Three categories—traditional techniques, microstructure approaches. Also, methods based on the properties of soil are used to illustrate collapse techniques.
(Sprafke and Obreht, 2016)	A type of residue that accumulates over time is called loess and is made up of windblown sediment. However, to fully appreciate its unique characteristics, one must take into account the complex cycle that occurs both before and after the resulting statement. These cycles, which play a crucial role in shaping its constituent parts, are overlooked in the conventional definition of loess.
(Nokande et al., 2020)	In semi-arid areas, losses are unsaturated and have a metastable structure. Loss is vulnerable to a range of geotechnical hazards, including landslides, collapsibility, and seismic settlements, as well as abrupt collapse and settlement brought on by disturbance, stress, and soaking.
(Khodabandeh and Nagy, 2022)	Buildings built on deformable soils may sink as a result of soil saturation for a variety of causes, including burst water and oil pipes, sewage leaks, rising groundwater levels, chemical, and industrial effluent leaks, etc.
(Khodabandeh et al., 2023)	The application of chemical stabilization (lime, cement, nano, fibers, etc.) to loess soils to improve their engineering properties is a frequently utilized approach worldwide. Loess soils have a higher collapse potential as saturation stresses rise to 500 kPa.

7.3 Further forms of Collapsible Soil

Collapsible soils refer to a variety of materials that can collapse. These materials include Aeolian, colluvium deposits, residual soils, and wind or water deposits. Most collapsible soil layers are caused by flows of debris, alluvial accumulation, and wind-blown particles. **(Beckwith, 1996; Bell and Bruyn, 1997)** found that most naturally produced collapsed soils are Aeolian deposits. **(Jennings and knight, 1975)** identified soil deposits that are most prone to collapse as loose fills, changed wind-blown sands, hill wash with loose, and acid igneous rocks.

Aeolian deposits, including loess, dunes, and other wind-blown deposits, occur globally. According to **(Clemence and Finbarr, 1981)**, loess is distributed throughout approximately 17% of the USA, 17% of the European Union, 15% of Russia and Siberia, and enormous parts of China. Calcareous windblown dune sands are found in Kuwait and sections of the Arabian Peninsula **(Ismael et al., 1987).** Aeolian contains a loose soil, meta-structure bound by cementing elements. When wet, it becomes unstable and may disintegrate, leading to collapse.

Water sediments consist of alluvial drainage systems, mud flow, and flash flood deposits. Water deposits occur when it is wet. Once they dry, they grow harder, less compressible, and have a lower density. Soil grains are often bound by cementing chemicals during accumulation, causing a permeable structure. When these minerals come into contact with water with or without extra load they collapse and cause significant settlement. **(El-Nimr et al., 1992)** describe collapsible alluvial deposits in Saudi Arabia and other Middle Eastern regions. Residual soils come in a variety of sizes, including clay and gravel. The collapsible form results from leaching of soluble and colloidal particles from residual soil.

7.4 Long-Term Performance of the Collapsible Soil

There are numerous strategies for reducing or eliminating the collapse of some particular soil and achieving the long-term performance of the collapsible soil. The right procedure depends on the depth of the soil layer, the structure to be built, the cost and the feasibility. Table8. Illustrates several of these methods

Table 8. Many techniques to reduce collapsibility and evaluate long-term performance

Description	Authors
An easy option is finding the desired depth and removing the collapsed layer. The excavated soil can be reused as a foundation after compacting. This approach is typically employed for compressible soil in shallow depths. The compacted density for the replaced soil must be between 95-100% and the moisture level more than 2% lower than the optimum.	**(Anayev and Volyanick, 1986)**
In order to reduce soil collapse after the building is completed, pre-wetting includes flooding or watering the soil that is expected to exhibit collapse upon saturation before the structure is constructed. It is possible to wet the soil by using trench, boreholes, or bonding.	**(Hansen et al., 1989)**
Pre-wetting and controlled wetting are comparable, with the exception that controlled wetting is carried out after the structure is installed. Water should be supplied gradually and in approximate measurements.	**(Bally and Oltulescu, 1980)**
Using compaction is one of the most useful and efficient ways to reduce soil collapse. Compaction has been applied to collapsible soils that are both deep and shallow. This technique reduces the level of collapsible soil in the area with significant stress, deepens the absorption depth required for water to reach collapsible materials, and lessens the stress. This method enhances both the engineering performance and the attributes of the soil.	**(Rollins and Rogers, 1994)**
For many years, chemical stabilization or grouting using additions like calcium chloride and sodium silicate has been attempted, with varying degrees of effectiveness. By creating cementation inside the soil structure, the technique prevents the soil from collapsing when moist. For the procedure to be successful, chemical solutions must penetrate to the appropriate depth.	**(Houston and Houston, 1997)**
In Southeast Europe and Russia, heating loess soil in boreholes by burning fuel oil and gas improved collapsible soil. The close spaced holes with temperatures reached 1000 C°, resulted in a 2m diameter stabilized soil column.	**(Bell and Bruyn, 1997)**
An expansive method of decreasing the risk provided by collapsible soils is a dynamic compaction method (DC), especially if the soil layer falls deeper than 4 meters. The study presents 15 projects in the United States involving collapsed soils that have been improved with DC.	**(Rollins and Kim, 2010)**
Circumstances in dry and semi-arid climates, such as Borg El Arab in Alexandria, Egypt, establish the creation of the most problematic collapsible soils. This research investigates the performance of compacted sand replaced over prepared collapsible soil using pre-wetting and compaction. Plate loading experiments were used in the site to investigate the compressed replacement sand on enhanced collapsible soil.	**(Ali, 2015)**
Long- term performance of cement/lime materials for improving the collapsible loess soil in Eastern Europe.	**(Jefferson et al., 2015)**

Grouting dilute solution of clay nanoparticles was utilized to improve collapsible soil against wetting. Clay nanoparticle solution proved more effective than cement grout in reducing the collapse potential.	**(Seiphoori and Zamanian, 2022)**
The physicochemical features of soil stabilizing additives such as nanoparticles, fibers, polymers, and industrial materials were utilized to collapse soil stabilization.	**(Khodabandeh et al., 2023)**
Hydrated lime and cement are frequently utilized to enhance the geotechnical characteristics of problematic soils. After 7 days of mixing these additives with collapsible soil at various rates to assess their shear strength parameters and collapsing behavior. The results shown decreased in collapsibility and increased in shear strength parameters.	**(Hasan et al., 2024)**

8. Case Study

This section described some of a real-world project where collapsible soil was encountered, and the methods for mitigating the risk. **Table 9** includes some case studies of collapsible soil and the way that may be improved or enhanced.

Table 9. Examples of the collapsing soil case study

Case study	Solutions	Researchers
1- Mosul Dam is the second largest dam in the Middle East by reservoir full capacity. Since its beginning in 1986, this dam has been troubled by seepage problems at its base due to gypsum dissolution. It is constructed above gypsum bearing stones that dissolve and collapse upon wetting.	Regular grout effort has been performed to fill all gaps caused by dissolved gypsum. Massive operations grouting processes were used to reinforce the base of the foundation	**(Obead and Fattah, 2022)**
2-inexpensive road construction in Al-Anbar province	A successful way of stabilizing gypseous sandy soil that spans a significant region in Western Iraq with bituminous materials. Alternative method is to combine pre-wetting and soil replacement process with chemical stabilization.	**(Shubber et al., 2009)**
3-Karbala has collapsible soil types, especially in suburban areas where silty sand soil predominates. Many residential and business projects experienced problems soon after finishing constriction due to unanticipated behavior of collapsible soils	A deep foundations program was carried out to avoid collapsible soil layers and translate loads to deep strata	**(Al-Khalidi and Atiya, 2019)**
4-Basra roadways occasionally collapse in layers and bases, causing cracking, crushing, and huge cavities. In the development of Basra´s water-treatment plant, the building workers discovered collapsible soil layers.	The stabilizing approach includes combining soil with cement and pumping cement slurry into collapsible layers	**(Al-Kawam, and Mahmood, 2022)**

5- Crakes and settlement in semi-dry soil in New Mexico city due to unequal settlement of the collapsible soil layer beneath the foundation.	Reduce collapsibility by common techniques such as chemical stabilization (lime, cement, and fly ash), mechanical methods (compaction, grouting, and deep mixing the soil to enhance the density), and pre-wetting by pre-saturated the site before construction	**(Houston et al., 2001)**
6- Khoda Afarin water canal in the north of Iran, the collapse risk resulted significant fissures on both sides of the canal	Pre-pounding the water storage facility	**(Noutash et al., 2010)**
7-comprehensive investigation on one of the problematic soil layers in San Diego, California. The soil is termed as a problematic soil or moisture sensitive region	Pre-loading method was used to compress and strengthen the weak soil with cementing agents and deep foundation was used to pass loads to deep layers.	**(Kalantari, 2013)**
8- The guest house project in Al-Ain city of UAE. Villas and open green spaces in Abu Dhabi (UAE).	Remove or compress the weak sensitive soil, control moisture-damaging issues, and use of deep foundation (piers and piles).	**(Vandanapu et al., 2016)**

9. CONCLUSIONS

Collapsible soils provide global difficulties to building and geotechnical design. A soil that suffers a drop in volume due to an increase in moisture content, whether natural or manufactured, will result in the formation of an unstable form due to the high void ratio. To prevent collapsibility soil issues like cracking, rotating, and a high settlement, it is important to understand how such soil behaves during moist and dry circumstances, with or without external forces. The points listed below can possibly be described together from the evaluated literature: -

1- Any unsaturated soil that, when wet, exhibits a significant change in practice quality and an enormous variation in quantity regardless of additional loads, is considered collapsed soil.
2- The minimal densities, large pores, high displacement, and elevated sensitivity to hydration mode are characteristics shared by collapsed soils.
3- Noticeable increases in the amount of moisture or decreases in the volume of the soil may lead to a semi-stable structure that can be solved through geotechnical solutions.
4- In arid circumstances, the problematic layers support a heavy load under low pressure or deformation, although they can lose a significant amount of mass if moisture.
5- Different boundaries that influence the CP might be assessed utilizing SOT and DOT during the immersion, depending on the sort of soil, starting moisture state, and compaction efforts. This survey concentrates on demonstrating two sorts of collapsible soils, gypseous and loess.
6- Research conducted in Iraq revealed many synthetic and real ways to treat, address and enhance the properties of gypsum layers. These methods included the use of $CaCl_2 \cdot 2H_2O$, fume of nano-silica or nano-fly ash, bacterial calcium carbonate precipitation, and combining magnesium oxide and carbonated magnesium oxide with natural gypseous soil, among several additional techniques.

7- Establishing a structure in this type of soil is a challenging task due to rapid volume misfortune and unanticipated settlement of the soil that supports the structure without any indication.
8- The extent of the collapse soil level, magnitude of the collapse, and financial consideration all impact the selection of the foundation.
9- To strengthen collapsible soils and increase their capacity to support real loads, this weaker layer may be healed by solidifying materials such as Portland cement or using prestressing procedures.

NOMENCLATURE

Symbol	Description	Symbol	Description
e_B	Proportion of voids prior to saturation at a certain stress threshold.	CP	The possibility of collapse potential.
e_I	Void ratio with a certain amount of moisture stress.	Δe	Change in void ratio
e_o	The original proportion of voids.	σ_v	Vertical stress, kPa
SP	Poorly graded sand	SM	Silty sand

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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التربة القابلة للانهيار، تعريفها وإستراتيجيات تخفيف الانهيار: ملخص دراسات

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الخلاصة

تعتبر التربة الانهيارية إحدى فئات التربة الصعبة التي تمثل تحديا كبيرا حيث تظهر قدرا كبيرا من القوة عندالجفاف ولكنها تتعرض لفقدان كبير في الصلابة أثناء الترطيب، مما يؤدي إلى حصول هطول مفرط. إن إدراك استجابة وتأثر المنشأ بالترطيب يمثل تحديًا هندسيا في هذه الأنواع من التربة. مع مرور الوقت، يؤدي الترطيب الى زيادة متوقعة في الانهيار، ويرجع ذلك أساسا" الى ذوبان الجبس. تعتبر التربة الجبسية أكثر أنواع التربة الانهيارية شيوعا" حيث تتأثر هذه التربة بالعوامل الجيوتقنية مثل التحميل والترطيب، وكثافة التربة، وظروف التشبع والغمر. في العراق والعديد من المناطق الأخرى تكون التربة الانهيارية مثل الجبس في حالة جافة صلبة وتنهار بشكل ملحوظ عندما تصبح رطبة. تهدف هذه الدراسة إلى تقديم ملخص دراسات عن معنى التربة الانهيارية وتصنيفها وتحسينها وتصميم الأسس فيها وتخفيف الانهيار.حيث يحدث الانهيار بشكل أسرع مع زيادة المسامية وزيادة نسبة الجبس. مع توسع المراكز الحضرية سيكون احتمال وصول الماء والترطيب الى التربة الجبسية بشكل أكبر وبالتالي سيكون احتمال ارتفاع في حدوث الانهيار. وهنالك عدة أنواع من إجراءات تحسين التربة الجبسية، بما في ذلك الإزالة والاستبدال واستخدام المضافات وان لكل طريقة تطبيق خاص بها، ولكن الطريقة الأكثر شيوعا" لتحسين التربة هو رص التربة وزيادة كثافتها وفي النهاية فإن الغاية هي الوصول الى تصميم هندسي جيد بوجود الجبس. يمكن أيضا تعزيز استقراريه التربة الجبسية بإضافة الكاولين والجير وكلوريد الكالسيوم للحصول على بنية تحتية امنة وفعالة من حيث التكلفة واستقرار المنشأ على المدى الطويل.

الكلمات المفتاحية: محتوى الجبس، التربة الانهيارية، احتمالية الانهيار، الكثافة الجافة، تحسين التربة.