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Etude de la pathologie des fissurations de bâtiment suite au phénomène de dissolution du gypse cas des bâtiments de Ouled Djellal.

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Abstract

This thesis investigates the pathology of building cracks caused by ground movement resulting from gypsum dissolution in Ouled Djellal. The research begins with a comprehensive literature review addressing gypsum soils, the dissolution process, associated geohazards, structural risks, assessment methodologies, and engineering solutions within a broader risk management framework. A pre-diagnosis phase was conducted on 55 buildings, revealing significant damage affecting structural and non-structural elements. Issues included tilting, cracking, swelling, detachment of exterior cladding, and functional impairments such as door and window sticking. Environmental analysis led to the hypothesis that these issues stem from ground movement triggered by the dissolution of gypsum, primarily initiated by water infiltration due to leakage.A detailed diagnostic phase followed, focusing on 11 buildings to confirm the failure mechanisms hypothesized earlier. The findings revealed the presence of gypsiferous soils, which considerably degrade mechanical behavior when exposed to moisture. This hydro-collapse phenomenon is driven by the dissolution and transport of soil particles within the Pliocene layer (3 to 7 meters deep), where the building foundations are anchored. The affected soil comprises sandy clay, sandstone, and a conglomerate matrix, characterized by pores, cavities, and cracks that contribute to instability. Additionally, inadequate foundation designs—featuring isolated and combined footings—have exacerbated the damage. Differential settlement, caused by the heterogeneity of the soil's depth and composition, was identified as the primary failure mechanism, resulting in stress concentrations and material degradation. Based on these findings, a comprehensive risk management strategy is proposed. Preventive measures include improved water management, piezometric monitoring, and ongoing observation of subsurface warning signs. Remedial techniques discussed include grouting using the GIN method and the enlargement of isolated footings to form cross-strip footings. The recommendations also integrate urban planning strategies for both local (Ouled Djellal) and national implementation.

Keywords: Durability; Cracking; Repair; Gypsum; Diagnosis.

Résumé

Cette thèse porte sur la pathologie des fissures dans les bâtiments causés par les mouvements du sol induits par la dissolution du gypse à Ouled Djellal. L'étude débute par une revue bibliographique complète traitant des sols gypseux, du processus de dissolution, des aléas géotechniques associés, des risques pour les structures, des méthodes d'évaluation des bâtiments affectés, ainsi que des solutions d'ingénierie intégrées dans une approche globale de gestion des risques.Une phase de pré-diagnostic a été menée sur 55 bâtiments, révélant des dommages significatifs affectant les éléments structuraux et non structuraux : inclinaisons, fissures, gonflements, décollement du revêtement extérieur, ainsi que des dysfonctionnements tels que le collage des portes et fenêtres. L'analyse de l'environnement a permis d'émettre l'hypothèse que ces désordres résultent des mouvements de sol déclenchés par la dissolution du gypse, elle-même provoquée par des infiltrations d'eau issues de fuites.Une phase de diagnostic approfondi a ensuite été réalisée sur 11 de ces bâtiments à l'aide de méthodes détaillées afin de confirmer les mécanismes de défaillance supposés. Les résultats ont mis en évidence la présence de sols gypsifères qui altèrent fortement le comportement mécanique du sol, notamment en conditions humides. Ce phénomène d'effondrement hydrique est principalement dû à la dissolution du gypse et au transport des particules de sol dans la couche pliocène située entre 3 et 7 mètres de profondeur, là où sont fondées les structures. Ce sol est composé d'argile sableuse, de grès et d'une matrice conglomératique, présentant des pores, des cavités et des fissures aggravant l'instabilité.Par ailleurs, des conceptions de fondations inadaptées — qu'elles soient isolées ou combinées — ont amplifié les désordres observés. Le tassement différentiel, causé par l'hétérogénéité des propriétés du sol en profondeur et en extension, a été identifié comme le principal mécanisme de défaillance, générant des concentrations de contraintes et une dégradation des matériaux dans les structures affectées. Suite à l'identification de ces mécanismes, une stratégie complète de gestion des risques est proposée. Les mesures préventives incluent une meilleure gestion des eaux, un suivi piézométrique, et une surveillance continue des signes d'instabilité souterraine. Parmi les solutions correctives envisagées figurent la technique d'injection par la méthode GIN et l'élargissement des fondations isolées pour former des semelles filantes croisées. Les recommandations tiennent également compte de la planification urbaine future, tant à l'échelle locale (ville de Ouled Djellal) qu'à l'échelle nationale.

Mots clés : Durabilité ; Fissuration ; Réparation ; Gypse ; Diagnostique.

ملخص

تتناول هذه الأطروحة دراسة باثولوجيا الشروخ والتشققات في المباني الناتجة عن حركة التربة بفعل تحلّل الجبس في منطقة أولاد جلال. تبدأ الدراسة بمراجعة شاملة للأدبيات المتعلقة بترب الجبس، وآلية تحلّله، والمخاطر الجيولوجية المرتبطة به، وتأثيره على المباني، وطرق تقييم المنشآت المتأثرة، بالإضافة إلى الحلول الهندسية ضمن إطار شامل لإدارة المخاطر. تم تنفيذ مرحلة تشخيص أولي شملت 55 مبنى، كشفت عن أضرار كبيرة طالت العناصر الإنشائية وغير الإنشائية، تمثلت في ميلان المباني، وتشققات، وتورّم، وانفصال في الكسوة الخارجية، إلى جانب اختلالات وظيفية مثل التصاق الأبواب والنوافذ .وقد أدى تحليل البيئة المحيطة إلى افتراض أن هذه الأضرار ناتجة عن حركة تربة ناجمة عن ظاهرة تحلّل الجبس، والمحفّزة أساسًا بتسربات المياه. في المرحلة التشخيصية الثانية، تم التركيز على 11 مبنى باستخدام وسائل فحص تفصيلية لتأكيد آليات الفشل المفترضة في المرحلة السابقة. أظهرت النتائج وجود تربة جبسية تؤثر بشكل ملحوظ على السلوك الميكانيكي للتربة، خاصة في ظل الظروف الرطبة، مما يؤدي إلى ظاهرة الانهيار الهيدروليكي الناتجة عن تحلّل الجبس ونقل الجزيئات في الطبقة البليوسينية الواقعة على عمق يتراوح بين 3 و7 أمتار، حيث ترتكز الأساسات. تتكوّن هذه التربة من طين رملي، وحجر رملي، ومصفوفة من الكونغلوميرات، وتحتوي على فراغات وتشققات تفاقم حالة عدم الاستقرار. كما ساهمت التصاميم غير الملائمة للأساسات —— سواء كانت منفردة أو مشتركة —— في زيادة حدة الأضرار. وقد تم تحديد الهبوط التفاضلي الناتج عن التفاوت في خصائص التربة من حيث العمق والتركيب كآلية الفشل الرئيسية، مما أدى إلى تركز الإجهادات وتدهور المواد في المباني المتضررة. بناءً على هذه النتائج، تم اقتراح استراتيجية شاملة لإدارة المخاطر، تشمل تدابير وقائية مثل تحسين إدارة المياه، والمراقبة البيزومترية، والرصد المستمر لمؤشرات الخطر تحت السطح. كما تشمل المعالجات التقنية تقنيات الحقن باستخدام طريقةGIN ، وتوسيع الأساسات المنفردة لتكوين أساسات شريطية متقاطعة. كما تأخذ التوصيات بعين الاعتبار استراتيجيات التخطيط الحضري المستقبلية على المستويين المحلي (مدينة أولاد جلال) والوطني.

الكلمات المفتاحية: المتانة؛ التشقق؛ الإصلاح؛ الجبس؛ التشخيص.

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General Introduction

1. Background and context

The construction industry plays a vital role in the development of infrastructure and the built environment. However, buildings are susceptible to various pathologies that can affect their structural integrity, performance, and functionality. One common issue that has been observed in buildings worldwide is the occurrence of cracks. These cracks can lead to significant damage and pose risks to occupants and the surrounding environment. Therefore, understanding the causes and mechanisms behind building cracks is crucial for ensuring the safety and longevity of structures.

In certain regions, building cracks have been associated with ground movements caused by the dissolution of gypsum in the underlying soil. Gypsum, a mineral present in certain geological formations, can undergo dissolution when exposed to water or moisture over time. This process weakens the gypsum layers within the soil, leading to ground movement and subsequent structural damage in buildings above.

The region of Ouled Djellal has been identified as an area affected by the phenomenon of gypsum dissolution-induced ground movement, resulting in building cracks. This geological condition poses significant challenges for the construction and maintenance of buildings in the region. Therefore, it is essential to comprehensively study the pathology of building cracks resulting from gypsum dissolution in the soil to develop effective mitigation strategies and ensure the safety and stability of structures.

By examining the specific case study of buildings in Ouled Djellal, this research aims to identify the characteristics, patterns, and severity of cracks associated with ground movement induced by gypsum dissolution. Furthermore, the study intends to propose appropriate diagnostic methods and recommend effective measures for mitigating the adverse effects of gypsum dissolution-induced ground movement on buildings.

Through this research, it is anticipated that building owners, construction professionals, and relevant stakeholders in the construction industry will gain valuable insights into the detection, prevention, and mitigation of building cracks resulting from ground movements triggered by gypsum dissolution in the soil. By addressing this geological challenge, it is possible to enhance the structural integrity, durability, and overall performance of buildings in Ouled Djellal and similar regions, thus contributing to the sustainable development of the built environment.

2. Problem statement

The differential movements of the ground beneath a construction result in disorders that affect the entire structure. The nature, intensity, and location of these disorders (cracks) depend on the construction structure, the type of foundation, and the magnitude of the differential ground movements. In order to assess the risks associated with these disorders, specific geotechnical studies are necessary to identify and consider this phenomenon in civil engineering projects. The severity of cracks can vary depending on their location on the wall (at the base, lintel, or sill). They compromise the structural integrity of the building and often have a stepped pattern. Cracks can have various causes, and it is important to determine their origin. Ground movements induce instability in the foundation soil, which in turn leads to the formation of cracks in structures. If the soil is unstable, the foundations can shift, crack, and exert stress and tension on different masonry elements, leading to stepped cracks on the façade walls. The methodology for assessing the hazard of ground movements related to gypsum dissolution must be adapted to each site based on the available data and context. However, even with varying data from site to site, it is possible to define two main criteria for assessing predisposition: the presence or absence of sufficient gypsum deposits at a depth capable of causing surface-visible ground movements, and the hydrodynamic and hydrochemical potential of the water, specifically the presence or absence of aggressive water circulation with respect to gypsum. The use and acquisition of hydrogeological data are crucial for evaluating predisposition. These data help understand the dissolution system and the parameters that influence it, such as the nature and facies of the soluble material, chemistry and temperature of the fluid, water circulation rate on the mineral surface, and specific hydrogeological context. To quantify the spatial evolution of dissolution and assess the overall extent of the dissolution system, data on the chemistry of the water present is necessary. In-situ measurements of water electrical conductivity, coupled with chemical analyses, help determine if the subsurface water flows have come into contact with gypsum. Saturation index calculations are also used to characterize the dissolution potential of different water flows with respect to gypsum. The intensity of the anticipated phenomena is determined based on the expected extent of the disorders. The probability of the occurrence of the hazard, or rather the predisposition of the site to the appearance of surface disorders, mainly depends on two criteria: the presence of gypsum deposits and the hydrodynamic and hydrochemical potentials of the water. These criteria are evaluated through a detailed analysis of the geological and hydrogeological contexts. The combination of these two parameters allows for the determination of the predisposition level, adjusted by the criteria of void presence in the subsurface and knowledge of ground movements associated with dissolution. The intersection of intensity and predisposition enables the assessment of the hazard into three classes: low, moderate, and high.

3. Objectives

The primary objectives of this research are as follows:

1. To investigate the characteristics, patterns, and severity of building cracks resulting from gypsum dissolution-induced ground movement in Ouled Djellal.

2. To identify the factors and mechanisms contributing to the occurrence and progression of building cracks in the context of the specific geological conditions of Ouled Djellal.

3. To develop a comprehensive diagnostic framework for assessing and evaluating the extent and severity of building cracks caused by gypsum dissolution-induced ground movement.

4. To propose effective mitigation strategies and recommendations tailored to the unique geological conditions of Ouled Djellal to prevent, control, and repair building cracks resulting from gypsum dissolution-induced ground movement.

5. To evaluate the feasibility and practicality of the proposed diagnostic and mitigation measures through case studies and practical implementation.

4. Research questions

This research aims to address the following research questions:

1. What are the characteristics, patterns, and severity of building cracks resulting from gypsum dissolution-induced ground movement in Ouled Djellal?

2. What are the factors and mechanisms contributing to the occurrence and progression of building cracks in the context of the specific geological conditions of Ouled Djellal?

3. What diagnostic methods can be employed to assess and evaluate the extent and severity of building cracks caused by gypsum dissolution-induced ground movement in Ouled Djellal?

4. What are the effective mitigation strategies and recommendations tailored to the unique geological conditions of Ouled Djellal to prevent, control, and repair building cracks resulting from gypsum dissolution-induced ground movement?

5. How feasible and practical are the proposed diagnostic and mitigation measures, and how can they be implemented in real-world scenarios?

5. Significance of the Study

The study of building cracks resulting from gypsum dissolution-induced ground movement in Ouled Djellal holds significant importance for various stakeholders and the field of construction. The findings and outcomes of this research are expected to contribute to several areas:

5.1. Practical implications for building owners and construction professionals

- Building owners (maitres d'ouvrage) in Ouled Djellal and similar regions will benefit from a deeper understanding of the causes and effects of building cracks resulting from gypsum dissolution-induced ground movement. This knowledge will assist them in making informed decisions regarding the construction, maintenance, and renovation of buildings, ultimately enhancing the safety, durability, and value of their assets.

- Construction professionals, including architects, engineers, and contractors, will gain insights into the specific diagnostic methods and mitigation strategies required to address this pathology effectively. The research outcomes will enable them to design and implement appropriate measures to prevent and repair building cracks, improving the overall quality of construction projects.

5.2. Contribution to scientific knowledge

- This research will contribute to the scientific understanding of building pathologies, particularly in relation to ground movements induced by gypsum dissolution. The investigation of the specific case study in Ouled Djellal will generate valuable data and insights into the characteristics, patterns, and severity of building cracks, expanding the knowledge base on this specific pathology.
- The proposed diagnostic methods, mitigation strategies, and recommendations will add to the existing body of knowledge, providing practical solutions for addressing building cracks resulting from gypsum dissolution-induced ground movement. This knowledge can be used by researchers, academicians, and professionals in the field to further advance the understanding and management of similar pathologies in different contexts.

Societal Impact and sustainable development:

- The research outcomes will contribute to the safety, stability, and resilience of buildings in Ouled Djellal and similar regions facing similar geological challenges. By providing effective diagnostic techniques and mitigation measures, the study aims to minimize the risks associated with building cracks, ensuring the well-being of occupants and the surrounding community.
- The implementation of appropriate measures to prevent and repair building cracks will promote sustainable development in the region. By enhancing the durability and longevity of structures, the research outcomes will reduce the need for costly repairs, optimize resource utilization, and minimize the environmental impact associated with building failures and demolitions.

6. Scope of the Study

The scope of this research is focused on the study of building cracks resulting from gypsum dissolution-induced ground movement in the region of Ouled Djellal. The research will primarily investigate the specific case study of buildings in this region to gain insights into the characteristics, patterns, and severity of building cracks associated with this phenomenon. The scope encompasses:

- Examination of the geological conditions and factors contributing to gypsum dissolution-induced ground movement in Ouled Djellal.
- Analysis of building cracks in terms of their types, locations, sizes, and other relevant parameters.
- Development of diagnostic methods to assess and evaluate the extent and severity of building cracks caused by gypsum dissolution-induced ground movement.
- Proposal of appropriate mitigation strategies and recommendations tailored to the specific geological conditions of Ouled Djellal.

7. Limitation of the Study

While this research aims to provide valuable insights into building cracks resulting from gypsum dissolution-induced ground movement in Ouled Djellal, it is important to acknowledge certain limitations:

1. The study is focused on a specific region, namely Ouled Djellal, and the findings may not be directly applicable to other regions with different geological conditions.

2. The research will rely on available data and information, which may have limitations in terms of accuracy, completeness, and reliability. Efforts will be made to obtain the most reliable data sources, but some uncertainties may remain.

3. The implementation of diagnostic methods and mitigation measures proposed in this research will depend on various factors, including cost, feasibility, and local regulations. The practical

applicability and success of these measures may vary depending on specific project requirements and constraints.

8. Thesis Organization

This thesis is organized into four main chapters, each addressing critical aspects of the study on building pathologies resulting from gypsum dissolution-induced ground movement in Ouled Djellal.

Chapter 1: Gypsum-Rich Soils and Building Pathologies: A Comprehensive Literature Review

This chapter provides a comprehensive review of existing literature on the pathologies associated with gypsum dissolution in buildings. It covers the geological characteristics of gypsum soils, various hydration states of gypsum, and relevant terminology. The chapter discusses the formation and stratification of gypsum, its global distribution, and the engineering challenges presented by gypsiferous soils, particularly focusing on the formation of geohazards and their risks to buildings, as well as the mitigation measures for these hazards.

Chapter 2: Prediagnosis of the Case Study

In the northwestern part of Ouled Djellal, preliminary inspections have revealed that 53 out of 55 buildings exhibit typical damages attributed to unidentified soil movement mechanisms. To identify the mechanisms underlying these building pathologies, an investigative approach starting with a prediagnosis phase has been applied. This chapter discusses the findings and methodologies employed during this phase.

Chapter 3: Diagnosis of the Case Study

This chapter focuses on the investigation and diagnosis aimed at identifying the mechanisms behind building failures in Ouled Djellal, based on the conclusions drawn from the prediagnosis chapter. It details the diagnostic methods used to assess the structural integrity of the buildings and analyze the contributing factors to their damages.

Chapter 4: Risk Management and Recommendations for Ouled Djellal

This chapter addresses the management of risks associated with geohazards, particularly subsidence and sinkholes resulting from the gypsum dissolution phenomenon. It explores both preventative and remedial measures, including water management, piezometric monitoring, surface event monitoring, and the application of advanced grouting techniques. A comprehensive risk management strategy is formulated, along with recommendations for reinforcing structures and planning future investigations to mitigate the long-term impacts of these geohazards on the built environment of Ouled Djellal.

Chapter 1: *Gypsum-Rich Soils and Building Pathologies: A Comprehensive Literature Review*

1.1. Introduction

The sequence of a building issue chronically begins with a source or error, which subsequently leads to a cause. This cause results in a defect that has symptoms, ultimately leading to failure and damage [1]. However, in the context of building pathology linked to the gypsum dissolution phenomenon, the chronology can take various scenarios from dissolution to the occurrence of ground movement and the appearance of symptoms, depending on the local geological and hydrogeological settings.

The main symptoms associated with the gypsum dissolution phenomenon are the cracking of the building’s facades or the collapse of a part or the entirety of the structure. After the occurrence of a building pathology, an investigation is required. According [1], the investigative process works in reverse to the sequence of building pathology development. It starts with identifying the failure, loss, or damage, then tracing back to the anomaly and defect, followed by uncovering the cause, and finally pinpointing the original source or error.

According to [2], this investigation process is essentially a decision-making task that may be affected by various disruptive factors such as time constraints, missing or inaccessible information, and irrationalities. Consequently, the investigator must deal with uncertainties, and because of these uncertainties, a concept of risk arises. The concepts of hazard and risk are intimately related.

The ground movement resulting from the gypsum dissolution process is directly connected to the concept of hazard, while its consequences on buildings are associated with the notion of risk. Preventative and curative measures are integral to risk management. This literature review chapter will explore the pathology, beginning with an understanding of gypsum soils and concluding with a discussion of preventative and curative measures based on the previous work of the scientific community.

1.2. Gypsum soils

Gypsum, a hydrated calcium sulfate mineral ($CaSO4 \cdot 2H_2O$), is commonly found in various geological environments, especially in arid to semiarid regions[3] .

Moreover, gypsum rocks showcase diverse facies influenced by their formation processes and geological history. Among the most prevalent types are saccharoidal gypsum (Fig. 1.1(a)), recognized for its texture resembling sugar crystals, and gypsum alabaster (Fig. 1.1(b)), characterized by a milky white appearance containing numerous automorphic crystals and microcrystals.

Fig. 1.1. Facies of gypsum rock (from Ouled Djellal): (a) Saccharide, (b) Gypsum alabaster.

The failures observed in highways, dams, and other structures constructed on gypsum-rich soils or rocks emphasize the significance of comprehending the chemical and physical characteristics of gypsum [4], [5]. underscores the necessity for specific physicochemical models to accurately predict the behavior of soils primarily composed of gypsum. These soils, known as gypsum soils, present challenges for the scientific community, from defining appropriate terminology to understanding their effects and interactions [3].

1.3. Hydration states of gypsum

Anhydrite ($CaSO_4$), bassanite ($CaSO_4 \cdot 0.5H_2O$), and gypsum ($CaSO_4 \cdot 2H_2O$) represent the three distinct hydration states in which calcium sulfate is found in nature. These hydration states correspond to the chemical names dihydrate, hemihydrate, and anhydrous or anhydrate, respectively [3].

Experimental and theoretical findings on the stability of sulfate minerals and the mechanisms behind their transformations are often debated, with differing perspectives sometimes causing confusion [6].

Calcium sulfate hemihydrate is a partially dehydrated form of gypsum, represented by the chemical formula $CaSO_4 \cdot mH_2O$, where m varies from 0 to 2/3; at industrial levels, m normally equals ½ [5].This form of calcium sulfate becomes unstable when exposed to air, as it absorbs moisture from the environment until it reverts to gypsum [5].Once hemihydrate transforms to gypsum and remains exposed to moisture at temperatures below 58°C, the gypsum will dissolve into the solution [5].

Calcium sulfate hemihydrate, a partially dehydrated form of gypsum, is represented by the chemical formula $CaSO_4 \cdot mH_2O$, where m ranges from 0 to 2/3; in industrial applications, m is typically 1/2 [5]. This form of calcium sulfate becomes unstable when exposed to air, absorbing moisture until it converts back into gypsum [5]. Once the hemihydrate reverts to gypsum and is continuously exposed to moisture at temperatures below 58°C, the gypsum will eventually dissolve into the solution [5].

Calcium sulfate anhydrite ($CaSO_4$) is the water-free form of calcium sulfate that typically exists at deep depths, often found beneath layers of gypsum [5].

Furthermore ,according to [3], the system of $CaSO_4$–H_2O omprises five solid phases: anhydrite III (soluble anhydrite or γ-$CaSO_4$)), anhydrite II (natural anhydrite or β-$CaSO_4$), anhydrite I (α-$CaSO_4$), anhydrite I (α-$CaSO_4$), hemihydrate ($CaSO_4 \cdot 0._{5H2O}$) and dihydrate ($CaSO_4 \cdot 2H_2O$).

According to [7], the $CaSO_4$.II phase of anhydrite remains thermodynamically stable up to 1180°C and is found naturally as the mineral anhydrite. Additionally, it can be synthesized through the high-temperature calcination (approximately 600°C) of natural or byproduct gypsum.

1.4. Terminology of soil containing gypsum

[8] Emphasized the need for precise classification systems and terminology to effectively communicate the unique properties and significance of gypseous soils in both scientific and practical contexts. To address this, the terminology proposed by [8] as supported by [3] is adopted, facilitating clearer discourse on gypsum-containing soils.

The term "gypseous" refers to soils that are mainly made up of gypsum, whereas "gypsiferous" describes soils in which gypsum is not the dominant component, typically containing parent sediments like basin fill, alluvium, or fan alluvium. Additionally, according to [9] " Gypsosols" and "Gypsic Soils" are synonyms for gypsiferous soils.

The term "gypsum soils" encompasses both gypseous and gypsiferous soils [3]. Additionally, for describing gypsum bedrock, "rock gypsum" is preferred over the outdated term "gyprock" [10] cited by [3]. Rock gypsum is characterized as a sedimentary rock that consists predominantly of the mineral gypsum, typically exhibiting a range of textures from coarse crystalline to finely granular, frequently exhibiting disrupted bedding as a result of expansion during the hydration of the parent anhydrite [10] cited by [3].

In soil science, the term "secondary gypsum" can lack precision when applied to gypsum-rich soil materials due to variations in its definition and challenges in distinguishing between pedogenic gypsum and gyprock relics [8].

However, the problematic terminology related to gypsum soils remains a recent topic of discussion. [11]. Highlight the inadequacy of the term "gypsiferous silts" for geomorphological, pedological, and mapping purposes in the northeastern Ebro Basin of Spain.

1.5. The Genesis of gypsum in soils

The genesis of gypsum in soils is influenced by various local conditions [5]. Highlights that typically, gypsum is regarded as an evaporitic deposit, originating from the precipitation of minerals from saline water [12]. Highlight this minerals predominantly originate from crystallization. The genesis of these crusts involves processes like lacustrine accumulation, upward or downward migration [13], or lateral input of gypsum formed elsewhere [14].

The crystallization is chemical process commonly observed in marine environments with notable evaporation. [15] highlights the widespread occurrence of evaporitic deposits throughout Spain, spanning from the Cambrian to the Quaternary periods.

The presence of Gypsosols is occasionally associated with tectonic activity or corresponding geomorphological features [9]. In Egypt, tectonic activity linked to the rifting of the Gulf of Suez has had a major impact on Miocene sedimentation patterns in the northwest Gulf of Suez. Comprehensive microfacies analysis has revealed 14 distinct sedimentary microfacies types, which include gypsiferous laminated shales [16].

While gypsum can also form in continental environments, a periodic link to the sea is vital. The crystallization process typically occurs in expansive, shallow basins closely associated with the sea, where intense evaporation leads to the precipitation of ions in solution [12]. In Spain, [15] identify periods of intense evaporitic sedimentation during the Lower Jurassic, Cretaceous, and Cenozoic eras, often associated with tectonic activity related to the Alpine Orogeny.

In certain environments, the formation of gypsum is attributed to diagenesis rather than conventional evaporite processes. like glacial deposits in Ohio, in this diagenetic model proposed by [17], calcium bicarbonate-rich water oxidizes pyrite present in gray prodelta muds. This oxidation process leads to the generation of iron oxides, hydroxides, and sulfates, which then interact with calcium-rich water, leading to the crystallization of gypsum. Similarly, gypsum formation has been observed in areas where seepage water containing saline Na_2SO_4 interacts with weathered dolomite [9].

Another observed case of diagenesis noted in Egypt occurs in the Girza and Qattamia regions, where the crusts are linked to pedogenic processes that involve the leaching of gypsum from underlying or neighboring gypsiferous shale or marl layers, followed by displacive crystallization in the upper soil layer [18]. According to [19], leaching is described as the process by which liquids, whether artificially introduced or naturally occurring, pass through a porous material, leading to the dissolution and removal of soluble components from the infiltrated material. However, in soil mechanics, leaching has a different meaning. It refers to a process that removes dissolved substances, such as salts and cementing agents, from a specific area within the soil profile.

[20] Emphasize that gypsum is present in soils originating from the loess of the Central-German Chernozem area, resulting from precipitation mechanisms on living roots and within pores, as well as from the interaction of sulfuric acid with materials present in the soil.

Without the need to invoke tectonic phenomena or anhydrite-gypsum transformations, [21] point out that Tumuli develop-empty, circular dome-shaped structures found in the uppermost layer of gypsum-primarily due to dissolution and precipitation processes within the gypsiferous layer.

1.6. Stratification of gypsum formations

According to [12], Gypsum precipitation usually follows the deposition of carbonates, succeeded by anhydrite as the water volume diminishes to 35% to 20% of the initial volume, and salt (NaCl) formation occurs when the volume reduces to 10%. This sedimentation process, primarily influenced by evaporation, leads to the formation of stratified layers comprising limestone, gypsum, anhydrite, and potentially salt, with no influx of new water from the sea or continent.

[22]Proposes a common diagenetic process involving calcium sulfate minerals. Gypsum forms initially through precipitation in stagnant water or the formation of displacement gypsum crystals within existing sediment or weathered rock, leading to the establishment of calcium sulfate mineral beds. As burial takes place, gypsum is transformed into anhydrite, while uplift

and the removal of overlying materials result in the conversion of gypsum into anhydrite. Existing voids within rocks can be occupied by either anhydrite or gypsum, and carbonate rock can be substituted with anhydrite.

Geological data indicate that in evaporitic environments, gypsum is predominantly found at shallow depths, while anhydrite becomes more prevalent at depths exceeding 450 meters. Nonetheless, many deviations from this pattern exist, including cases where gypsum is found at deeper levels and scattered anhydrite is present within the shallow subsurface [6].

1.7. Gypsiferous soil distribution across the globe

Climate, topography, parent material, organisms, and time collectively dictate the prevailing soil-forming processes, thereby influencing the soil types characteristic of a particular region [23].

Extensively discuss Spain's gypsum resources, several factors influence the origin, distribution, and volume of Spanish evaporite deposits [15]. These factors include global climate patterns, tectonic settings, and regional geological conditions.

According to [12], while gypsum formations can be found in various sedimentary landscapes globally, the most extensive deposits are typically situated near large regional evaporite complexes or in geologically stable areas over extended periods Countries with significant underground gypsum deposits include Canada, the United States, Germany, Australia, France, Italy (especially in Tuscany and Sicily), Poland, Spain, Mexico, Chile, Great Britain (notably England, such as in North Yorkshire), and Russia.

[9] Created a map representing the global distribution of gypsiferous soils by adapting from FAO (1993) (Fig. 1.2).

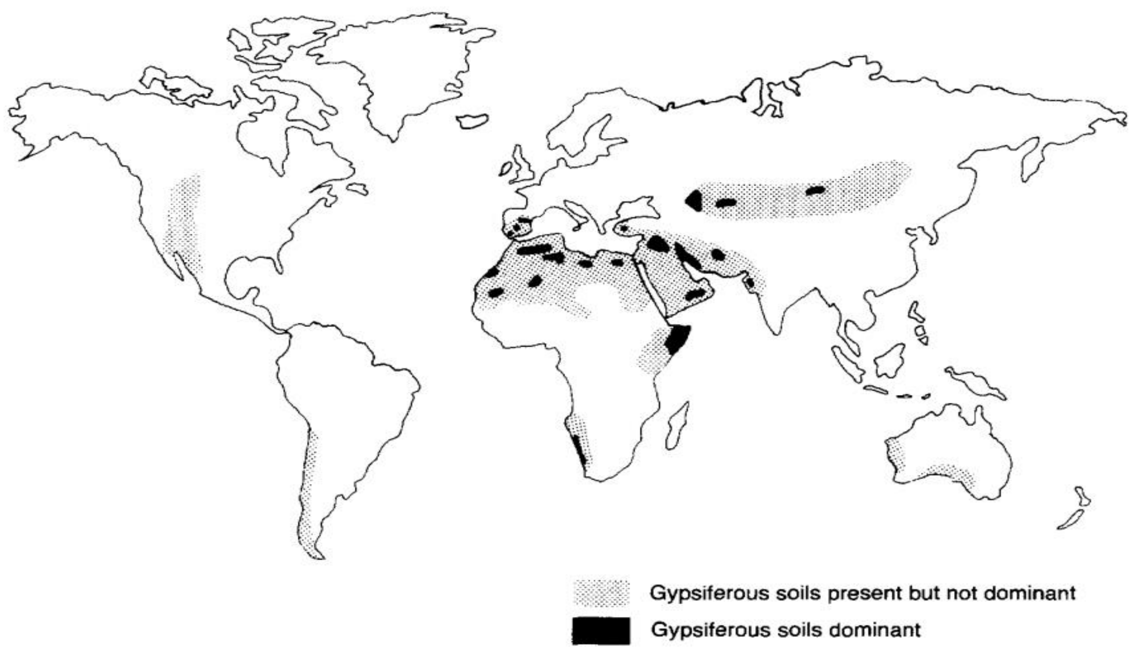


Fig. 1.2. Global Distribution of Gypsiferous Soils (Source: Adapted from FAO, 1993 by [9])

1.8. Engineering challenges on gypsum soils

[5] Outline the engineering challenges associated with gypsiferous terrains, emphasizing the unpredictable nature of these geological formations. Land subsidence, collapse of strata, and the development of sinkholes present higher risks in these types of soils compared to different types of soluble rocks [24].

Gypsum soils pose potential hazards to structures due to the interactions between gypsum and water. According to [25], this interaction creates landscapes defined by elements including epikarst, sinkholes, springs, caves, and intricate subsurface drainage systems.

In the UK, geohazards associated with anhydrite and gypsum encompass subsidence, dissolution, heave, and the formation of sinkholes [26]. Moreover, the use of gypsum as structural fill or in various engineering applications, such as embankments, highway subgrades, and load-bearing soils, is typically discouraged [5]. The challenges encountered by civil engineers in constructing structures on gypsum-rich terrain have led to the widespread recognition of these layers as hazardous foundation materials [25].

1.9. Gypsum dissolution phenomenon

1.9.1. Which hydration state?

The interaction of the hydration states of gypsum with water in nature depends on the nature of the hydration state itself and the local geological environment. According to [5], calcium sulfate dihydrate (gypsum) is less prone to significant expansion or heaving compared to calcium sulfate anhydrite, which lacks bonded water.

Hemihydrate and anhydrite, in the presence of water, undergo a hydration process and transform into gypsum, leading to an increase in volume and heave [5]. Meanwhile, the dihydrate form of calcium sulfate dissolves until an equilibrium state is reached between the water and the gypsum, resulting in downward movement [12].

1.9.2. Dissolution process

Dissolution is a heterogeneous process that occurs at the boundary between two distinct phases [6]. According to [6], Gypsum dissolves via a straightforward two-phase dissociation involving the solid and the solven. When gypsum ($CaSO_4 \cdot 2H_2O$) becomes submerged in water that has not been in contact with this mineral, its chemical components dissolve into ions. As represented by the equation:

$$CaSO_4 \cdot 2H2O(s) \rightarrow Ca^{2+(}aq) + SO_4^{2-(}aq) + 2H_2O(l) \text{ [27]} \qquad (1.1)$$

The dissolution process occurs because the water is under-saturated with Ca^{2+} and SO_4^{2-} ions compared to the levels present in the gypsum. It continues until the concentrations of Ca^{2+} and SO_4^{2-} ions in the solution achieve equilibrium with the mineral [28],[6],[12].

1.9.3. Solubility of gypsum

The solubility of a substance denotes the highest quantity of that substance that can dissolve in a specified volume of water [5]. Gypsum has a higher solubility compared to limestone [27]. About 2.5 kg of gypsum can dissolve in 1 cubic meter of water [27]. However, under specific laboratory conditions of pure water at a temperature of 25°C and a pressure of 0.101 MPa, the solubility of gypsum amounts to 2.6 $kg \cdot m^3$.

Furthermore, the solubility in a natural context varies depending on the presence of other salts in the system[9],[6],the pressure exerted on the rock, the grain size of the gypsum [6].

According to [29],in unconfined hydrogeological conditions in western Ukraine, gypsum dissolution rates have been measured at up to 29 mm per year.

According to [28], in the eastern part of the United States, where annual rainfall exceeds 75 cm, gypsum deposits are generally worn away or dissolved to depths ranging from several meters to tens of meters below the surface. In contrast, in the western areas where annual rainfall is below 75 cm, gypsum is typically more durable against erosion and frequently forms the caps of ridges, mesas, and buttes. Despite this durability, gypsum in these dry regions often shows karst characteristics, including cavities, caves, and sinkholes, which emphasizes the importance of groundwater flow, even in areas with low precipitation.

1.10. Hazard associated with gypsum dissolution phenomenon

1.10.1. Formation of sinkholes

Sinkholes, or dolines, are enclosed depressions that develop as a result of soluble rocks and sediments being dissolved either near the surface or beneath it. This phenomenon is frequently associated with internal erosion and deformation processes [30]. The word "doline," derived from Slavic origins, is predominantly favored by European geomorphologists, while "sinkhole" is more frequently found in global literature, especially in topics concerning engineering and environmental matters [30].

Evaporite karst sinkholes typically show a broader range of formation processes [31]. The process from dissolution to the development of sinkholes is complex and can follow various scenarios depending on the local context.

According to [32], the physical and chemical processes driving dissolution are intricately linked to a variety of geological and environmental factors. According to [33], In the central part of the Ebro Basin, north of Zaragoza in northeastern Spain, geomorphological and geophysical research was carried out to explore and assess the processes responsible for sinkhole development and their stages of evolution. The findings reveal three main phases in the formation of sinkholes: (1) the dissolution of evaporite bedrock leading to the creation of caves, (2) subsurface erosion of the alluvial material through piping, and (3) the eventual collapse or compaction of the caves and pipes within the alluvial cover.

1.10.2. Conditions for continues dissolution and sinkhole development

According to [28],25], in a natural context, continues dissolution that contributes to sinkhole development requires four essential conditions:

1) The existence of a gypsum deposit that allows water movement;
2) A source of water that is unsaturated with calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$);
3) An outlet for the resulting brine to exit; and
4) Sufficient energy, such as a hydrostatic head or a density gradient, to facilitate water flow through the system.

1.10.3. Common sinkholes (hazards)

Gypsum, due to its high solubility, can contribute to the development of geohazards. According to [34], the dissolution and removal of material primarily occur along pre-existing fissures and bedding planes, which initially provide pathways for water flow. This process significantly increases the permeability of the host rock, particularly in anhydrite and gypsum, over short timescales. As permeability expands in a karst aquifer, fissures and bedding planes grow into larger voids and cavities, causing mechanical instability. Collapse often begins at the cavity roof and propagates upwards, potentially reaching the surface, where it can lead to sudden ground failure and infrastructure damage.

According to [35], in the evaporite karst of the Ebro Valley (NE Spain), sinkholes are primarily caused by the downward movement (ravelling) of alluvial material through small karst conduits, coupled with the upward progression of soil overburden from collapsing cavity roofs.

According to [33], In this case study, various mechanisms of sinkhole formation can be deduced based on the characteristics of the overlying alluvium and the distinct shapes of the dolines. Furthermore ,in a 50 km² section of the same case , Three primary types of sinkholes have been identified [36] as outlined in Table 1.1.

Table 1.1. Overview of sinkhole types observed in the Ebro River Valley [36].

Type of Sinkhole	Characteristics	Formation	Occurrences
Large Collapse Sinkholes	Diameter of up to 50 m and depth of 6 m	Result from the upward expansion of dissolution cavities in the evaporitic bedrock due to rising groundwater flows	23 identified in the floodplain, often hosting saline ponds
Large Shallow Subsidence Depressions	Length of up to 850 m	Formed through structurally controlled interstratal karstification of soluble layers, driven by rising groundwater and gradual settlement of bedrock and overburden	24 mapped in the floodplain
Small Cover-Collapse (Dropout) Sinkholes	Diameter ranging from 1.5 to 2 m	Caused by the upward movement of voids within the alluvial mantle, resulting from the downward migration of detrital sediments into dissolution voids, often influenced by human activities	447 documented along a perched alluvial level on the southern edge of the valley

In the Alps of western Italy [37], seven study cases analyzed reveal a dual mechanism of subsidence and collapse effects. These mechanisms include immediate, catastrophic sinkholes typically occurring in flat or low-lying areas, and gradual, variable-size subsidence that can affect both valley bottoms and slopes.

[12] Use the criteria of the nature of the overlying soil (or overburden) to generalize common hazards due to gypsum dissolution into two main types: subsidence and collapse. This classification aligns with [37] and encompasses the three types documented by [36].

Specifically, collapse in the classification by [12] includes both large small cover-collapse (dropout) sinkholes and collapse sinkholes.

1.10.3.1. Collapse (Case of rigid overburden)

This typical sequence starting with the dissolution of underground gypsum formations under ***rigid overburden*** leads to the formation of voids or cohesionless layers within the gypsum [12]. Acording to [25,12],Under an active dissolution or hydraulic stresses, enlargement and destabilization occur due to dissolution and erosion caused by water-borne particles traversing the cavity, leading to the propagation of the cavity towards vertically to the surface, resulting in soil collapse. According to [25],collapse refers to a sudden and significant vertical movement of the ground, which can have severe impacts on buildings, infrastructure, and communication networks.

[38] Conducted finite-element (FE) analysis without considering the impact of unsaturated soil, which can vary with rainfall and water infiltration. An increase in the ratio of overburden thickness to cavity size correlates with a higher safety factor, suggesting a reduced risk of sinkhole failure. Furthermore, the analysis shows that greater soil cohesion and/or reduced effective overburden pressure above the cavity enhance the safety factor.

Collapses typically extend both horizontally and vertically over several meters, as demonstrated in Fig 1.3 and 1.4. The expansion of an underground vault is a gradual process that can span years or even decades. In contrast, the collapse that subsequently occurs on the surface happens suddenly and without warning [12]. These collapses often appear with no prior noticeable signs, making their occurrence both unpredictable and potentially devastating [30]. This rapid onset of surface collapse poses significant risks to individuals and property located nearby. The immediate identification and proactive alerting of sinkhole development are critical issues in urban areas. Recent research, such as experimental investigations on sinkhole monitoring using fiber optic strain sensing technology, aims to improve the detection and warning of sinkhole formation [39].

Fig. 1.3. Collapse of a sinkhole located at the western boundary of the Acquarotta Canal, with the Marina Lesina residential area (Italy) visible in the background. This image illustrates both the anthropogenic ground and the aeolian sands revealed along the steep walls of the active sinkhole [40].

Following their formation, collapse sinkholes can increase in size as their initially steep sides erode and degrade through mass wasting and erosion. This progression typically evolves from a cylindrical form to a conical shape and ultimately to a bowl-shaped geometry, with cover-collapse sinkholes capable of developing rapidly. The initial volume of a collapse sinkhole serves as a minimum estimate for the size of the subsurface cavities below, since the voids might not be completely filled, and the material from the collapse can settle and lose density over time [41].

Fig. 1.4. The sinkhole collapse occurring downstream of the Mosul Dam in Iraq is linked to the dissolution of gypsum and anhydrite layers (source: U.S. Army Corps of Engineers, 2007; public domain).

1.11.2. Special case of suffosion (Case of overburden that lacks of cohesion)

In the central region of the Ebro Basin, located to the north of Zaragoza in northeastern Spain, [33] highlight that the movement of alluvial cover material through dissolutional conduits creates voids and cavities that eventually lead to surface collapse. because of the alluvial cover's ***lack of cohesion***, ,the surface disorder in this case is termed suffosion [12].

1.10.3.2. Subsidence

The sinking or lowering of a land surface can occur either suddenly or gradually over time, affecting areas that can range from a few square meters to several square kilometers (Fig. 1.5) [25]. In this context, [12] suggest that in cases where the overburden ***lacks solid mechanical properties***, sustaining large open cavities becomes challenging, leading to subsidence hazards through bending or flexion of the overlying layers.

The void initially formed progressively diminishes over time. When dissolution mechanisms operate over a sufficiently extensive surface area concerning depth, a continuous, flexible movement transpires towards the surface. This process is typically slow and progressive, unfolding gradually over time [12].

Fig. 1.5. The subsidence, measuring 8.5 m x 9.5 m, caused the flexion of the roadway (indicated in red) observed on the ramp of the A15 motorway in Franconville, Val d'Oise (95) in 2014, as reported by Cerema [12].

1.10.4. Classifications of common sinkholes hazards

According to [35], categorizing sinkholes using morphometric and morph-stratigraphic criteria seems to have genetic implications, as indicated by previous study of [36] in the Ebro River valley located south of Zaragoza, NE Spain, this differentiation in criteria helps to elucidate how various elements, including hydrological processes, geological formations, and human influences, contribute to the development of different sinkhole types.

As stated by [30], sinkholes are primarily divided into two genetic categories. The first category includes solution sinkholes, which develop due to the uneven dissolution of the ground in regions where evaporites are exposed at the surface, often referred to as bare or uncovered karst. These sinkholes typically manifest as shallow depressions that can span several hundred meters. The second category encompasses various sinkhole types that arise from both subsurface dissolution and the downward gravitational movement of the overlying material, characterized by internal erosion and deformation. This category is particularly important regarding ground stability and engineering implications.

Numerous studies have suggested relatively comparable genetic classifications for common sinkhole hazards 31,30,42]. This classification system describes most sinkholes using compound terms, with the exception of solution dolines. The first part of the term specifies the material affected by internal erosion and deformation processes (such as cover, bedrock, or caprock), while the second part denotes the main process involved (including collapse, suffosion, or bending) (Fig. 1.6).

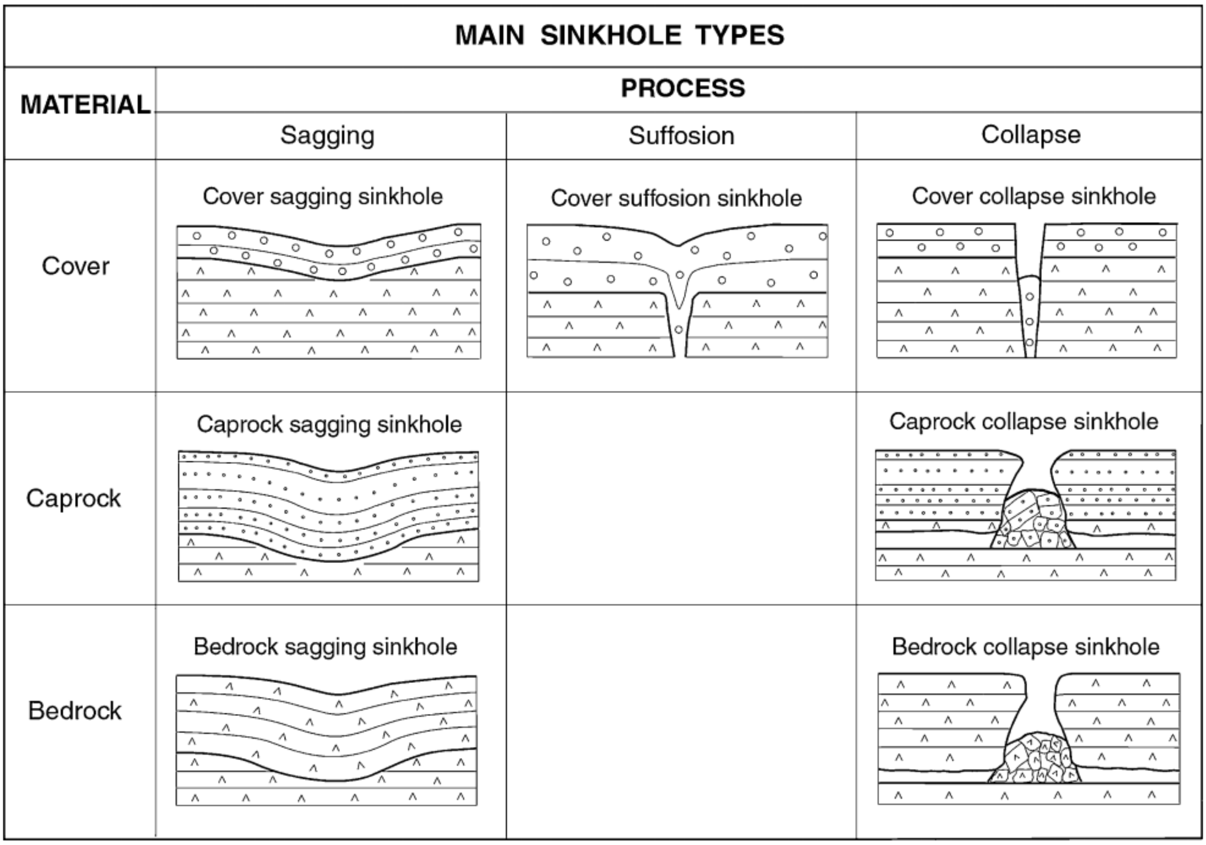


Fig. 1.6. The primary types of subsidence sinkholes are illustrated. However, solution sinkholes, formed by the corrosive erosion of the ground surface, are excluded from this classification [31].

According to [30], in practice, the formation of many sinkholes involves multiple material types and processes. These intricate sinkholes, termed polygenetic, an be categorized using combinations of the suggested terms, with the primary material or process mentioned first, and then the secondary one. For instance, they may be referred to as cover and bedrock collapse sinkholes or cover suffosion and bending sinkholes.

Describe a type of sinkhole called a liquefaction-collapse sinkhole, which develops in areas where karstified rocks are covered by loose soils, either saturated or unsaturated, resting on an impermeable layer [43]. The formation requires specific geological conditions: soluble rocks with cavities or cracks, an impermeable layer with breaches that connect to the cavities, and loose soils above the rocks or layer. The breakdown of the overlying soils happens in a cycle, forming two types of cavities—water-filled (liquefaction) and empty (collapse)—which eventually fill with water, creating inverted cone-like water-filled cavities. (Fig. 1.7).

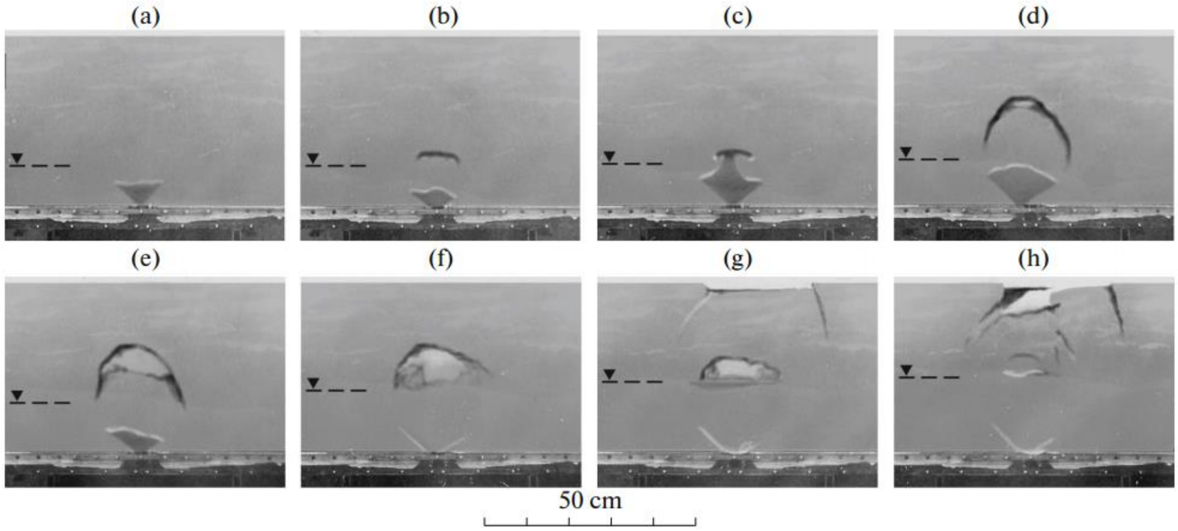


Fig. 1.7. Figure presents the outcomes of a physical model demonstrating sinkhole formation due to groundwater level rise above soluble rock layers, covered by cohesionless soils. The sequence of soil destruction is illustrated as follows: (a) Onset of liquefaction; (b) Initial collapse; (c) Combined collapse and liquefaction; (d–f) Progressive collapse stages; (g) Further collapse and liquefaction; (h) The ultimate development of the sinkhole [43].

1.10.5. Major changes and activities that can trigger sinkhole formation

Natural or anthropogenic changes in karst environments frequently expedite sinkhole formation processes, facilitating or initiating their development or reactivation. Sinkholes resulting from or influenced by human activities are often termed induced sinkholes [30].

According to [33] observed that in the Ebro River valley, situated downstream of Zaragoza in northeastern Spain, the progression of sinkholes was intensified due to human interventions, including irrigation activities and groundwater extraction in industrial zones. Such actions result in abrupt changes in the water table.

Both naturally occurring and human-driven changes can disrupt the karstification process, water aggressiveness, internal erosion, deformational activities, or surface phenomena.

According to [36], several key factors affect the process of evaporite karstification, including:

- Evaporite and aquifer composition: This includes the lithological and mineralogical characteristics of the evaporites and surrounding aquifers.
- Physical structure and texture: Refers to the inherent physical features of the soluble rocks and the adjacent aquifers.
- Water interaction: Encompasses the volume of water that interacts with the evaporites, along with its physicochemical attributes, such as saturation index and temperature.
- Hydraulic conditions and flow dynamics: Considers whether the water flow is laminar or turbulent and whether the conditions are phreatic or vadose.
- Changes in the water table: Also known as variations in the piezometric level.

According to [28], multiple factors contribute to increasing water "aggressiveness" toward specific areas of karst landscapes. Major influences include lithology, climate, and geomorphology, which dictate the rate of dissolution. These factors affect various elements, including temperature, precipitation, effective runoff, soil and rock permeability, and water's chemical composition. As a result, they can intensify deep dissolution processes and trigger surface-related phenomena, such as sinkholes, gravity-driven effects, and localized deterioration of the geomechanical properties of rocks.

Based on [30,42], internal erosion and deformation are largely driven by several elements, including:

- The thickness of the overlying sediments, which refers to the depth of materials situated above the karst zone and voids created by dissolution or upward migration.
- The mechanical characteristics of the cover materials, which can be modified due to dissolution and fluctuations in water content.

- The geometry and dimensions of the subsurface voids, mainly related to the span of cavity roofs.
- The position and movement of the water table, with changes in water levels or piezometric conditions.

According to [37], the surface impacts resulting from deep dissolution are influenced by several key factors:

- The initial volume of the soluble rock.
- The degree and spread of the dissolution process.
- The depth at which the dissolution takes place.
- The rock type and geomechanical properties of the material lying between the soluble rocks and the surface.
- The geomorphological characteristics of the slope.

The main alterations and actions that could trigger sinkhole development are outlined in Table 1.2, as mentioned by [30].

Table 1.2. Key factors affecting the development of sinkholes in karst terrains [30].

Nature of change	**Effects of change**	**Natural Progressions**	**Man induced**
Increased water infiltration	Promotes dissolution and accelerates percolation, leading to increased suffosion; adds weight to sediments, potentially reducing their mechanical strength	Rainfall events, floods, snowmelt, thawing permafrost	Irrigation, leaks from pipes or utilities, water impoundments, runoff redirection from urbanization or soakaways, drilling, unsealed wells, fluid injection

Lowering of the water table	increases the effective weight of sediments due to loss of buoyancy; slow groundwater flow is replaced by faster downward percolation, promoting suffosion, especially when water table drops below the bedrock; drying may weaken mechanical strength; suction effect occurs	Climate change, sea-level drop, drainage network entrenchment	Water extraction for industrial or mining purposes, lowering of water levels in lakes (e.g., Dead Sea)
Water impoundment	Creates steep hydraulic gradients, encouraging dissolution and internal erosion, while also adding additional load	Natural lakes	Reservoirs, man-made lagoons
Thawing of permafrost	Enhances dissolution; significantly weakens sediment strength	Climate change	Development, deforestation
Static loading	Promotes collapse of cavity roofs and compaction processe	Accumulation of natural deposits	Man-made structures, dumping, heavy vehicles
Dynamique loading	Promotes the collapse of cavity roofs and may induce liquefaction or fluidization, leading to a significant drop in soil strength	Earthquakes, volcanic eruptions	Artificial vibrations from blasting or explosions
Sediment thinning above voids	Weakens cavity roofs and may direct runoff, creating local groundwater flow bases	Erosion	Excavation activities
Excavations	Disrupts groundwater movement and can weaken sediments above voids	Formation of natural pipes	Mining, tunneling

1.12. Hazard assessment, prediction and mapping

1.12.1. The evolutive of gypsiferous karst environment

According to [12], the approach for evaluating the hazard of ground movements linked to gypsum dissolution should take into account the various characteristics of soluble environments and their evolution. The approach for the assessment should consider several scenarios, including:

1. **Areas with active dissolution mechanisms:**

These are areas where dissolution processes are actively occurring, causing the development of unstable cavities. The presence of water flow that is unsaturated with calcium sulfate can enhance gypsum dissolution, creating voids that may eventually result in ground subsidence or collapse.

2. **Sectors with pre-existing voids:**

In these regions, voids have been formed due to past dissolution processes. Even if the dissolution is not currently active, these pre-existing voids can pose a risk of collapse or subsidence if they are not properly identified and managed.

3. **Regions with Both Active Dissolution and Pre-existing Voids:**

These areas are particularly hazardous as they combine the risks associated with ongoing dissolution and existing voids. The interaction between active dissolution and pre-existing voids can accelerate the process of ground movement and increase the likelihood of significant surface disorders.

4. **Areas with observed past collapses:**

These regions have a history of past collapses, indicating the presence of voids that may still exist and pose a risk. Monitoring and assessing these areas for potential future collapses are crucial for mitigating hazards and protecting structures and human activities.

1.12.2. Notion of predisposition (susceptibility)

According to [12], unlike earthquakes and floods, which can be approached probabilistically due to their recurring nature, ground movements are irregular events(non-periodic). They evolve gradually and almost unnoticed over extended periods before abruptly accelerating, which makes them challenging to anticipate.

Rather than calculating the probability of occurrence for a specific return period (e.g., yearly, every 10 years, every 100 years), the emphasis is placed on evaluating the site's vulnerability or tendency to experience such phenomena (predisposition or susceptibility) [12].

The core principles of the methodology proposed by [12], include various scenarios of active dissolution and void formation, and are based on data collection to develop a series of parameters that define the hydrogeological, geological, and geomechanical conditions. These parameters consist of:

- Whether soluble materials are present or absent.
- The type of fluid interacting with the soluble materials.
- The patterns of water circulation over time.
- The local geological conditions, as well as the structural and geomorphological setting.
- The mechanical properties of the overlying layer.
- The history of past ground movements, including subsidence or collapses.

1.12.3. Assessment of predisposition

According to [30], reducing the risk of sinkholes requires identifying existing sinkholes and charting areas vulnerable to future events. This process includes gathering precise data on the size and frequency of sinkhole occurrences, along with a thorough understanding of the mechanisms and rates of subsidence. Nevertheless, accurately identifying areas affected by subsidence due to evaporite dissolution remains a difficult task.

According to [25], in order to implement an effective strategy to avoid significant structural failures and damage to buildings and infrastructure, it is essential to evaluate the potential collapse risk and/or vulnerability level. Despite differences in available site-specific data, this information can still be used to establish key criteria for assessing the initial predisposition level [12]. These criteria include:

1. ***Deposit (Geological Data):*** Relates to whether gypsum is present or absent in the subsurface in amounts sufficient to trigger significant surface ground movements. Geological data plays a key role in evaluating this factor.
2. ***Hydrodynamic and Hydrochemical Water Potential (Hydrogeological Data):*** Involves evaluating whether there is aggressive water circulation around gypsum. Hydrogeological data provides insights into the presence or absence of such conditions.

These fundamental criteria offer a foundational assessment of predisposition and serve as essential starting points for evaluating the hazard associated with gypsum dissolution.

Table 1.3 shows the predisposition levels established by cross-referencing the two criteria, which have been classified using summarized data

Table 1.3. Initial qualification of the predisposition [12]

Predisposition to the hazard of ground movements linked to gypsum dissolution		**Hydrodynamic and hydrochemical water potentials**	
		Unlikely circulation or saturated water	**Aggressive water circulation around gypsum**
Deposit	**Absent**	None	None
	Suspected	Unlikely	Likely
	Proven	Unlikely	Likely to highly likely

Predisposition can also be assessed using prediction models based on local settings. After identifying the mechanisms and conditioning factors contributing to past sinkholes, geostatistical analysis via machine learning can be utilized with GIS to create prediction maps. These maps can serve as decision-making tools for engineering and cost insurance assessment.

In this case, prediction models of predisposition are based on assumptions. According to [25,35], To forecast collapse, it is essential to consider the following assumptions:

(1) The occurrence of collapses is influenced by particular factors related to the collapse. (2) Future collapses are likely to happen under conditions similar to those experienced in the past

However, [35] emphasize that predictive models generally incorporate a third assumption:

(3) All historical sinkholes, or a representative subset of them, within the study area have been recognized and incorporated into the analysis.

Also [35] point out that if these assumptions were completely valid, the models would deliver "perfect predictions." However, since this is rarely the case, the predictive potential of these models may be limited.

1.12.4. Assessment of the intensity

Table 1.4 displays the intensity classifications for localized collapses and subsidence according to [12].

Table 1.4. Intensity categories for localized collapses and subsidence phenomena, excluding expected outcomes [12]

Intensity Level	Phenomena	Main judgment criteria (not exhaustive)
Low	Ground Subsidence	Slope <3%
	Collapse	Collapse diameter<3 m
Moderate	Ground Subsidence	Slope <6%
	Collapse	Collapse diameter<10 m
High	Ground Subsidence	Slope >6%
	Collapse	Collapse diameter>10 m

[44] Categorizes subsidence and collapse as a hazard termed subsidence, divided into seven levels: the first five involve no visible to significant depression, while the final two lead to partial or total collapse (Table 1.5).

Table 1.5. Intensity classifications subsidence ground damage [44]

Class	**Subsidence ground damage**
0 None	Not visible
1 Very slight	Not visible
2 Slight	Not visible
3 Moderate	Slight depression in open ground or highway, noticeable to vehicle users, but may not be obvious to casual observers. Repairs generally superficial, but may involve local pavement reconstruction.
4 Severe	Significant depression, often accompanied by cracking, in open ground or highway. Obvious to the casual observer. Small hole may form. Repairs to the highway generally require excavation and reconstruction of the road pavement.
5 Very severe	Rotation or slewing of the ground or significant depression, often accompanied by cracking, in open ground or highway. General disruption of services in highways. Significant repair required.
6 Partial collapse	Collapse of ground or highway, significant open void, services severed or severely disrupted
7 Total collapse	Large open void.

1.12.5. Hazard matrix

According to [12], for the evaluation of hazards associated with ground movements related to gypsum dissolution, a standardized reference grid has been selected, akin to the ones commonly employed in mining risks or natural hazard assessments (Table 1.6). This grid maintains homogeneity and avoids any bias toward either intensity or predisposition when analyzing hazard levels.

Table 1.6. Ground movement hazard matrix [12]

		Predisposition		
		Unlikely	**Likely**	**Highly likely**
Intensity	**Low**	Low	Low	Medium
	Moderate	Low	Medium	High
	High	Medium	High	High

1.12.6. Hazard mapping

To avert subsurface subsidence or collapse and safeguard lives and property, it is crucial to gather and apply comprehensive geoscientific data in urban planning initiatives [25]. The likelihood of sinkhole formation can be evaluated statistically by analyzing the historical frequency of new sinkholes arising per unit area within a specified timeframe. This historical data serves as the foundation for risk analysis modeling, from which a sinkhole frequency map can be generated [42].

Hazard maps should illustrate the likelihood of sinkhole occurrences within each hazard zone, including the frequency of sinkholes per unit area and time or the annual probability of a specific area experiencing a sinkhole event [35]. Furthermore, susceptibility maps represent the relative likelihood of a sinkhole developing at any given location in the future [35]. The assessment of sinkhole hazards must also take into account the anticipated maximum width of new sinkholes, as this determines the maximum distance that must be covered to avert the failure of any building or structure [42].

As stated by [42],hazard mapping in sinkhole-prone areas is carried out through several levels, as outlined in Table 1.7.

Table 1.7. Levels of hazard mapping in areas susceptible to sinkholes [42]

Level	Type of Map	Description
1	Environment maps	Analytical maps providing essential data for future mapping efforts. They include topography, solid and drift geology, geotechnical properties, hydrogeology, surface water drainage, climate, and vegetation.
2	Danger maps	Inventory maps showing the locations of identified sinkholes, including details like size, age, and other relevant characteristics.
3	Hazard maps	Maps that show the likelihood of sinkhole occurrences, combining inventory data with spatial and temporal probabilities. Often referred to as hazard susceptibility maps, zoning is classified into none, low, medium, or high, with clear definitions for each.
4	Risk maps	Maps that combine hazard data with potential consequences. These maps evaluate risk in terms of property, life, and environmental impact. A simple example includes combining a sinkhole hazard map with land-use data to assess risk severity.
5	Management maps	Maps showing the required mitigation efforts, engineering solutions, and procedures. These can also include regulatory maps to guide or restrict development in areas prone to sinkhole hazards.

As noted by [26], Ripon, UK, has implemented a structured planning policy, backed by checklists and formal documentation, to manage and protect development within the region. To streamline this process, the area has been divided into three distinct development control zones: A, B, and C (see Fig. 1.8).

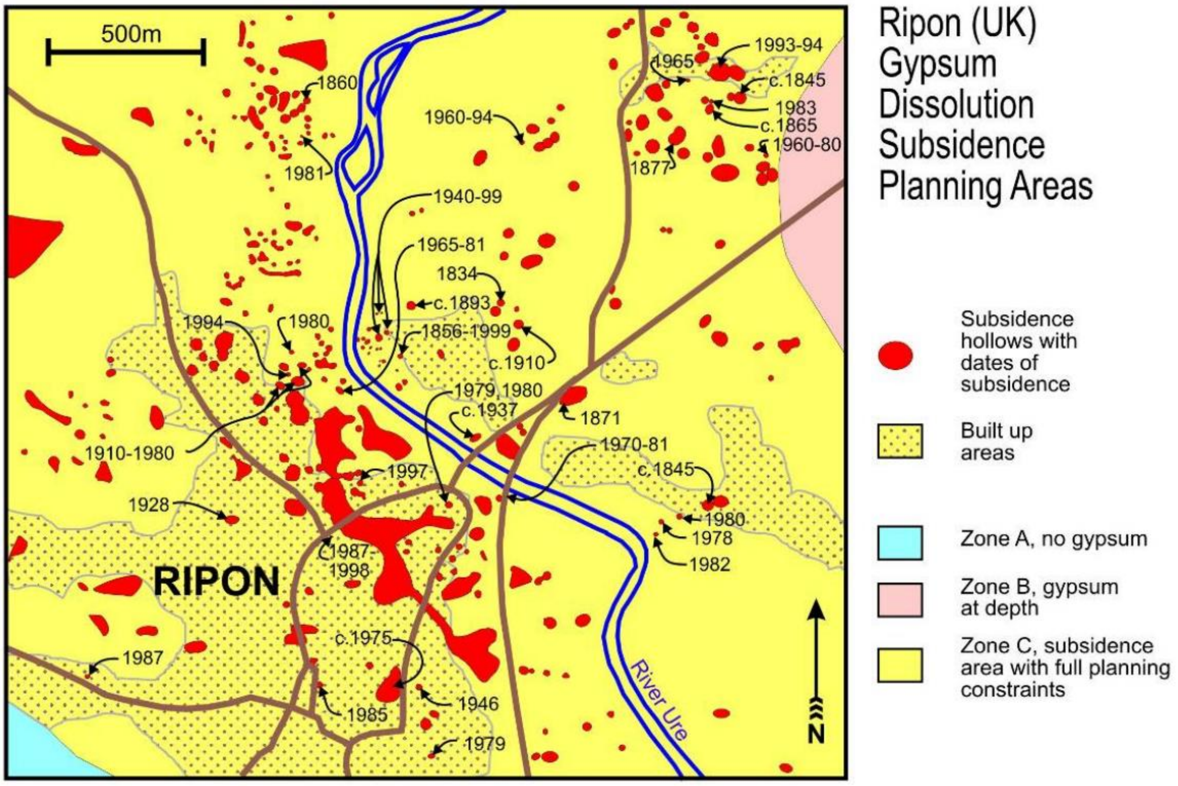


Fig. 1.8. The planning zones and the locations of subsidence hollows within the Ripon area, alongside the available collapse dates (danger map) [26].

- (A) No gypsum detected: No special planning restrictions apply in this zone.
- (B) Gypsum detected at depth: In this area, the subsidence risk is considered low. A stability report, prepared by a qualified expert, is generally required, and the potential risk is factored into local planning decisions.
- (C) Gypsum present and prone to dissolution: This zone is under significant regulatory restrictions and development controls. Local authorities must carefully evaluate the subsidence risk, typically requiring a stability report from a professional before any planning decisions regarding new constructions or changes in building use. This report generally includes a geotechnical desk study, site assessment, and ground investigation to inform foundation design, unless existing data are available from previous studies. Conditional planning approval may be

given, contingent upon applying appropriate mitigation measures, such as specialized foundations, to reduce subsidence risks. A standardized checklist, signed by a competent professional, is essential for this process.

Furthermore, in French, the Tussion park, located near Paris, is experiencing sinkholes attributed to gypsum dissolution. However, the lack of understanding regarding the development and evolution of these sinkholes complicates the implementation of appropriate protective measures. To bridge this knowledge gap, INERIS initiated a hydrogeological and geotechnical study of the area in July 2009. he main goal of the study is to evaluate the risk of subsidence. The obtained hazard map (Fig. 1.9) allows for the implementation of a development strategy aimed at making this green space accessible to the public, at least locally [45].

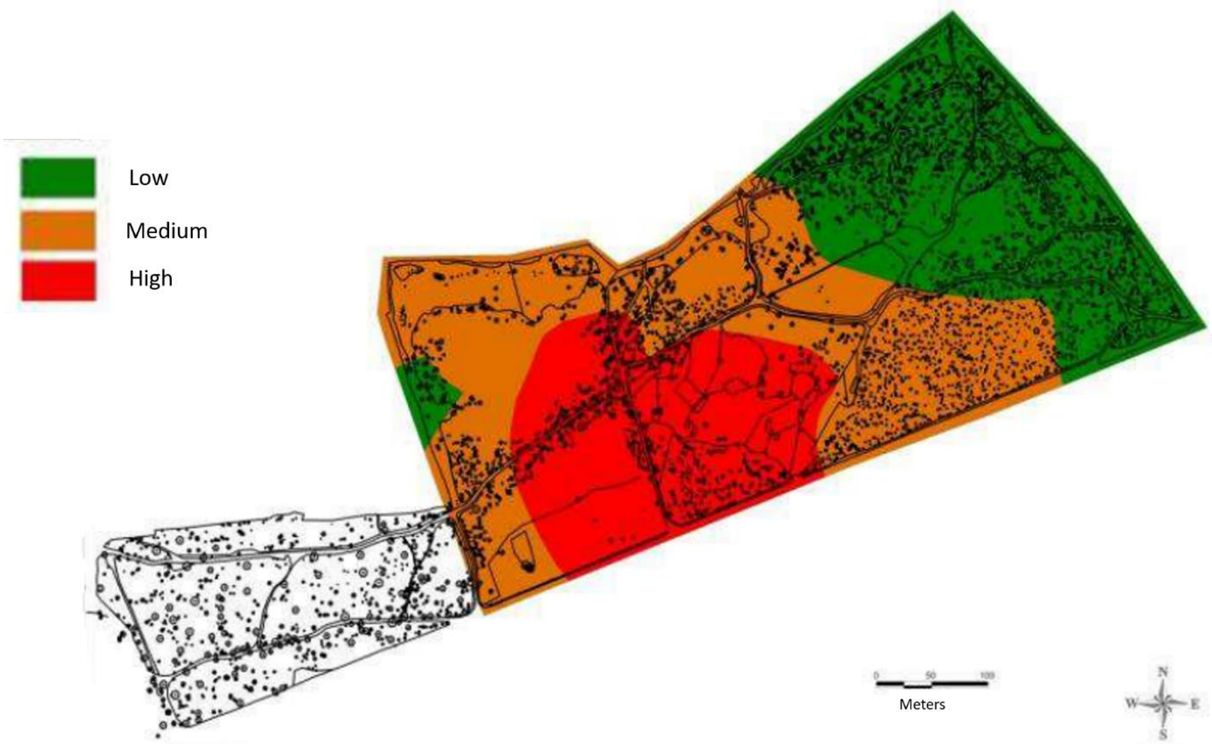


Fig. 1.9. Map of "sinkhole" hazard levels [45].

1.13. Risk on human activity and buildings

Risk assessment typically involves the intersection of hazard, which refers to the likelihood of a phenomenon occurring at a specific intensity, and the exposed vulnerable elements at the surface. Risk is expressed as:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerable Elements} \tag{1.2}$$

According to [36], collapse sinkholes in the Ebro River valley, located downstream of Zaragoza city in northeastern Spain, have an occurrence probability exceeding 140 sinkholes per square kilometer annually. These sinkholes result in significant damage to infrastructure such as roads and railways, buildings, and agricultural lands, while also posing a threat to human safety. [35] also highlight the consequences of sinkhole development in the evaporite karst of the Ebro Valley, which often leads to damage to human-made structures, such as the historic Madrid–Barcelona railway, the N-232 highway, and several buildings.

[37] emphasize through case studies in the Western Italian Alps that the impacts of deep dissolution on human activities and structures become significant when surface movement velocities are measured in centimeters per year, as these rates are incompatible with the stability of buildings and infrastructures. In certain instances, structures have suffered direct damage due to the abrupt sinking of depressions that can extend over several meters (Fig. 1.10).

Fig. 1.10. Severe damage (including open fractures and wall collapses) observed in a rural building at the Cimabosco site in the Susa Valley, Western Italian Alps [37].

The impact of the gypsum dissolution phenomenon on buildings depends primarily on the type of hazard: subsidence or collapse. The range of effects varies from minor cracks to total collapse. In this context, [12] outline the expected consequences in relation to the intensity classification of the phenomenon, whether it leads to subsidence or collapse, as illustrated in the table below (Table 1.8).

Table 1.5. Intensity classifications for localized collapses and subsidence phenomena considering anticipated effects [12].

Intensity classification	Phenomena	Main judgment criteria (not exhaustive)	Expected consequences
Low	Ground Subsidence	Slope <3%	Light ground movement - isolated cracks that do not affect the functionality of the building
	Collapse	Collapse diameter<3 m	A potentially deep hole but sufficiently narrow so as not to immediately affect a conventional foundation
Moderate	Ground Subsidence	Slope <6%	Cracks visible on the exterior. Doors and windows become stuck and some pipes break
	Collapse	Collapse diameter<10 m	Crater +/- deep and wide enough to ruin a recent concrete construction, even in raft foundation
High	Ground Subsidence	Slope >6%	Serious structural ground movement. Buildings uninhabitable
	Collapse	Collapse diameter>10 m	Large crater with steep sides and a risk of the building collapsing into it or complete and immediate destruction of several constructions

Nevertheless, [44] suggests a comprehensive framework that acknowledges the commonalities in ground movement data between landslides and subsidence. This framework includes seven classifications, spanning from minimal subsidence to complete collapse. Each classification is linked to specific types of damage typically observed in buildings corresponding to the respective levels of subsidence ground damage [44].

Table 1.9. Classification of building damage categories according to Cooper's framework [44].

Class	Subsidence ground damage	Typical building damage
0 None	Not visible	Hairline cracking, widths up to 0.1mm. Not visible from outside
1 Very slight	Not visible	Fine cracks, generally restricted to internal wall finishes. Rarely visible in external brickwork. Typical crack widths up to 1mm. Generally, not visible from outside
2 Slight	Not visible	Cracks not necessarily visible from outside, some external repointing may be required. Doors and windows may stick slightly. Typical crack widths up to 5mm. Difficult to record from outside
3 Moderate	Slight depression in open ground or highway, noticeable to vehicle users, but may not be obvious to casual observers. Repairs generally superficial, but may involve local pavement reconstruction.	Cracks can be repaired by a builder. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking, slightly tilting to walls. Service pipes may be fractured. Typical crack widths between 5 and 15mm. Visible from outside

4 Severe	Significant depression, often accompanied by cracking, in open ground or highway. Obvious to the casual observer. Small hole may form. Repairs to the highway generally require excavation and reconstruction of the road pavement.	Extensive damage that requires breaking out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floors sloping noticeably; some loss of bearing in beams, distortions in the structure. Service pipes disrupted. Typical crack widths ranging from 15 to 25mm, with variable number of cracks. Noticeable from outside
5 Very severe	Rotation or slewing of the ground or significant depression, often accompanied by cracking, in open ground or highway. General disruption of services in highways. Significant repair required.	Structural damage requiring major repairs, sometimes involving partial or complete rebuilding. Beams lose their bearing capacity; walls lean badly and require shoring. Windows broken due to distortions. Danger of instability. Typical crack widths are greater than 25mm, with a varying number of cracks. Very obvious from outside
6 Partial collapse	Collapse of ground or highway, significant open void, services severed or severely disrupted	Partial collapse, very apparent from outside
7 Total collapse	Large open void.	Total collapse, very apparent from outside

The damage scheme's lowest 1-5 categories have been effectively employed in the past to document building damage in Ripon, North Yorkshire (Fig.1.11, 1.12 and 1.13).This methodology has also been adapted for use in assessing historical structures in the city of Calatayud, Spain (Fig.1.14 and 1.15) [44].

Fig. 1.11. Category 7 Structural Damage at Ure Bank Terrace, Ripon: This damage, resulting from gypsum dissolution and collapse, has led to a loss of support beneath a significant portion of the building [44].

Fig. 1.12. Category 5 Damage from Sagging Buildings: This damage is attributed to gypsum dissolution and related settlement on peat deposits, located on Princess Road, Ripon [44].

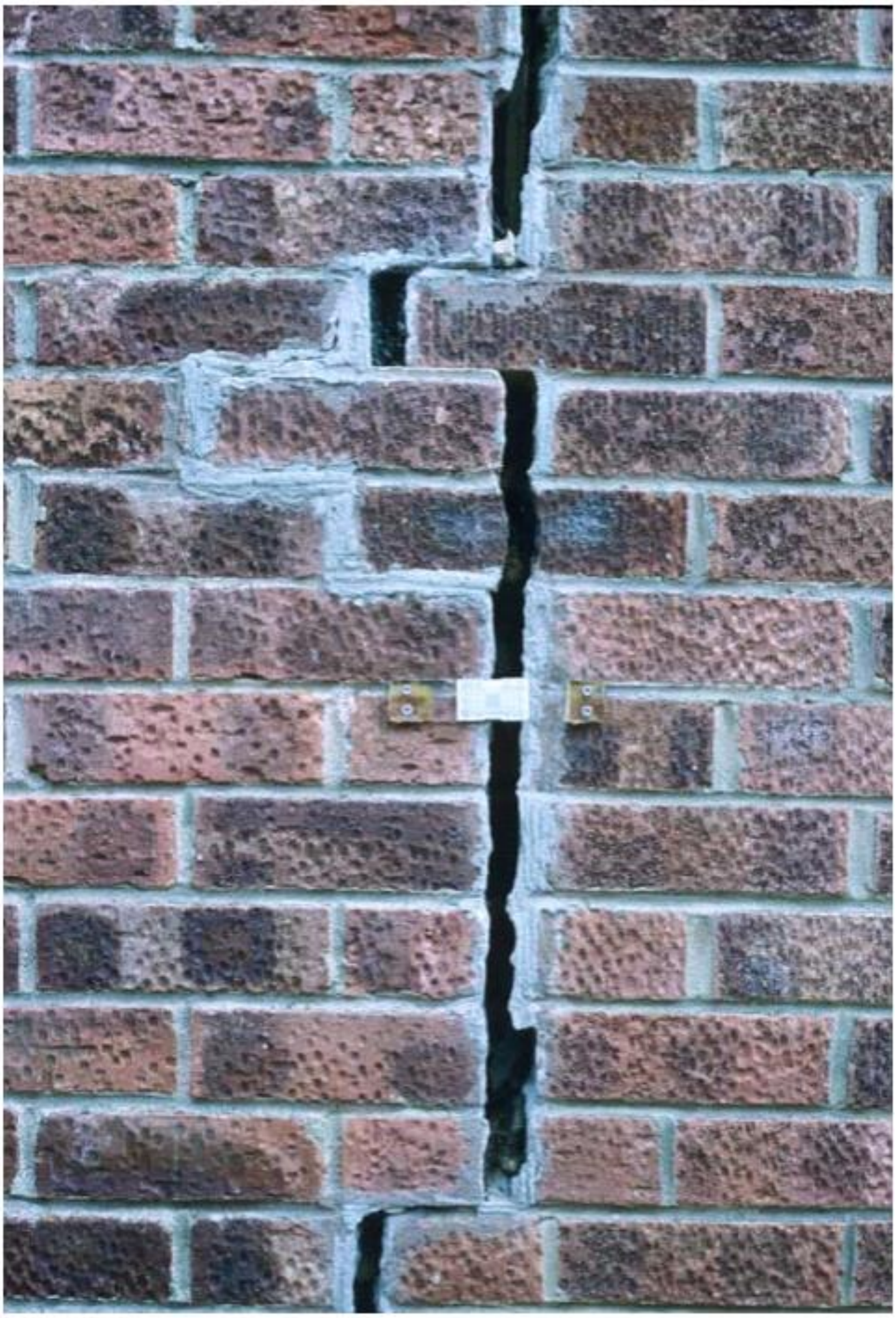


Fig. 1.13. Category 4 Damage: An 18 mm crack in the wall of a house in Hutton Conyers, near Ripon, resulting from subsidence at the edge of a large doline caused by gypsum dissolution. This damage is associated with loss of support and rotation of the floor slab [44].

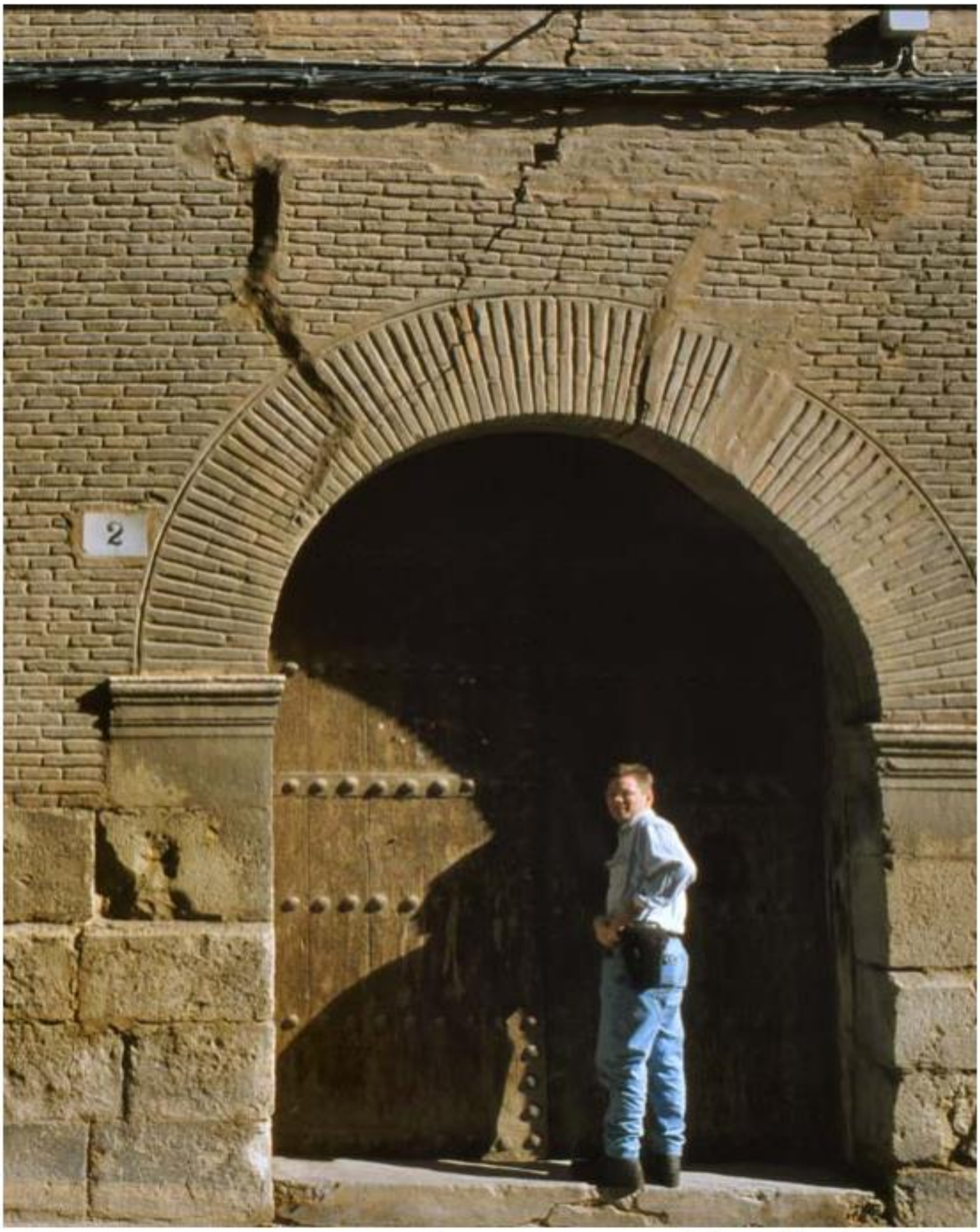


Fig. 1.14. Category 5 Damage: An historic building in Calatayud, Spain, displaying significant damage concentrated in the arch. This damage represents a hogging mode of failure, characterized by loss of support on the right side of the image [44].

Fig. 1.15. Cracks in the historic Colegiata Sta. Maria La Mayor building in Calatayud, Spain, with some cracks reaching widths of up to 30 mm, while others are even larger. The extent of the damage justifies a Category 5 classification [44].

1.14. Investigation of buildings affected by ground movement hazards related to gypsum dissolution and their environments

1.14.1. Approaches

In the building pathology investigation process (Fig.1.16), it is crucial to provide a clear and precise description of the defect and to employ a suitable investigation method that identifies the most probable cause(s) [2].This approach ensures that the root causes of building issues are accurately determined and addressed.

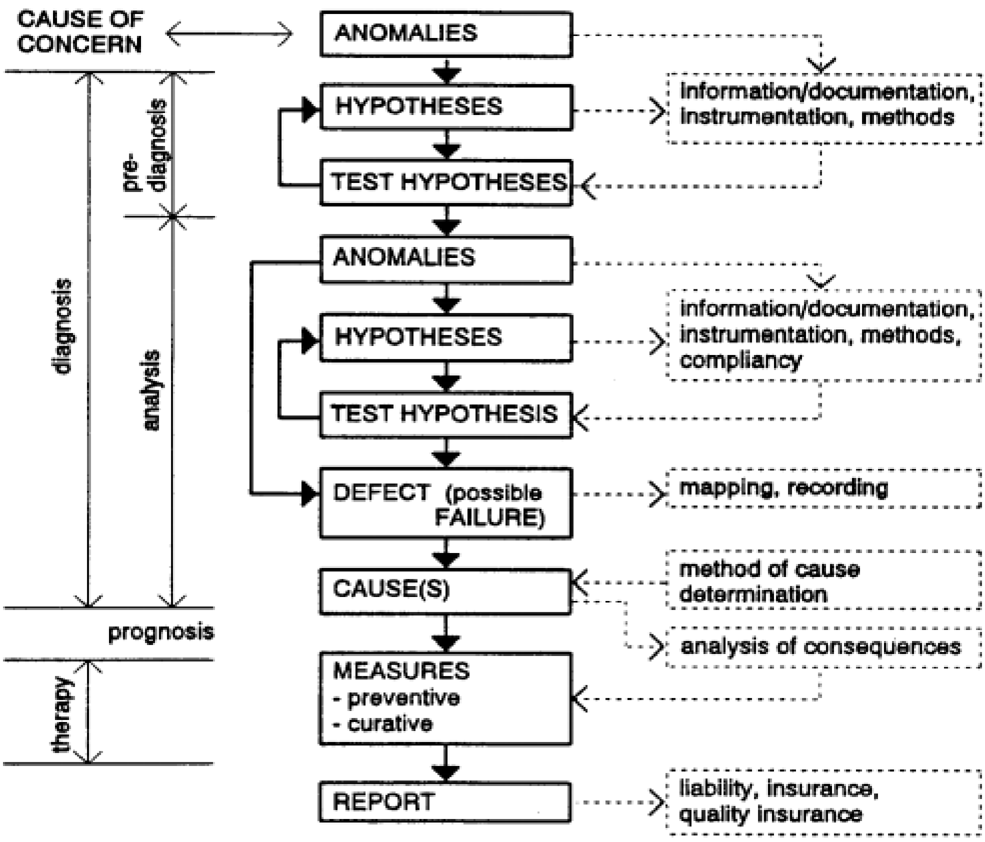


Fig. 1.16. The investigative procedure (After [2]).

When addressing areas susceptible to sinkholes, it is essential to perform a feasibility study before moving forward with any development plans. This study should lead to a thorough ground investigation conducted prior to finalizing the site design and constructing buildings and structures. In karst regions, the ground investigation should focus on locating voids or caves, assessing the properties and characteristics of the soil and rock masses, understanding the configuration of the rockhead, and evaluating the hydrogeological conditions [42].

A decision-making framework for examining potential hazard issues linked to gypsum karstification was introduced by [46]. This framework aims to assist in the characterization and classification of observed gypsum karst, along with the formulation of an appropriate monitoring plan. The framework involves six sequential steps, as outlined below:

1. Accurately describe the observed subsidence.
2. Identify potential causal mechanisms.
3. Create conceptual ground models that include processes influencing the identified mechanisms.
4. Gather data to evaluate various essential processes.
5. Parameterize key fundamental processes.
6. Develop a management plan based on a thorough understanding of these mechanisms.

A standardized approach is the G5 mission in accordance with the NFP94-500 standard. The G5 geotechnical diagnosis is a crucial step in the management of rehabilitation projects and the restoration of existing structures. It involves an expert assessment of the site's geotechnical conditions, aiming to minimize ground-related risks and ensure the stability and safety of the structures.

1.14.2. Stages and techniques

As noted by [42], the initial phase of the investigation includes a desk study and reconnaissance survey. This is succeeded by an in-depth field exploration and ground investigation. Data assessment persists throughout the construction process, as ground excavations uncover additional information about the subsurface conditions.

1.14.2.1. Preliminary stages

The main objective of the preliminary investigation is to assess the appropriateness of a site for the intended projects. If the site is considered suitable, the data collected from the desk study and walkover survey will form the basis for planning additional site exploration. Furthermore, the walkover survey allows for the validation and refinement of certain conclusions made during the desk study [42].

a) Desk study

According to [47], the desk study serves as the initial phase of a site investigation. It's primarily designed to identify and comprehend the fundamental geological aspects, including any potential geological issues such as the presence of gypsum within a specific area. This phase involves reviewing existing geological maps, reports, and available data to gain insights into the geological composition and possible challenges that might affect the site under consideration. The aspects and details of the reviewing process are outlined in Table 1.10.

Table 1.10. The aspects and details of the reviewing process (adapted from [47]).

Aspect	Details
Regional Geology	Examine broader basin configuration and geological formations (e.g., red beds, dolomites, salt deposits). Helps in identifying potential gypsum presence and related issues.
Groundwater Quality	Understand groundwater conditions, including depth, water table, seasonal changes, and chemistry. Evaluate the direction and scale of groundwater flow. Indicators like sulphate-rich or saline springs suggest gypsum presence.
Stratigraphic Information	Study sedimentary basin layers and distribution of gypsum deposits. Contextual geological history aids in predicting gypsum locations.
Mineral Deposits	Review reports and documentation on mineral deposits for insights into gypsum formations. Presence of gypsum extraction industries or mines indicates potential issues.
Borehole Records	Analyze geological data from boreholes for gypsum presence and dissolution signs. Gypsiferous sequences associated with aquifers pose higher risks for subsidence and ground movement.

Historical Records	Investigate historical records of subsidence or collapse events. Prior incidents can signal underlying gypsum-related hazards.

b). Ground investigation field work

As stated by [42], investigation methods can be classified into two main categories: intrusive and non-intrusive. Intrusive methods consist of probing, boring, augering, drilling, trenching, pitting, sampling, and testing. In contrast, non-intrusive methods include aerial or satellite remote sensing and geophysical techniques. Drilling and sampling are essential components of nearly all ground investigations, and their effectiveness is maximized when combined with a comprehensive desk study and appropriate non-intrusive investigations, especially in the complex and varied ground conditions commonly found in karst areas.

b).1. Assessment of air photographs

Airborne survey data is a key method for collecting information in areas where subsidence is suspected. Stereographic aerial photographs, particularly those captured at large scales and under low lighting conditions, are particularly effective. In areas experiencing significant subsidence, these surveys can reveal distinctive patterns, such as poorly drained zones with varied vegetation or water-filled depressions. Scale-accurate orthophotographs offer distortion-free images that can be annotated and utilized as foundational maps for developing subsidence pattern maps [47].

Advanced remote sensing techniques such as airborne multispectral scanning and thermal imaging show promise for locating cavities, especially with modern advances in computer power. High-resolution scanners operating at 1-2 meters per pixel and thermal imaging can help detect subsidence features [47].

The effectiveness of aerial photography and remote sensing imagery can be limited for detecting sinkhole subsidence features only a few meters in diameter. However, advancements in satellite technology are improving this capability. Modern radar systems can now measure ground movements with millimeter precision, even in urban areas (Waltham et al., 2005.

b).2. Geological mapping

According to [47],geological mapping is a crucial step in assessing the risks associated with gypsum-related hazards like subsidence. In areas where local subsidence records are lacking, field geologists play a vital role in gathering this information. Engaging with local landowners and farmers who might have witnessed or experienced unusual events, such as subsidence, provides valuable insights into potential hazards.

According to [47],field techniques, especially when combined with aerial photographs or similar imagery, can aid geologists in identifying crucial features like enclosed hollows or areas where local drainage sinks below ground. Gypsum, due to its solubility, might not be prominently exposed in certain regions, especially in northern regions such as Germany and Britain. Conversely, countries like Spain and Italy may have more frequent exposures.

According to [47], comprehensively mapping the surrounding rock formations is essential for effectively integrating subsidence information into a larger geological and hydrogeological framework. Identifying aquifers and delineating gypsiferous sequences alongside other geological elements helps in establishing a robust framework for assessing and understanding potential hazards linked to gypsum dissolution.

b).3. Building damage survey

According to [47], conducting a comprehensive survey of building damage in urban areas can significantly enhance geological information gathering. In the UK, a technique involving the classification of visible building damage, similar to the approach used for assessing subsidence in coal mining regions, has proven effective. This classification typically includes five recognized categories of building damage.

According to [47], categorizing different types of damage facilitates the generation of subsidence damage data, which can be represented as a contoured map or as a layer in Geographic Information System (GIS) tools. This data illustrating the subsidence pattern can subsequently be compared and integrated with the observable patterns of subsidence hollows identified during geological surveys and aerial photography analysis. By aligning and cross-referencing these datasets, a more comprehensive understanding of subsidence-related risks in urban areas can be achieved.

b).4. Geophysical investigation technique

In areas prone to gypsum-related subsidence, comprehensive site investigations are crucial. Traditionally, these investigations involve drilling numerous boreholes, which can be costly and may miss areas of instability if not spaced closely enough [47]. Geophysical techniques offer valuable tools to address this challenge. Methods such as microgravity and resistivity tomography, as well as ground-penetrating radar in specific areas, help identify anomalies and enable a more targeted borehole program [47].

Geophysical exploration methods are effective for identifying anomalies and variations in ground physical properties that may indicate the presence of subsurface cavities (whether filled with water, air, or sediment), subsidence features (such as breccia pipes, raveling zones, downthrown blocks, or synclinal sags), irregularities in concealed sinkholes, or rockhead topography [30].

Geophysical investigations provide information about larger ground volumes at a lower cost compared to intrusive methods, a significant advantage in sinkhole terrains. For example, the probability of locating a 10 m^2 target with 15 sampling points on a 0.5-hectare site is only 3%, dropping to 1.7% with 85 sampling points over a 5-hectare area. This example is two-dimensional, and uncertainty increases further with the vertical dimension. However, geophysical surveys should complement boreholes rather than replace them, helping to guide their placement [42].

Following the acquisition and analysis of geophysical data, a focused drilling program can be planned, targeting anomalous and potentially stable areas. This approach reduces overall drilling costs while effectively pinpointing areas for further investigation [47].

According to [48], the subsurface geology of Lesina Marina village was investigated using integrated geological mapping, petrographic analysis, and geoelectrical surveys. This approach effectively distinguished between impermeable bedrock and the overlying rock affected by mineral transformations and karstification. These integrated surveys are valuable for hazard mitigation in the area.

b).4.1. Microgravity

Gravity and microgravity surveys detect minor variations in the Earth's gravitational field due to local changes in soil and rock density. These methods are especially effective in karst regions, as negative gravity anomalies can signal "missing mass," which may indicate the presence of open or water-filled cavities, as well as caves and sinkholes containing materials of lower density than the surrounding rock [42].

This method utilizes a highly sensitive gravity meter and requires meticulous leveling of measurement points to calculate gravity anomalies accurately. It is non-invasive and can work within buildings and on concrete but is sensitive to vibrations [47].

In this technique, gravity stations are arranged in a grid pattern across the site, usually 2-4 meters apart. The accuracy of the method can be influenced by external factors like the moon and tides, requiring meticulous calibration and computation of results. This includes conducting repeat measurements and returning to a designated base station on-site. Data processing and analysis are performed using computers [47].

The resolution of microgravity surveys is influenced by the size and depth of the anomaly being studied. Generally, a cavity can be detected at a depth similar to its diameter, with larger cavities, such as breccia pipes, creating more pronounced anomalies. However, certain conditions can complicate microgravity data interpretation. For example, a vertical contact between two deposits with a significant density difference may mask or conceal even a large anomaly related to a cavity or breccia pipe, rendering it undetectable [47].

b).4.2. Resistivity tomography

Resistivity tomography involves deploying electrode arrays into the ground to measure subsurface electrical resistivity. This method is effective in open areas like agricultural land but struggles in areas with cultural interferences such as buried infrastructure, concrete foundations, wire fences, or overhead cables. It is faster and less dependent on precise leveling compared to microgravity [47].

Electrical geophysics evaluates ground resistance to electric current flow, noting that resistivity increases (or conductivity decreases) in the presence of air-filled voids, while the opposite occurs when bedrock voids contain wet clay soils. The objective is to identify and analyze areas of anomalous apparent resistivity. However, the effectiveness of these surveys may diminish in developed regions where buried metal or electrical cables are present [42].

In this method, long cables with electrodes spaced at intervals are laid out on the ground and inserted into the soil, creating a grid pattern. These electrodes are connected to gather resistivity readings, which are digitized to scan between various electrodes and compile a dataset. The site is surveyed at intervals of 2-10 meters, with electrode spacings of 5-10 meters. Closer electrode spacing yields higher resolution data. The collected measurements are processed by a computer to produce vertical and horizontal sections, or "slices," of the area being studied. The resolution diminishes with depth, meaning that deeper layers have less detailed coverage compared to surface layers [47].

A resistivity survey entails placing electrodes on or within the ground surface. In this method, a current is transmitted between two electrodes while the voltage is measured across two others. The resistance is determined by calculating the ratio of voltage to current, and the apparent resistivity is obtained by multiplying this resistance by a factor related to the electrode spacing. Modern equipment enables the deployment of multiple electrodes in a grid arrangement, facilitating different combinations of input and measurement electrodes. Depth profiles are created by increasing the distance between measuring electrodes, while lateral variations are assessed by maintaining a constant electrode spacing. By combining these measurements, an apparent resistivity profile is generated along a section through the ground. Various electrode configurations can be utilized to meet specific survey requirements [42].

Resistivity tomography offers good resolving power and can effectively image bedrock, cavities, and breccia pipes. However, its current depth limit is around 40 meters. For optimal imaging, it is advantageous to survey beyond the immediate area of interest, allowing better visualization of subsurface structures and anomalies. Electrical surveys often exhibit a resolution of about 10% of the depth, making them less effective in karst terrains where distinguishing between large dissolution features and areas with multiple narrow fissures can be challenging. Drilling into identified anomalies often reveals variable conditions that the survey might not accurately capture. Moreover, an area containing hazardous dissolution cavities—some filled with air and others with clay—might not reveal a significant anomaly. This limitation occurs because electrical surveys may struggle to distinguish the individual features that exhibit differing resistivity characteristics [47,42].

The Electrical Resistivity Tomography (ERT) technique has been extensively used by various researchers to study regions linked to gypsum formations.

2D electrical resistivity tomography has been shown to be a reliable non-invasive technique for identifying solution conduits, soil-filled voids, and fractured bedrock in shallow subsurface investigations, as evidenced by its successful application in Culberson County, Texas, USA [49].

Additionally, a significant case study in the Sivas gypsum karst region of Turkey highlights the importance of electrical resistivity tomography (ERT) as an investigative tool for karst issues. Research conducted by [50] illustrates the effectiveness of this method in determining various features, including the depth, size, shape , sedimentary and dissolution zones of gypsum karsts.

Another investigation using electrical resistivity tomography (ERT) at an abandoned gypsum mine in Blackhawk, South Dakota, USA, revealed that the resistivity method effectively distinguishes between flooded and dry zones [51].

b).4.3. Ground probing radar

According to [42], ground Penetrating Radar (GPR) employs high-frequency electromagnetic pulses (ranging from 25 to 1,000 MHz) transmitted into the ground via an antenna, as noted by [42]. This technology detects reflections resulting from differences in the electrical impedance of the ground, which occur at locations where there are contrasts in dielectric constants. GPR surveys can be performed in a linear fashion, like along a highway with equipment towed by a moving vehicle, or arranged in a grid pattern.

[47] report that Ground Probing Radar (GPR) has been successfully employed along a railway line in Spain to identify the surface of underlying gypsum deposits and potential cavities. However, GPR has a limited depth penetration of about 2 to 5 meters in dry granular deposits, and this capability is considerably diminished when clay or water is present. They found that Ground Penetrating Radar (GPR) results in Spain demonstrated a reasonable correlation with approximately half of the anomalies detected by microgravity along the same route.

GPR is effective at detecting near-surface cavities and breccia pipes due to its ability to penetrate the upper layers of the ground. However, its effectiveness is limited by depth constraints and the presence of moisture or clay-rich substrates. [42] further note that the performance of GPR is affected by the ground's electrical conductivity, as wetter materials with higher conductivity and clay soils with lower electrical impedances can restrict depth penetration. In wetter conditions, GPR depth penetration may be reduced to around 2 meters, while in dry conditions, it can reach up to 6 meters. Despite these limitations, GPR can still identify soil disturbances or shallow anomalies that might precede sinkhole development. For instance, in southern England, GPR was able to identify soil cavities at a depth of 1 meter in gravel above chalk; however, it faced difficulties detecting voids at greater depths due to the saturated conditions.

[52] examined the effectiveness of integrating trenching with geophysical methods like ground penetrating radar (GPR) and electrical resistivity tomography (ERT) for sinkhole analysis in a mantled karst region. They investigated two active sinkholes obscured by human-

made materials, caused by different subsidence processes: collapse and sagging. The ERT results for the collapse sinkhole revealed a distinct low resistivity zone indicating the clayey fill within the depression, which helped identify the approximate edges of the sinkhole. Additionally, the GPR surveys offered critical information about the boundaries and 3D structure of the hidden subsidence features, clarifying the prevailing subsidence mechanism.

b).5. Direct investigations

According to [42], no single investigation method is suitable for identifying and measuring sinkholes in every situation. The most effective site investigation in karst areas typically combines both indirect and direct methods. This usually includes a mix of techniques, with drilling and probing being essential. Drilling and probing are also crucial for validating most geophysical surveys.

b).5.1 Drilling

For shallow soil assessments, methods like pitting and trenching are commonly used to allow for block sampling and visual examination. Nonetheless, the depth that can be reached is constrained by safety issues, which may not always be adequate for a comprehensive sinkhole investigation (Waltham et al., 2005). According to [47], drilling remains a conventional technique in site investigations. In certain subsidence-prone sites, a grid-based drilling approach has been employed, aiming to locate subsidence features; however, this method is costly. Geophysical methods, as described earlier, aid in defining anomalous and regular areas on a site.

According to [47], when sites are investigated solely by drilling, closely spaced boreholes (approximately 10 meters apart) are often required, drilling can reach the base of gypsum, which may be significantly deep. However, one concern with drilling investigations is the risk of intersecting a breccia pipe or cave at shallow depths, which could trigger a subsidence event from vibrations or the movement of drilling fluids. This risk should be taken into account when designing site investigations and determining relevant insurance coverage.

In gypsum regions, utilizing sulfate-resistant grout is essential, whereas for other evaporite types, it's important to select grout that is appropriate for the specific saline conditions present. Improperly grouted boreholes can become sites of dissolution, potentially leading to subsidence. For example, in Ukraine, drilling a borehole into a cave led to dissolution caused by aggressive surface water drainage, resulting in the creation of a pipe several meters in width[30].

Drilling methods, as outlined by [47], can be categorized into open hole (chippings) and rotary coring techniques. While open hole drilling tends to be more economical, it can pose difficulties in identifying the collected chippings. During this type of investigation, it's essential to keep a record of the drilling rate, either manually or through an automatic penetration rate logger, as this can indicate cavitation in the area. Cores obtained through drilling should be thoroughly examined for signs of dissolution and cave deposits. A common problem is the misidentification of gypsum as limestone, especially with chippings, leading to many sites in the UK being incorrectly classified as solid limestone when they are actually located on cavernous gypsum.

b).5.2 Probing

According to [42], in karst areas, the main concerns are locating soil cavities (or regolith arches) that can rise to create dropout sinkholes, and identifying areas where the soil becomes disturbed and unstable because of losses into underlying limestone fissures, which could evolve into suffosion or dropout sinkholes. Soil voids can be located using simple probing techniques, though the results of such probing are often considered subjective.

According to [42], the standard penetration test (SPT) is frequently employed in less cohesive soils for probing purposes. This technique consists of driving a split sample tube into the ground by dropping a fixed weight from a predetermined height onto a drive head attached to drilling rods (British Standards, 1999; A.S.T.M., 1999). The N-value, which represents the number of blows needed to penetrate the tube 300 mm, is recorded, typically at intervals of 1.5 meters. Although this method is basic, it is effective and widely recognized, yielding results that are easily interpreted. The split sampler also yields a disturbed sample. Areas of ravelling are indicated by lower N-values, which reflect disturbed and unstable soil conditions. In

Florida's soil-mantled karst regions, ravelling is identified as a vertical zone of cohesive soil with N-values of 2 or below, or non-cohesive soil with N-values of 4 or less. This vertical zone creates a pipe within firmer, denser, or stiffer soil, distinguishing it from a laterally continuous layer of very soft or loose soil.

The Dutch cone or cone penetrometer test (CPT) is particularly effective for investigating cohesive soils. This technique involves the continuous pushing of a friction cone into the ground using hydraulic rams. During the test, both the cone resistance (Qc) and the friction (Fs) on a sleeve behind the cone are measured, allowing for the creation of a continuous depth profile. A porous sensor can also be attached to gauge fluid pore pressure. The friction ratio (Rf), calculated as Fs/Qc, is useful for detecting variations in soil lithology and density. Ravelling zones are typically characterized by low cone resistance, high friction ratios, and negative.

The CPT is cost-effective and straightforward to conduct, requiring minimal supervision and providing easily interpretable results to identify voids and weak zones. For example, over 300 CPT soundings were completed at a 200 ha site in Pennsylvania, where the technique was deemed the most efficient for assessing small areas for building foundations [42].

A study comparing the results of the Standard Penetration Test (SPT) and the Cone Penetrometer Test (CPT) at four sinkhole sites in Florida [53] found that CPT is the more effective method. It offers extensive data, is responsive to subtle changes in lithology, and excels at identifying potential conduits and piping failures. These attributes make CPT a superior technique for assessing ground conditions in sinkhole-prone regions.

b).5.3 Trenching

Trenching provides an effective means to closely analyze the stratigraphy and structure of geological deposits. When used alongside absolute dating methods, it becomes an effective approach for investigating sinkholes in mantled karst environments [30].

This method provides in-depth information on various aspects, including [30]:

- Geophysical Anomalies and Topographic Depressions: It helps clarify the origins of ambiguous geophysical anomalies and depressions.
- Sinkhole Boundaries: It accurately defines the boundaries of filled and inadequately understood sinkhole.
- Deposit Structure: It reveals the structural features of deposits such as synclines, failure planes, and raveling zones, and sheds light on subsidence mechanisms and magnitudes.
- Retrodeformation Analysis: This involves progressively restoring sedimentary bodies to interpret past subsidence events and episodes.
- Absolute Dating: Methods such as radiocarbon dating and luminescence techniques (OSL and TL) offer average rates of subsidence and the timing of subsidence events.

Additionally, trenching, along with topsoil or overburden stripping, can reveal subsidence features on a site during construction, aiding in predicting future sinkhole behavior.

1.15. Mitigation of risks

Once the geohazard associated with gypsum dissolution is assessed, national planning is necessary to avoid constructing buildings in high-risk areas [47]. However, in cases where avoidance of constructing buildings in gypsum-prone areas fails (Occurrence of building pathology due to gypsum dissolution phenomenon), the mitigation approach shifts to preventive and protective measures.

1.15.1. Preventative measures

Defining effective prevention measures relies on a comprehensive understanding of geological and hydrogeological conditions. Technical studies, including geotechnical and hydrogeological assessments, are crucial tools for prevention [12]. These measures should target the underlying causes to halt or reduce the subsidence-inducing processes [54].

1.15.1.1. Water management

Human activities or natural factors have the potential to disrupt sinkhole hazards [30]. Water management measures are a primary approach to preventing the exacerbation of natural dissolution phenomena by altering existing hydraulic gradients [12]. Here are some recommendations that can help mitigate the risk of exacerbating natural dissolution phenomena related to gypsum (Table 1.11).

Table 1.11. Recommended water management measures to reduce the risk of structural issues and ground movement in areas with gypsum deposits adapted after [12,26,25, 54,].

Measure	Details
Avoid Heavy Infiltration due to leakage of pipelines	Using flexible pipes equipped with telescopic joints to reduce the risk of cracks and damage. Examples of failures: Spain [54], Iraq [56], Turkey [55].
Avoid Heavy Pumping	Avoid pumping activities near of buildings. Examples of failures: France [57].
Avoid Disturbing Chemical and Thermal Balances	Minimize activities that disrupt chemical or thermal equilibrium, including geothermal activities. Example of failures: Central Storage Facility in Spain [58].
Monitor Potential Water Inflows	Regularly inspect and monitor sources of water inflows to detect and manage risks from water ingress.
Properly Fill Boreholes and Survey Drillings	Ensure filling materials for boreholes and drillings create an effective seal to prevent water infiltration.
Water Storage Structures	Avoid construction near water Storage structures. Implement measures to waterproof storage structures to prevent excessive water infiltration in gypsum areas.
Divert Surface Water Flow away	Divert surface water flow away from structures using correct drainage to prevent water from concentrating around the foundation (Fig. 1.16).

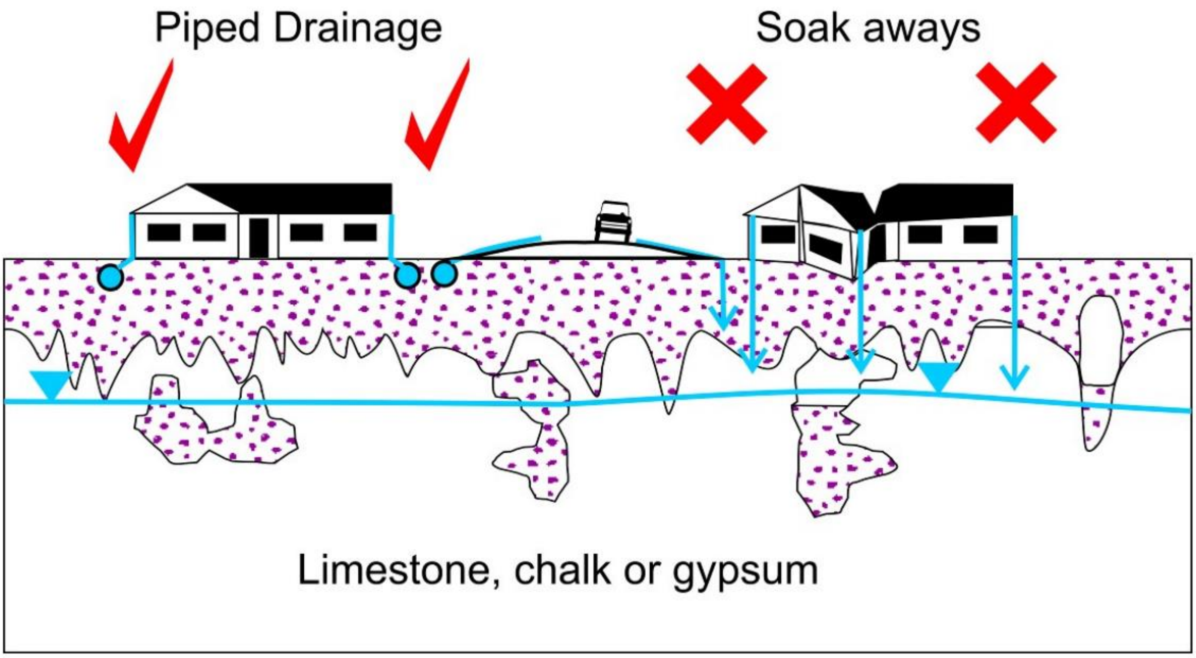


Fig. 1.17. Issues of subsidence due to soakaways and their prevention through proper drainage [26].

1.15.1.2. Piezometric monitoring

Monitoring the piezometric levels of water tables interacting with the gypsum layers offers important perspectives on the whereabouts and progression of the dissolution process [12].

According to [12]**,** continuous and thorough monitoring, especially through a closely spaced piezometric network, is essential for identifying active dissolution zones. Additionally, monitoring water conductivity can help in this identification. However, it's crucial to complement conductivity measurements with chemical analyses to confirm that the observed changes in conductivity are indeed linked to gypsum dissolution.

1.15.1.3. Surface events monitoring

Monitoring historical ground movements is a crucial step in assessing the anticipated level of ground movement and pinpointing active regions, as well as understanding their potential geographic progression. According to [12]**,** to effectively monitor historical ground movements, it is essential to establish a comprehensive database that records surface events. This database should include detailed information such as location (georeferencing), dimensions (diameter, depth, slope), date of occurrence, and the surrounding conditions (environment, exacerbating factors, etc.).

1.15.2. Protective measures

Protective measures encompass the strategies and actions implemented to diminish the vulnerability of assets or prevent significant incidents that could impact people [12].

A conceptual site model is a crucial tool for understanding sinkholes and planning their remediation. It involves gathering data in four key areas: the sinkhole's characteristics, physical site features, the impact of land use and socio-economic factors, and human activities that might influence sinkhole formation. This information helps project teams assess risks, plan interventions, and communicate findings effectively [59].

1.15.2.1. Grouting

Grouting of rock with highly permeable or karstic characteristics involves challenges that are different from those encountered with normal to low permeability rocks. Conventional soil improvement techniques, such as different grouting and densification methods, can be applied to overburden on karst. However, it is crucial to emphasize that these soil treatments are only effective when they are coupled with proper drainage control [42].

According to [12]**,** Based on the condition of the gypsum deposits, injections can serve two main purposes: filling injection and treatment injection.

1. **Filling Injection**

This type of injection is used to fill the voids created by gypsum dissolution. Its purpose is to replace the missing material, stabilizing the ground and preventing further subsidence or collapse.

According to [12]**,** To effectively fill voids, it is recommended to use a cement mortar (Fig. 1.17, box a) that contains a high mineral content, such as sand, fly ash, or fillers for pre-mixed mortars, which helps maintain fluidity. This mixture is injected through a grid of boreholes designed around the vulnerable surface elements. After a 7-day period, a more concentrated grout mixture, with a higher cement content, should be pressurized at approximately 5 bars at the rotary head into the boreholes to fill any remaining voids. This technique, known as grouting, ensures thorough filling and stabilization of voids.

2. Treatment Injection

Treatment injections are designed to consolidate altered or weakened soil by enhancing its mechanical properties to make it suitable for construction or site stabilization. The process consists of injecting the ground and saturating the soil or rock mass with a fluid grout that has a higher cement concentration. This is accomplished using sleeved tubes, which are sealed devices embedded in the ground, enabling targeted injections in specific areas (Fig. 1.17, box b) [12]. This approach aims to increase the soil's resistance and stability.

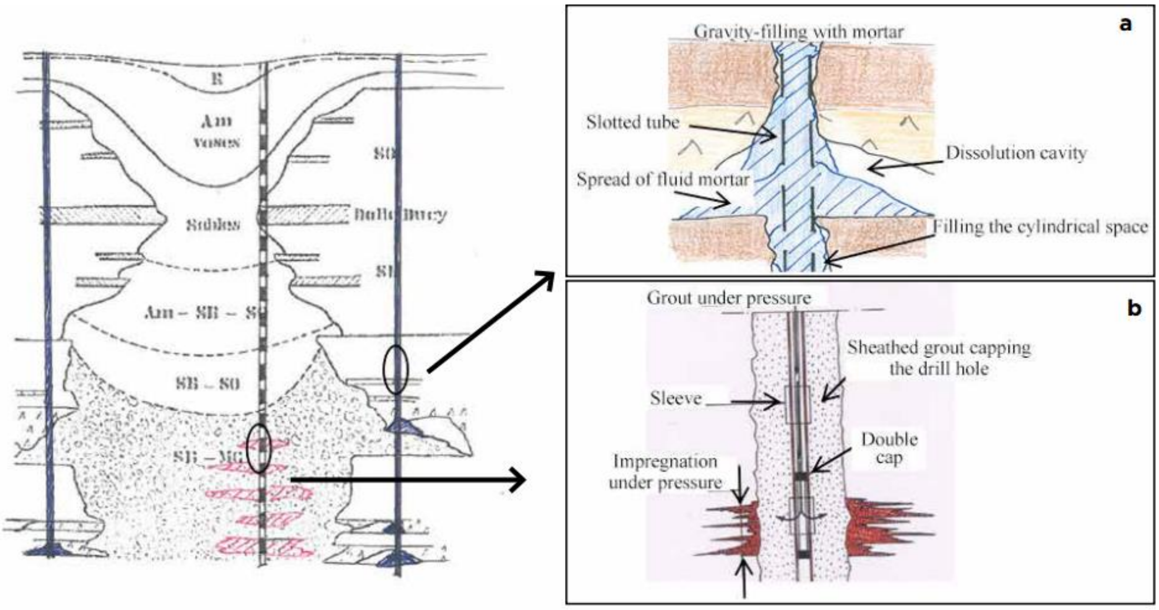


Fig. 1.18. The injection treatment process includes filling the area with mortar, represented in blue, and applying grout treatment, indicated in red, to remediate a dissolving gypsum sinkhole from the Lutetian Paris Basin (Cerema) [12].

Unfortunately, our understanding of these processes remains limited. It is concerning that the effectiveness of grouting still heavily relies on the operator's experience and can only be fully evaluated once the grouting work is completed [42].

In the absence of proper drainage control, failure to manage water flow and gradients can result in dam effects and further ground movement. It is crucial to closely monitor the surface conditions and adjust injection pressures as needed to prevent additional issues during the grouting process [12].

The study by [60] highlights the challenges of managing karstification at the Mosul Dam in Iraq, where water seepage has led to the dissolution of gypsum/anhydrite formations, creating voids that exacerbate the problem. Traditional cementitious grouts have proven inadequate in addressing these issues. The study explores how high-velocity water flow and pressure impact the dissolution of rock and evaluates the use of colloidal silica grout as an alternative. The findings suggest that colloidal silica grout is significantly more effective in reducing seepage-induced rock dissolution, offering a promising solution for stabilizing the dam foundation.

Additionally, grouting can sometimes induce ground heave and lead to building damage, as demonstrated by A case study of the Shenzhen Metro Line 10 construction in Guangdong, China, revealed ground heave of up to 500 mm in this densely populated area with water-rich strata, causing severe damage to nearby buildings, including a customs building that experienced a 200 mm heave. The primary cause was attributed to advanced curtain grouting used during tunnel construction [61].

One recommended approach to controlling grouting parameters is the Grout Intensity Number (GIN) method, proposed by Lombardi (1993) [62].

1.15.2.2. Filling from the surface

According to [12]**,** the surface filling technique is used when a collapse happens near an existing structure or during excavation activities. However, using "hardcore" to fill the collapsed area is often not a long-term solution. Although it may offer temporary stability, there is a significant risk of new subsidence or collapse occurring in the same spot within a few years. This can be especially true following fluctuations in the water table level or significant water infiltration. Effective remediation for a sinkhole should include proper drainage management [42].

To ensure stability during filling, even in the presence of water, two approaches can be considered:

1.15.2.2.1. Filling with Frictional Granular Materials (Inverted filter fill):

According to [42], for effective sinkhole remediation while preserving natural drainage, a common approach is to use simple inverted filter fills, especially for subsidence sinkholes that are relatively shallow . This means starting with fine particles at the surface and gradually transitioning to coarser particles at the bottom of the sinkhole [12].

The procedure starts by filling the sinkhole with large boulders, followed by a soil-cement slurry to seal off the sinkhole's opening [42]. After the slurry has hardened, any loose material from the walls is removed using a backhoe. The next step involves backfilling with a mixture of coarse gravel and sand on top of the boulders, followed by layers of progressively finer sand. Each layer of backfill is compacted using small mechanical compactors. Additionally, soil within a 3–5 meter radius around the sinkhole is excavated, replaced, and compacted, potentially using anchored geogrid for added stability [42]. However, It is essential to recognize that it doesn't eliminate the hazard itself, but rather mitigates the potential consequences of sinkhole formation [12].

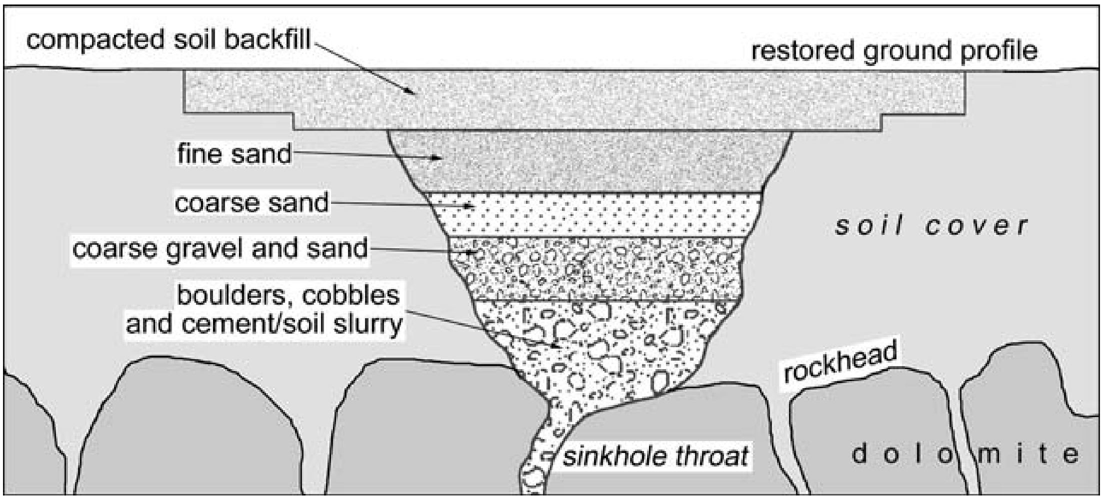


Fig. 1.19. Inverted filter placement for the restoration of a small subsidence sinkhole over dolomite [42] and adapted for gypsum case by [12].

1.15.2.2.2. Closure of the Sinkhole Throat

Sealing a sinkhole requires installing a concrete slab or similar structure at the appropriate depth to effectively close the sinkhole opening [12].

According to [42],when addressing a large subsidence sinkhole beneath a road, comprehensive remediation is often required to restore the road's usability. The traditional repair approach involves a three-stage process: sealing the sinkhole's opening to stop additional collapse, filling the majority of the cavity, and covering the fill with a reinforced structure to stabilize the road.

According to [42], a road in Saucon Valley, Pennsylvania, was repaired after a sinkhole approximately 30 meters in diameter formed over a karstic limestone base, covered by at least 15 meters of soil. The initial repair involved blocking the sinkhole's throat with quarry rock measuring between 150 and 300 mm, followed by a concrete slab and filling with locally sourced silty clay. A gravel mattress, 35 meters long and 1.2 meters deep, was reinforced with 13 layers of polyethylene geogrid with a unit strength of 70 kN/m to support the road and accommodate potential future subsidence of up to 12 meters in diameter. Despite these efforts, the sinkhole reactivated within a year, damaging the road. A later repair involved a 30-meter-long reinforced concrete slab, which has proven effective. The initial failure was linked to the lack of exposed bedrock, which allowed ongoing drainage to erode the soil and plugging materials.

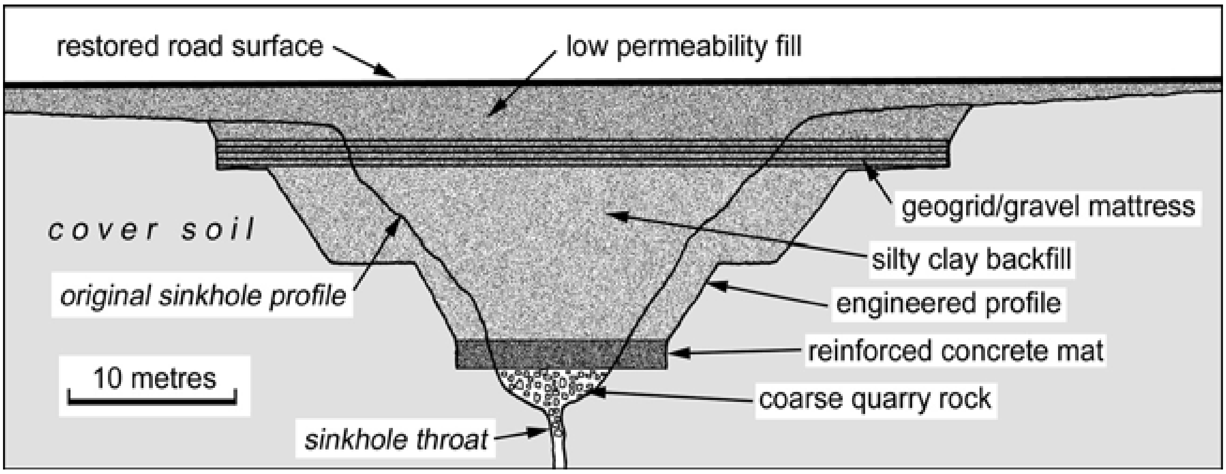


Fig. 1.20. Inclusion of a concrete plug and geogrid mattress in the repair fill for the sinkhole beneath a road in Saucon Valley, Pennsylvania [42] and adapted for gypsum case by [12].

In contrast, a repair effort for a caprock sinkhole in Macungie, Pennsylvania, proved more effective (Fig. 1.20). This sinkhole, which measured up to 26 meters in diameter and 13 meters in depth, had formed above karstic dolomite located 30 meters below a layer of shale and soil. The site previously housed an old pond that had been filled with mixed soil and debris, which was subsequently forgotten. Learning from the Saucon Valley repair experience, the Macungie sinkhole was tackled by filling its throat with 800 m^3 of large dolomite boulders, some reaching up to 1 meter in size, secured with lean-mix concrete. While deeper excavation was limited due to surrounding apartment buildings, the conical plug was capped with a 900 mm thick reinforced concrete slab, and the surface was restored with soil fill. The repaired road has remained stable with minimal settlement, thanks to the effective compaction of the soil fill [42].

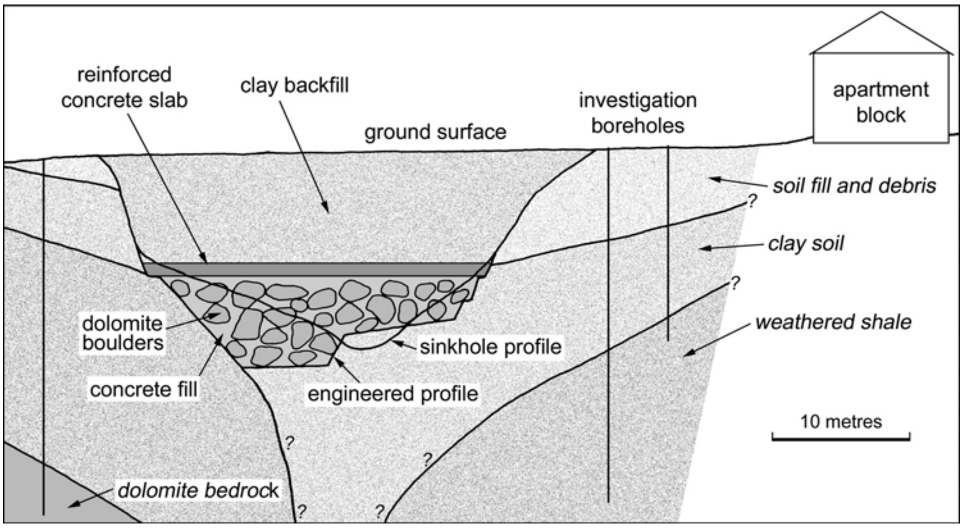


Fig. 1.21. Cross-sectional view of the Macungie sinkhole showing its engineered repair and backfill [42]

For roads, where drainage is managed away from the plugged sinkhole, the situation is less problematic. Geogrid installation beneath a road can be highly effective in preventing immediate sinkhole appearances, but it is not a standalone solution for repair. In cases involving large sinkholes with deep soil coverage, geogrid can function as an early warning system rather than a permanent fix, particularly when the potential for future sinkhole reactivation does not warrant the cost of a substantial concrete slab [42].

[63] address the persistent problem of a sinkhole impacting a driveway in Nashville, Tennessee (USA), which has led to recurring pavement subsidence despite numerous repair efforts. Their investigation involved site visits, drilling, soil and rock analysis, and groundwater assessment. Three potential repair methods were evaluated: standard inverted rock filter repair, the construction of a land bridge, and the use of compaction grouting. The study concluded that compaction grouting was the most effective solution based on technical, situational, and cost considerations.

1.15.2.3. Reinforcement of structures

The need for specific construction measures to ensure foundation stability or minimize structural damage in the event of ground movement depends on the sensitivity of the planned construction and the feasibility of ground treatment. These measures may be necessary to mitigate the impact of potential ground movements on the structures [12].

1.15.2.3.1. Designing shallow foundations considering the possibility of localized collapse

This method involves engineering the support structures (foundations and load-bearing walls) to endure a collapse of a specified diameter anywhere within the foundations' limits without incurring major damage [12].

The stiffening and enlargement of foundation elements (such as the invert section or footing) should be designed to enable the "bridging" of the collapse. This indicates that the remaining contact area between the ground and the foundation must be adequate to efficiently transfer the loads [12].

This method typically requires larger dimensions compared to conventional foundations to achieve greater foundation rigidity (Fig. 1.21). This may involve extending the footings and increasing the thickness of the rafts [12].

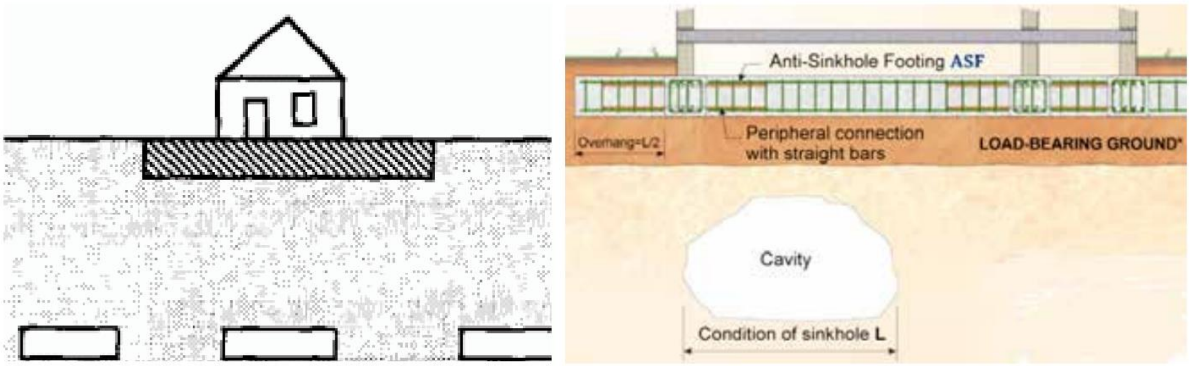


Fig. 1.22. A diagram illustrating the principle of foundation stiffening and an example demonstrating the concept of determining the dimensions of an anti-sinkhole footing [12].

1.15.2.3.2. Ladder structure (According to [47])

In cases involving small buildings where potential collapses may have dimensions comparable to those of proposed developments, one possible solution is to link the foundations to form a "ladder" framework that can bridge the collapses (Fig. 1.22). Additionally, to safeguard the main services (such as water, electricity, drainage, and gas) for the developments, these services should run on reinforced sections of the foundation structure and be constructed with flexibility.

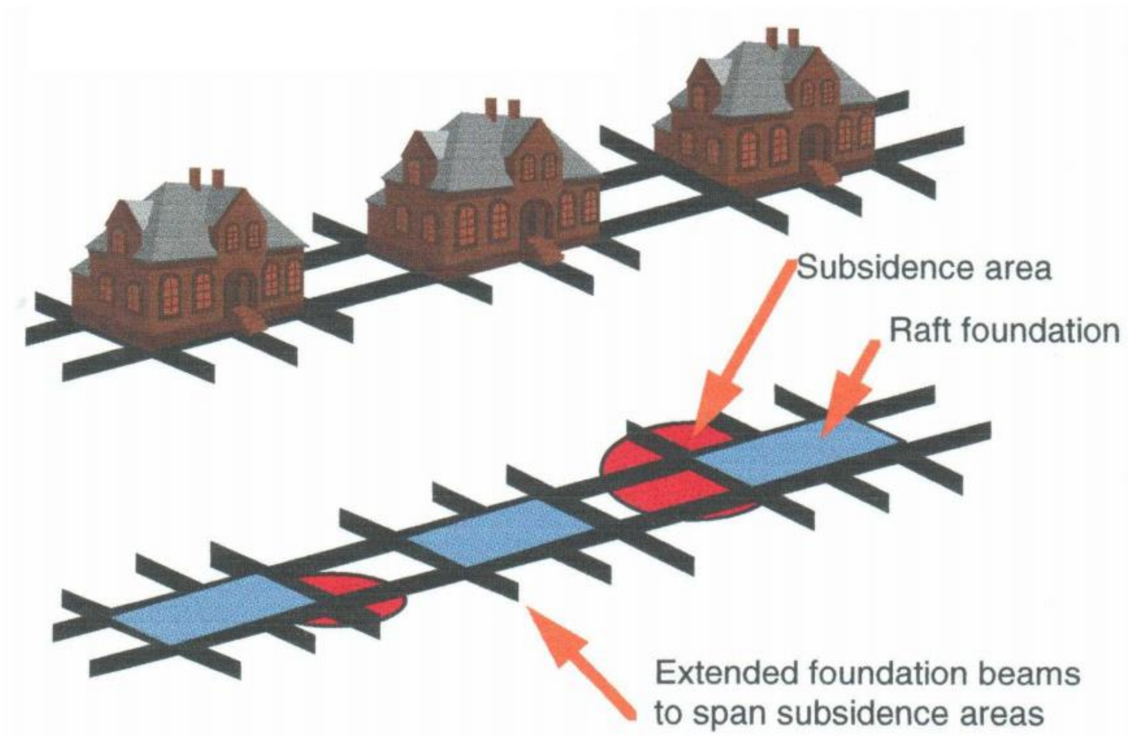


Fig. 1.23. Ladder structure capable of spanning the collapses [47].

1.15.2.3.3. Adjustment for deep foundations

According to [12], when gypsum layers are located at a relatively shallow depth, deep foundations can be used with their bases anchored below the horizons affected by dissolution. The design of these foundations considers both their main load-bearing points and any additional forces, such as negative friction, that may affect regions with cohesionless or altered soil resulting from dissolution.

According to [12], Constructing this type of foundation may require initially filling the voids created by dissolution or installing a lining to prevent the loss of concrete (Fig. 1.23).

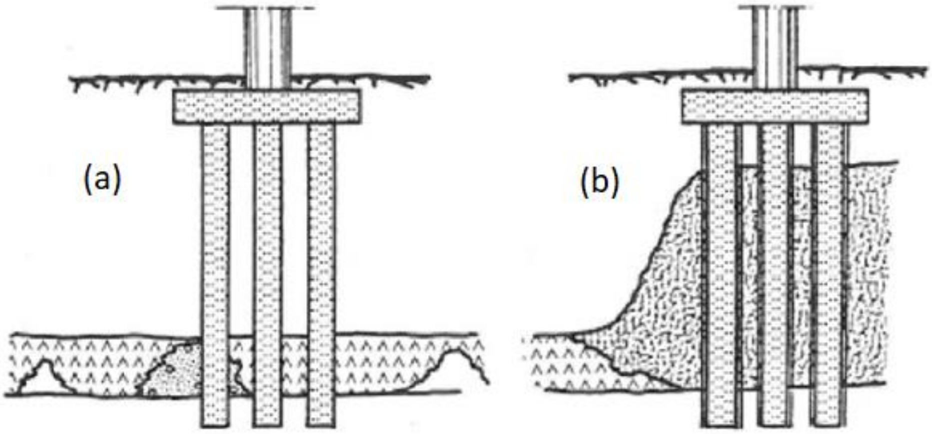


Fig. 1.24. Deep foundations secured beneath a dissolution zone can be accomplished using two techniques: (a) gravity filling of the cavities or (b) lining with pile footings [12].

However, the use of piling may establish hydrological pathways that connect to the upper gypsum layers, which are susceptible to dissolution. The paleokarst in the Calatayud region of northeastern Spain suggests that deep-seated dissolution within the halite and glauberite-bearing evaporite sequence could lead to stability problems for foundations situated on the rockhead [54].

Additionally, significant harm to historical structures in Calatayud, including the Colegiata de San Pedro de los Francos and Santa Maria la Mayor, has resulted from incomplete underpinning and minipiling. Incomplete or prolonged work has led to severe subsidence, particularly where finished and unfinished sections meet [54].

1.15.2.4. Techniques for repairing building cracks [64]

Several effective methods exist for repairing building cracks [64]:

1. ***Epoxy injection***: This technique seals cracks as narrow as 0.002 inches (0.05 mm) by creating entry and venting ports, sealing exposed surfaces, and injecting epoxy under pressure. While suitable for various structures, recurrence may occur if the underlying cause remains unaddressed.
2. ***Routing and sealing:*** This method is ideal for remedial repairs that do not require structural intervention. It involves widening the crack and sealing it with an appropriate joint sealant, commonly used on flat surfaces like floors and pavements but applicable to vertical and curved surfaces as well.
3. ***Stitching***: Involves drilling holes on either side of the crack and placing U-shaped metal units (staples) across the crack to restore tensile strength. This process requires cleaning the holes and securing the staples with a non-shrink grout or epoxy resin.
4. ***Drilling and plugging***: This method entails drilling along the crack and grouting it to create a key, making it suitable for relatively straight cracks accessible from one end. It is typically used for vertical cracks in retaining walls, involving a 2 to 3-inch diameter hole.
5. ***Gravity filling***: This technique uses low-viscosity monomers and resins to seal cracks ranging from 0.001 to 0.08 inches (0.03 to 2 mm). The surface must be cleaned and allowed to dry before filling for optimal results.
6. ***Overlays or surface treatments:*** hese techniques are used for cracks with no significant movement. Unbonded overlays can be applied over slabs, while surface treatments help prevent further deterioration. Overlays serve as protective layers that enhance reinforcement and protection.

1.16. Conclusion

Building pathology linked to the gypsum dissolution phenomenon encompasses defects resulting from the mechanical instability of building foundations. This instability stems from the chemical dissolution process of gypsum minerals within underground formations containing gypsum. The resultant disturbance in the equilibrium of stress distribution within the building leads to structural damage, safety concerns, and substantial economic repercussions.

From the literature review, it is concluded that the issue of building cracking associated with soil movement due to the gypsum dissolution phenomenon can be divided into two major problematics:

- **Diagnosis**: The primary objective here is to link the observed cracking to soil movement caused by a mechanism associated with the gypsum dissolution process. This involves understanding the underlying factors from the dissolution to the appearance of cracks on the buildings. This includes the utilization of all possible approaches, methods, and techniques to describe the mechanism of failure.
- **Mitigation of Building Failures**: This problematic focuses on developing appropriate risk prevention plans. The primary objectives include:
    - ✓ Avoiding construction in areas predisposed to soil movement hazards due to gypsum dissolution.
    - ✓ Implementing preventive measures or remediation strategies in areas where buildings are already affected. This could involve soil stabilization techniques, improving conception systems, or other engineering solutions to minimize the impact of gypsum dissolution on existing structures.

Chapter 2: Prediagnosis of the Case Study

2.1. Introduction

Ouled Djellal is a recently formed state, established in 2019 when it was separated from the larger Biskra state. Located in the arid Sahara region, it lies approximately 100 kilometers southwest of Biskra. It borders M'sila to the north, Ourgla to the south, Elm'ghair to the east, and Djelfa to the west. In the northwestern part of the capital city of this state, 53 out of 55 buildings exhibit typical damages attributed to a pathology associated with unidentified soil movement mechanisms, according to preliminary inspections.

In order to identify the mechanism underlying building pathology, an investigation approach starting with a prediagnosis phase has been applied. This chapter discusses this phase.

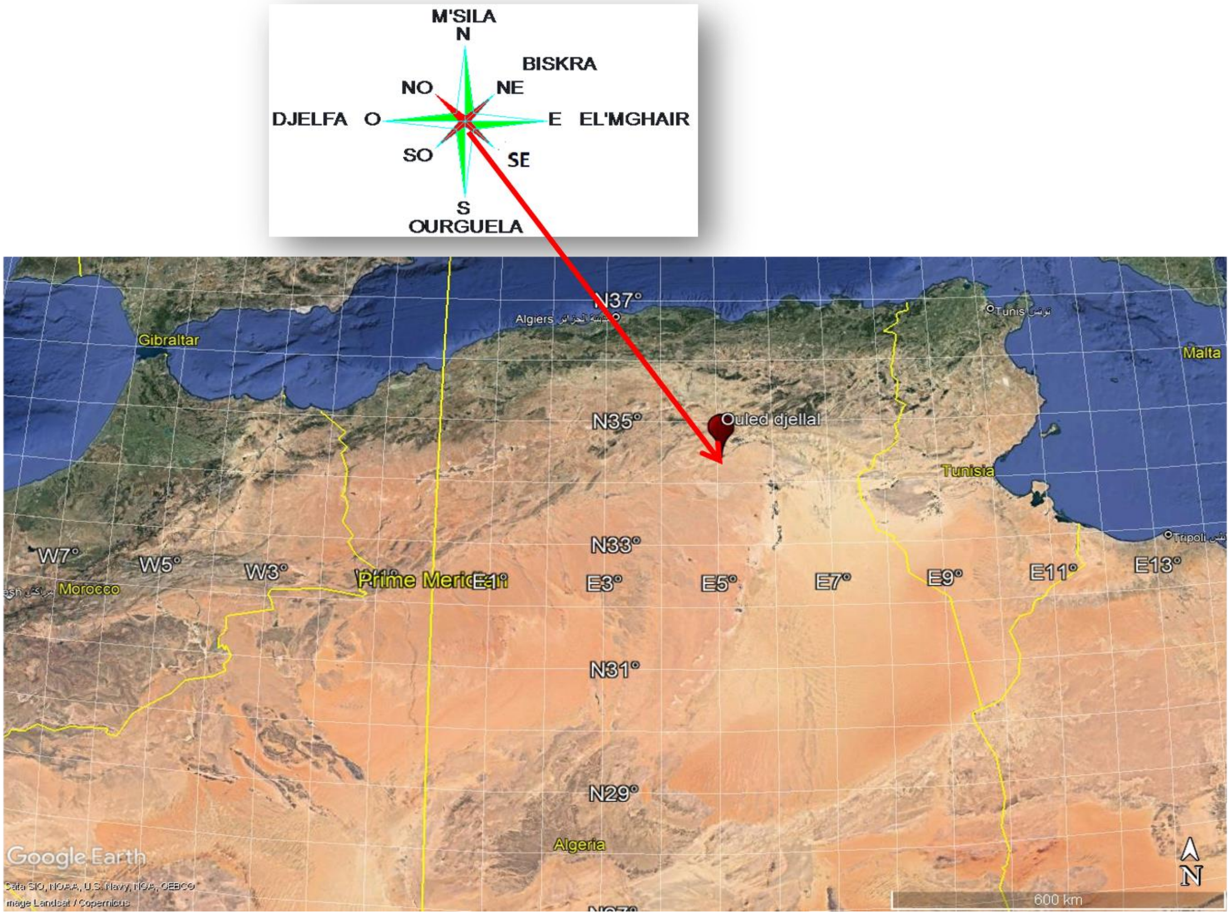


Fig. 2.1. Geographic localization of Ouled Djellal state.

2.2. Materials and methods for the prediagnosis

2.2.1. Selection of Buildings

Fifty-five (55) have been carefully selected as the sample for the prediagnosis. The selection process was guided by several criteria. Firstly, these buildings were constructed using similar materials, designs, and construction techniques, allowing for a comparative analysis of the defects. Secondly, they were all built within the same time frame, which facilitated the identification of common factors contributing to the building failures. Additionally, the selected buildings shared similar occupancy rates and maintenance histories.

The building documentation showed that the affected buildings in this area were built between 2014 and 2019; they comprised a ground floor and four stories. It is worth noting that the construction of these buildings encompassed various shapes, including T-shape and rectangular-shape building configurations. In addition, a number of expansion joints were integrated between the buildings with the aim of accommodating any potential movement. The overall structure was constructed using a concrete shell with a reinforced concrete portal frame. Moreover, for masonry construction, hollow red clay bricks were used in conjunction with cement-based mortar. In addition, the foundation system employed a combination of isolated or combined footings anchored at a depth of 1.50 meters without any waterproofing measures that could contribute to the water infiltration problem, according to the analyzing of initial geotechnical report (2014) and the construction plans.

Table 2.1. Statistics of the affected buildings across the area 1, 2, 3 and 4.

Area	Statistics
01	• 19 residential buildings (17 affected) (05 blocks were still under construction and 03 were affected)
02	• 18 residential buildings (17 affected)
03	• 04 residential buildings (04 affected)
04	• 14 residential buildings (13 affected)

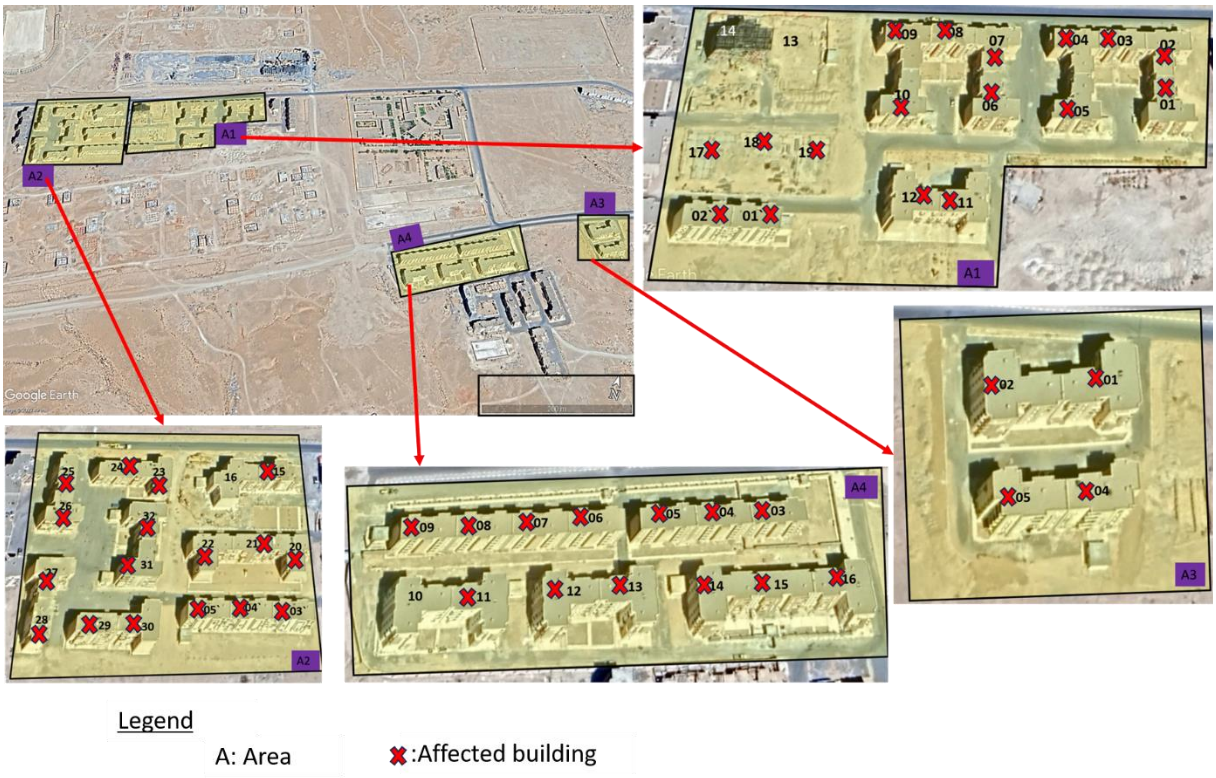


Fig. 2.2. Distribution of buildings across different areas (A1, A2, A3, and A4) and identification of those affected by the pathology of cracking in the northwest of Ouled Djellal city, Algeria.

2.2.2. Prediagnosis methods

The initial diagnosis was conducted by analyzing all available data related to the buildings. This process involved examining the buildings' documentation, including the initial geotechnical report (2014) and the construction plans. Additionally, the geological map of the region and visual inspections were reviewed, both at the regional level and within the specific area where the buildings were situated. The prediagnosis is divided into two major parts: the analysis of the buildings' defects and the analysis of the surrounding environment.

2.3. Prediagnosis results and discussion

2.3.1. The analysis of the buildings' defects

The locations and severity of the building's defects were carefully documented during the inspection process. It was observed that the buildings experiencing failures exhibited varying typical building defects that have an evolving character and various degrees of damage.

2.3.1.1. Buildings titling

The observed building tilting refers to the horizontal displacement of the building due to underlying ground movement. In situ, at the dilatation joint between adjacent buildings, this tilting was visually apparent in the form of divergence that increases along the height of the adjacent buildings in the case of isolated acroter (Fig. 2.3(a)). Additionally, concrete cracking (Fig. 2.3(b)) and dilation of the steel reinforcement bars (Fig. 2.3(c)) were observed in the case of combined acroter.

This dynamic of the building may serve as an indicator of subsidence hazard. In such hazards, sagging and hogging zones form, which may explain the divergence due to the combined footing situated on hogging zones that experience an uplift.

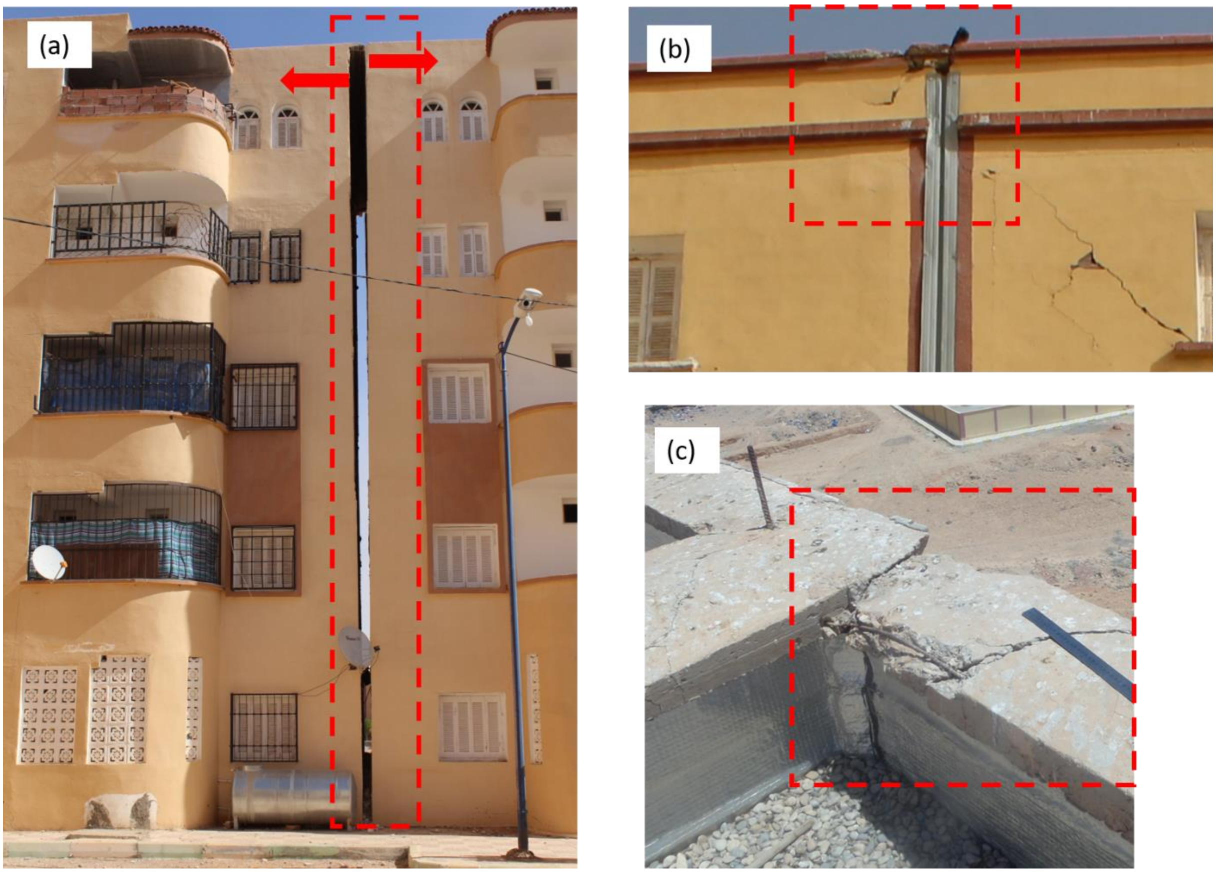


Fig. 2.3. Tilting of buildings: (a) buildings 12 and 13 of area 4. (b) and (c) buildings 4 and 5 of area 3.

2.3.1.2. Horizontal column cracking at the ground floor

Horizontal column cracking refers to the formation of horizontal cracks in the columns of buildings (Fig. 2.4). These cracks typically appear parallel to the transverse section of the column and often coincide with the swelling of the plaster. Horizontal column cracking may occur due to the differential tilting between the ground and the fourth floor of the buildings resulting from foundation settlement and subsidence hazards.

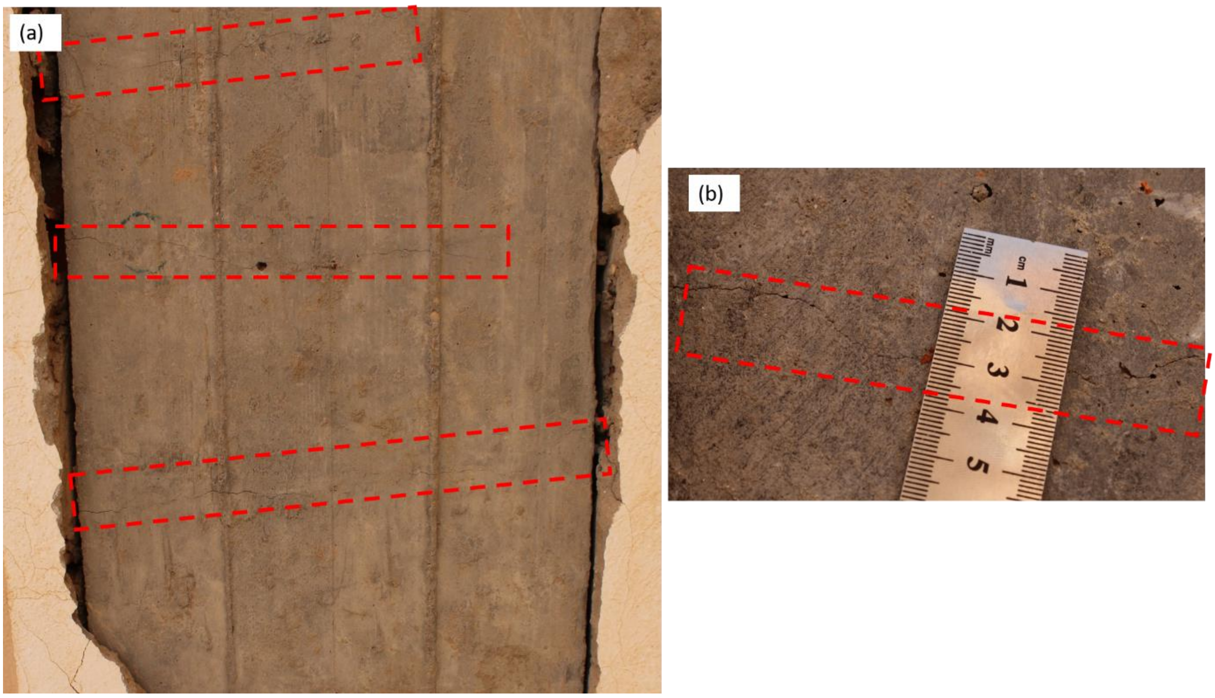


Fig. 2.4. Horizontal column cracking recorded: (a) on the building 1of area 1 ;(b) on the building 4 of area 3.

2.3.1.3. Plinth beam cracking

Plinth beam cracking is a notable type of building defect commonly observed in situ (Fig. 2.5). This damage has been recorded both on the interior (Fig. 2.5(b)) and the exterior (Fig. 2.5(a)) of the buildings. It refers to the formation of cracks in the plinth beams, which serve to solidify the building's support structure. The subsidence of the soil beneath the foundation may impose horizontal tensile and shear forces on the plinth beams, resulting in cracking. These cracks typically appear along the transverse section of the beams and may have vertical or inclined orientations.

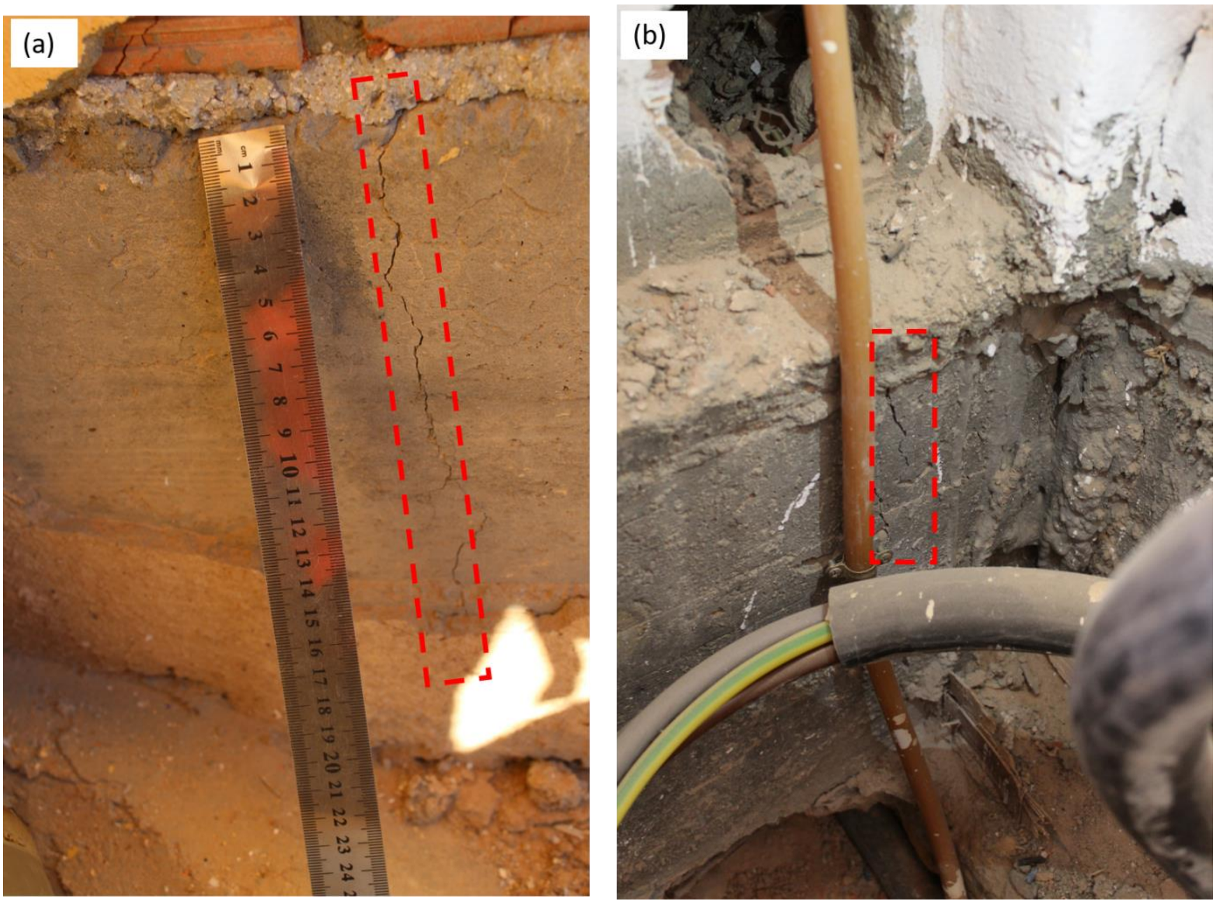


Fig. 2.5. Plinth beam cracking recorded on: (a) Exterior of the building 4 of Area 3; (b) Interior of the building 13 of Area 4.

2.3.1.4. Diagonal masonry wall cracking

Diagonal masonry wall cracking is a prominent type of building damage (Fig. 2.6) observed in situ. It is characterized by its distinctive zigzag pattern and may result from the relative rotation of the masonry blocks, initiated by the differential settlement of the building's support system.

These cracks originate from the corners of windows or doors and propagate diagonally across the walls. A notable observation during the investigation was that diagonal masonry wall cracking was particularly evident on the ground floor, gradually diminishing in visibility, and eventually becoming absent on the third floor (Fig. 2.6 (a)). This distribution pattern suggests that the lower levels of the building experience a greater response to the effects of differential settlement.

Furthermore, it was notable that the interior walls, which have the role to separate the variety of functional designs such as kitchen and room areas, experienced high cracking (Fig. 2.6 (c)). This may be explained by two main causes: the high loadings of the building's interior and the absence of plinth beams beneath those interior walls.

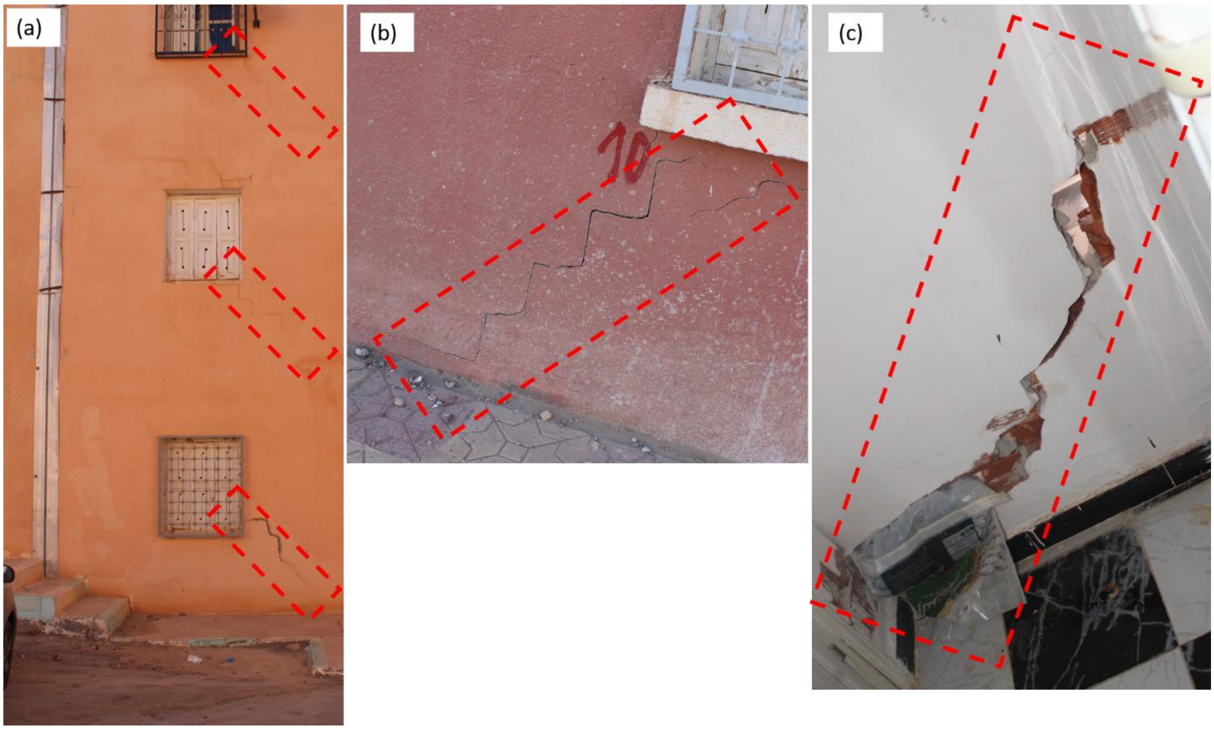


Fig. 2.6. Diagonal masonry wall cracking recorded on: (a) Building 5 of Area 1; (b) Building 8 of Area 1, (c) Interior of the building 4 of Area 3.

2.3.1.5. Diagonal decorative perforated concrete panel cracking

The diagonal decorative perforated concrete panel cracking is characterized by the development of cracks in decorative concrete wall panels that feature perforations or openings intended to enhance the aesthetic appeal of the building's facade. The presence of numerous openings and the material of these panels may exacerbate any movement, leading to the formation of diagonal cracks.

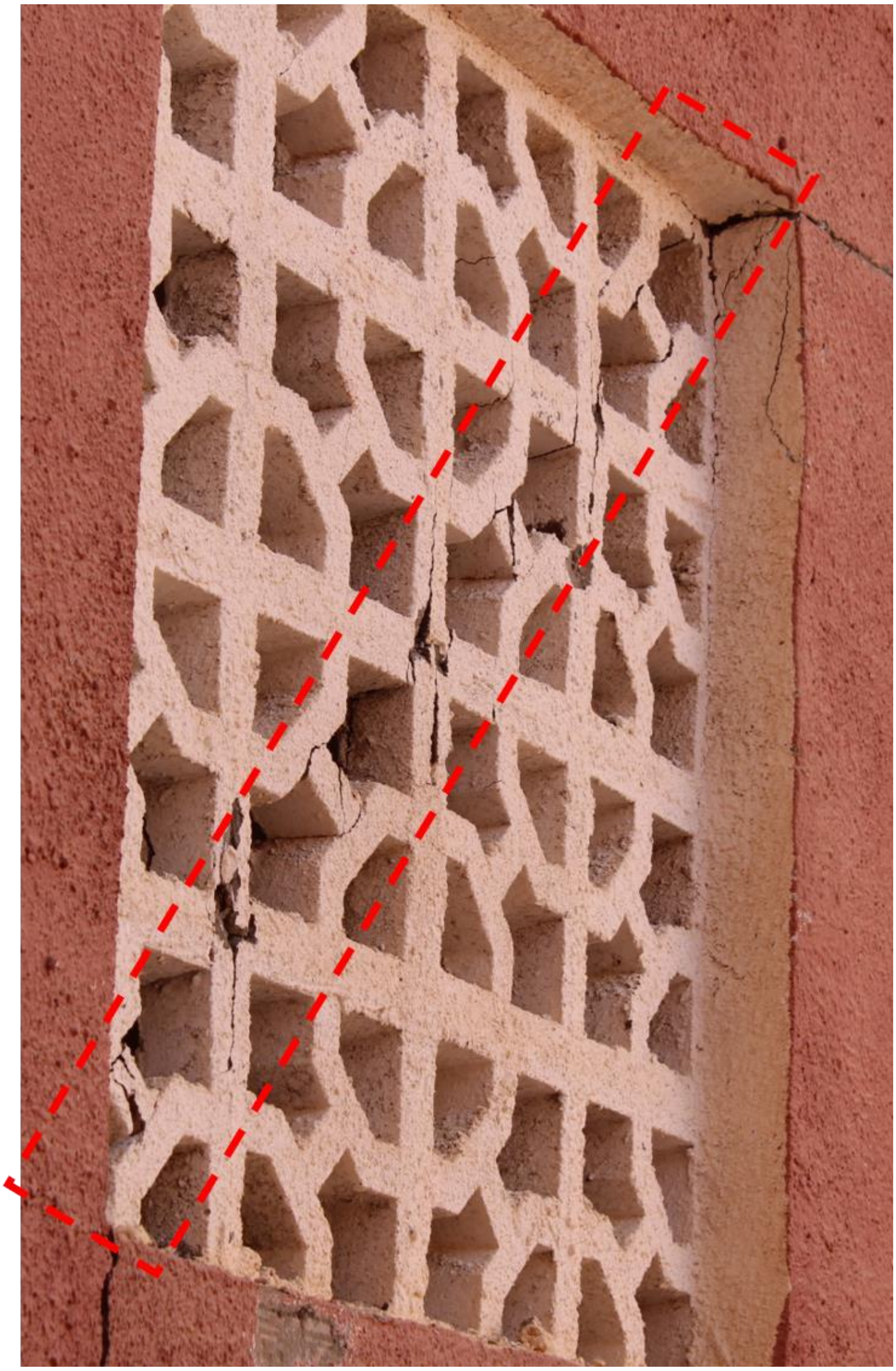


Fig. 2.7. Diagonal decorative perforated concrete panel cracking recorded on building 8 of Area 1.

2.3.1.6. Sticking of doors and windows

The sticking of doors and windows refers to the difficulty or resistance experienced when trying to open or close doors and windows within the affected buildings. Differential vertical displacement of the building's supports may cause the misalignment or distortion of door and window frames. This misalignment can lead to doors and windows becoming misshapen or out of plumb, making them difficult to operate smoothly.

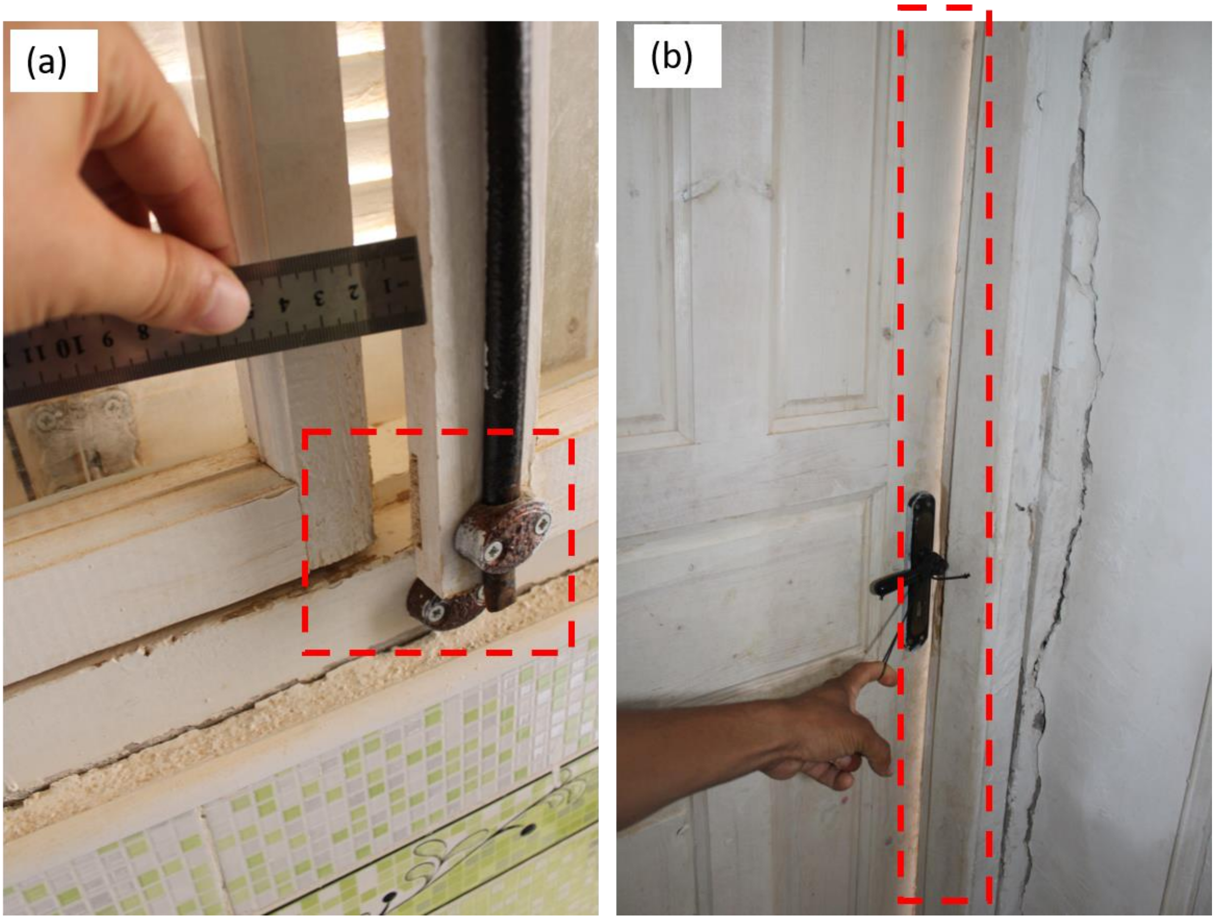


Fig. 2.8. (a) Sticking of window at building 8 of Area 1; (b) Sticking of door at building 4 of Area 3.

2.3.1.7. Decollement of the exterior cladding

During in-situ observations, it was noted that the external cladding, which serves as a protective layer against elements such as rain, wind, moisture, and external temperature fluctuations, exhibited swelling at the surface of the structural frames. The response of these structural frames to ground movement may generate mechanical stresses that coincide with the low cohesion between the cladding and the structural frames, ultimately leading to the decollement of these claddings.

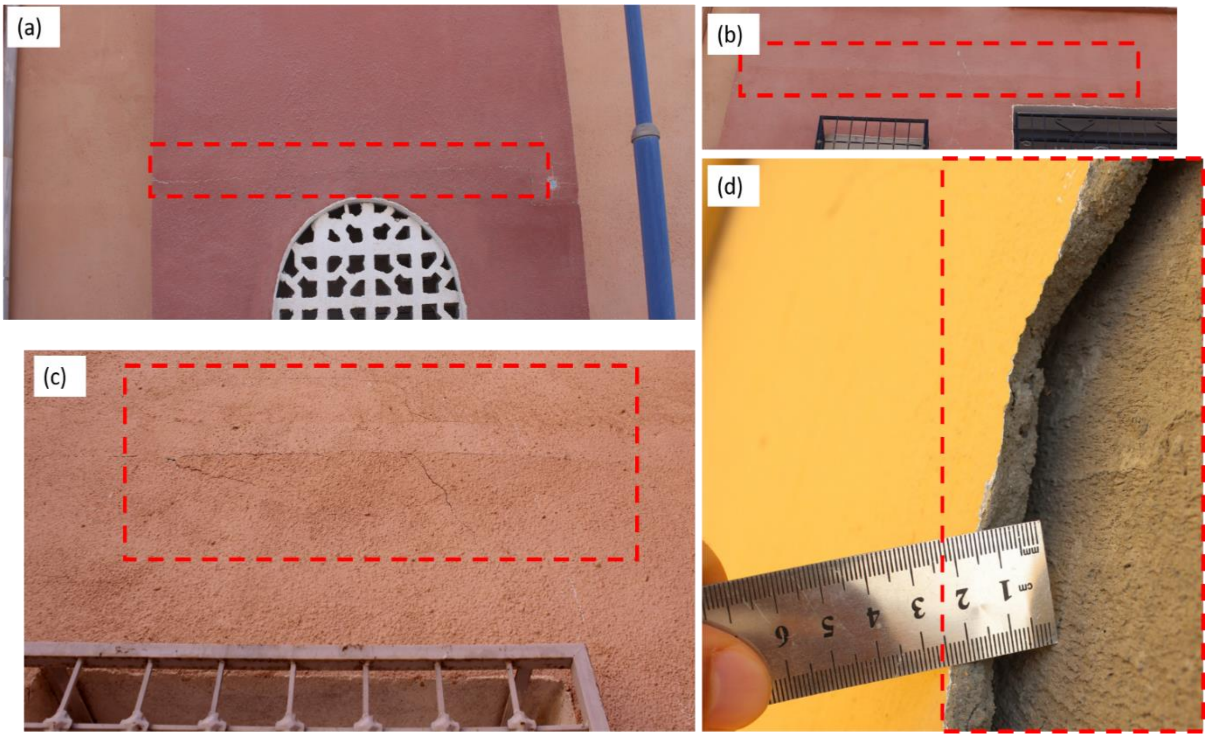


Fig. 2.9. Decollement of the exterior cladding that covers the structure elements recorded on the buildings: (a), (b) 8 of area 1; (c) 4 of area 1; (d) 4 of area 3.

2.3.2. The analysis of the building's environment

To formulate hypotheses regarding the mechanism behind the buildings' defects, an examination of the initial geotechnical report, which was conducted to characterize the building foundation soil, and the geological map of the region was performed to extract any relevant information. Additionally, visual inspections were carried out both at the regional level and within the specific area where the buildings were located.

At the regional level, inspections aimed to identify any past or recent land movements or construction damages in the region. Within the specific area where the buildings were situated, a thorough visual inspection of the environment surrounding the affected buildings was conducted.

2.3.2.1. The analysis of the initial geotechnical reports

2.3.2.1.1. Description, objectives and methods of the the initial geotechnical reports

The initial geotechnical reports were prepared by the National Laboratory for Housing and Construction unit of Batna (Laboratoire National de l'Habitat et de la Construction - LNHC) with the following primary objectives:

- Describing the Lithology of the Underground: The reports provide a detailed description of the subsurface lithology, offering insights into the types of soils and rock formations present beneath the building foundations.
- Specifying the Anchor Level and Type of Foundation: The reports clarify the depth and type of foundation used for the buildings, ensuring that the foundation design is appropriate for the subsurface conditions.
- Determining the Allowable Bearing Capacity: The reports establish the maximum load that the soil can safely support without risking excessive settlement or failure, which is crucial for ensuring the stability and safety of the structures.

The phases of investigation mentioned in the reports include the following:

- *Preliminary Phase:*

This phase involves a surface-level assessment to understand the superficial soil characteristics, vegetation, presence of embankments, and accessibility for investigation equipment.

- *In-Situ Investigation Phase:*
    - ✓ First Campaign (Penetration Testing)

This involves dynamic penetration testing using a penetrometer, specifically the BORRO-B2 type. This equipment tests the terrain and provides a soil characteristic known as dynamic soil resistance.

Dynamic penetration testing can guide the selection of foundation types and estimate the bearing capacity of the soil.

The principle of the test involves continuously driving a rod with a metal tip into the ground by repeated hammering. The number of blows required for every 20 cm of penetration is recorded, and this data is used to calculate the apparent dynamic resistance using the conventional Dutch formula.

- ✓ Second Campaign (Core Drilling)

This phase includes conducting core drilling using a SEDIDRILL 1000 drilling rig, which operates by rotation and water cooling, to obtain samples for a more detailed analysis of the subsurface layers and their properties.

2.3.2.1.2. Results of the In-Situ Investigation Phase:

2.3.2.1.2.1. The areas A1 and A2

- ✓ Regarding First Campaign (Penetration Testing)

The fifty-five penetrometer tests conducted provided penetrograms, with resistance plotted on the x-axis and depth on the y-axis, indicating that the sites generally exhibited very high soil resistance to penetration, up to refusal (Allowable bearing capacity of 1.8 bar at an anchor depth of 1.50 meters). However, a critical reassessment of these results revealed a significant concern. Specifically, 18 out of the 55 penetrometer points showed a noticeable drop in resistance at certain intervals, with a severe decrease in dynamic strength at shallow depths of less than 40 cm.

These fluctuations in resistance, despite the overall high values, suggest potential anomalies that require further investigation. The observed anomalies could indicate variations in soil composition, the presence of voids, or other subsurface issues that may compromise the stability of the building foundations in these areas. Understanding the underlying causes of these resistance drops is crucial to ensuring the long-term safety and integrity of structures built on these sites.

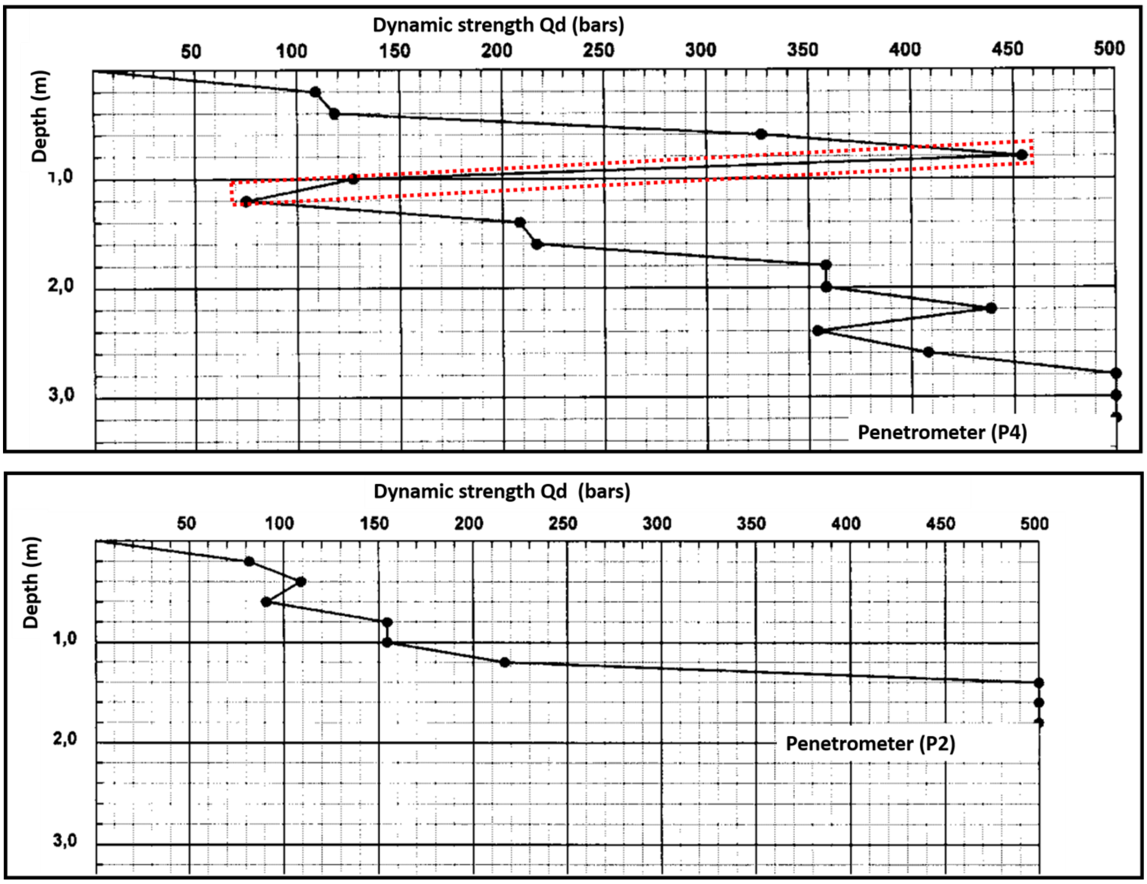


Fig. 2.10. Penetrometer tests 4 (P4) and 2 (P2) at area A1and A2: The P4 showed a noticeable disturbance in the dynamic strength, while the P2 did not exhibit such disturbance.

- ✓ Regarding Second Campaign (Core Drilling)

The second campaign involved core drilling, where 14 core samples (SC01 to SC14) were extracted. Of these, 13 were drilled to a depth of 6.0 meters, while one (SC07) reached 9.0 meters.

The laboratory analysis of these core samples revealed two primary formations beneath a superficial cover layer approximately 0.2 meters thick:

Horizon 1: This is a heterogeneous formation composed of clayey to silty sand, sometimes gravelly silty sands, and in one instance, anhydritic material (noted in borehole SC01). It also contains occasional conglomerates and sandstone blocks. The depth of this formation varies between 2.0 to 5.5 meters, depending on the specific location, and it extends down to the stopping points of certain boreholes (SC06, SC08, SC11, and SC14) at 6.0 meters. The vertical distribution of this layer is uneven. In some areas, tuffogenic silty sands were detected just below the surface, under the cover soil, extending to depths of 1.7 to 6.0 meters in boreholes SC05, SC11, and SC13. This horizon generally presents beige, yellowish, to ochre colors.

Horizon 2: This layer consists of marl to calcareous marl, with a generally ochre color, sometimes showing whitish hues. In borehole SC01, carbonate traces or signs of oxidation were observed. This formation is mostly compact but includes locally friable, laminated sections. Horizon 2 was encountered down to the end of drilling at 6.0 or 9.0 meters, except in boreholes SC06, SC08, SC11, and SC14.

After core extraction, the following laboratory tests were performed:

- ✓ 13 Granulo-Sedimentometric Analyses: Determined the grain size distribution and sediment characteristics.
- ✓ 13 Physical Soil Characteristics Measurements: Assessed the physical properties such as density, porosity, and moisture content.
- ✓ 4 Atterberg Limit Tests: Measured the plasticity and consistency of the soils.
- ✓ 13 Chemical Aggressiveness Analyses: Revealed soil aggressiveness levels of A3 and A4 according to NFP18-011, leading to a recommendation for high sulfate-resistant cement.
- ✓ 0 Mechanical Tests: Mechanical testing was deemed impracticable due to the remanent or disturbed nature of the sampled materials.

2.3.2.1.2.2. The areas A3 and A4

The characterization of areas A3 and A4 revealed results similar to those of areas A1 and A2, with key findings including:

- ✓ Two Distinct Horizons: Horizon 1 and Horizon 2.
- ✓ Notable Disturbances in Dynamic Strength: Observed in both areas.
- ✓ Soil Aggressiveness Levels: Classified as A4 according to NFP18-011, leading to a recommendation for high sulfate-resistant cement.

2.3.2.1.3. Conclusion regarding the initial geotechnical reports

The analysis of the initial geotechnical reports indicates that a clear diagnosis of the mechanism responsible for the building failures remains uncertain. The soil is heterogeneous, and multiple mechanisms may be contributing to the observed issues.

2.3.2.2. Occurrence of foundation settlement and subsidence hazards signs

In addition to the observed building damage, a careful examination of the soil surrounding the buildings revealed perceptible signs of foundation settlement and subsidence as well (Fig. 2.11). Such signs of ground movement confirm that the building defects are associated with ground movement. However, they cannot provide further information about the triggering factors.

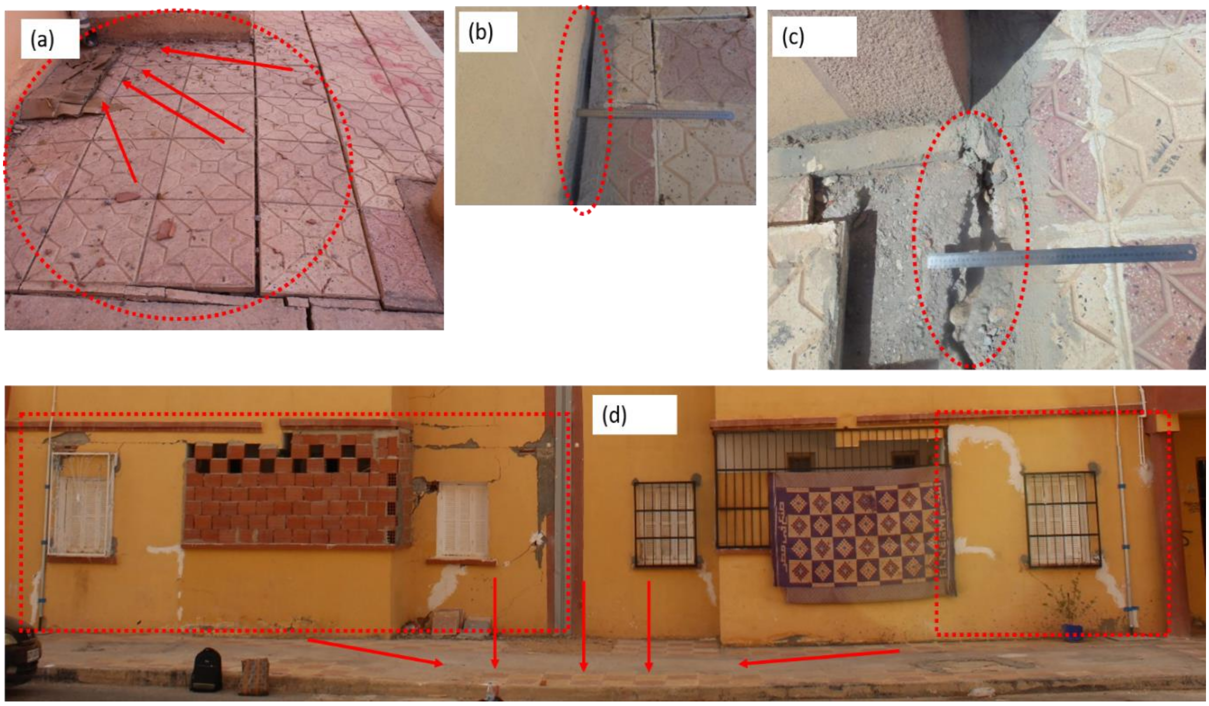


Fig. 2.11. Signs of settlement in the building foundations and subsidence: (a) Settlement in the foundation and cracking of the surrounding pavement, (b) Voids between the building and its pavement that are supposed to be associated with ground sliding resulting from the excessive settlement of adjacent foundation, (c) Significant cracking that crosses the tile layer until the soil (d) Subsidence parallel to intensive cracks on the building facade.

2.3.2.3. Presence of water infiltrations signs

In addition to the signs of foundation settlement and subsidence hazards, signs of water infiltrations have been identified in-situ (Fig. 2.12). The presence of these signs may explain a part of the triggering factors, as the interaction of this water with a type of soil predisposed to triggering a mechanism of subsidence hazard could have affected the buildings by causing defects. Especially noteworthy is that the location of the building defects aligns with these signs of water infiltrations.

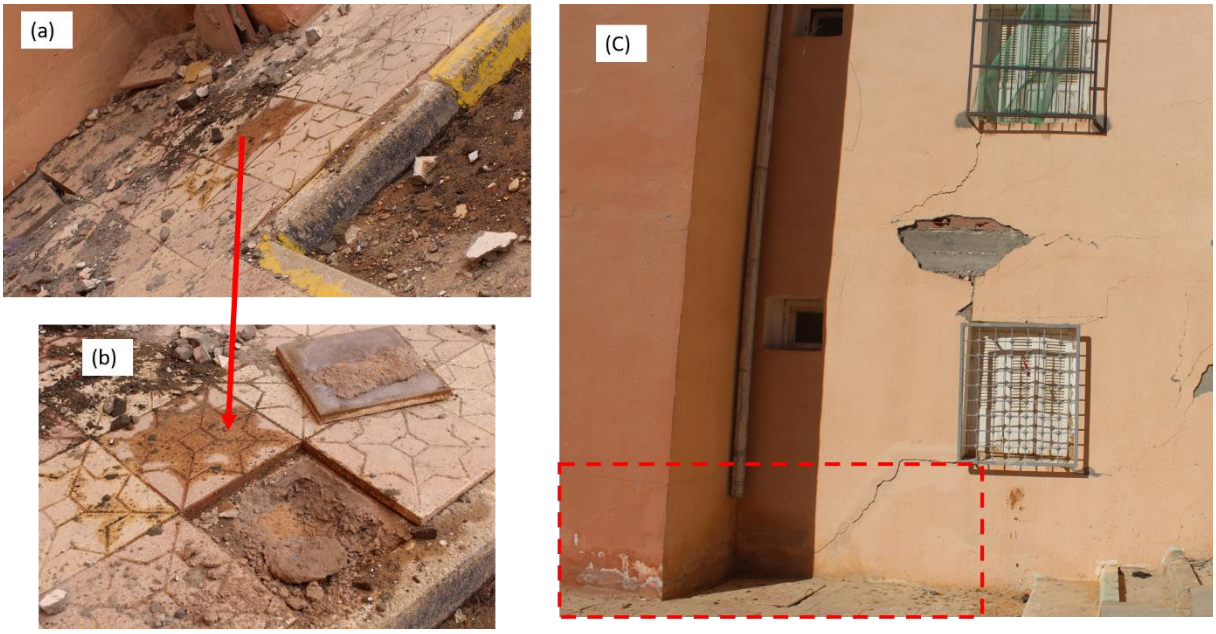


Fig. 2.12. Presence of water infiltrations signs: (a) High humidification of the pavements and its base adjacent to the affected building 6 from area 1. (b) Traces of high previous humidification on the bottom of the wall of the affected building 1 from area 1 that align with very obvious cracking of the same wall.

2.3.2.4. The examination of the geological map of the region

In order to explain the triggering factors, an examination of the geological map of Biskra, which encompasses the town of Ouled Djellal and is still recognized as an official document to this day, was conducted.

The geological mapping and explorations of this document were carried out between 1950 and 1955 by geologist Mr. N. Gauskou V and soil scientist Mr. P. Dutil, both collaborators of the Algerian Geological Map Department. The project was supervised by the Director of the same service and Mr. G. Bétier, a mining engineer in Algiers.

According to this geological map, the geological formations in the region of Ouled Djellal consist of sedimentary terrains ranging from Quaternary at the top to Barremian at the base, representing a transitional formation in terms of structure and sedimentation. The northern part of the region is mountainous, while the southern part is a collapse zone belonging to the Northern Sahara. The transition between these two zones occurs through flexural-slip faults, fold faults, and east-west oriented faults known as the South Atlas Fault.

Regarding groundwater supply in this region, it is primarily ensured through the Djeddi River (Wadi Djeddi) basin, which is fed by several tributaries originating from high altitude mountains with steep slopes. This results in more runoff than infiltration, reducing groundwater supply to the aquifer of Ouled Djellal.

However, according to the georeferencing of the geological map, the study area including affected constructions is situated in a transition zone between the Pliocene, mainly composed of conglomerate, sandstone, and sandy clay, and the middle Eocene formations, primarily composed of clay with outcrops of gypsum, anhydrite, and dolomitic limestone (Fig. 1.13). The presence of gypsum in the form of anhydrite and gypsum in the middle Eocene formations, even if not the first layer where the buildings are anchored (at a depth of 1.5 meters), may provide additional answers to the underlying triggering factors of subsidence and foundation settlement signs.

Gypsum formations or gypsiferous formations beneath the buildings, in contact with unsaturated water, undergo a gypsum dissolution process or destabilization of previous dissolution environments through infiltration. This triggers subsidence and foundation settlement of the buildings.

Fig. 2.13. Localization of the study area according to the georeferencing of the geological map of the region.

2.3.2.5. Occurrence of geomorphological evidence in the form of previous cover sagging sinkholes

Moreover, it's worth noting that significant geomorphological evidence in the form of previous cover sagging sinkholes (Fig. 2.14) has been observed, both parallel to the masonry fence of the National Institute of Vocational Training in the study area (Fig. 2.14 (a)) and within a proximity of less than 1,8 kilometers from the affected buildings (Fig. 2.14 (b)). These geological features could be indicative of past hydrogeological hazards related to gypsum dissolution processes.

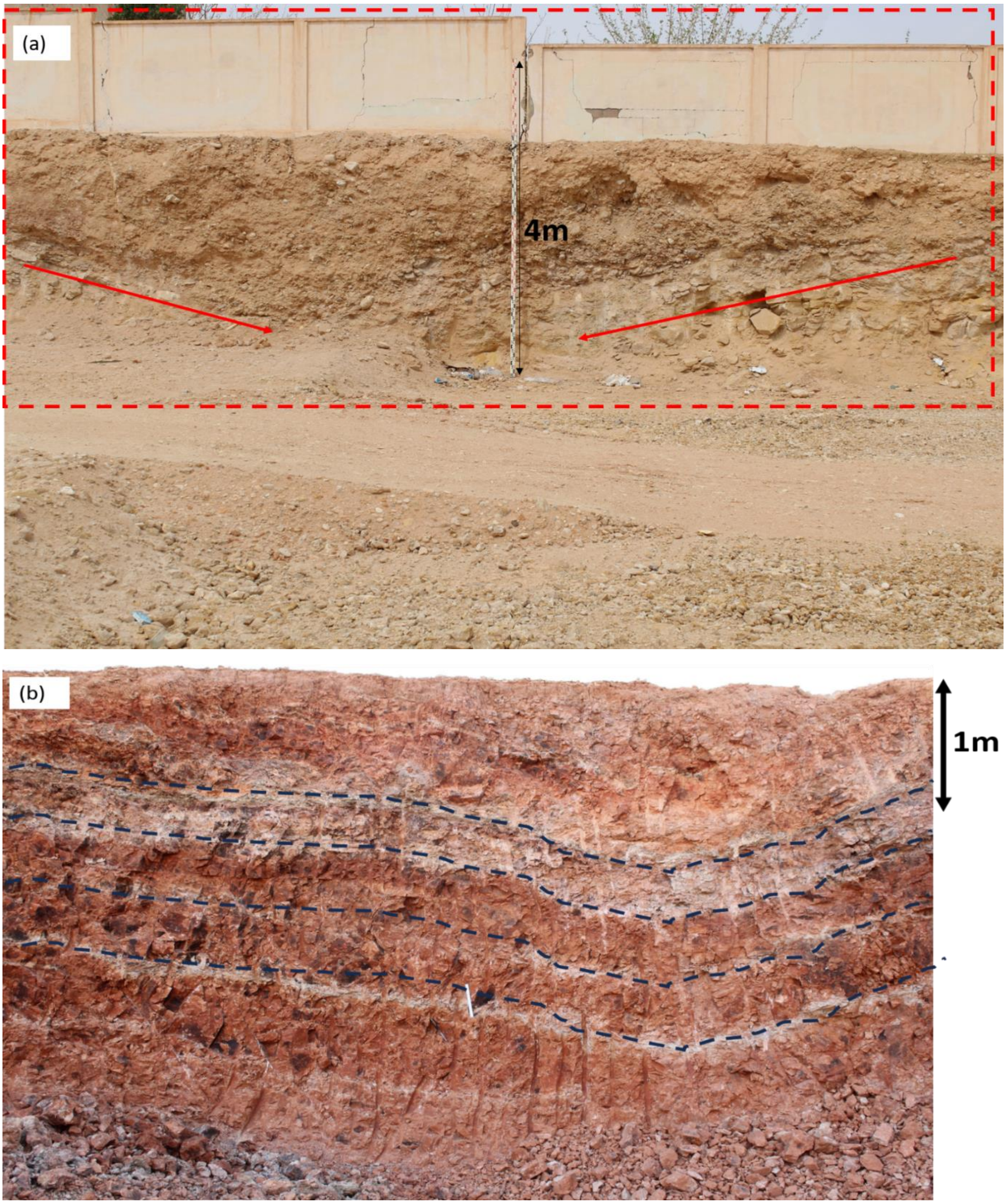


Fig. 2.14. Geomorphological evidence in the form of previous cover sagging sinkholes: (a) Parallel to the masonry fence of the National Institute of Vocational Training in the study area; (b) Within a proximity of less than 1,8 kilometers from the affected buildings.

2.3.2.6. Occurrence of subsidence event

Furthermore, it's worth noting that a notable subsidence event was reported in Sidi Khaled city, located approximately 8 kilometers to the south of the study area (Fig. 2.15). This subsidence event further underscores the geological dynamics and susceptibility to ground movements in this region.

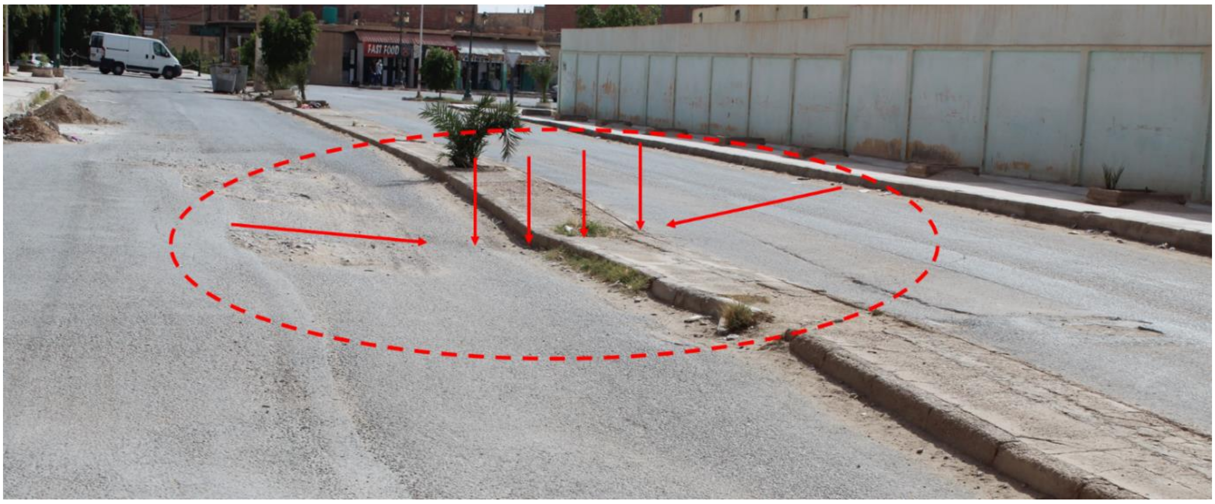


Fig. 2.15. Subsidence that occurs in Sidi Khaled city, approximately 8 kilometers south of the study area.

2.3.2.7. Occurrence of collapse sinkhole event

At this inspection, an intriguing event was noticed approximately 22 kilometers south of the study area (visible at the Google Earth coordinates: (Latitude: 34°23'40.59"N; Longitude:4°47'28.70"E)); it occurred in 2020 according to the adjacent populations, and within the middle Eocene formation, according to the previous geological map, comprising clay with outcrops of gypsum, anhydrite, and dolomitic limestone. It involved a remarkable sinkhole phenomenon with a diameter extending up to 40 meters adjacent to the Djeddi River, offering further evidence of the region's susceptibility to ground movements, including those associated with gypsum dissolution (Fig. 2.16).

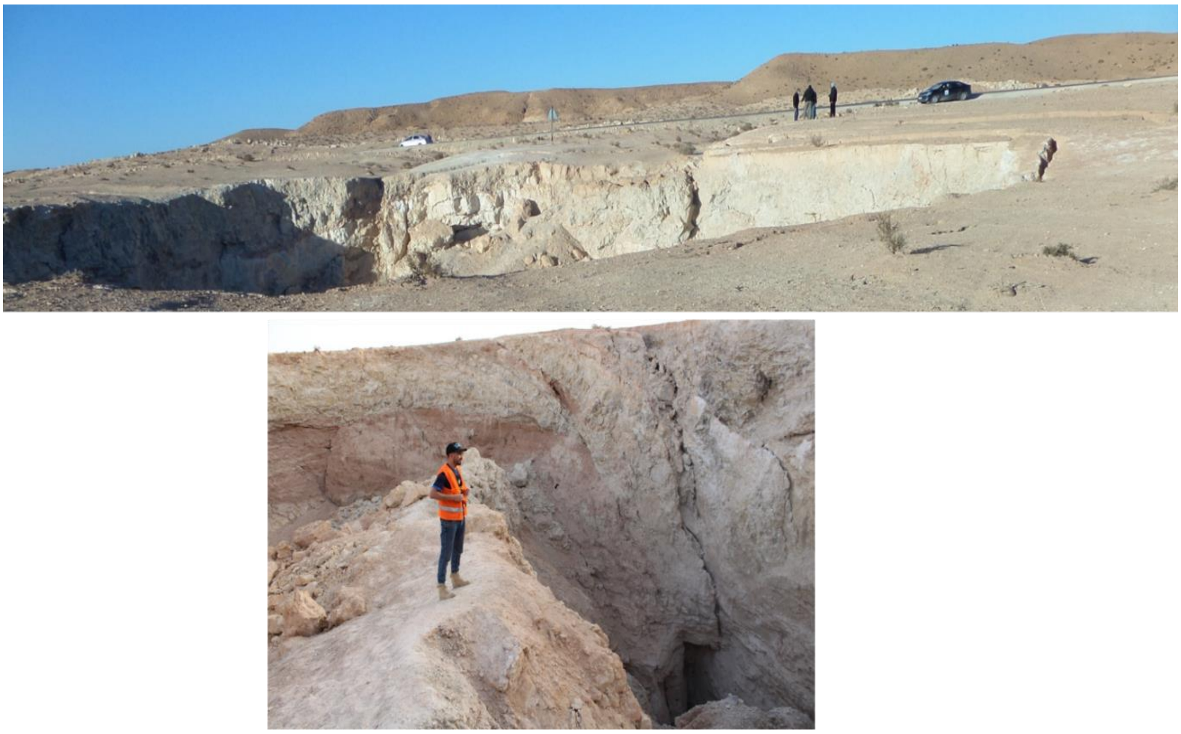


Fig. 2.16. Collapse sinkhole that occurs in 2020, approximately 22 kilometers south of the study area.

2.4. Conclusion and recommendations from the prediagnosis phase

The initial diagnosis involved analyzing all available data concerning the buildings, including the examination of the geological map of the region, building documentation, and visual inspections conducted at both the regional and specific area levels. However, the prediagnosis was divided into two major parts: the analysis of the buildings' defects and the analysis of the environment.

The locations and severity of the building's defects were carefully documented during the inspection process. It was observed that the buildings experiencing failures exhibited varying typical building defects that have an evolving character and various degrees of damage. Some exhibited extensive cracks, while others had only minor ones.

The analysis of the building's environment identified signs of foundation settlement and subsidence hazards, which may be associated with observed water infiltrations adjacent to the affected buildings. These water infiltrations, along with the gypsum-rich nature of the soil indicated by the geological map of the region, are likely trigger factors for subsidence hazards that affect the building through the observed building defects. Additionally, previous geomorphological evidence in the form of sagging cover sinkholes, subsidence, and sinkholes in the region further supports the predisposition of the region to ground movement associated with gypsum dissolution phenomenon.

From the prediagnosis phase, it can be suggested to plan a deep investigation to better understand the failure mechanism of the buildings and to efficiently develop mitigation measures should carefully and primarily focus on the following aspects:

- *Identification of the gypsiferous soil*: The investigation should aim to accurately identify the presence of the gypsiferous soil and understand its distribution in situ, both in terms of depth and surface area. This information is crucial for assessing the extent of gypsiferous soil and its potential impact on the surrounding buildings.
- *Dissolution process analysis*: The occurrence of the dissolution process within the gypsiferous soil needs to be thoroughly examined. This analysis should involve studying and identifying the factors that could eventually contribute to the dissolution process, such as water infiltration and chemical reactions. It is worth noting that understanding the dissolution process is essential for evaluating its potential effects on the stability of the soil and the adjacent structures.
- *Assessment of dissolution rate:* Quantifying the dissolution rate of the gypsiferous soil can help to estimate the long-term soil stability and its impact on the surrounding infrastructure.
- *Soil stability beneath building foundations:* The investigation should thoroughly assess the impact of the dissolution process on soil stability beneath building foundations. This assessment should include an evaluation of parameters such as variations in soil strength when compared to the initial geotechnical report from 2014. Additionally, continuous monitoring of building movements is essential to comprehensively understand the evolving soil-structure interaction dynamics.
- *Assessment of building damage*: The investigation should also include a comprehensive assessment of building damage resulting from the foundation instability. The analysis involves documenting and evaluating the extent and severity of the damage observed in the affected buildings. Consequently, understanding the nature and magnitude of the

damage is crucial for determining the relationship existing between the soil behavior, dissolution process, and building failures.

Chapter 3: Diagnosis of the Case Study

This chapter discusses the investigation and diagnosis aimed at identifying the mechanisms behind building failures in Ouled Djellal city, based on the conclusions drawn from the pre-diagnosis chapter.

3.1. Buildings selection and the overall investigative approach

Buildings 1 to 12 in area 1 were chosen as part of the study sample intended for the analysis of building failures, as depicted in Fig. 3.1. This selection was made based on the reasons outlined in the prediagnosis, as well as their similar usage patterns, which facilitate the extraction of common factors to identify the failure mechanism.

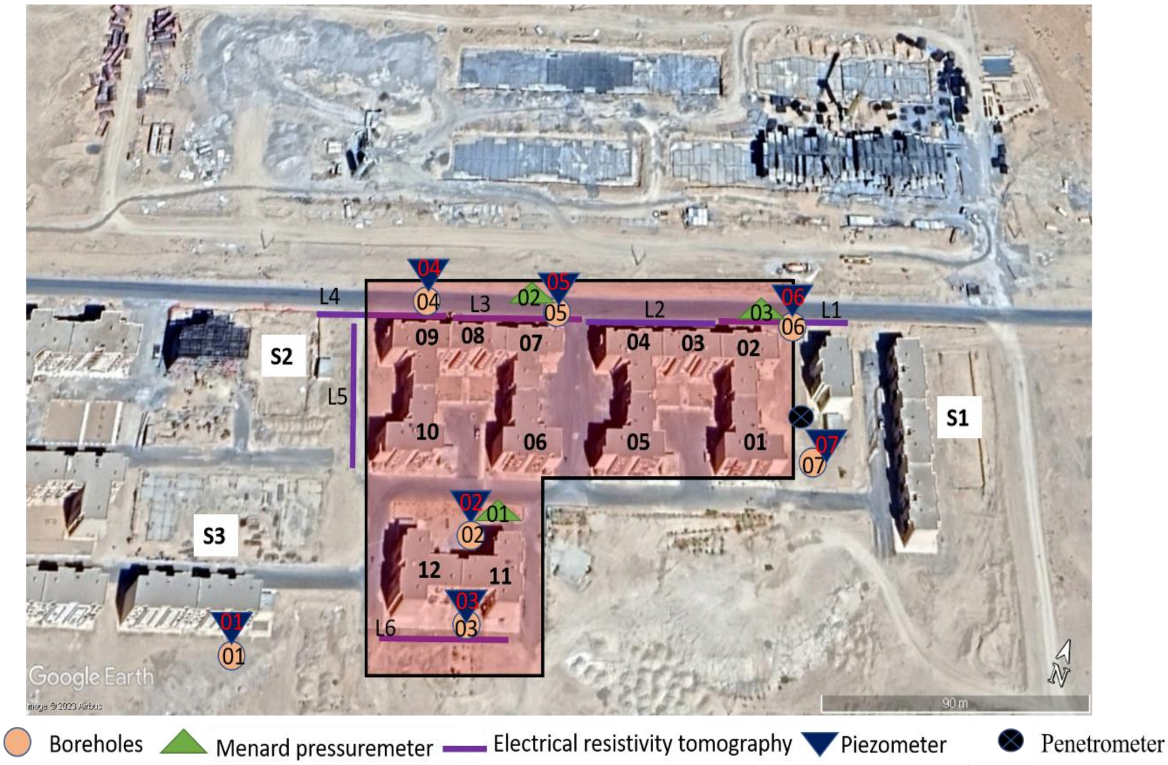


Fig. 3.1. Distribution of *in-situ* measurements.

In light of the preliminary diagnosis and the aim of establishing a definitive connection between the building's failure in the northwestern town of Ouled Djellal and the interaction of seepage water with the gypsiferous soil through gypsum dissolution, a G5 mission was undertaken in accordance with the Standard NFP 94-500. This mission entailed extensive geotechnical investigations conducted on-site to evaluate the soil conditions and collect pertinent information.

The main goals of the in-situ investigations were as follows:

- Identify the presence of gypsiferous soil within the area.
- Evaluate the occurrence of the gypsum dissolution process.
- Assess the dissolution rate in comparison to the soil stability adjacent to the damaged building facades.
- Examine any discrepancies in cone penetration limit measurements between the findings outlined in the initial geotechnical report from 2014 and those obtained subsequent to water infiltration in the gypsiferous soil, leading to building damage.

As a result, a comprehensive set of in-situ investigations was undertaken, comprising excavations, thirteen (13) boreholes, ten (10) piezometers, six (06) electrical resistivity tomography (ERT) surveys, twenty (20) penetrometer pressure tests, and three (03) Menard pressuremeter measurements. The distribution of these in-situ measurements is depicted in Figure 8, while Table 3.1 offers a summary of the recorded measurements at sites 1, 2, and 3

Table 3.1. Summary of *in-situ* measurements at sites 1, 2, and 3.

Site	Boreholes	Piezometers	Penetrometer test
01	02	01	08
02	02	01	06
03	02	01	05

Furthermore, as a component of the investigation into the failure mechanism, monitoring of building facades was conducted to describe and identify any movement that occurred under service loads. Additionally, the assessment of the impact of this movement on the buildings involved ranking the recorded building damages. The methodology and corresponding results of each measurement will be elaborated upon in the forthcoming sections.

3.2. Characterization of the gypsiferous soil

The identification of the gypsiferous soil involved employing a combination of geological cross-sections, georeferencing techniques, analysis of excavation data, and stratigraphic characterization. The objective was to ascertain the presence and distribution of gypsiferous soil within the study area. To achieve this, the following steps were undertaken:

3.2.1. Development of geological cross-section

Geological cross-sections were created by georeferencing the geological map of the study region and ensuring their intersection with the building site. Upon analysis, it was determined that the buildings are situated on a surface layer dating back to the Pliocene epoch. This layer, ranging from 3 to 7 meters thick, comprises sandstone, conglomerate, and sandy clay. Beneath this layer lies a middle Eocene formation characterized by clay, with exposures of gypsum, anhydrite, and dolomitic limestone (Fig. 3.2 (b)).

3.2.2. Analysis of field excavations

Excavation operations were conducted at multiple sites across the study area. Soil samples obtained during these excavations underwent thorough analysis to ascertain their composition and to detect any irregularities in the geological formations.

The excavation analysis corresponds well with the geological cross-sections created through georeferencing the regional geological map (Fig. 3.2). The soil predominantly consists of a mixture of conglomerate, sandstone, and sandy clay from the Pliocene epoch, underlain by clay from the middle Eocene epoch. However, indications of deformations, particularly faults within the upper layer, were observed, along with the presence of middle Eocene clay at relatively shallow depths. Such deformations and variations in geological formations may stem from various factors, such as tectonic activities, weathering, or erosion.

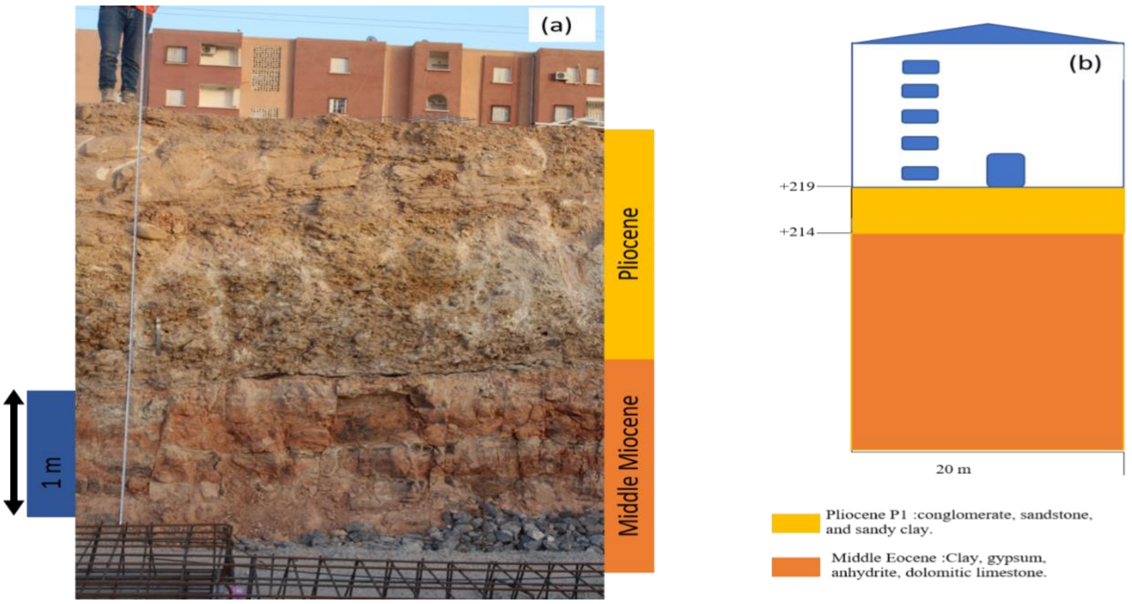


Fig. 3.2. The geological section under the buildings: (a) Real section parallel to the buildings 7 and 8; (b) Cross section parallel to the buildings, based on the georeferencing of the geological map of the region under study.

Additionally, anomalies exhibiting a random distribution within the conglomerate and sandstone formations were noted. These anomalies may suggest the presence of localized disturbances or irregularities within the geological strata. Of particular concern is their occurrence at the depth of the foundation anchor (1.5 m), which could potentially exacerbate any building movement. Notable anomalies include:

- *Porous crystals crystals embedded within the sandstone***:** These crystals exhibit a thickness of approximately 10 cm and display a fragile nature, suggesting potential weakness or instability within this segment of the sandstone formation (Fig. 3.3);

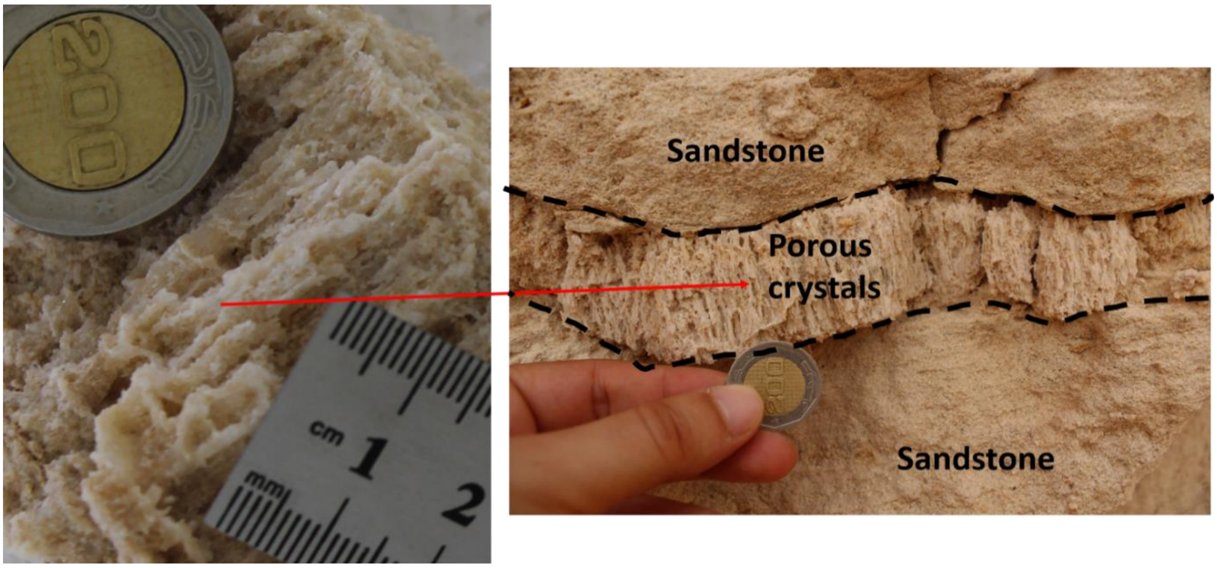


Fig. 3.3. Porous crystals within the sandstone.

- *Geodes within the* conglomerate: These geodes harbor voids or crystals akin to those identified in the sandstone, indicating potential similarities in the geological processes that have influenced both formations (Fig. 3.4).

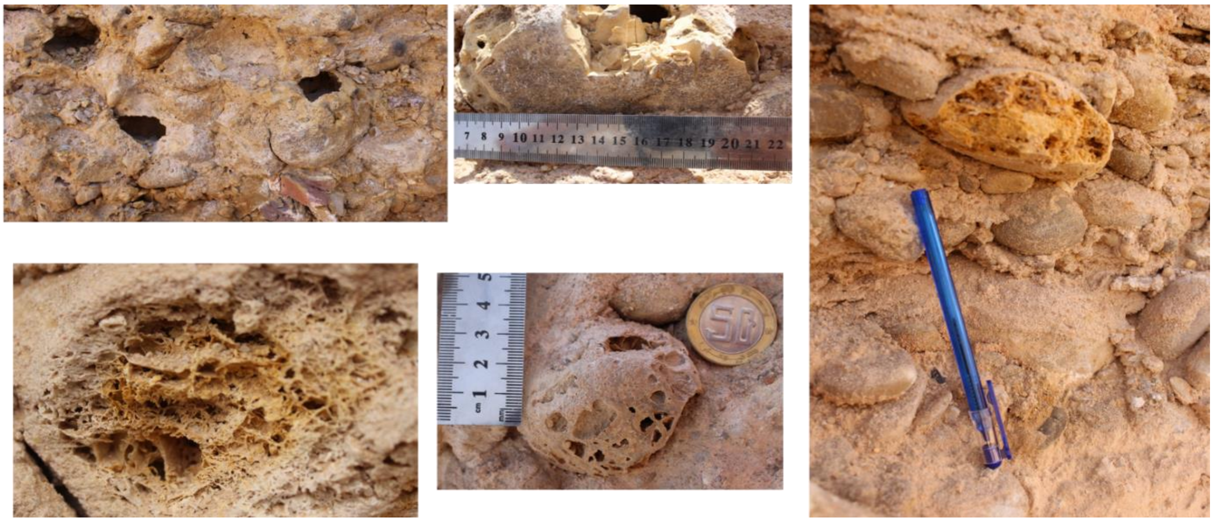


Fig. 3.4. Geodes detected within the conglomerate formations.

- *Regions of voids present in both formations*: The identification of zones characterized by minimal conglomerate matrix and highly porous layers, influenced by geological processes affecting both formations, implies the potential presence of cavities within the Pliocene formation. This indicates an unstable building foundation anchoring layer (Fig. 3.5) ;

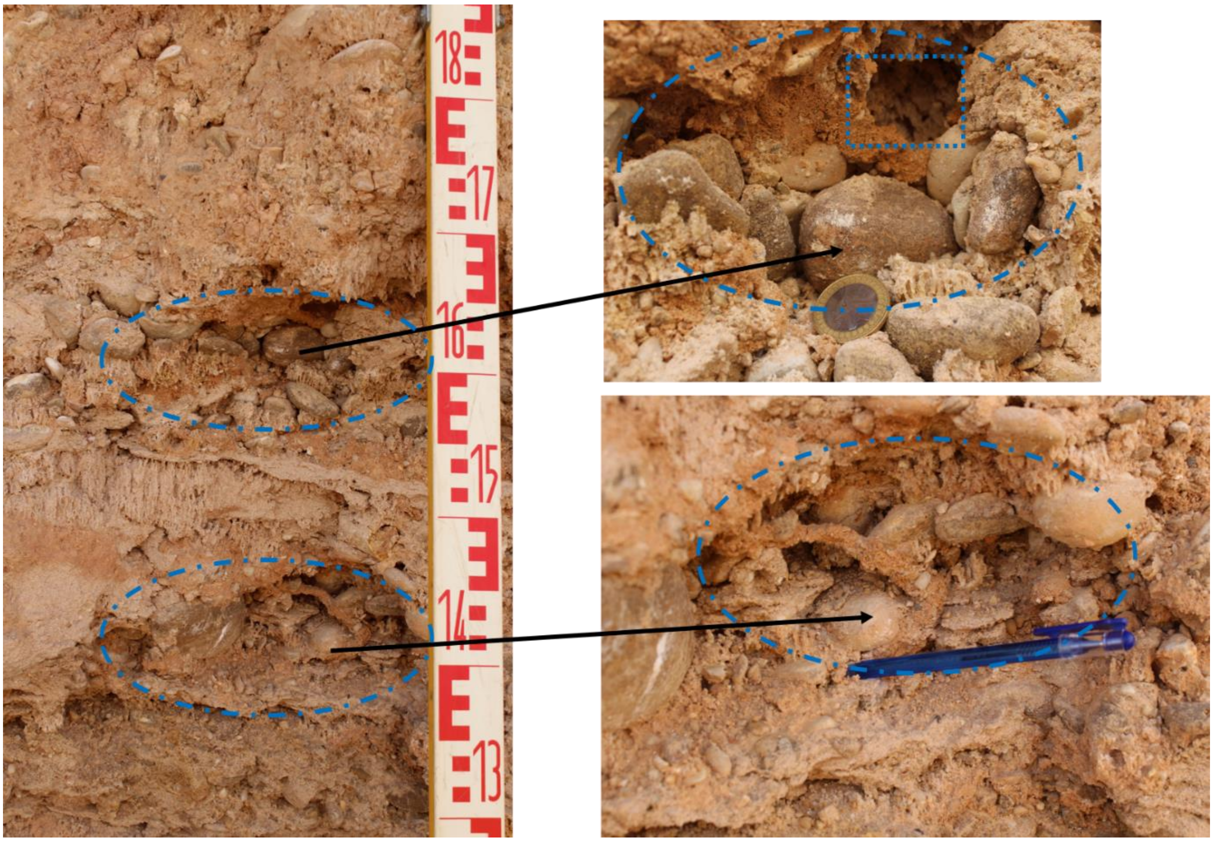


Fig. 3.5. Areas exhibiting minimal to no conglomerate matrices and highly permeable layers of chemically altered sandstone.

- *Deformations in the sandstone:* The presence of deformations in the sandstone could be associated with tectonic activity or other geological processes that may have affected the formation over time (Fig. 3.6).

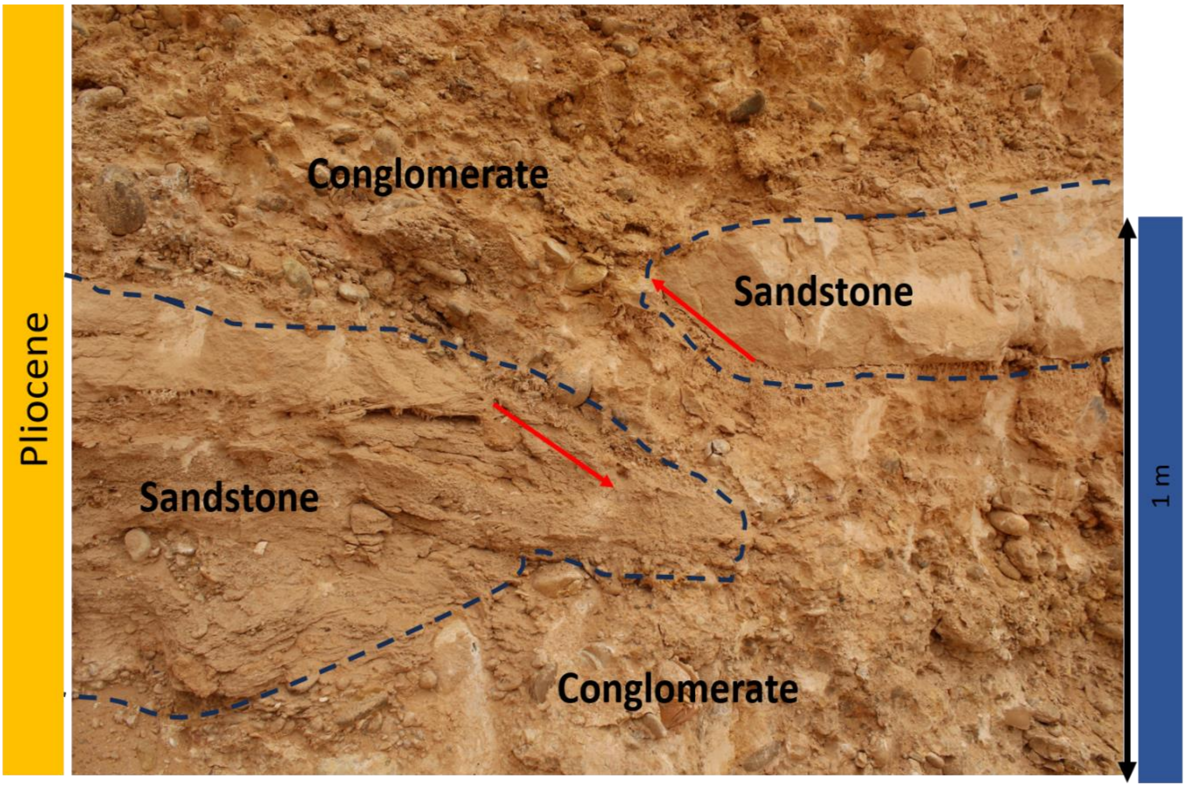


Fig. 3.6. Faults observed within the sandstone exhibiting reverse deformation.

3.2.3. Description and analysis of the stratigraphy of layers

Thirteen boreholes were strategically drilled to facilitate a thorough examination of the geological layers through stratigraphic characterization. The selection of borehole locations was meticulously planned to ensure a representative sampling of the study area. Utilizing standard drilling techniques, samples of soil and rock were collected at depths ranging from a minimum of 7 meters to a maximum of 15 meters. These samples underwent meticulous laboratory analyses to determine the lithological composition and ascertain the potential presence of gypsiferous soil (Fig. 3.7).

Fig. 3.7. Core drilling and soil sampling for the laboratory characterization.

3.2.4. Examination of soil composition

Soil samples obtained from excavation and digging operations underwent thorough analysis to detect specific minerals and formations. Selected samples were subjected to X-Ray Diffraction (XRD) analysis to ascertain their mineral composition, with a particular emphasis on identifying gypsum minerals.

X-Ray Diffraction (XRD) analysis was performed at the Lafarge-Souakri Cement Factory to ascertain the presence or absence of gypsiferous minerals within both the Pliocene and middle Miocene formations.

The analysis of the middle Miocene clay sample indicated a notably low gypsum content, comprising only 1.06% of the composition. Alongside the clay facies, two predominant minerals were identified: calcite (73.72%) and illite (15%). This clayey formation, identified as marl, is distinguished by its high calcite content and significant level of illite.

In contrast, the Pliocene layer revealed a significant presence of gypsum forms within the porous crystals found in the sandstone. Specifically, the composition of these crystals comprised 46.97% gypsum forms, including 31.05% gypsum, 15.52% hemihydrate, and 0.4% anhydrite. This gypsiferous sandstone was identified as interbedded within the sandstone formation (Fig. 3.8). Additionally, the sandstone formation itself exhibited a minor presence of gypsum, totaling 2.06% across all three gypsum forms. However, the predominant mineral observed in the sandstone was calcite, accounting for a substantial 90.92% of its composition.

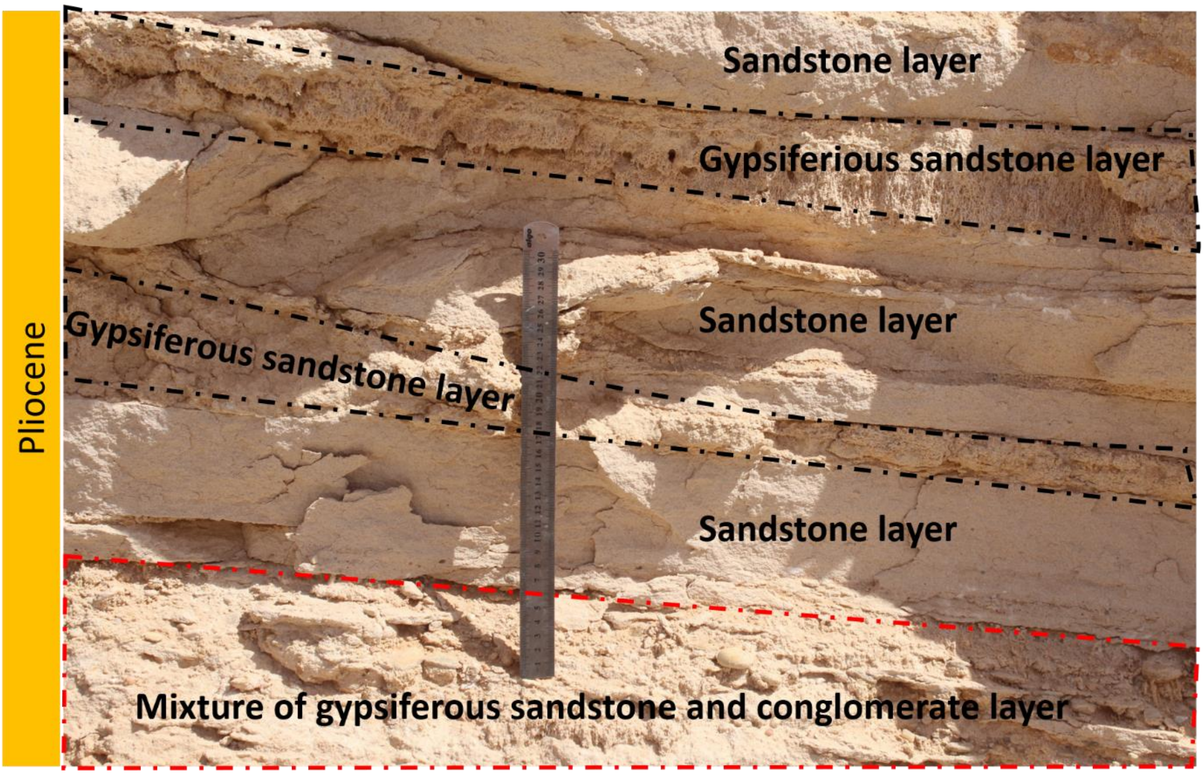


Fig. 3.8. Gypsiferous sandstone interbedded within the Pliocene sandstone layer.

It's noteworthy to mention that the oxidation of pyrite stands as a potential mechanism fostering the development of gypsum within the sandstone. The interaction of pyrite with oxygen and water over time triggers its oxidation, yielding sulfuric acid. Subsequently, this acid can react with calcium-rich rocks like limestone or dolomite, culminating in the formation of gypsum [65],65,66] .This mechanism offers a viable explanation for the occurrence of both dolomitic geodes and gypsiferous crystals which detected in the calcareous sandstone unearthed at the excavation sites.

Moreover, thorough examination of the sandy clay samples revealed a notable abundance of gypsum forms in samples 1 and 2 (Fig. 3.9). These forms comprised approximately 40% and 43% of the compositions of samples 1 and 2, respectively. In contrast, calcite constituted 59% and 51% of the composition, while quartzite accounted for only 1% and 6% of the two samples.

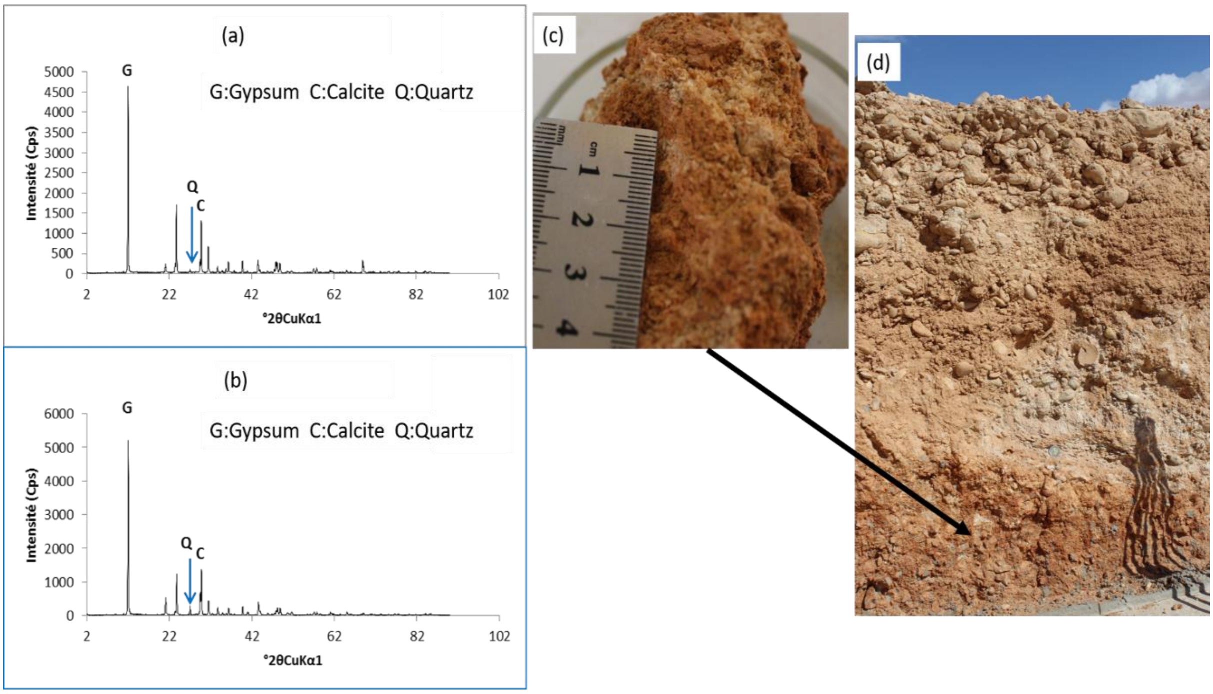


Fig. 3.9. Analysis of sandy clay: (a) X-ray diffraction spectrum of sample 01; (b) X-ray diffraction spectrum of sample 02; (c) Sandy clay sample; (d) Random distribution of sandy clay at the first Pliocene layer.

3.2.5. Mechanical and physical characteristics of the soil

Laboratory examinations carried out following NF P94-050 and NF P94-053 standards yielded various physical parameters including bulk density, dry density, natural moisture content, saturation moisture content, and saturation rate. These findings are summarized in Table 3.2.

Table 3.2. Overview of physical parameters derived from laboratory testing.

Formation	Depth (m)	Bulk density (T/m^3)	Dry density (T/m^3)	Natural moisture content w (%)	Saturation moisture content (%)	Saturation rate (%)
Conglomerate	1,50-2.00	2,03	1,83	10,73	17,63	60,46
	2,50-3,00	1,98	1,72	15,33	21,27	73,04
Sandy clay	6,60-6,80	2,02	1,75	15,45	21,23	90,83
	6,40-6,70	2,03	1,71	18,83	22,09	90,70
Marl	5,50-5,70	1,91	1,67	14,70	24,03	67,55
	10,50-11,0	1,89	1,65	14,69	23,90	62,73

Within the conglomerate formation, sandy clay, and marl layers, saturation rates ranging from 60.46% to 90.70% were observed. These rates suggest a notable presence of water stored within the soil's pores, likely due to ongoing water infiltration. This infiltration could be linked to potential leakages from water pipes, especially considering the arid conditions in the area and the lack of shallow aquifers.

Additionally, direct shear tests (CD) following NF P 94-071-1 and oedometer tests following XP P94-090-1 were conducted on the sandy clay and marl formations (Table 3.3). Results indicate that both formations exhibit properties that render them prone to settling under loads.

Table 3.3. Summary of mechanical characteristics derived from laboratory examinations.

Formation	Consolidation pressure (bars)	Compression index (%)	Swelling index (%)	Drained cohesion (bars)	Drained friction angle (°)
Sandy clay	1,75	18,55	4,20	0,832	15,80
Marl	1,58	18,74	3,87	0,489	18,80

The outcomes of the gypsiferous soil identification efforts in the area offer significant insights. It's confirmed that the Pliocene formation harbors gypsiferous soils, tightly intertwined with the gypsiferous soil present within the sandy clay, sandstone, and conglomerate matrix. This intimate connection renders these soils highly prone to gypsum dissolution processes and particle transportation, particularly when exposed to concentrated water flow, such as water infiltration from leakages. This vulnerability may be exacerbated by preexisting pores, filled cavities, and cracks within the same layer.

Additionally, it's crucial to acknowledge that isolated and combined footings anchored within this formation might lead to non-uniform building movements instead of uniform ones. This disparity in movement can be ascribed to the erratic distribution of gypsiferous soils in terms of depth and area, making the soil exceedingly heterogeneous (Fig. 3.10).

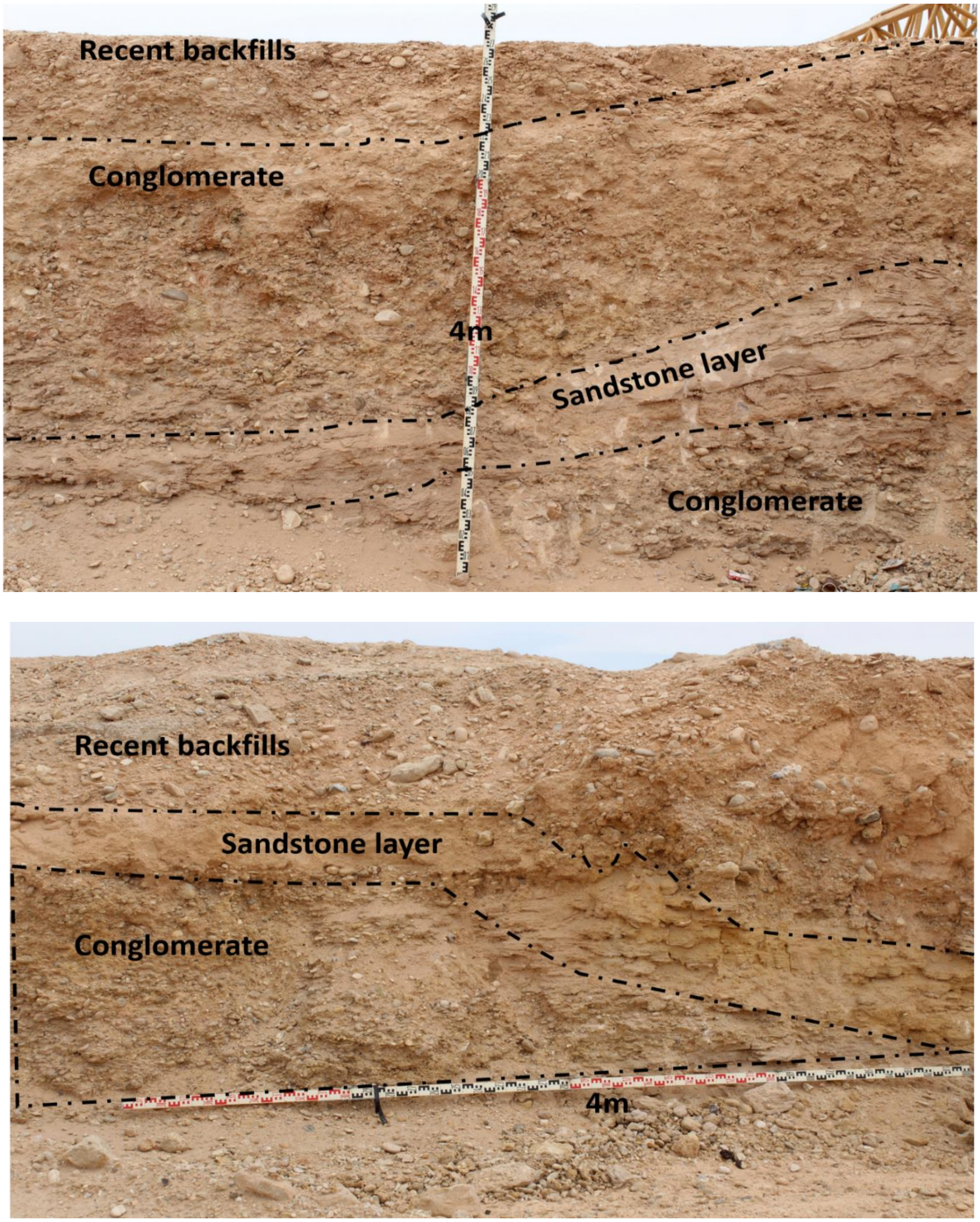


Fig. 3.10. The erratic distribution of the geological formations containing gypsiferous soil, both in terms of depth and area, within the initial Pliocene layer.

3.3. Enhancing the occurrence of gypsum dissolution process

When water seeps into soil containing gypsum minerals, it triggers a dissolution process that affects both the soil and the water's chemical properties. It is widely known that gypsum, whose chemical formula is $CaSO4•2H2O$, dissolves in water and releases Ca^{2+} and SO_4 ions into the solution.

For the purpose of enhancing the occurrence of the dissolution process within the gypsiferous soil, several steps were undertaken:

3.3.3. Installation of piezometers

To monitor water seepage into the gypsiferous soil, 10 piezometers were strategically installed at critical points across the study area (see Fig. 3.11). These instruments were specifically designed to accurately measure groundwater levels. However, significant fluctuations in water levels were observed at a depth of 15 meters, as detailed in Table 3.4.

Table 3.4. Piezometer measurements taken on various dates.

Date of reading	PZ1	PZ3	PZ4	PZ5	PZ6
January 13th, 2022	4.50	10.70	Not measured	Not measured	Not measured
March 31st, 2022	0	0	5.00	7.20	5.00
June 1st, 2022	7.00	9.00	Not measured	Not measured	Not measured

The water levels recorded varied widely, ranging from a shallow depth of 4.5 meters to complete absence. For instance, on January 13th, 2022, piezometers PZ1 and PZ3 showed water levels at depths of 4.5 meters and 10.70 meters, respectively. However, by March 31st, 2022, the water had disappeared, only to return with depths of 7 meters and 9 meters on June 1st, 2022. These fluctuations are likely due to seepage from water and sewage pipelines, this supported by the identification of multiple leakages in front of the buildings (as depicted in Fig.

3.11(a)). This reinforces the earlier hypothesis and validates the interactions between gypsiferous soils and water near the buildings.

Fig. 3.11. (a): An instance of leakage was identified in front of the impacted building 1. Additionally, (b) Piezometer 05 was installed in front of the affected building 7.

3.3.2. Collection of water samples and subsequent chemical analysis

Samples of water were withdrawn from the piezometers to perform chemical analysis. The aim was to assess parameters like conductivity, as well as concentrations of calcite and sulfate. Collection followed standard protocols to ensure sample integrity and prevent contamination. Analysis of groundwater samples from piezometers at sites 01, 02, and 03 revealed elevated sulfate and calcite concentrations, alongside high conductivity values for samples 1, 2, and 3, respectively, as detailed in Table 3.5.

Table 3.5. Chemical analysis was performed on groundwater samples collected from three distinct piezometers, alongside reference values provided by the World Health Organization (WHO).

Sample	Calcium concentration [Ca $^{2+}$] (Mg/l)	Sulfates concentration [So_4^{2+}] (Mg/l)	Conductivity (μS/cm)
01	326.25	1028.38	4946
02	326.25	1044.86	4960
03	326.25	1020.38	4940
Standard (W.H.O)	200	400	2800

These results indicate that CaSO4•2H_2O dissolves in groundwater, releasing Ca^{2+} and SO_4^{2-} ions into the solution. As a result, both the calcium and sulfate concentrations, as well as the electrical conductivity of the water, increase compared to the standard values recommended by the World Health Organization (WHO).

3.3.3. Assessing the soil's sulfate content comparatively

The sulfate content within the gypsiferous soil underwent initial analysis, followed by a comparison with the sulfate content reported in the initial geotechnical assessment from 2014. To investigate the dissolution process further, soil samples were meticulously collected from the study area using appropriate methods to ensure their representativeness. Subsequently, a laboratory gravimetric analysis technique was employed in accordance with Standard NF EN 1744-1+A1 to precisely determine the sulfate content. By comparing the current sulfate content with that of the previous report, any changes or trends in sulfate content over time could be identified. This comparison offers valuable insights into the dissolution phenomena occurring within the gypsiferous soil in the presence of water.

Indeed, the soil chemical analysis unveiled a sulfate content exceeding the levels reported during the building's construction in 2014 (Table 3.6). These results imply that the dissolution of gypsum particles within the soil may be accountable for the observed alterations in soil compositions.

Table 3.6. The sulfate content observed in 2022 exceeds that reported during the building's construction in 2014.

Sulfate (So_4^{2-} ions) content in soil (%)	
2014	**2022**
2.22	5.22
1.79	5.78
1.80	6.29
1.24	4.55
1.58	3.14
1.53	3.43
1.52	6.63
1.43	5.63

3.4. Evaluation of the dissolution rate

Determining the dissolution rate of gypsum required the utilization of electrical resistivity tomography (ERT) technique. ERT is widely recognized for its ability to non-invasively visualize variations in subsurface electrical resistivity, making it suitable for assessing the presence of dissolved gypsum and its dissolution rate. Previous studies have demonstrated the effectiveness of ERT in identifying and characterizing gypsum karstification[67,68,[70].

Therefore, six (6) lines were positioned parallel to the buildings' facades (Fig. 3.12), each covering a span of 50 meters. Along these lines, ERT measurements were carried out meticulously, employing specialized equipment and adhering to proper protocols.

The ERT technique involves the injection of electrical currents into the ground via electrodes, followed by the measurement of voltage differences across other electrodes. By analyzing the variations in electrical resistivity at different depths, it becomes possible to infer the presence of gypsum and its dissolution rate. Moreover, the resistivity values obtained from ERT can be correlated with the dissolution rate, offering valuable insights into the dissolution process.

The collected ERT data along the designated lines underwent processing and interpretation through the Res2DInv software. Subsequently, the resulting resistivity profiles were scrutinized to identify anomalies indicative of gypsum dissolution areas. These anomalies were categorized into four levels: no dissolution, low dissolution, moderate dissolution, and high dissolution. This classification system not only enables a quantitative evaluation of the dissolution rate but also aids in prioritizing areas warranting further examination. Moreover, the ERT methodology employed in this investigation, coupled with the measurements taken along the specified lines, facilitated the mapping of the gypsum dissolution rate distribution.

The in-situ electrical resistivity measurements, carried out at a depth of 12 meters, provided valuable insights into the soil composition. Within this depth, two distinct layers were identified: the Pliocene layer overlaying the middle Miocene marly layer (Figs. 3.12, 3.13, and 3.14). Interestingly, the electrical resistivity of the Pliocene layer, consisting of conglomerate, sandstone, and sandy clay, was notably higher than that of the marls present in the middle Miocene layer.

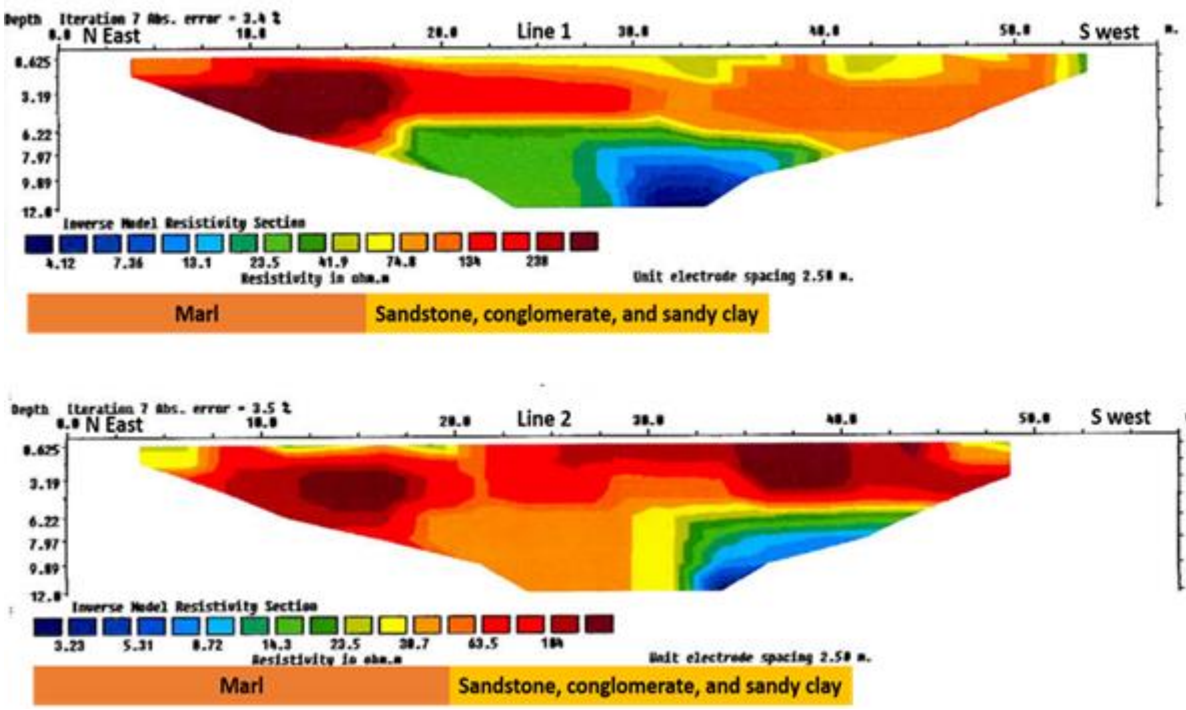


Fig. 3.12. Evaluation of the soil utilizing electrical resistivity tomography lines 1 and 2.

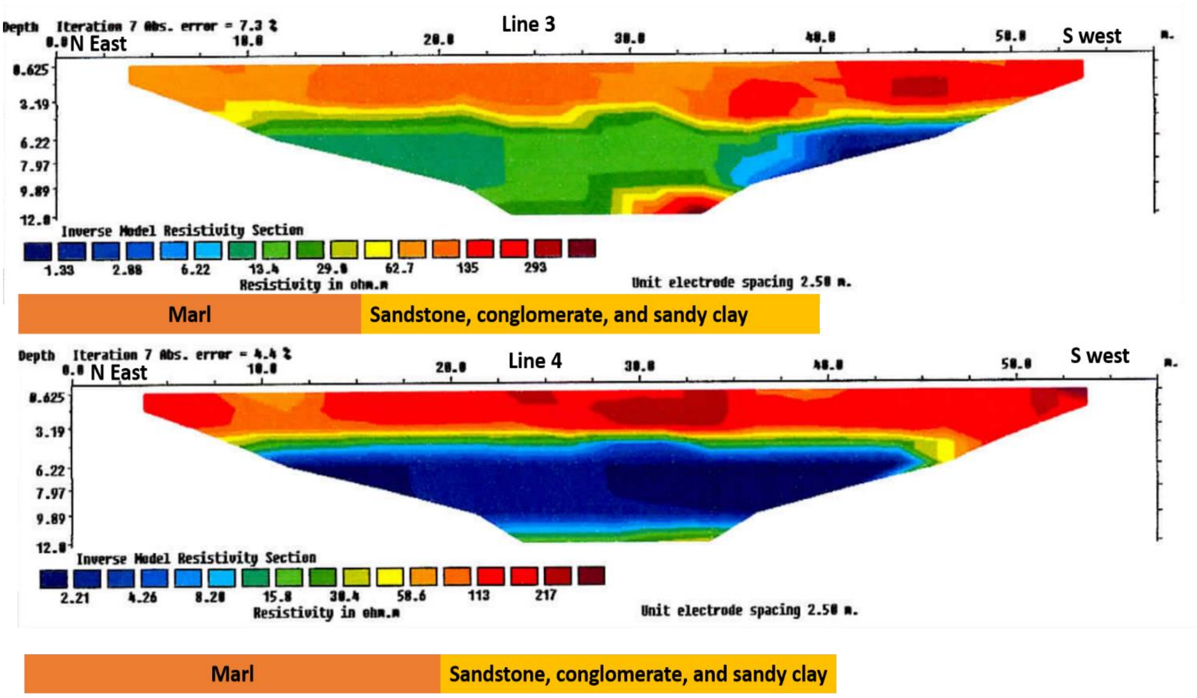


Fig. 3.13. Evaluation of the soil utilizing electrical resistivity tomography lines 3 and 4.

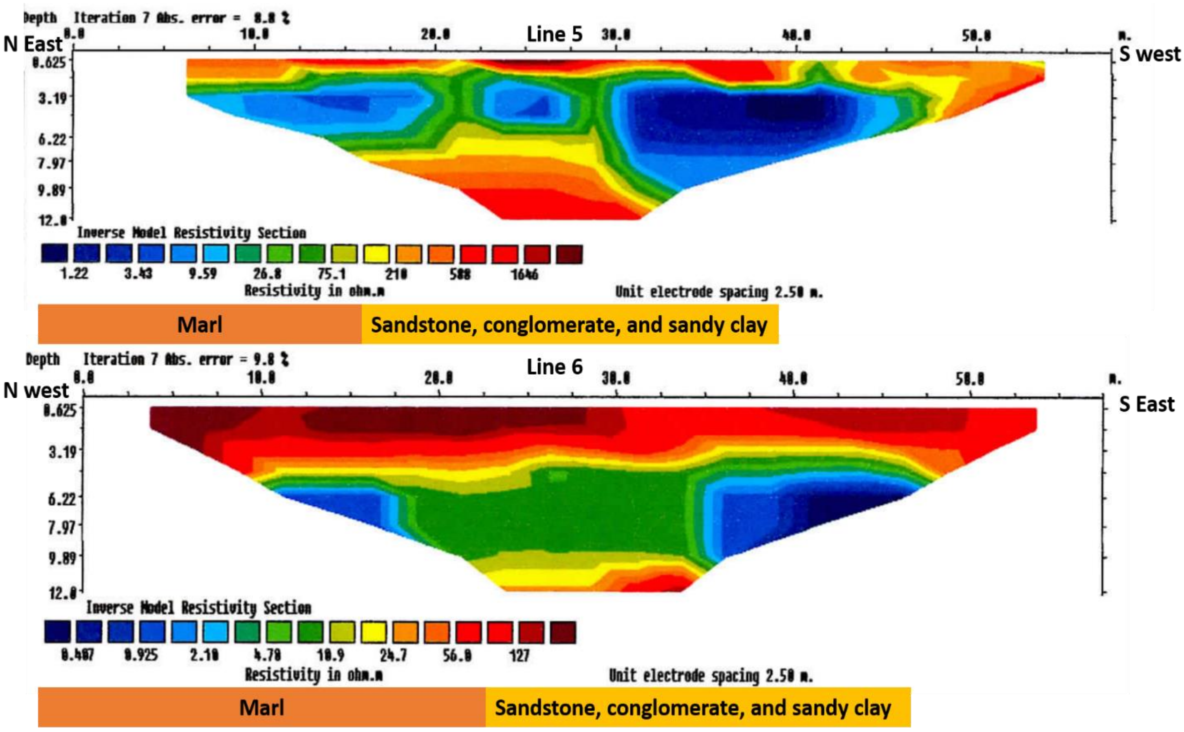


Fig. 3.14. Evaluation of the soil utilizing electrical resistivity tomography lines 5 and 6.

The variations in electrical resistivity noted in the upper layer can be ascribed to randomly distributed factors like moisture content, porosity, and granularity. Conversely, the reduced electrical resistivity values observed in the underlying marlstone layer can be linked to its elevated clay content, which is recognized for its high electrical conductivity.

In the first layer, where gypsum dissolution was detected, the electrical resistivity values ranged from 62.7 ohm·meter (Ω·m) in the wet zones to 238 ohm·meter (Ω·m) in the dry zones. These values suggest a moderate to low rate of gypsum dissolution. Detailed resistivity values and their respective rates are outlined in Table 3.7.

Table 3.7. Assessment of dissolution rate at the first layer using the electrical resistivity.

Line	Dissolution rate at the first layer consisting of conglomerate, sandstone, and sandy clay		
	Moderate	**Low**	**Undissolved**
1(Ω·m)	74.80	134	238
2(Ω·m)	63.50	184	/////
3(Ω·m)	62.7	135	293
4(Ω·m)	/////	113	217
5(Ω·m)	/////	/////	210, 588, 1646
6(Ω·m)	/////	127	/////

Additionally, it's crucial to recognize that the distribution of the evaluated dissolution rate was not consistent along the length of the lines. The in-situ electrical resistivity measurements aided in mapping the distribution of the predominant assessed gypsum dissolution rate parallel to the affected buildings (Fig. 3.15).

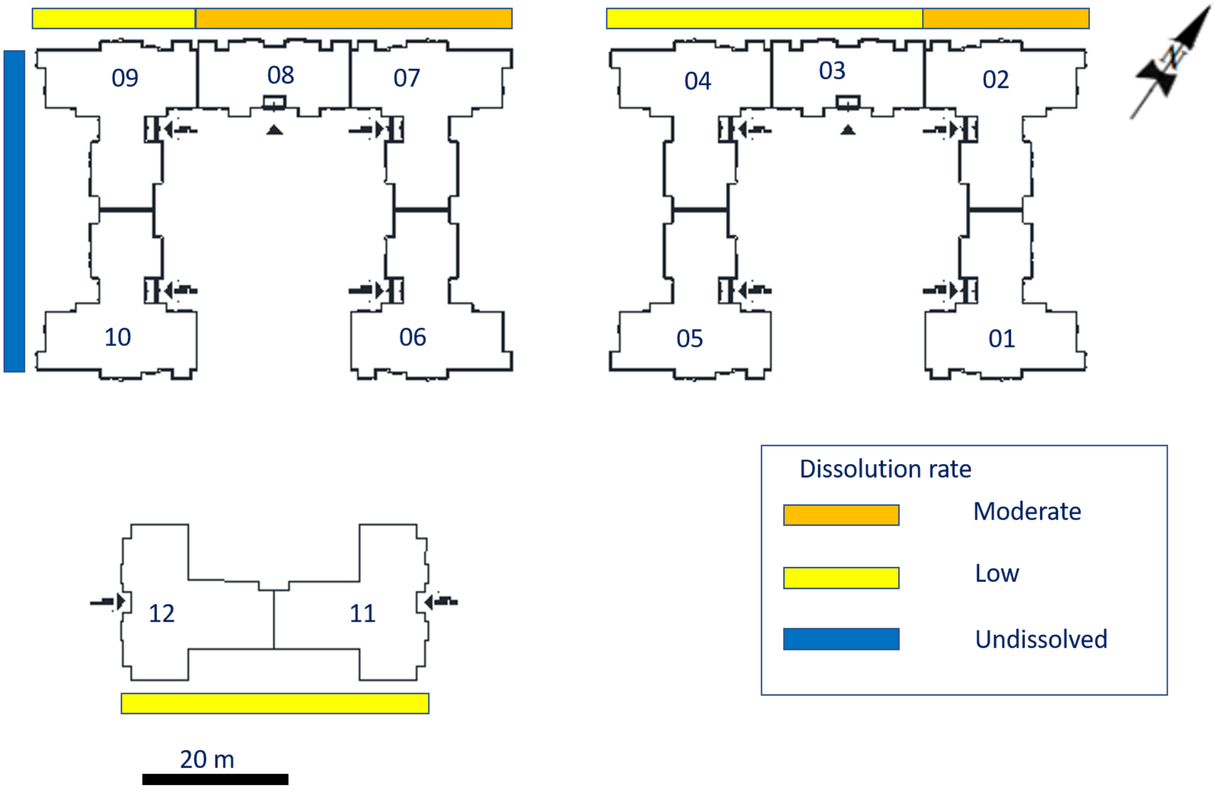


Fig. 3.15. Variations in the dissolution rates along the buildings affected by the phenomenon.

3.5. The impact of the dissolution rate on the stability of the soil beneath the foundations

3.5.1. Changes in the in-situ cone penetration limits following water infiltration into the gypsiferous soil

The methodology involved comparing the penetrometer pressures measured in 2022 with those recorded in 2014 at the same location adjacent to building 1, following the guidelines of Standard NFP 94-115. This comparison was conducted primarily to assess the variations in penetrometer pressure resulting from water infiltration into the gypsiferous soil.

Fascinating insights emerged when comparing the results of the penetrometer tests conducted in 2022 with those from 2014, at the same location adjacent to the damaged building

1. These findings highlighted that the pressure required to penetrate the soil in 2022 was generally lower compared to that of 2014, as depicted in Fig. 3.16.

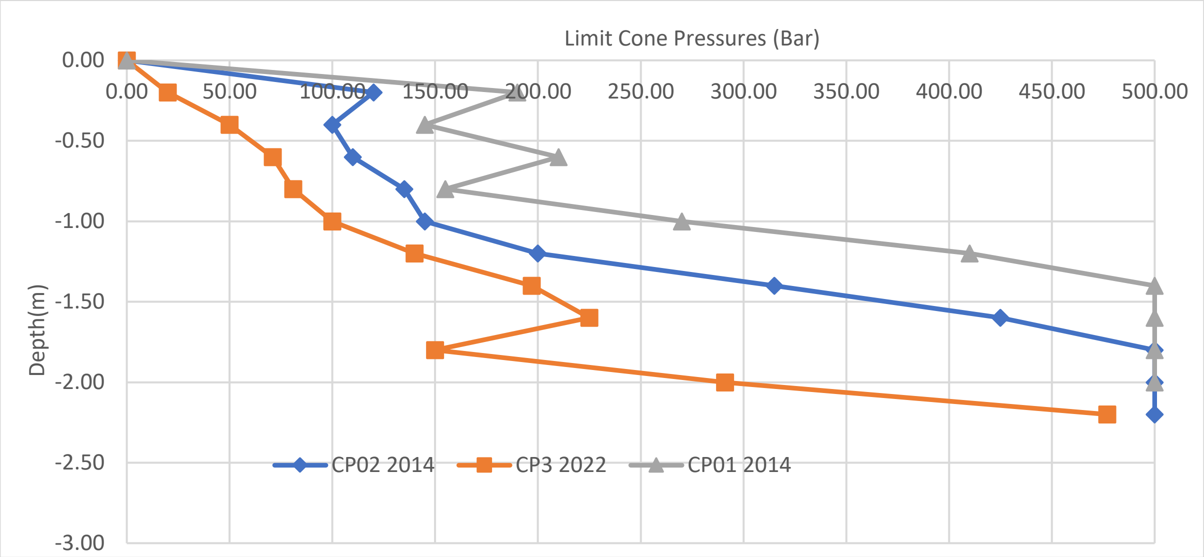


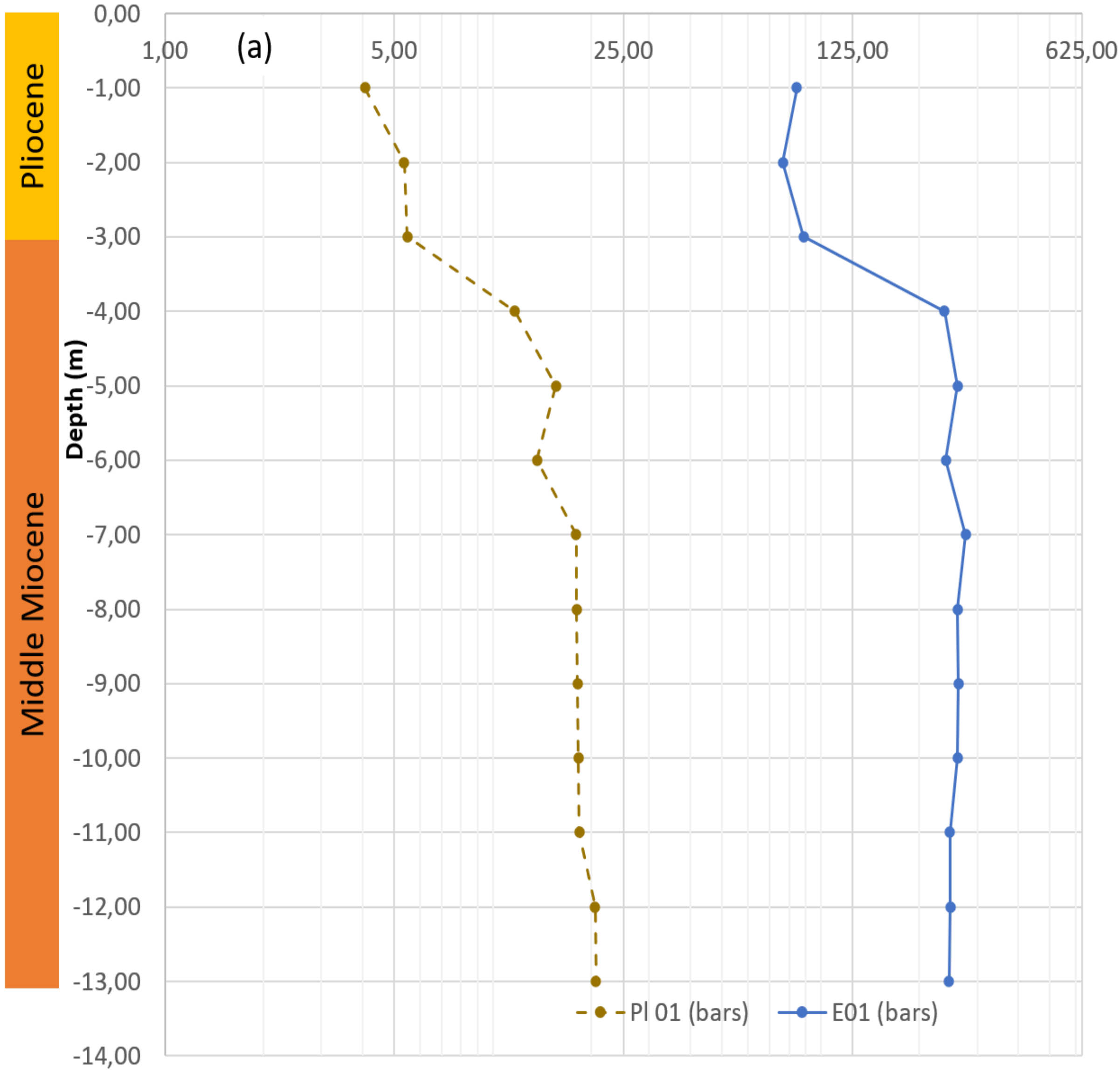
Fig. 3.16. Contrasting the results of the penetrometer tests conducted in 2022 and 2014 adjacent to building 1 Area 1.

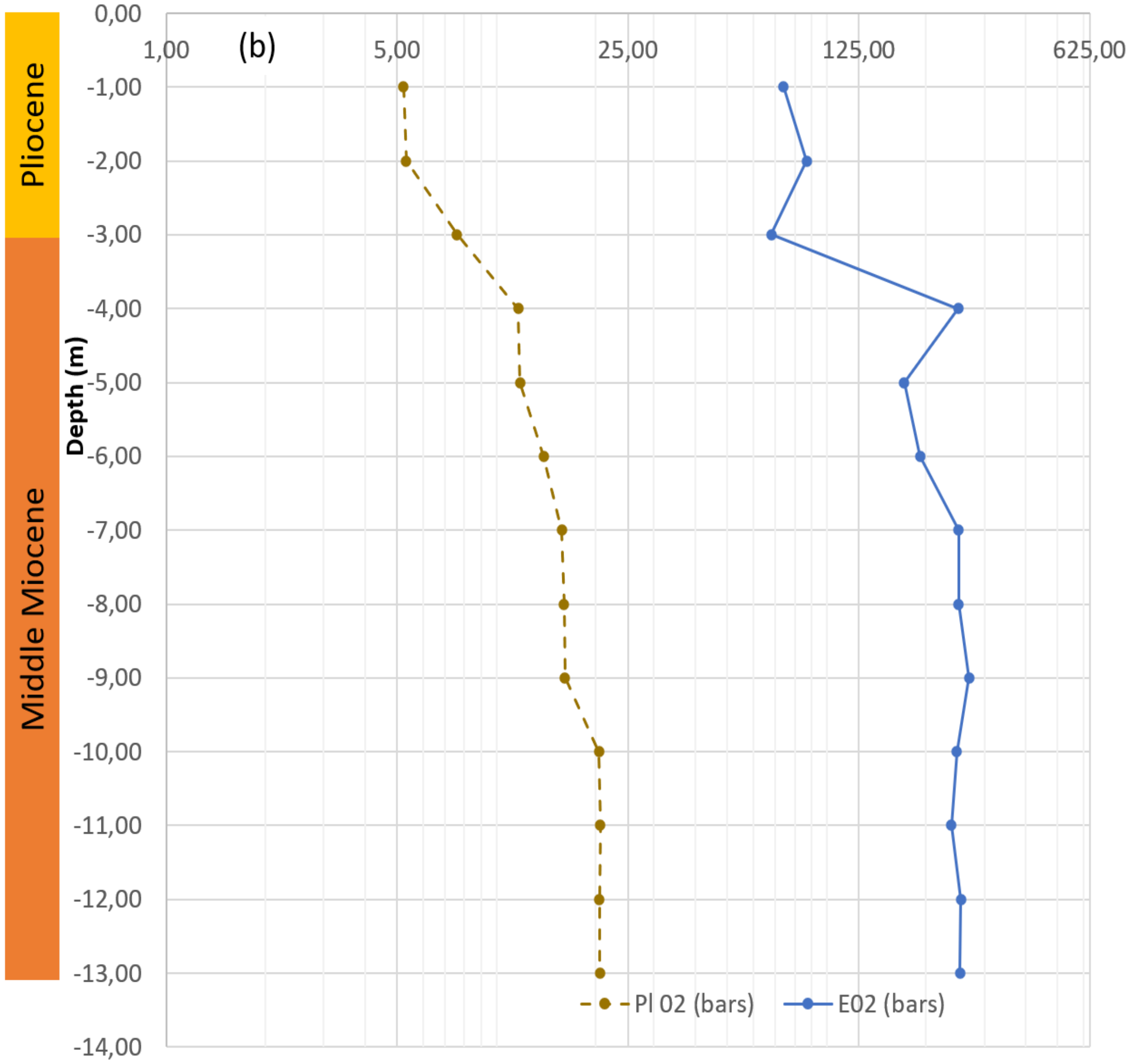
The observed decrease in the recorded limit cone penetration pressure tests can be attributed to the process of gypsum dissolution and particle transportation when exposed to concentrated water flow, such as water infiltration from detected leakages within the first Pliocene layer. This process may result in the formation of new small cavities or the reactivation of existing ones, leading to the enlargement of these voids. Without external loads to collapse the soil structure at the measurement points, the void ratio of the soil increases without a change in volume. This enlargement facilitates easier penetration by the cone, as evidenced by the lower penetration limit values observed in 2022 compared to those recorded in 2014.

3.5.2. Evaluating soil properties through Menard pressuremeter tests

Menard pressuremeter tests, conducted in accordance with Standard NFP 94-110-1, aimed to evaluate the limit pressure and pressuremeter modulus of soils within the study area.

The Menard pressuremeter tests (MPTs) yielded intriguing insights into the soil's limit pressure, extending to a depth of 13 meters. Across SP01, SP02, and SP03 tests, the pressure limit values varied from 4.08 to 20.66 bars, as depicted in the figure below (Fig. 3.17).





(b)
Pliocene
Middle Miocene
Depth (m)
1,00
5,00
25,00
125,00
625,00
0,00
-1,00
-2,00
-3,00
-4,00
-5,00
-6,00
-7,00
-8,00
-9,00
-10,00
-11,00
-12,00
-13,00
-14,00
Pl 02 (bars)
E02 (bars)

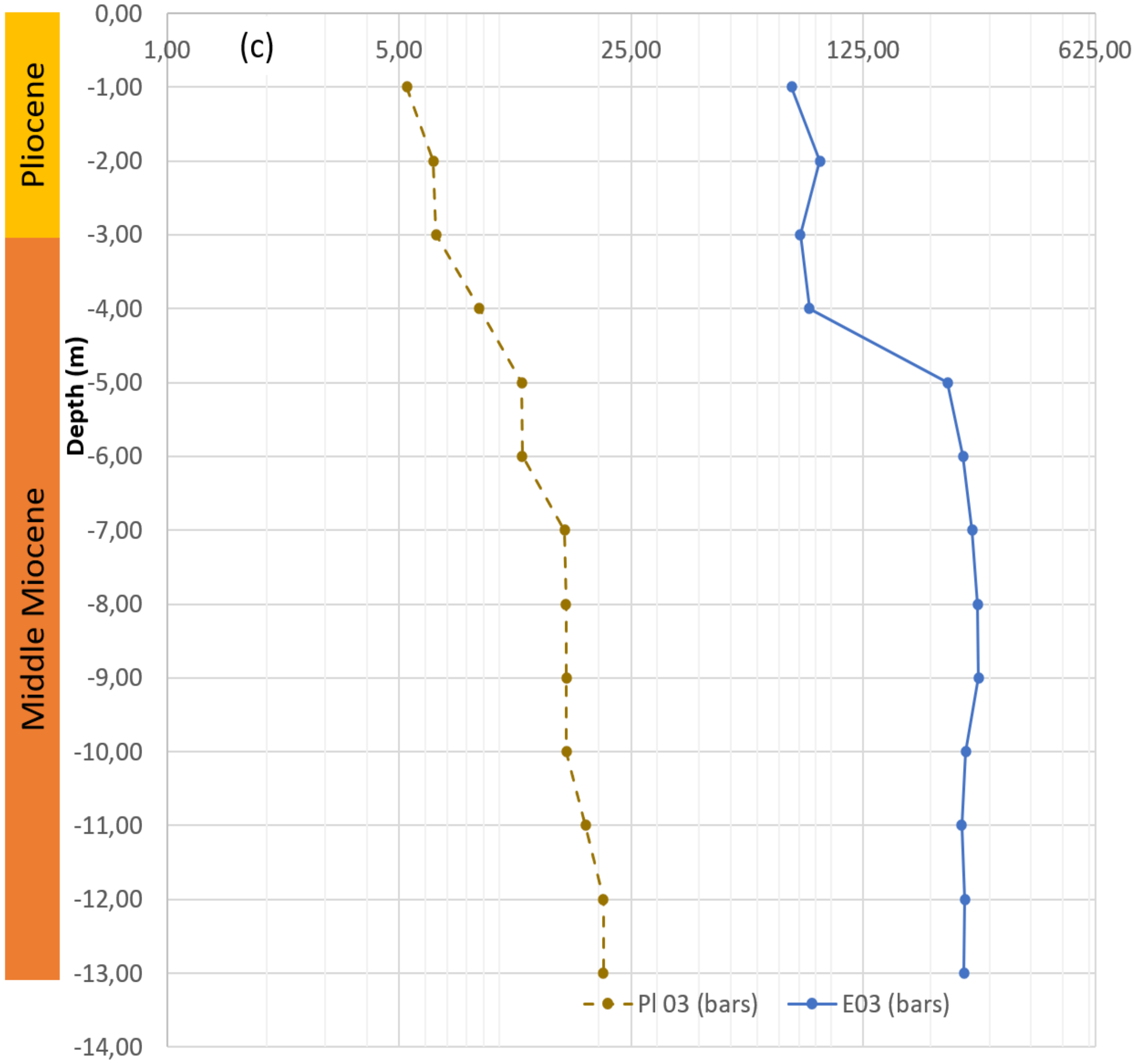


Fig. 3.17. Assessment of Pressuremeter Modulus (E) and Limit Pressure (Pl) of Soil Using Menard Pressuremeter Tests: (a) SP01 results, (b) SP02 results, (c) SP03results.

The analysis of results from the Menard pressuremeter tests unveiled a discernible pattern: the limit pressure values displayed an upward trend with increasing depth. Particularly noteworthy was the observation that within the initial layer of the Pliocene, where a moderate gypsum dissolution rate was evident, the limit pressure values derived from the SP01, SP02, and SP03 tests remained relatively low, measuring below 10 bars at depths of 3, 3, and 4 meters, respectively.

Similarly, within the layer exhibiting a moderate gypsum dissolution rate, the pressuremeter modulus values obtained from the SP01, SP02, and SP03 tests were relatively low, measuring less than 100 bars at depths of 3, 3, and 4 meters, respectively.

On the contrary, within the second layer of the middle Miocene, characterized by marl, notably higher values were observed, progressively increasing to 20.66 bars in the limit pressure and 278.71 in the pressuremeter modulus.

3.5.3. Comparison of dissolution rate and pressuremeter modulus along damaged building facades

To explore the correlation between soil stability, dissolution rate, and building damage, an evaluation was conducted at two points (SP02 and SP03) corresponding to pressuremeter tests aligning with resistivity lines 1 and 3. These points registered a moderate gypsum dissolution rate in front of damaged buildings 2 and 7, respectively (refer to Fig. 3.18 and Table 3.8).

Table 3.8. Evaluation of the dissolution rate using the ERT technique (line1 and line 3) versus the pressuremeter modulus using the Menard pressuremeter tests SP02 and SP03.

Depth (m)	**Line 3 / SP02(bars)/Damaged buildings 7 and 8**		**Line 1/SP03(bars)/Damaged Building 2**	
1.00	Moderate	73,98	Moderate	76,06
2.00	Moderate	87,11	Moderate	92,76
3.00	Moderate	67,99	Moderate	80,95
4.00	Undissolved marl	249,93	Moderate	86,04
5.00	Undissolved marl	171,77	Undissolved marl	224,31

The analysis revealed a correlation in depth between the moderate dissolution rate observed in the Pliocene layer containing gypsum, as assessed by the electrical resistivity tomography lines, and the low pressuremeter modulus values measuring less than 100 bars parallel to the damaged building facades.

These findings suggest a potential connection between the low pressuremeter modulus values and the moderate dissolution rate observed in situ when water infiltrates the gypsum soil. This infiltration can initiate the process of gypsum dissolution and particle transportation when exposed to concentrated water flow, possibly leading to the enlargement of underground voids and a decrease in the pressuremeter modulus of the soil in the absence of external loads.

Furthermore, these findings imply that the structure of the Pliocene gypsiferous soil in the area has become more prone to collapse under the load of foundations. According to the DTU 13.12 standard, foundation settlement tends to increase as the pressuremeter modulus decreases.

Moreover, these findings align with the characteristics of collapsible soil, including gypsiferous soil. Such soils are known for experiencing significant decreases in void ratio and rapid settlement of a meta-stable soil structure during wetting and loading. In laboratory settings, the collapse potential (Ic) of these soils can be determined at various stress levels using the Standard Test Method for Measurement of Collapse Potential of Soils (ASTM D5333-03).

3.5.4. Tracking building facade movements

Building facade movements were monitored using a Leica TS16 0.5" Second Hand Total Station. A total of 176 reflective targets were affixed to the facades of blocks 1 to 12. This total station boasted a precision of 1mm. Initially, a first vision was programmed to establish the initial coordinates of the targets. Subsequently, four additional visions were added to capture variations in the x, y, and z coordinates, aligning with north, east, and the vertical direction, respectively. By tracking changes in the reflective target coordinates between successive visions, movements of points on the building facades were recorded. This monitoring spanned a period of (30 ± 3) days, with four additional visions conducted at 10-day intervals following the first vision.

The reflective targets were strategically installed at two distinct levels on each building, positioned at +2.20 and +14.70 from the platform paving level. These dual reflective targets facilitated the monitoring of ground-floor and fourth-floor movements, respectively. This multi-level approach to tracking movements offers a comprehensive insight into the structural behavior and stability of the buildings.

Over time, the variations in the coordinates of the reflective targets were meticulously recorded along the three axes (x, y, and z), as depicted in Fig. 25, 26, and 27. This detailed monitoring provided a comprehensive understanding of the dynamic soil-structure interaction unfolding at the site.

The analysis of ground-floor movement data revealed movement along all three axes, with vertical (z-axis) movement exceeding that along the horizontal x and y axes. This disparity indicates that the initiation of movements likely occurs along the z-axis. These findings highlight the vulnerability of the area's buildings to ground movements, potentially associated with the hydro-collapse of the soil structure under the load of foundations.

The movement along the z-axis indicates vertical displacement or settlement of the building foundation. As the foundation settles or undergoes changes in elevation, it influences the position of the structure along the horizontal x and y axes. This is because foundation settling can cause the building to tilt or shift, resulting in displacements along the corresponding horizontal axes.

As a result, the significant movement detected along the z-axis can be viewed as the main contributor to deformation and settlement, impacting the movements observed along the x and y axes. Therefore, comprehending and evaluating the z-axis movement is essential for evaluating the stability and functionality of the building foundation.

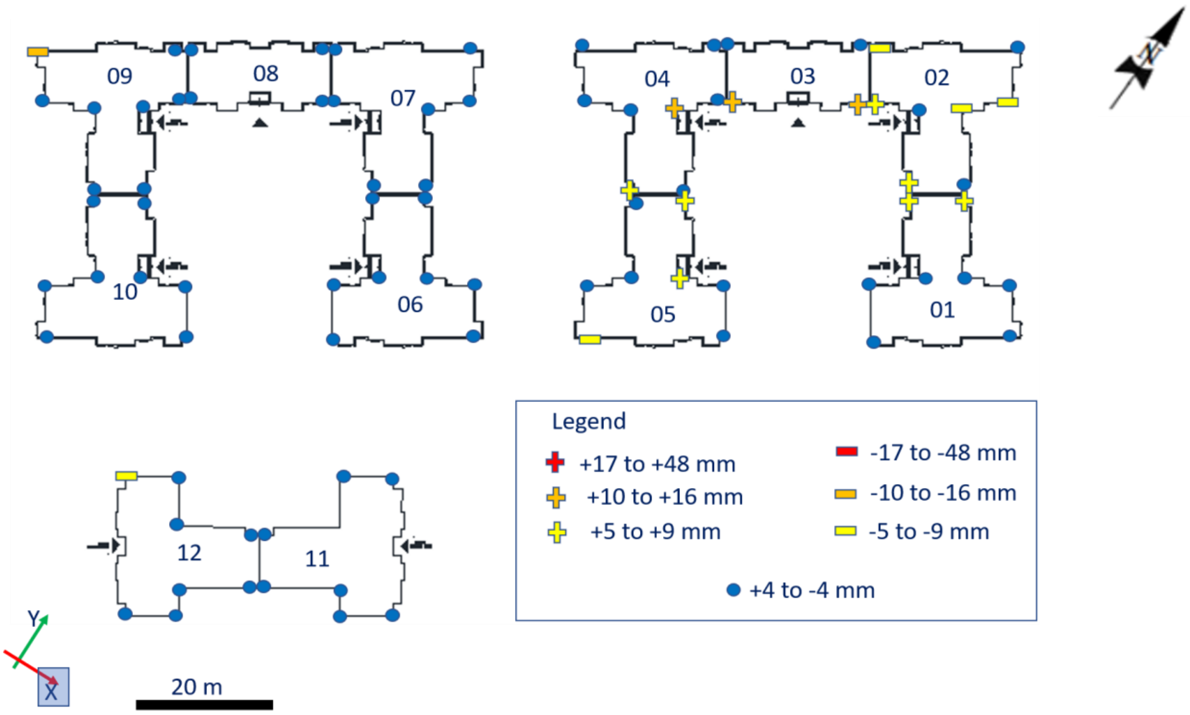


Fig. 3.18. Horizontal displacement along X-axis of the building's ground level.

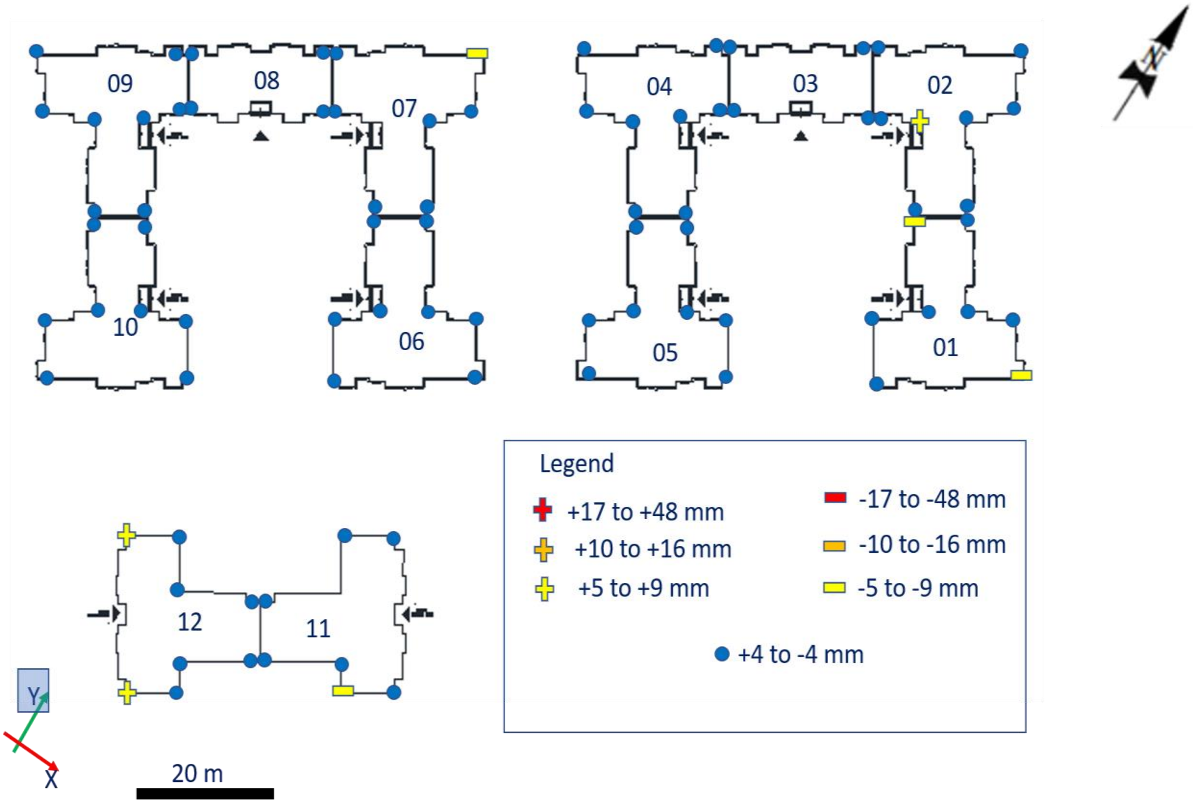


Fig. 3.19. Horizontal displacement along Y-axis of the building's ground level.

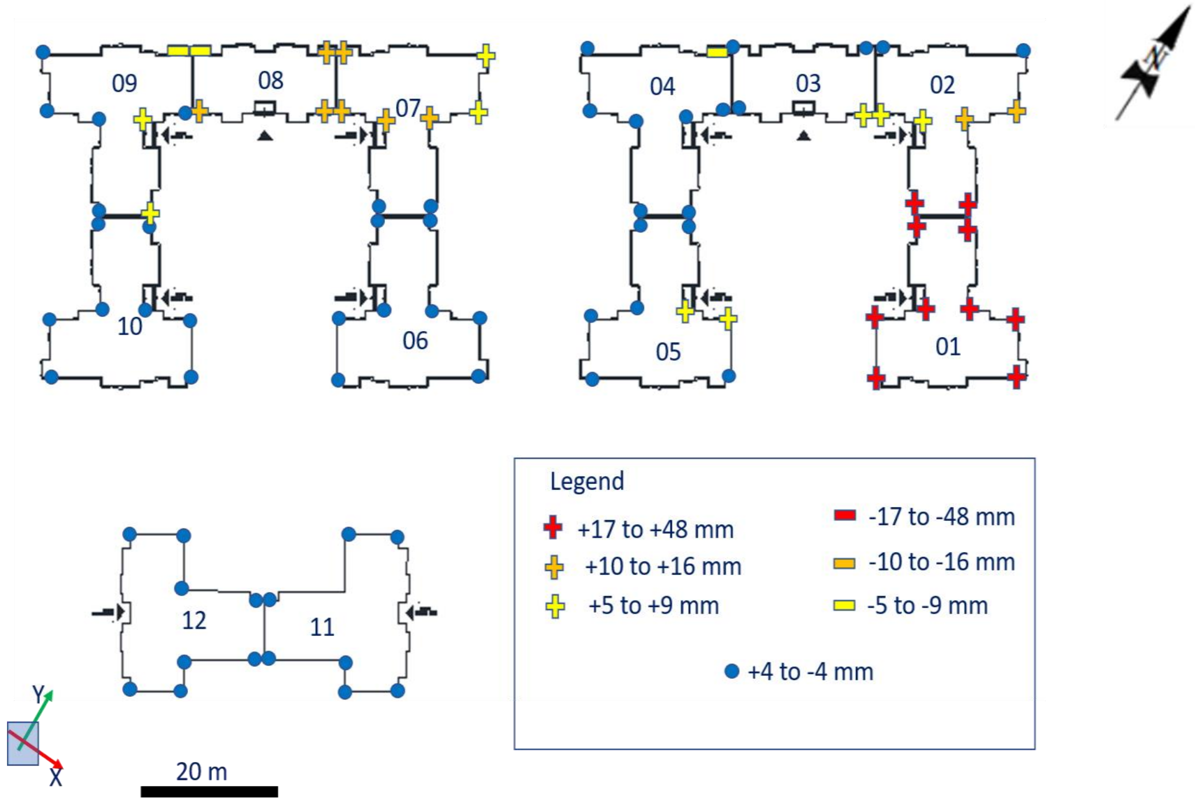


Fig. 3.20. Vertical displacement along Z-axis of the building's ground level.

The buildings experiencing the most significant movement were identified as 1, 2, 7, and 8. Continuous monitoring of these structures offered valuable insights into the dynamic relationship between their foundations and the underlying soil.

- Reflective targets positioned on the left side of Building 1 (targets 1, 3, 2, and 8) recorded settlements of less than 5 mm throughout the 39-day monitoring period, whereas targets on the right side of the same building indicated heaving movements under 10 mm. This disparate behavior may stem from various factors, including soil conditions and localized impacts. Notably, a leakage point detected on the left side of the building initially triggered settlement in that area. Over time, these settlements gradually shifted towards the central foundations subjected to higher loads, resulting in more pronounced settlement. Additionally, soil compression at the block's edges led to simultaneous heaving. Analogous to a beam under bending moments, this behavior can be characterized as sagging, with the central portion undergoing downward movement (settlement) – known as the sagging zone in subsidence studies – while the edges experience upward displacement or heaving, termed the hogging zone. This phenomenon is clearly illustrated in Fig. 3.21.

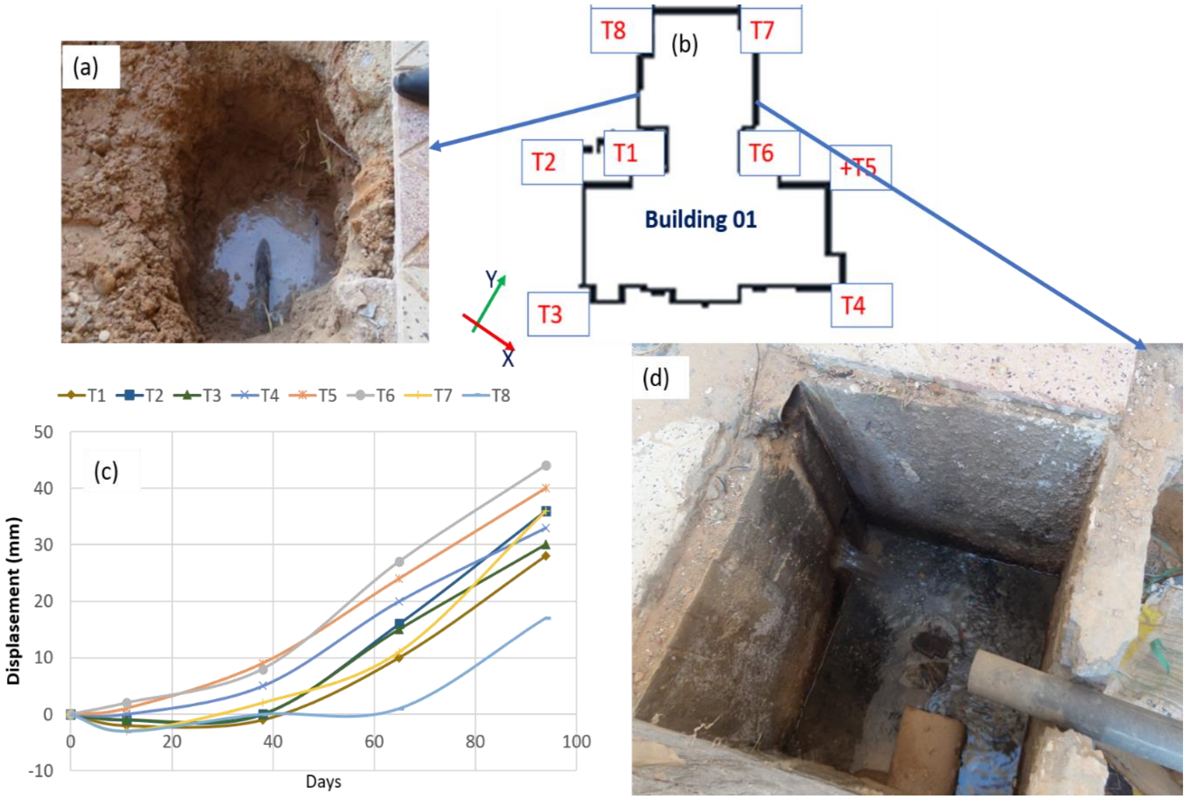


Fig. 3.21. Building 1: (a) Water Pipeline Leakage Adjacent to the Building, (b) Target References on the Building, (c) Target Movements Versus Time (Days), (d) Wastewater and Sewage Pipes Beneath the Block Infrastructure.

• The reflective targets positioned on the upper section of building 2 (targets 4 and 5) demonstrated settlements of less than 5 mm throughout the 94-day observation period.

Conversely, those situated on the lower part of the building displayed upward movements, indicating differential settlement within the structure. This phenomenon is likely attributable to the moderate dissolution rate observed parallel to this building's facade. Such dissolution can reduce the soil's strength, leading to settlements in some areas and heaving or upward displacement in others. Fig. 3.22 suggests that varying gypsum dissolution rates may contribute to differential settlement by causing soil compaction and stability variations. However, the maximum values observed for T8 and T1 are influenced by the building's foundation design. Building 2, where targets T1 and T8 were installed, shares combined foundations with building 1. Consequently, the recorded upward heaving of these targets is consistent with the displacements observed at targets T7 and T8 of building 1 (Fig. 3.22).

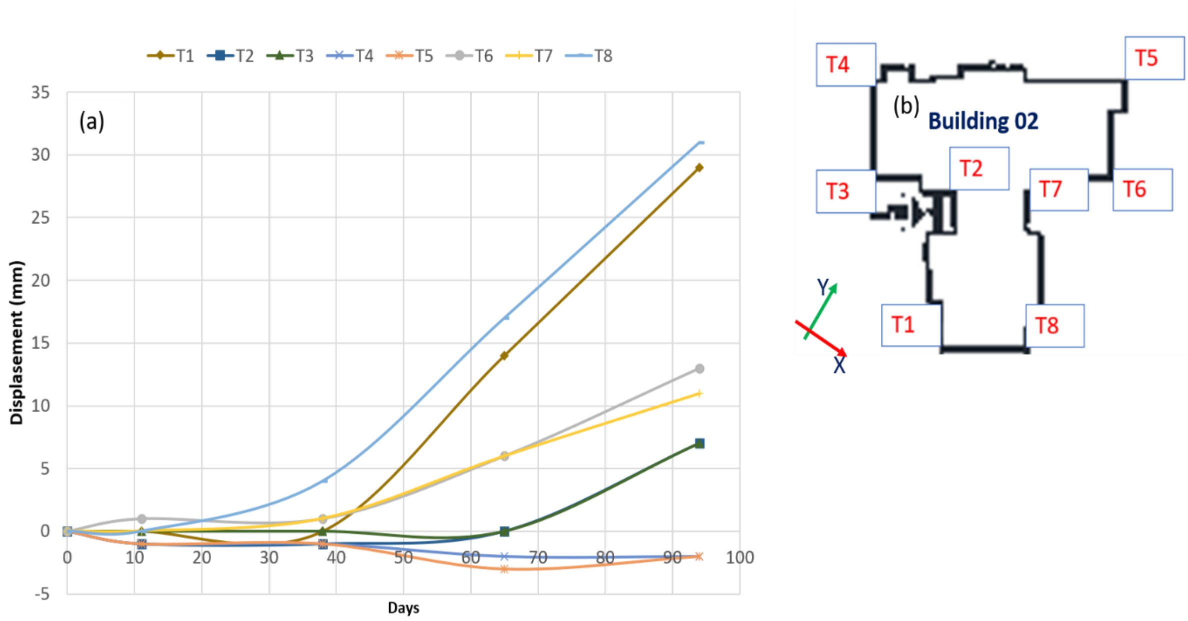


Fig. 3.22. Building 2: (a) Targets movement versus time (days), (b) Targets references on the building.

- Throughout the 94-day monitoring period, all reflective targets installed on building 7 displayed upward movements, indicating a sagging pattern akin to that observed in the first building. Consequently, the central area of this building experienced settlement, while its periphery exhibited upward displacement or heaving. This differential movement is likely attributable to the moderate dissolution rate observed parallel to the building's facade. The presence of such a dissolution rate may lead to alterations in soil strength, causing settlement in certain areas while others undergo heaving or upward displacement, as depicted in Fig. 3.23.

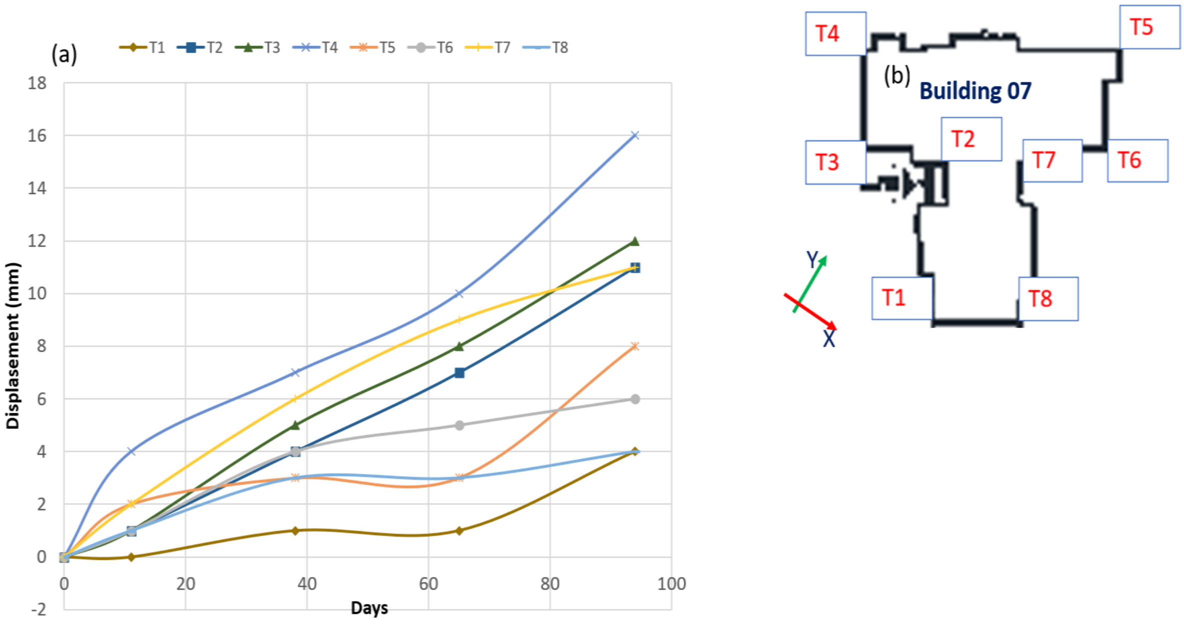


Fig. 3.23. Building 7: (a) Targets movement versus time (days), (b) Targets references on the building.

- During the 94-day monitoring period, reflective targets 1, 2, and 4 on building 8 displayed upward movements, while target 3 exhibited settlements, mirroring a pattern of differential settlement akin to that observed in building 2. This differential movement is likely linked to the moderate dissolution rate observed parallel to the building's facade, as illustrated in Fig. 3.24.

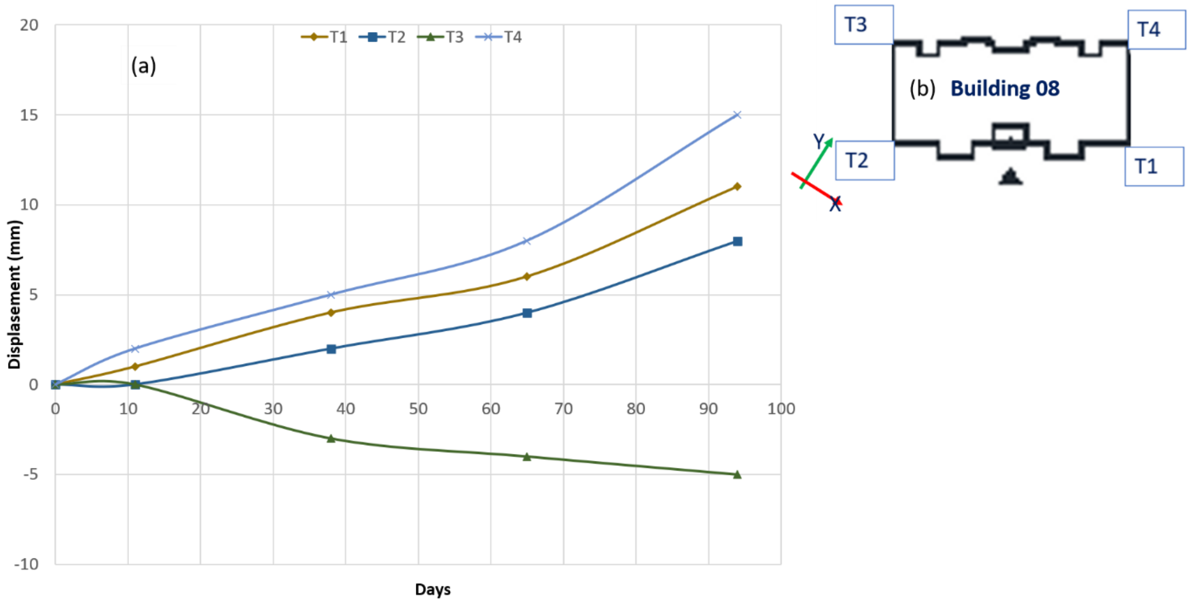


Fig. 3.24. Building 8: (a): Targets movement versus time (days), (b): Targets references the building.

On the fourth floor, extensive displacements were observed along all three axes, as depicted in Fig. 3.25, 3.26, and 3.27. However, there were no substantial changes noted along the z-axis. Instead, significant tilting of the building was observed along the x and y axes, indicating notable differential movement at the foundation level, likely the primary cause of the building's tilting. Regrettably, this phenomenon led to several adverse effects, including horizontal structural cracks in the columns. Additionally, there were instances of divergence among adjacent buildings, resulting in divergence that increases along the height of the adjacent buildings in the case of isolated acroter. Additionally, concrete cracking and dilation of the steel reinforcement bars were observed in the case of combined acroter.

This issue is commonly attributed to the tilting of buildings and the inadequate size of the expansion joints. The maximum thickness of these joints is 12 cm, which proves insufficient to accommodate the differential movement occurring in the structures.

The collected data suggest that, in general, the building's foundation is subjected to considerable stress and undergoes significant movement, often resulting in damage to the construction materials and structural elements of the building.

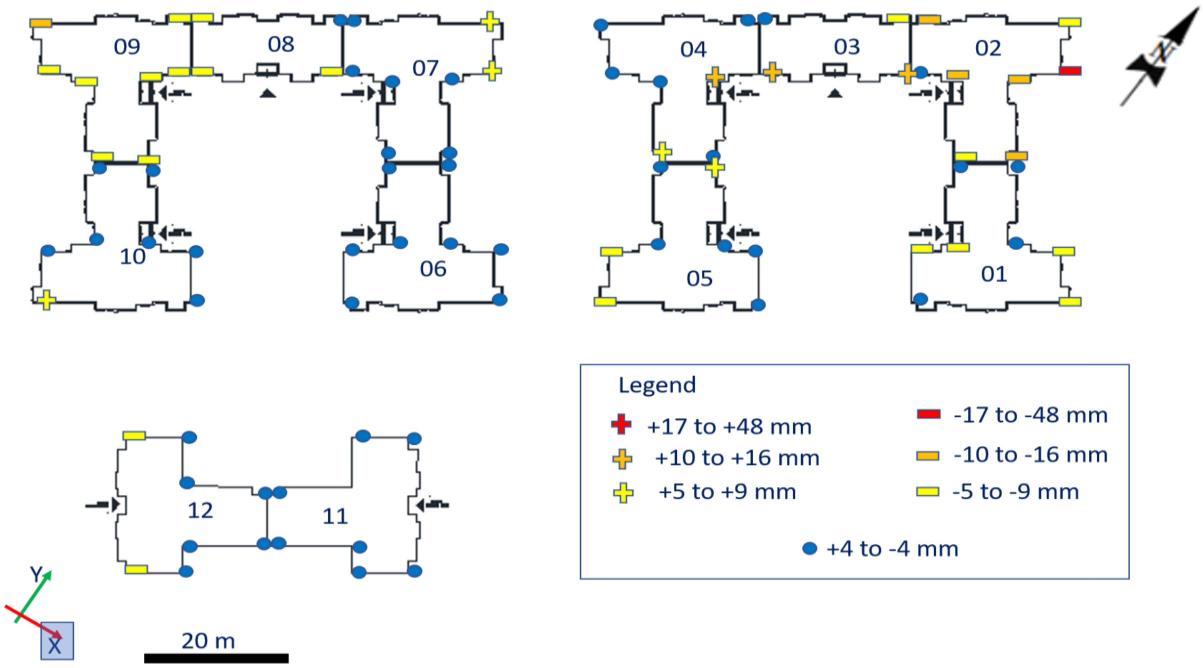


Fig. 3.25. Horizontal displacement along X-axis of the building's fourth-floor level.

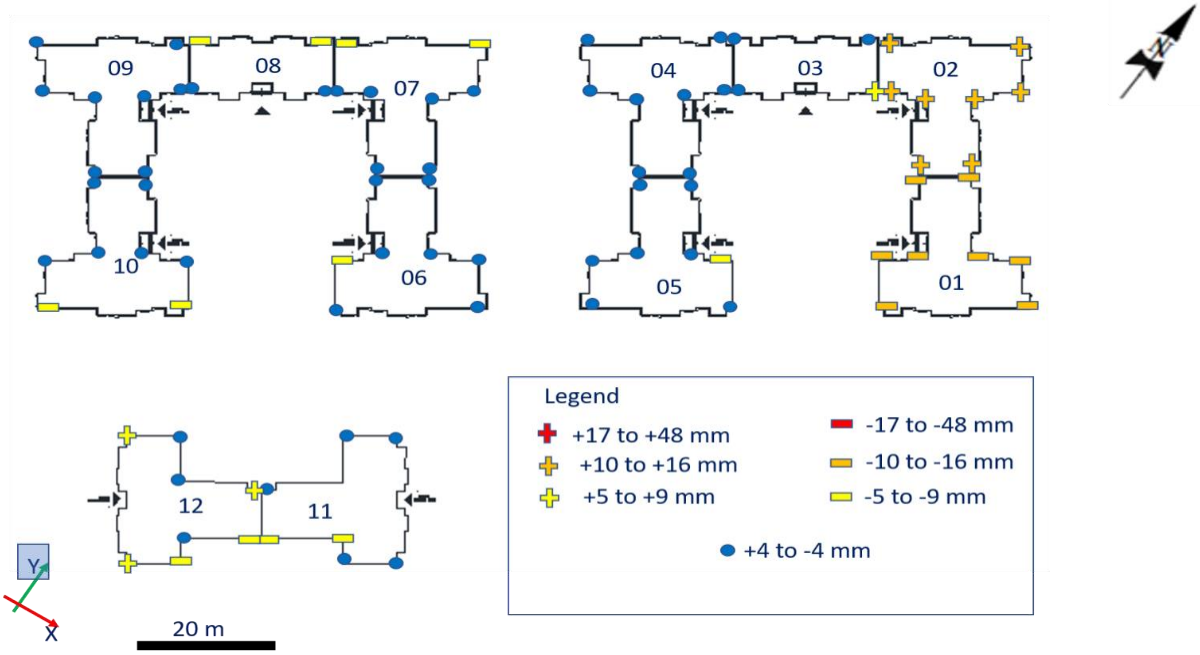


Fig. 3.26. Horizontal displacement along y-axis of the building's fourth-floor level.

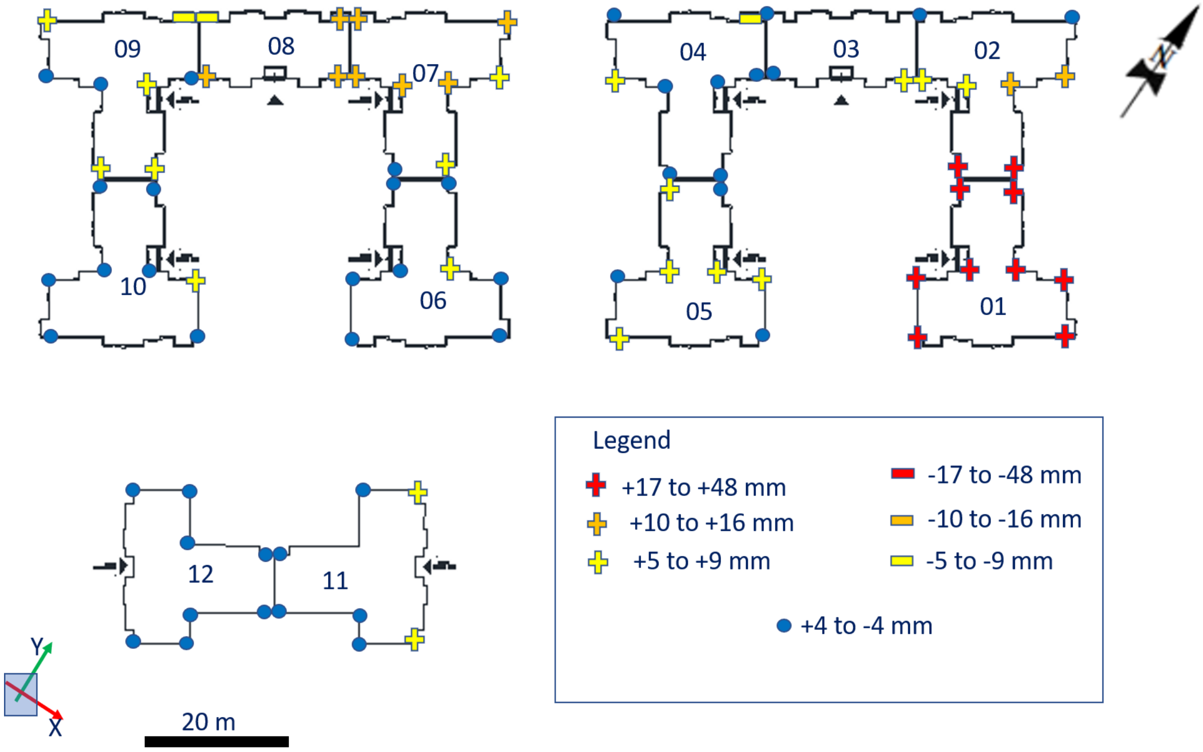


Fig. 3.27. Vertical displacement along Z-axis of the building's fourth-floor level.

3.6. Evaluating building damage caused by differential foundation movements

Recognized as pivotal, the assessment of building damage serves as a crucial step in identifying the underlying causes of structural failure. However, the selection of a classification system for categorizing building damage warrants careful consideration, particularly prior to pinpointing the root causes of deterioration. To address this concern, Cooper (2008) [41] introduced a unified scheme that accounts for similarities in ground movement observations between landslides and subsidence. This scheme aims to establish a comprehensive recording framework for various types of subsidence resulting from phenomena such as karstification, soil shrinkage and swelling, deep and shallow mining, compressible ground, and landslides (refer to Table 3.9)) [41]. Embracing this unified approach facilitates a more comprehensive understanding of building damage. In the case of subsidence attributed to evaporite dissolution, the initial five categories of the scheme were employed to evaluate damage in the Historical City of Calatayud, Spain [17].

Given that building cracks predominantly arise from foundation movements, especially from uneven settlement, the outcomes of building facade shifts, specifically along the z-axis over a span of 94 days, were integrated into the classification system for building damage categories.

Table 3.9. Ranking scheme of building damage categories using the typical building damage according to [41], with the consideration of the building façade displacements recorded in-situ along the z-axis during 94 days (criteria that shown in bold type).

Class	**Typical building damage and building façade displacement along the z-axis (94 days)**
0 None	Hairline cracking, widths up to 0.1mm. Not visible from outside.
1 Very slight	Fine cracks, generally restricted to internal wall finishes. Rarely visible in external brickwork. Typical crack widths up to 1mm. Generally, not visible from outside.
2 Slight	Cracks not necessarily visible from outside, some external repointing may be required. Doors and windows may stick slightly. Typical crack widths up to 5mm. Difficult to record from outside.
3 Moderate	Cracks can be repaired by a builder. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking, slightly tilting to walls. Service pipes may be fractured. Typical crack widths between 5 and 15mm. Visible from outside. **Uplift or settlement less than 4 mm on the reinforced concrete frame of the building façade.**
4 Severe	Extensive damage that requires breaking out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floors sloping noticeably; some loss of bearing in beams, distortions in the structure. Service pipes disrupted. Typical crack widths

	ranging from 15 to 25mm, with variable number of cracks. Noticeable from outside **Uplift or settlement more than 4 mm and less than 10 mm on the reinforced concrete frame of the building façade.**
5 Very severe	Structural damage requiring major repairs, sometimes involving partial or complete rebuilding. Beams lose their bearing capacity; walls lean badly and require shoring. Windows broken due to distortions. Danger of instability. Typical crack widths are greater than25mm, with a varying number of cracks. Very obvious from outside **Uplift or settlement more than 17 mm on the reinforced concrete frame of the building façade.**
6 Partial collapse	Partial collapse, very apparent from outside
7 Total collapse	Total collapse, very apparent from outside

During the assessment of building damage, several visible cracks were observed, ranging from 5 to over 25mm in width, prominently visible from the exterior. The damage was extensive, necessitating the removal, cutting, and replacement of certain sections of walls, especially around door and window areas. Additionally, the doors and windows exhibited difficulty in opening and closing, with their frames noticeably warped.

Utilizing Cooper's 2008 damage classification scheme and considering the building facade displacements recorded along the z-axis over a 94-day period, the damaged buildings were categorized from moderate (class 3) to very severe (class 5). Among the twelve buildings assessed, the majority fell under the moderate classification, with 7 buildings in this category. Four buildings were classified as severely damaged, while one was deemed very severely damaged. The severity of damage correlates closely with the underlying failure mechanisms causing soil movements and the susceptibility of buildings to such movements. Subsequently, the assessment findings were visualized on a color-coded map, highlighting the locations of the buildings, as depicted in Fig. 3.28.

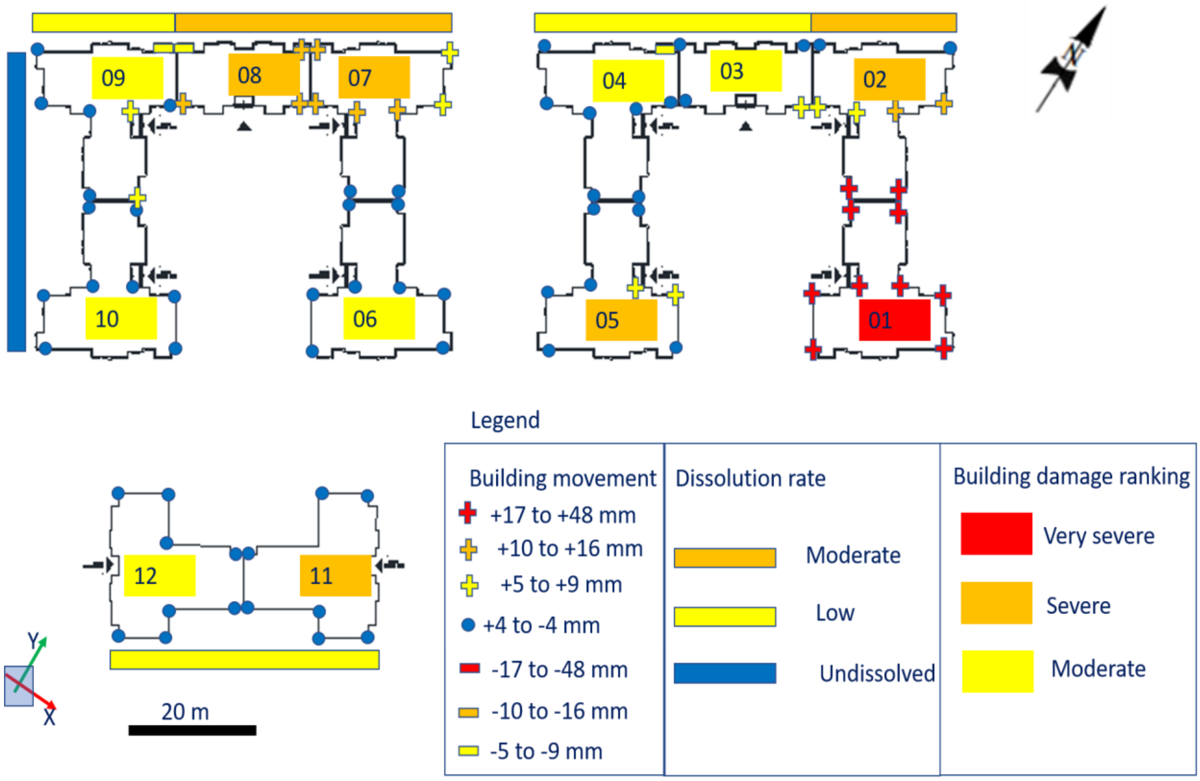


Fig. 3.28. Distribution of building damage ranking using the typical building damage. Classification scheme, dissolution rate, and building movement along the z-axis

The significant damage and substantial movement observed in buildings 2, 7, and 8, coupled with the presence of a moderate dissolution rate parallel to these structures, indicate a clear correlation between building failure and water seepage into the gypsiferous soil beneath them. The dissolution of gypsum within the soil, triggered by water infiltration, compromises foundation stability, resulting in considerable movement and damage.

Conversely, severe damage was documented in blocks 11 and 5, despite the low dissolution rate observed parallel to block 11. This indicates that the failure mechanism in these structures occurred before the monitoring period, implying that water infiltration into the gypsiferous soil had already initiated the failure process, which may have subsequently ceased.

3.7. Analyzing the failure mechanisms of the buildings

The findings underscore the significant impact of water infiltration and its interaction with gypsum-rich soil on the stability and structural integrity of buildings. The presence of gypsum alters the soil's response to external forces, rendering it prone to movement under service loads, particularly in moist conditions. This hydro-collapse phenomenon is primarily induced by the dissolution process and subsequent transportation of soil particles within the Pliocene layer, characterized by a composition of sandy clay, sandstone, and conglomerate matrix. Existing pores, filled cavities, and cracks within this layer exacerbate the instability.

Moreover, the inadequate design of building foundations, employing both isolated and combined footings, further compounds the issue. The failure mechanism of the buildings is attributed to differential settlement, which imposes stress on the building's materials and components, leading to structural failures. The heterogeneity of the Pliocene soil, varying in depth and area, exacerbates this differential movement of building foundations.

Fig. 3.29 depicts the mechanism observed in building 8 within the studied sample. Analysis of facade movement data unveiled substantial differential movement, likely attributed to a moderate gypsum dissolution rate in the soil supporting the building foundation. In this instance, the foundation on the right side settled into the ground, while its counterpart on the left side experienced uplift, resulting in localized compression in the masonry and structural cracks at the plinth beam. The pronounced differential movement stands as the predominant factor contributing to this severe damage.

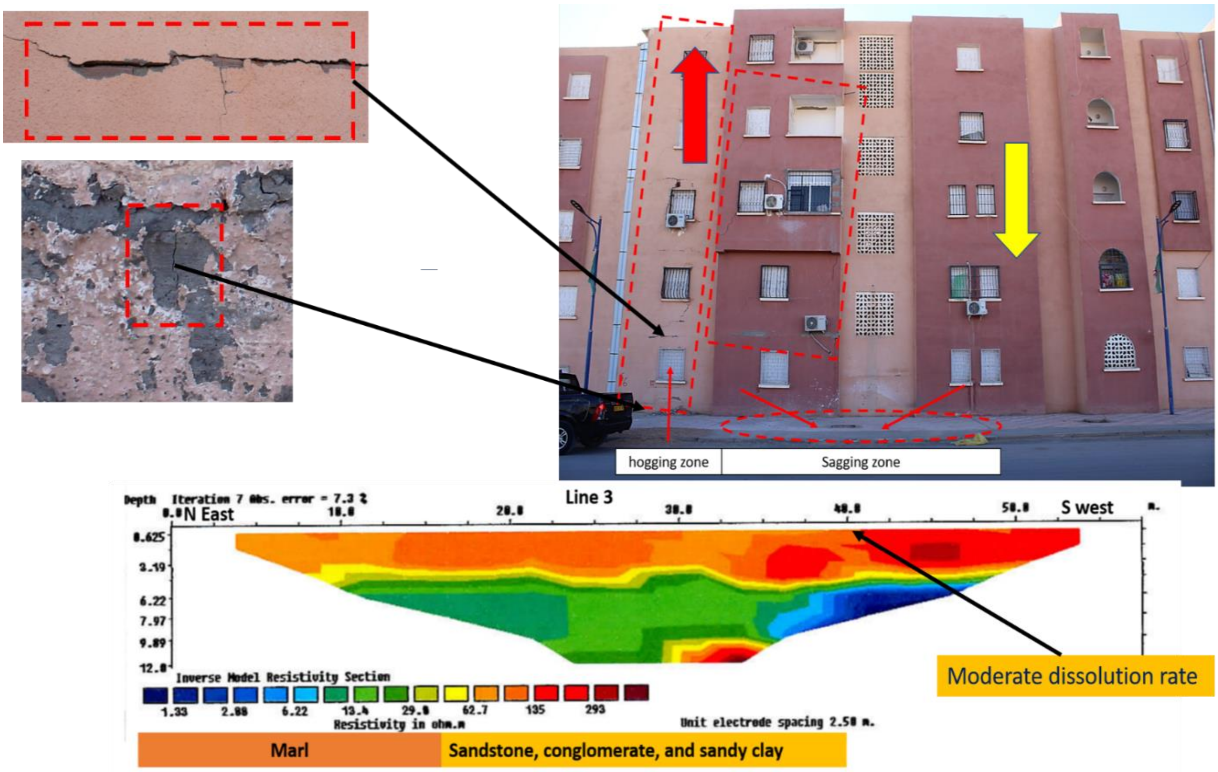


Fig. 3.29. Failure analysis of block 8.

3.8. Conclusion

The analysis of Buildings 1 to 12 in Area 1 revealed that the presence of gypsum significantly alters the mechanical behavior of the soil, making it susceptible to movement under service loads—particularly in moist conditions. This phenomenon of hydro-collapse is primarily driven by the dissolution of gypsum and the subsequent migration of soil particles within the Pliocene layer, which is composed of sandy clay, sandstone, and a conglomeratic matrix. The presence of existing pores, filled cavities, and cracks within this layer further exacerbates ground instability.

Additionally, the inadequate design of building foundations—utilizing both isolated and combined footings—has intensified the observed structural issues. The primary failure mechanism has been identified as differential settlement, which generates stress concentrations in structural components and leads to material degradation. The heterogeneous nature of the Pliocene soil, with its variability in both depth and extent, amplifies the uneven movement of building foundations, thereby increasing the risk of structural failure.

Chapter 4: Risk Management and Recommendations for Ouled Djellal

4.1. Introduction

This chapter aims to address the management of risks associated with geohazards, particularly subsidence and sinkholes resulting from the gypsum dissolution phenomenon, through both preventative and remedial measures. By focusing on water management, piezometric and surface event monitoring, and the application of advanced grouting techniques, a comprehensive risk management strategy can be formulated. Additionally, recommendations for reinforcing structures and planning future investigations will help mitigate the long-term impacts of these geohazards on Ouled Djellal's built environment.

4.2. Preventative actions

4.2.1. Water management

In order to address the trigger factors for subsidence hazard in the northwestern area of Ouled Djellal, effective water management measures need to be implemented. This includes verifying the functionality of all existing sewage pipelines and executing a new water pipeline system designed to minimize the possibility of leaks (flexible water pipelines). Additionally, implementing measures to monitor and maintain the sewage and water infrastructure regularly can help identify and address any issues promptly, reducing the risk of water seepage and potential subsidence hazards. Furthermore, investing in technologies such as leak detection systems and improved pipeline materials can enhance the resilience of the water distribution system and minimize the occurrence of leaks.

4.2.2. Piezometric monitoring

Regular and comprehensive monitoring, particularly employing a closely spaced piezometric network, remains imperative for identifying active dissolution zones. Furthermore, monitoring water conductivity can serve as a valuable tool in this identification process.

However, concerning the buildings in Areas A1, A2, A3, and A4 in the northwestern part of Ouled Djellal city, it has been observed that Areas A1 and A4 require the installation of new piezometers. Specifically, two piezometers are recommended for Area A1 and three for Area A4 (Fig. 4.1). Furthermore, some of the existing piezometers in Areas A1 and A3 may need to be relocated or replaced to ensure effective monitoring.

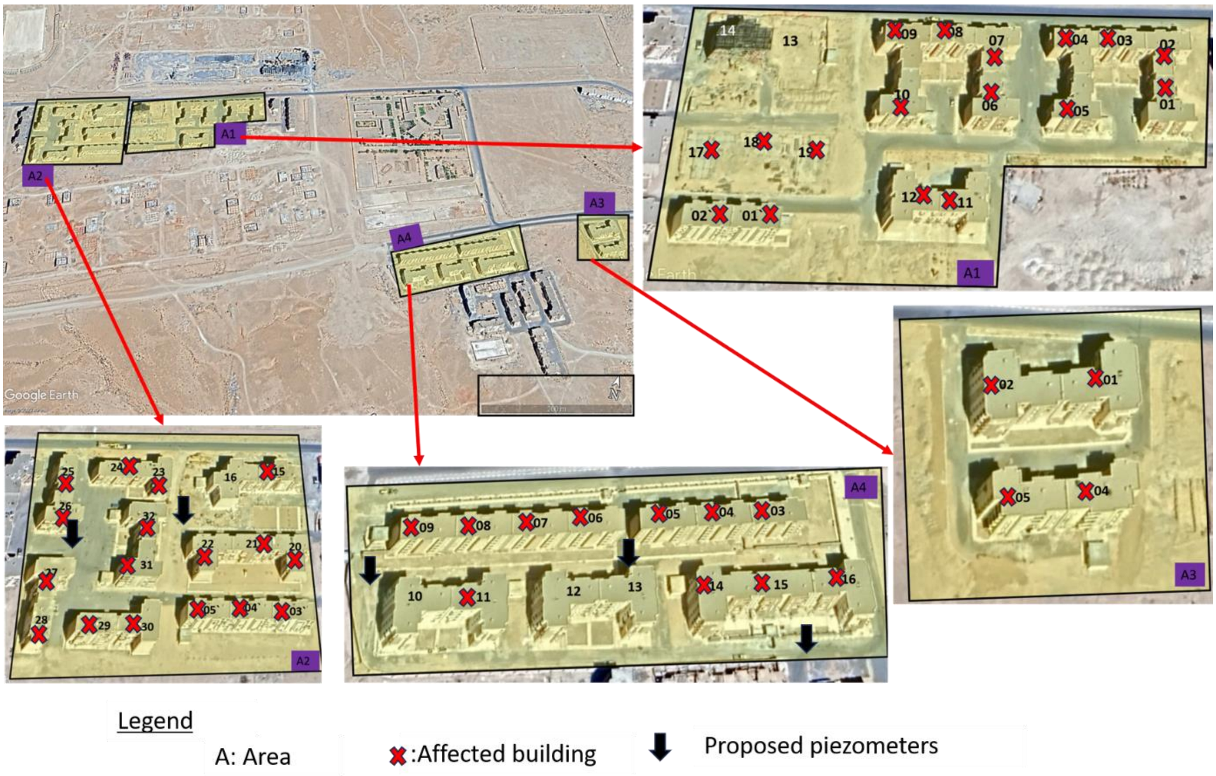


Fig. 4.1. The new proposed piezometers across the buildings study area.

4.2.3. Surface events monitoring

Monitoring historical ground movements is vital for assessing the anticipated intensity of ground movement and pinpointing active areas. Additionally, it aids in comprehending the potential geographical progression of these movements.

In the region of Ouled Djellal, two types of hazards have been recorded: subsidence affecting buildings in the northeastern part of the city and sinkholes observed in the southern area of the study region.

4.2.3.1. Subsidence monitoring

Monitoring subsidence affecting buildings in the northeastern part of the city involves several the topographical monitoring and the building defect development and its environment.

4.2.3.1.1. Topographical Monitoring

This entails regularly surveying the ground elevation around the affected buildings to detect any changes over time. High-precision surveying equipment of total station **Leica TS30 0.5''** have been used to measure vertical and horizontal movements accurately.

Until August 2023, the maximum movements of the reflective target installed on the facades of buildings across areas A1, A2, A3, and A4 have been documented and are summarized in the table below.

Table 6 The maximum movements of the reflective target installed on the facades of buildings across areas A1, A2, A3, and A4.

Area	Settlement		Heave		Tilting	
	Value(mm)	Building	Value(mm)	Building	Value(mm)	Building
1	-5,1	B 12	9,6	B 11	7,5	B 11
2	/////	/////	3,7	B 05`	1,6	B 03`
3	10	B 04	14	B 05	37	B 05
4	-4	B 07	12	B12	17	B 05

4.2.3.1.2. Building Defect Development and its Environment:

Conducting regular inspections of the buildings to monitor the development of new defects or the worsening of existing ones. This includes visually inspecting the structures for signs such as cracks, tilting, or any other indications of structural distress. Additionally, monitoring the development of subsidence signs on the ground at the perimeter of the buildings can provide valuable insights into the progression of subsidence.

During a recent inspection in February 2024, significant development of new defects was observed in Area 4. Specifically, buildings 03, 04, and 16 displayed notable degradation.

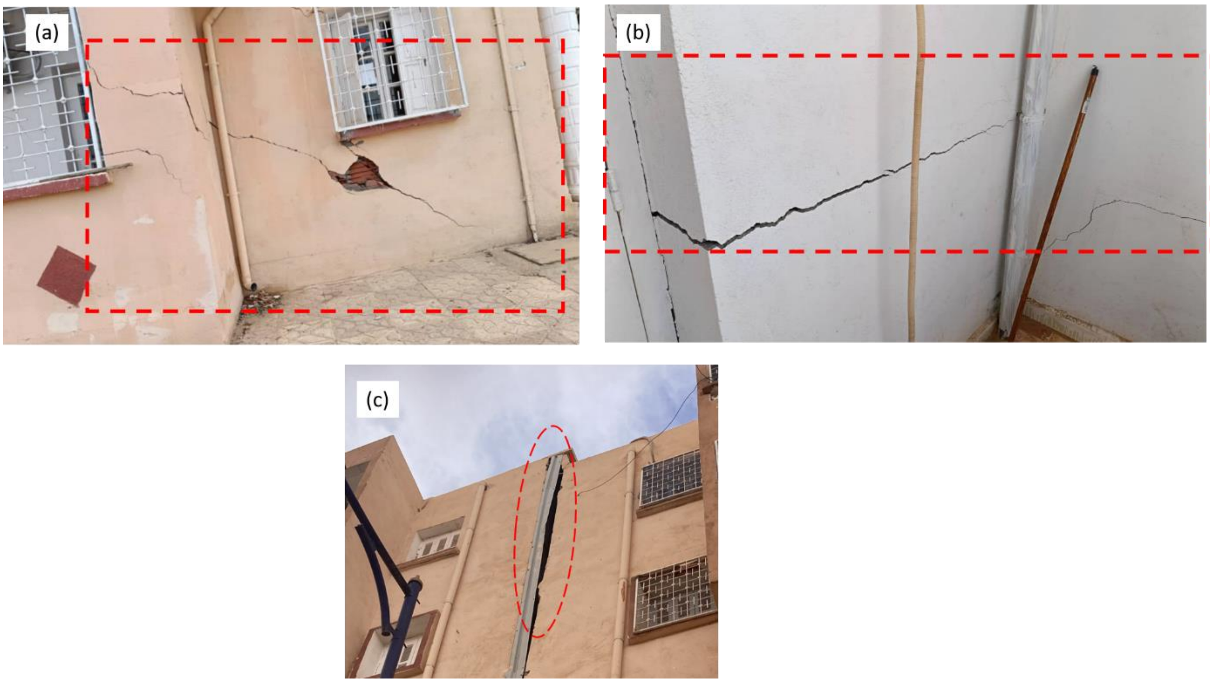


Fig. 4.2. Newly observed defects in Area 4: (a) Exterior masonry cracking of building 4, (b) Interior masonry cracking of building 4, (c) Divergence at the dilatation joint between buildings 4 and 5.

These deteriorations emerged following a ground movement event, with signs of cracks observed in the vicinity of these buildings.

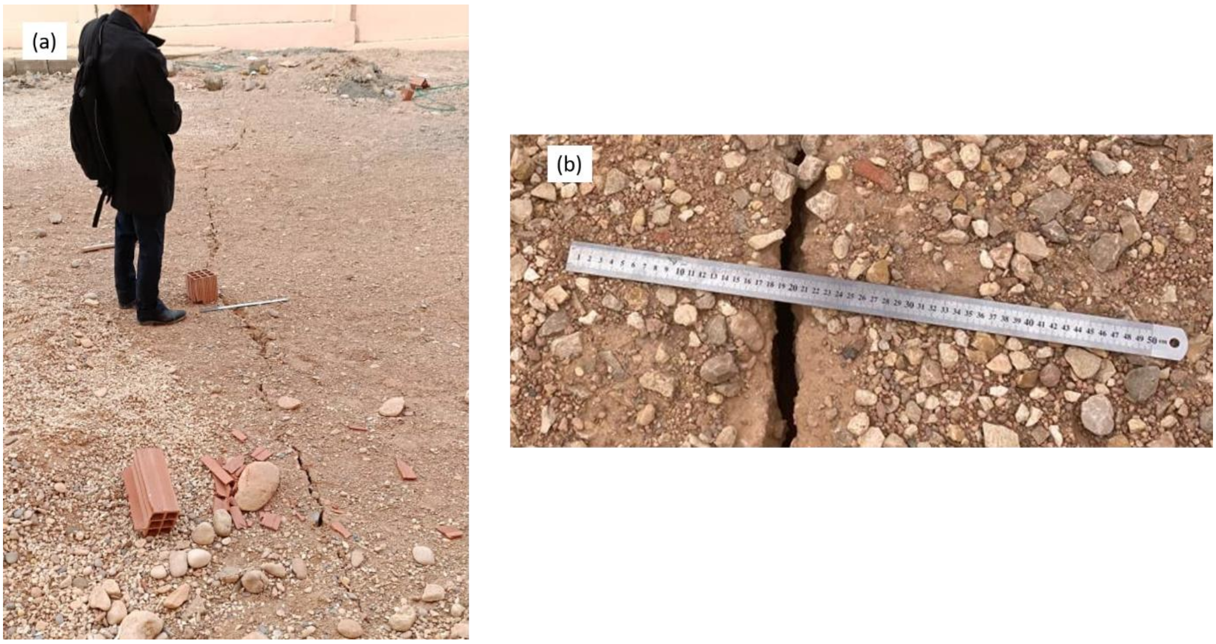


Fig. 4.3. Ground cracking signs reaching 30 mm width observed in the vicinity of buildings 4 and 5.

The development of the observed building defects is mainly caused by leaks from the water pipeline. A significant leak was identified on-site. However, the development of ground cracking signs reaching 30 mm in width is primarily associated with the dissolution of underground gypsum-rich soil caused by this leakage and the presence of nearby excavations for constructing new adjacent buildings that were abandoned for a long period. Consequently, the ground cracks propagated until reaching the excavation boundary.

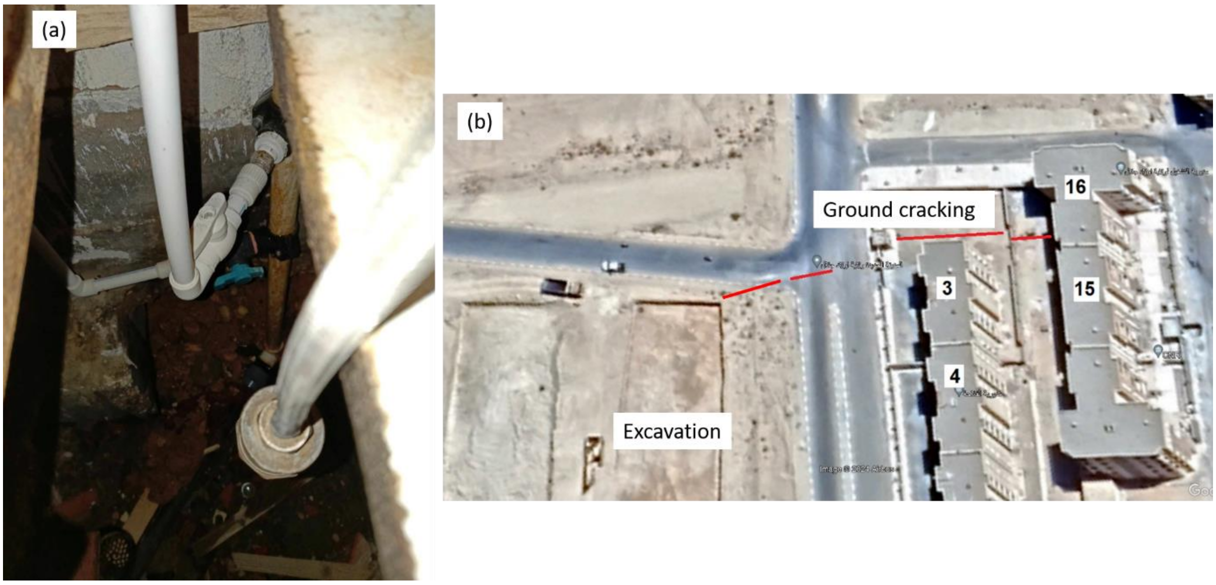


Fig. 4.4. (a) Water pipeline leaks, (b) Ground crack propagation along the red line to the excavation boundary.

4.2.3.2. Sinkhole monitoring

The sinkhole that formed in 2020 within the middle Eocene formation, characterized by clay with outcrops of gypsum, anhydrite, and dolomitic limestone, has expanded. Aerial photographs show the spread of ground cracks both north and south of the sinkhole, indicating its progression. However, these images cannot provide quantitative data on the sinkhole's growth.

Fig. 4.5. (a),(b): Enlargement of sinkhole occurring approximately 22 kilometers south of the study area three years after 2020.

4.3. Curative actions

4.3.1. Review of recommended injections work

Given the geological context of the Pliocene layer, which includes voids such as dissolved gypsiferous sandstone, conglomerate matrix, and geodes, as well as the possibility of deep and large cavities in the Middle Eocene formation, addressing these voids is essential. These voids, found as interstices between soil grains and rock fractures, pose a significant risk for ground instability. To mitigate this risk, injection work in accordance with NF EN 12715 (Execution of Special Geotechnical Works – Grouting) is necessary.

4.3.1.1. Methodological Approach

Regarding the heterogeneous ground conditions adjacent to the affected buildings, where maintaining control over grout spread is critical, the approach proposed by [62], known as the Grout Intensity Number (GIN) method, is particularly advantageous.

In general, with the GIN method, the energy exerted on the injected rock is approximately proportional to the product of the final injection pressure and the injection volume. This proportionality allows for precise control over the injection process, ensuring that the energy applied is within safe limits. It is important to note that excessive energy can lead to hydrofracturing, which must be carefully managed to avoid compromising the stability of the ground.

According to [71], the grouting pressure should be maximized to enhance the effectiveness of the treatment while remaining sufficiently low to prevent unnecessary hydrofracturing. This balance is essential for maintaining optimal "injection intensity."

The main characteristics of the GIN method are:

- *Single Injection Grout:* Utilizes a single grout mixture for the entire injection process.
- *Stable Medium-Low Injection Flow Rate:* The grout is injected at a controlled, stable flow rate, which gradually increases the pressure as it penetrates into fractures.
- *Termination Criteria:* The injection process is halted when one of the following criteria is met: a predetermined maximum volume limit, a maximum pressure threshold, or grouting intensity (GIN curve), which corresponds to specific limits on the product's maximum volume and pressure.

4.3.1.2. GIN curve

For a constant value of GIN, a parabolic curve can be constructed with the injected volume on the x-axis and the injection pressure on the y-axis. The curve is bounded by the maximum injection pressure and the maximum injected grout volume.

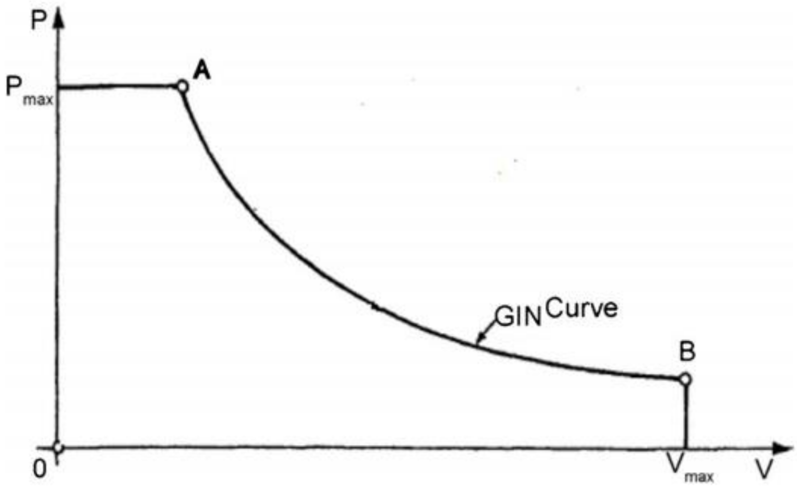


Fig. 4.6. GIN Graph Displaying Maximum Pressure (Pmax) and Maximum Volume (Vmax) [71].

4.3.1.3. The GIN curve reference

Throughout the works, the pressure, injected volume, and penetrability of the grout must be monitored in real-time. The injection stops when the GIN value becomes higher than the predetermined control value set at the beginning for the structure.

This approach allows for complete filling of large fractures where pressures are low, but enables higher pressures in areas where flow rates are low (very narrow fractures). At the same time, it prevents dangerous combinations of high pressures and high volumes, and avoids applying low pressures where low volume values suggest the need for higher pressures

The GIN curve reference categorizes grouting conditions into five degrees based on pressure and volume requirements. From "Very Low" to "Very High," the degrees represent varying levels of pressure and volume: lower pressures with higher volumes for large fractures, and higher pressures with lower volumes for narrow or challenging fractures. This classification helps optimize grouting by matching parameters to ground conditions, ensuring effective grout placement and minimizing risks.

Table 4.2 Grouting Conditions Based on GIN Curve Reference proposed by [62].

Degree	Pressure	Volume	Application
Very Low (1)	Very Low	High	Large fractures, stable ground
Low (2)	Low	Moderate	Moderately sized fractures
Moderate (3)	Moderate	Moderate	Intermediate size fractures
High (4)	High	Low	Narrow or high-resistance fractures
Very High (5)	Very High	Very Low	Extremely narrow or challenging fractures

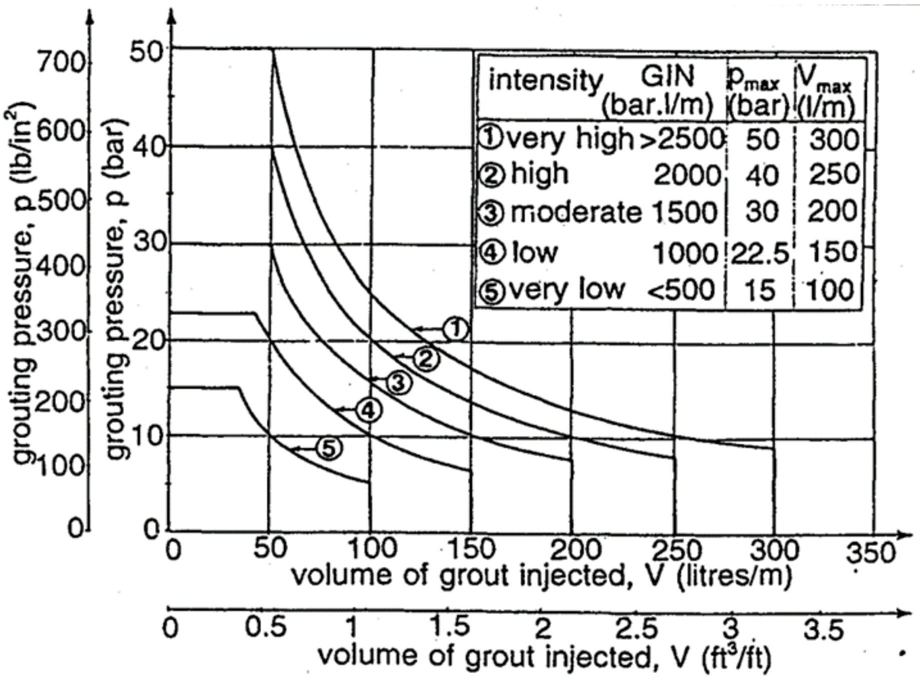


Fig. 4.7. GIN Curve Reference proposed by [62].

4.3.1.4. Identification of heterogeneities or fractures via the Lugeon test (NF P94-131)

The Lugeon test (NF P94-131) is designed to assess water flow through soil and identify any heterogeneities or fractures. The test involves injecting water under pressure into a borehole section of known dimensions and measuring the rate of injection at various pressure levels over a set period.

The results are expressed in Lugeon units, which represent the volume of water (in liters) injected per meter of borehole length per minute at a pressure of 1 MPa (MegaPascal). High Lugeon values indicate high permeability, often due to fractures or fault zones, while low Lugeon values suggest lower permeability and a more intact rock mass.

Sharp increases in Lugeon values typically point to the presence of fractures or highly permeable zones, reflecting higher water inflow due to increased transmissivity. Significant variations in Lugeon values at different depths can indicate fracture zones or heterogeneous rock conditions. These variations often result from differences in rock type, the presence of fractures, or other geological features.

4.3.1.5. The penetrability curve

The "penetrability curve" visualizes the specific flow rate (q/p) relative to the injected volume (V), helping monitor grouting. A declining q/p ratio indicates that grouting is proceeding normally. Maintaining a low flow rate as the process approaches the chosen GIN curve ensures proper filling of voids and prevents issues like hydrojackin

4.3.1.6. Perforation

The drilling must be carried out using a tricone or similar tool, with clear water (or bentonite when the drilling is unstable), and with a diameter larger than 100 mm. The drilling diameter should be consistent across all boreholes. The walls of the holes have been kept open without casing.

4.3.1.7. The grout characteristics

The characteristics of the consolidation grout and injection parameters, considering soil aggressiveness, are summarized as follows:

- Type of Cement: CEMI42.5N-SR3LH
- Water/Cement Ratio: 0.5 to 0.6
- Bentonite/Cement Ratio: 1.0 – 2.0%
- Superplasticizer/Cement Ratio: 2.0 – 4.0%

- Density: 1.40 – 1.50 t/m3
- Marsh Cone Viscosity: 20 – 40 s
- Minimum 28-day Strength: 16 MPa
- Injection Flow Rate at Steady State: 20 l/m

The characteristics of the grout mix should ensure that an injectable mixture is achieved, tailored to the permeability of the soils.

4.3.1.8. Test field

According to the European standard NF EN 12715 (Execution of special geotechnical works - Injection), full-scale tests and grout injection tests are carried out to define or validate an injection method. It is recommended to consider full-scale tests as an integral part of the initial site investigation.

The objectives of the test field are:

- Evaluation of the injection approach and method itself.
- Determination of injection parameters Pmax, Vmax, and the GIN number.
- Delimitation of injection perimeters for each site.
- Estimation of quantities (number of boreholes and grout volume).

4.3.1.9. Injection

The injection will be carried out using hydraulic or mechanical packers, with stages of approximately 3 meters and open-hole injection. As the injections continue, the average absorption will decrease progressively. If the chosen GIN curve combination is appropriate, a trend should be observed with a gradual increase in pressures and a decrease in volumes, as illustrated in the figure. If the observed decrease in absorption is either too modest or too rapid, the current GIN curve combination should be reconsidered.

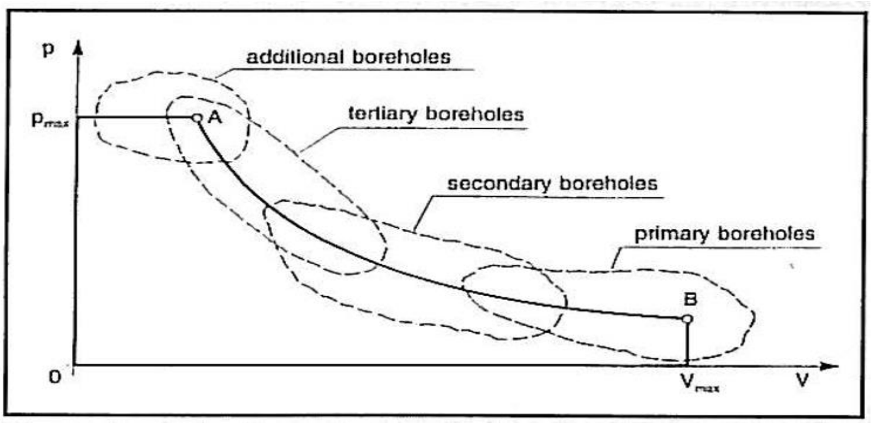


Fig. 4.8. Typical trend of absorptions along a GIN curve.

4.3.1.10. Meshing and Borehole Depth

The basic design stipulates injections in three phases:

- Injection of primary boreholes: These are 6m wide strips, each comprising 10 boreholes distributed along the width of the buildings (Fig. 4.9) spaced 22m apart.

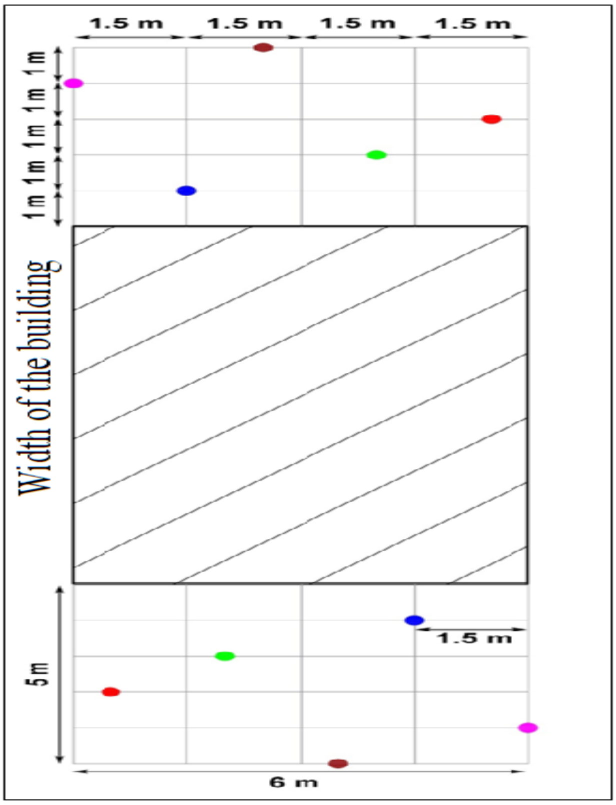


Fig. 4.9. Plan view of the proposed Meshing.

- Injection of secondary boreholes: Based on the results of the primary injections, secondary strips can be implanted adjacent to the primary strips.
- Injection of tertiary boreholes: Based on the results of the secondary injections, tertiary strips can be implanted on either side of the secondary strips.

4.3.1.11. Controls

Establishing GIN injection graphs is a valuable means of controlling the effectiveness of injection. The following examples (Figure 4.10) illustrate how these graphs can provide clear indications both of the state of ground depressurization and the effectiveness of injection.

(1) Infinitely small absorption and rapid pressure increase, indicating that the ground does not require injection.

(2) Directly proportional relationship between pressure and injected volume, meaning that the ground is relatively resistant and that the absorbed volume will further increase this resistance.

(3) Significant ground absorption at low pressure, indicating that the ground is heavily depressurized (possibility of void or cavity). The injected volume serves as filling and improvement of the ground.

(4) Pressure drop indicating that there has been fracturing (creation of cracks or widening of existing cracks). In this case, the injection flow rate should be kept low and the vicinity of the borehole visually inspected. Pressure may increase again, indicating that the depressurized area is filled with grout. If not, the depressurized area has a volume greater than Pmax, and it will be consolidated by the surrounding boreholes.

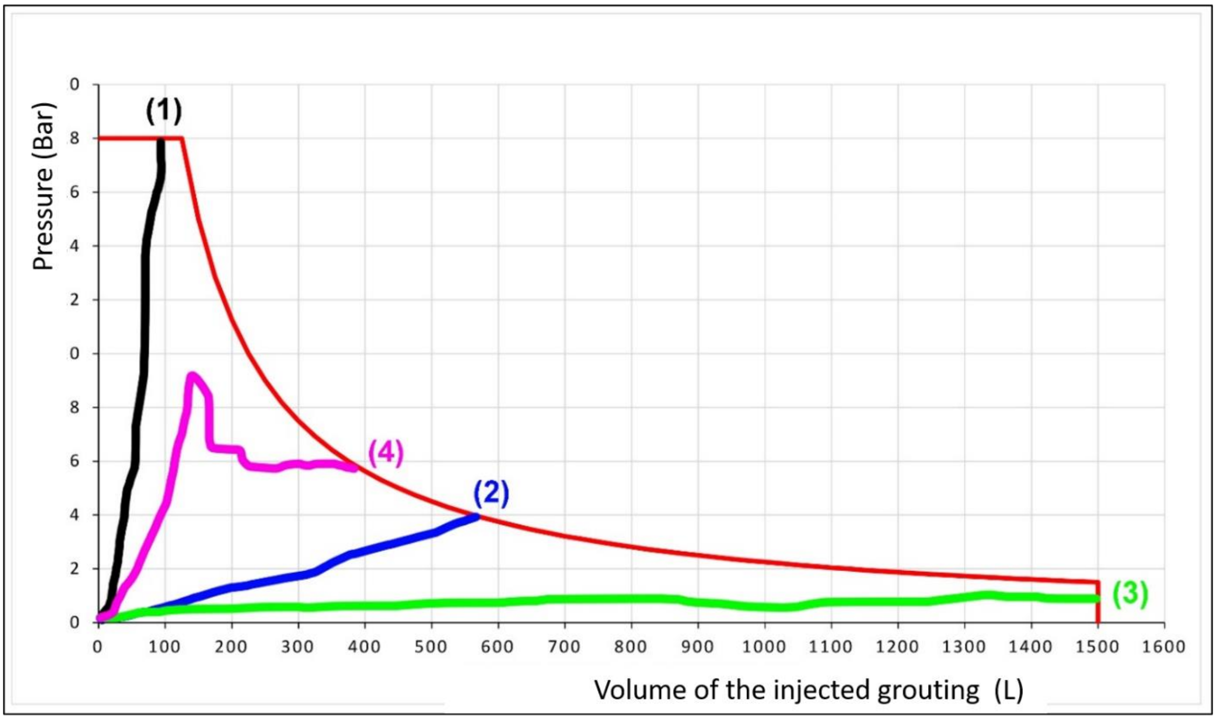


Fig. 4.10. Example of a recommended gin curve with possible indications of ground depressurization status and injection effectiveness.

4.3.2. Reinforcement of structures

Due to the low probability of collapse sinkholes occurring adjacent to the failed building in the northwestern part of Ouled Djellal city, the use of anti-sinkhole footings or ladder structures is not recommended. Instead, the focus should be on implementing anti-sagging measures to reinforce the failed buildings. These measures will help stabilize the structures and prevent further sagging, ensuring their structural integrity and safety.

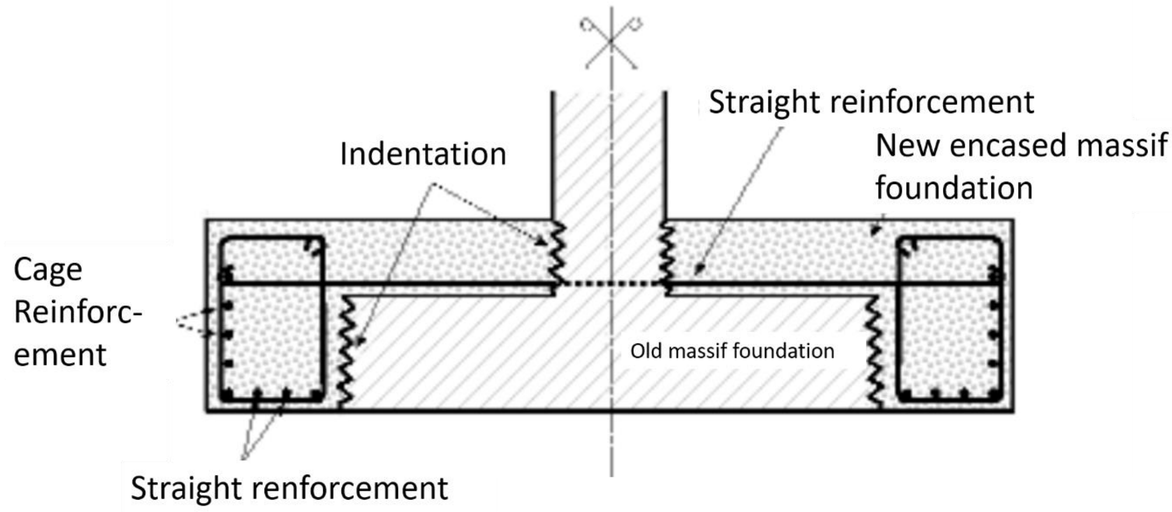


Fig. 4.11. Increasing the Surface Area of the Footing with Added Thickness. Objective: Expand the Surface Area to Reduce Soil Stress, Enhance Rigidity, and Strengthen Footing Reinforcement (Adapted from [72]).

4.4. Future planning regarding the geohazard on the local scale of Ouled Djellal City

Based on the diagnosis results of the Ouled Djellal city context, local planning authorities must take into account the specific configurations of the region, including the type and intensity of geohazards present. Precautions in the technique of any investigations should be considered to ensure accurate assessments of risks and hazards. Additionally, any residual ambiguities identified during the diagnosis process should be addressed through future research to further refine the understanding of the geohazard and its potential impacts on the built environment.

4.4.1. The type and intensity of geohazards

The type and intensity of geohazards present in the Ouled Djellal city region vary depending on the geological formations. The Pliocene layer, characterized by conglomerate, sandstone, and sandy clay, is predisposed to subsidence. However, sinkholes may occur in the middle Miocene formations, which primarily consist of clay with outcrops of gypsum, anhydrite, and dolomitic limestone, especially when high concentrations of water flow interact with this formation. The intensity of sinkholes, with diameters exceeding 40 meters, recorded in the south of the study region indicates a high risk of building collapse or complete destruction of several constructions. Particularly, in the urban zone situated in the middle Eocene gypsiferous formation in the western of Ouled Djellal city, the risk of sinkholes is particularly high, posing a significant threat to buildings in the area.

4.4.2. Experience feedback on precautions in investigating contributing factors to hazard

4.4.2.1. Regarding the misidentification of the gypsum mineralogy

The X-ray diffraction (XRD) technique played a crucial role in identifying gypsum minerals in the Pliocene layer, which was not previously mentioned in the geological map. This highlights the importance of utilizing XRD in future geotechnical investigations to accurately identify soil composition. t's noteworthy that gypsum can sometimes be misidentified, resembling limestone formations, as noted in the literature review.

Furthermore, the initial geotechnical report for the construction of buildings in Area 1 and 2 did not mention gypsum minerals except in one borehole stratigraphy where anhydrite was identified. However, standards like NF EN ISO 14688-1 emphasize the importance of identifying the mineralogy of the soil in the identification and classification process.

4.4.2.2. Regarding the misidentification of the granularity of the sandstone formation

The initial geotechnical report for the construction of buildings in Areas 1 and 2 misidentified the sandstone blocks as sand. This misidentification can be attributed to the fragile nature of these sandstone blocks, which have been subjected to sulfuric attacks over geological time periods. Additionally, the force applied during core drilling in-situ may have contributed to this misinterpretation.

4.4.2.3. Regarding the misidentification of the high gypsiferious red sandy clay formation

Regarding the misidentification of the high gypsiferous red sandy clay formation from the Pliocene epoch, it's important to note its high sensitivity to water due to its high solubility. Therefore, in future projects, when utilizing water in core drilling for soil identification in the Pliocene formation, this sensitivity should be taken into consideration to avoid potential inaccuracies or complications.

4.4.3. Future planning regarding the geohazard on the national scale

Given the cases of geohazards associated with gypsum dissolution phenomenon reported by local authorities in Tougguort (Fig. 4.12), Oran, Elwadi states, and Tebessa, it's imperative to adopt a national planning strategy in Algeria similar to the geological survey approach in the UK. This strategy would aim to prevent the construction of buildings in high-risk areas prone to gypsum-related geohazards. However, to ensure effectiveness and mitigate potential risks, this national planning should be accompanied by detailed local planning efforts. This dual approach is essential to minimize the impact of gypsum dissolution hazards on infrastructure and communities while avoiding costly and detrimental development in vulnerable regions.

Fig. 4.12. Sinkhole associated to gypsum dissolution process (Touggourt, Algeria, 2018).

In the same context, an interior planning policy is already in place, backed by the National Organization for Technical Control of Construction in Algeria. However, this policy was insufficient as it did not consider either the type (subsidence/sinkholes) or the intensity of the geohazard (Fig. 4.13).

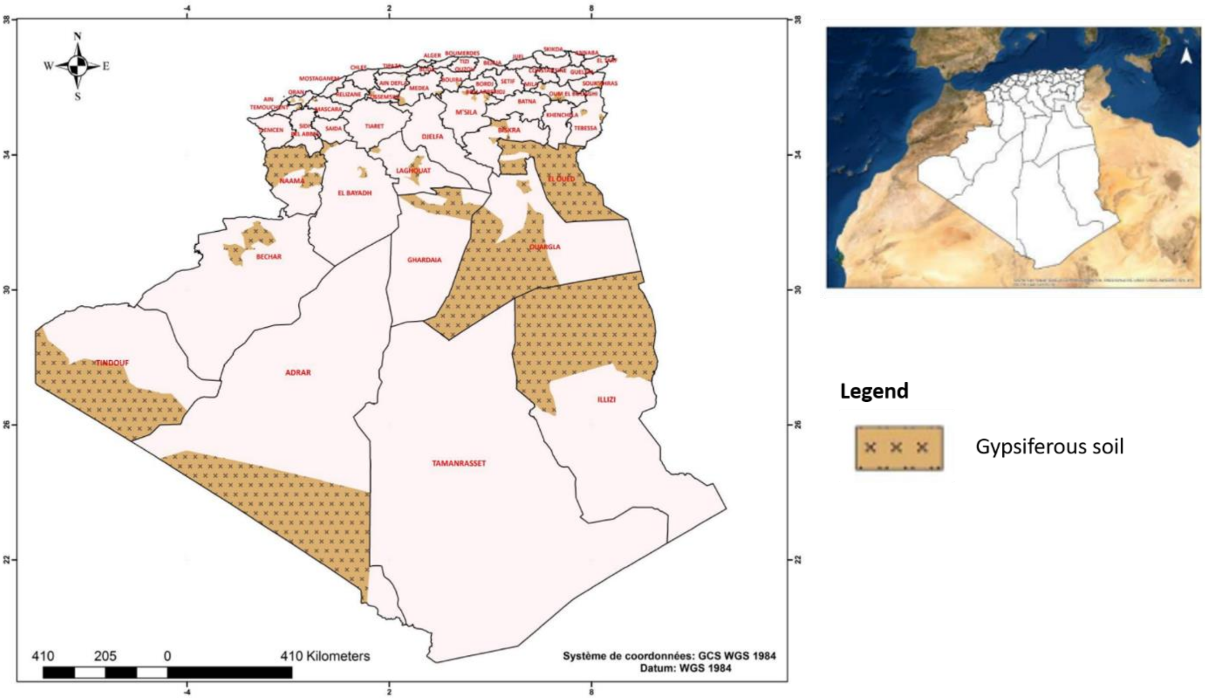


Fig. 4.13. Geotechnical Hazards on a National Scale (CTC Database - Phase I): Map of Gypsiferious Soils, 2021.

- The consideration of either the type (subsidence/sinkholes) or the intensity of the geohazard in a national plan, supplemented by a local one, offers a predefined categorized map. These categories should be comparable to the three categories A, B, and C mentioned previously in the literature review in Ripon, UK, where:
- Category A represents regions with known gypsum.
- Category B includes areas where some gypsum is present at depth.
- Category C covers regions where gypsum is present and susceptible to dissolution.

This categorization will clarify the areas:

- Constructible regions without any risk.
- Non-constructible regions with high risk.
- Constructible regions with risk presence, in which significant formal constraints and development controls are present. Local planning authorities must consider these

factors. Typically, a ground stability report, prepared by a competent professional, is required before determining planning applications for new buildings or changes in building use.

4.4. Conclusion

In conclusion, the effective management of geohazards—particularly those resulting from gypsum dissolution such as subsidence and sinkholes—demands a proactive, structured approach that integrates both preventative and curative strategies. Preventative measures such as water management, piezometric monitoring, and the systematic observation of surface deformations are essential for early detection and mitigation. Curative actions, including advanced grouting techniques like the GIN method and structural reinforcement, play a critical role in stabilizing affected zones and protecting built infrastructure. To ensure long-term resilience, tailored recommendations must be implemented at both local and national levels. For Ouled Djellal, this involves improving subsurface investigations, accurately identifying geohazard-prone areas, and understanding the behavior of gypsum-bearing formations. At the national scale, the reinforcement of institutional frameworks, documentation of case histories, and support for hazard assessment programs—such as those led by the CTC—are vital to building a robust and informed response to future geohazard risks.

General Conclusion

This thesis presents a comprehensive investigation into the pathology of structural cracking in buildings affected by ground movements induced by gypsum dissolution in the city of Ouled Djellal. In the northwestern sector of the city, previously undocumented ground instability has led to significant structural damage in numerous buildings. A detailed geotechnical investigation (G5), conducted in accordance with the French standard NF P 94-500, identified the root causes of the hazard as both the mis-execution and misinterpretation of the initial geotechnical study carried out prior to construction. The presence of gypsum plays a critical role in altering the mechanical behavior of the soil, rendering it highly susceptible to deformation under service loads, particularly in moist conditions. This hydro-collapse phenomenon is primarily driven by the dissolution of gypsum, followed by the transport of soil particles within the Pliocene formation, composed of sandy clay, sandstone, and a conglomeratic matrix. The inherently porous nature of this stratum—further compromised by cavities and pre-existing fissures—intensifies its instability. In addition, the use of inadequately designed foundations—such as isolated and combined footings—has exacerbated the structural distress. The affected buildings exhibit pronounced signs of differential settlement, which causes uneven stress distribution across structural elements and ultimately leads to cracking and, in some cases, structural failure. Furthermore, the effective management of geohazards—particularly those resulting from gypsum dissolution, such as subsidence and sinkholes—requires a proactive and integrated approach that combines both preventative and curative strategies. Preventative measures, including water management, piezometric monitoring, and systematic observation of surface deformations, are essential for early detection and mitigation. On the curative side, advanced techniques such as grouting using the GIN method and appropriate structural reinforcement play a crucial role in stabilizing affected zones and safeguarding built infrastructure.To ensure long-term resilience, tailored recommendations must be implemented at both the local and national levels. For Ouled Djellal, this involves enhancing subsurface investigations, accurately delineating geohazard-prone zones, and deepening the understanding of gypsum-bearing formations and their mechanical behavior. At the national scale, strengthening institutional frameworks, compiling and disseminating case histories, and supporting hazard assessment programs—such as those led by the CTC (Control

Technique de la Construction)—are fundamental to building a robust and informed response to future geohazard risks.

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