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A Study on the Weakening Effects and Evolution of Groundwater Discharge and Recharge on the Compressive Strength of Foundations Based on Water-Rock (Soil) Interaction Principles

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Abstract: Groundwater resources exist in diverse forms and undergo dynamic changes through recharge, runoff, and discharge. Groundwater discharge and recharge affect groundwater mineralization, buoyant forces on soil particles, soil expansion and contraction, and structural stability. This paper employs schematic analysis, case studies, and experimental methods to explore these effects using both classical and innovative water-soil relationship theories. The findings indicate that a critical zone formed by sudden rainfall over a short period significantly weakens the bearing capacity of soil foundations. Land subsidence is not solely attributed to excessive groundwater extraction leading to insufficient groundwater volume; rather, if high-mineralization water surrounding soil particles is replaced by low-mineralization water, the compressive bearing capacity of the soil-rock mass decreases, increasing the likelihood of land subsidence.

Keywords: Sponge cities, unsaturated aquifers, land subsidence, groundwater mineralization, water-rock (soil) interaction

1. Research background

Groundwater resources exist in various forms and dynamically transform through recharge, runoff, and discharge. Groundwater resources can generally be categorized into three forms: unsaturated aquifers, saturated aquifers, and perched water. Perched water is often localized and does not significantly influence the regional distribution of groundwater resources; thus, this study focuses on unsaturated and saturated aquifers.

Unsaturated aquifers are composed of solid, liquid, and gas phases and typically overlay saturated aquifers. Saturated aquifers, which are usually not directly exposed to the surface, are fully filled with groundwater in their underground voids (pores, fissures, or cavities), displacing underground gases and forming a solid-liquid mixture. These aquifers are often buried beneath unsaturated aquifers [1-10].

As groundwater levels in saturated aquifers decline, these aquifers cannot fully fill all underground voids, transitioning from a two-phase solid-liquid system to a three-phase solid-liquid-gas system resembling unsaturated aquifers. Consequently, the thickness of the overlying unsaturated aquifer increases, while the saturated aquifer beneath shrinks and thins (Figure 1(b)).

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Most engineering structures are located on the surface, with their gravitational impact directly applied to the unsaturated aquifer beneath them. Therefore, previous geotechnical studies on water-rock (soil) interactions have primarily focused on unsaturated aquifers without distinguishing them from saturated aquifers. Groundwater extraction, however, typically occurs in saturated aquifers beneath unsaturated ones, as the latter often holds little to no extractable water. Environmental issues caused by groundwater over-extraction are often attributed to negative effects or geological hazards resulting from over-extraction of saturated aquifers, with limited research distinguishing the two.

Rainfall infiltrates through unsaturated aquifers to recharge the underlying saturated aquifers, causing the latter to thicken upward (Figure 1(c)).

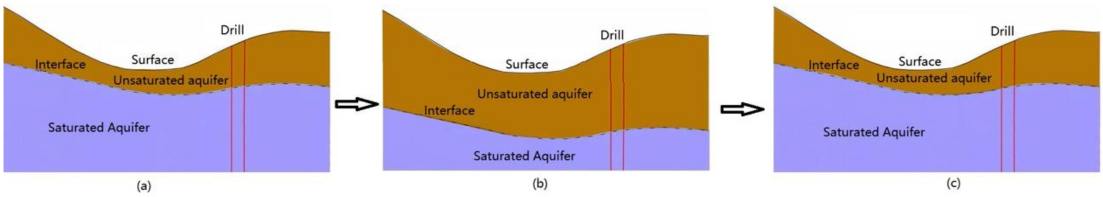

Figure 1: Schematic diagram of groundwater extraction and recharge

Water-rock (soil) interaction refers to a series of interactions and reactions between water and soil-rock masses, ultimately altering or weakening the mechanical properties of underground soil-rock masses. A key focus of aquifer studies is their impact on soil skeleton structure, load-bearing capacity, and compressive stability.

2. Objectives, significance, methods, and problems

2.1. Research objectives

This study investigates the effects of groundwater with high mineralization being discharged and subsequently recharged with low-mineralization water (or vice versa) on the strength and bearing capacity of soil-rock masses. It also explores the impact on the stability of soil particles and soil skeletons, aiming to further enrich the theoretical framework of water-soil interactions.

2.2. Research significance

The research contributes to enriching the theory of water-soil interactions and aids in understanding the correlation between groundwater mineralization and surface subsidence or collapse disasters.

2.3. Research problems

What factors influence the settlement and compressive bearing capacity of foundations (soil-rock masses)?

Can existing classical theories of water-soil interactions explain all phenomena of foundation settlement (land subsidence)?

2.4. Research methods

This study adopts methods such as schematic analysis, case studies, and experimental approaches to attempt explanations of natural disasters like foundation settlement using existing classical water-soil relationship theories. For phenomena that cannot be explained by these existing theories, the study seeks to propose new theoretical frameworks for water-soil interactions.

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3. Literature review on water-rock (soil) interactions

One of the focal points of geotechnical studies has been the research on water-soil relationships. Although previous studies did not explicitly state whether these water-soil mechanical relationships occurred in unsaturated aquifers, this paper posits that the subjects of such studies are indeed unsaturated aquifers, focusing on the interactions between the solid, liquid, and gas phases in unsaturated soils. However, prior research has not clearly distinguished between unsaturated and saturated aquifers. This study aims to differentiate aquifers based on their saturation levels, thereby refining and targeting future research in this domain.

Unsaturated soils consist of three phases: solid, liquid, and gas, which interact in complex ways. Variations in the water content of soil-rock masses indicate the extent and potential of underground microspaces where liquids are replaced by gases [1-20].

Ying Zhang (2023), in her paper Experimental Analysis of Bearing Ratios for Unsaturated Soil Foundations, noted that the bearing capacity of unsaturated soils in unsaturated aquifers initially increases and then decreases with rising water content. Groundwater interacts with soil particles in diverse and complex ways. These interactions are dynamic, involving motion, connection, and transformation. Groundwater can cause weathering, softening, and lubrication of soil particles, as well as inducing changes such as wet collapse, expansion, shrinkage, frost heaving, thaw settlement, and hydraulic fracturing. The expansion and shrinkage of soil particles refer to their characteristics of swelling when absorbing water and shrinking when losing water [1].

Yuzong Li (2024), in his paper Experimental Study on the Influence of Immersion Duration on Rock Strength and Failure Characteristics, conducted experiments on the swelling behavior of sandstone, marble, and granite with different lithologies during immersion. The results revealed that soil particles exhibit hydrological changes such as dissolution, filling, and swelling when exposed to water [2].

4. Theoretical foundations: water-soil relationship theory

4.1. Water-rock bonding states

Groundwater interactions with rocks and soils exist in four common forms: strongly bound water, weakly bound water, capillary water, and gravitational water.

Strongly bound water refers to the water molecules tightly attached to the surface of soil-rock particles through electrostatic adsorption, forming the most firmly bonded water film.

Weakly bound water refers to the thicker water film located outside the strongly bound water and soil-rock particles.

Capillary water is the groundwater held in the capillary voids between soil particles.

Gravitational water refers to groundwater that can flow freely under gravity within underground spaces such as rock pores and fractures.

Strongly bound water, weakly bound water, and capillary water are typically found in unsaturated aquifers. These, together with soil-rock particles, form stable structural bonds within the unsaturated aquifers, enabling them to bear overlying loads. Gravitational water is commonly found in saturated aquifers. The degree of groundwater mineralization and water density within rock voids and fractures varies significantly across locations.

The higher the rock's water content and the closer it is to saturation, the higher the gravitational water content. Conversely, strongly bound water predominates in rocks with lower water content. The four bonding states of groundwater and soil-rock particles can transform into each other. Sudden or rapid transformations between these states can lead to severe land subsidence or groundwater-related geological disasters.

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4.2. Optimal moisture content in unsaturated aquifers

In her 2023 paper, Experimental Analysis of Bearing Ratios for Unsaturated Soil Foundations, Ying Zhang [1] conducted experiments on natural soils devoid of gravitational and capillary water. She investigated the relationship between moisture content and the compressive strength of unsaturated soil-rock masses. Her findings are summarized below:

Table 1: Relationship between moisture content and compressive strength of unsaturated soil-rock masses

Moisture Content of Unsaturated Soil-Rock Mass	Compressive Strength of Unsaturated Soil-Rock Mass
1	Very Weak
2	Weak
3	Maximum
4	Weak
5	Very Weak

(Note: Moisture content is categorized into five levels, with higher numbers indicating higher moisture content.)

According to the results, the bearing capacity of unsaturated soil-rock masses initially increases and then decreases as moisture content rises. There exists an optimal moisture content at which the bearing capacity is maximized and compressive strength is optimal.

Since this experiment excluded gravitational and capillary water, which have softening effects on soil-rock masses, the moisture content should be adjusted to account for these components when discussing unsaturated soil-rock masses.

In his 2024 study, Experimental Study on the Influence of Immersion Duration on Rock Strength and Failure Characteristics, Yuzong Li [2] investigated the relationship between immersion duration and rock strength using natural rock samples. His findings are summarized below:

Table 2: Relationship between immersion duration and rock strength

Immersion Duration	Rock Strength
30 days	Weak
90 days	Maximum
180 days	Weak

(Note: Rock strength includes tensile, compressive, and shear strength.)

Li’s results indicate that rock strength, particularly compressive strength, initially increases and then decreases with prolonged immersion.

According to traditional water-soil theories, bound water does not flow freely or transmit hydraulic pressure. However, Guangxin Li (2007) experimentally demonstrated that under strong external compression, bound water can flow freely and transmit pressure, challenging the authority of traditional theories.

Combining Zhang's and Li’s findings, it can be inferred that bound water enhances the mechanical strength of soil-rock masses, while gravitational water diminishes it.

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4.3. Groundwater-induced soil-rock damage

Gravitational water flowing within soil-rock masses can, under certain conditions, carry soil particles and disrupt the soil skeleton, causing geological disasters such as mudslides, sand flow, piping, and soil liquefaction.

As shown in Figure 2, when new, higher-mineralization recharge water replaces the existing groundwater around soil particles, the particles lose water and shrink. Conversely, as shown in Figure 3, when new, lower-mineralization recharge water replaces the existing groundwater, the soil particles absorb water and swell. Over time, as the groundwater mineralizes again, the soil particles shrink, potentially accelerating the softening or structural damage of the soil skeleton.

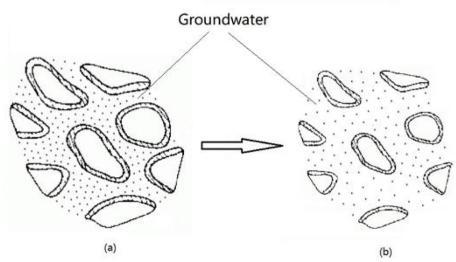

Figure 2: Soil particle shrinkage illustration

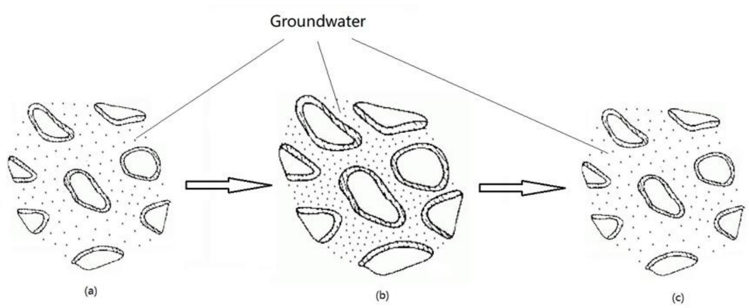

Figure 3: Soil particle swelling and reshrinkage illustration

5. Groundwater recharge, runoff, and discharge

The three most critical concepts in groundwater research are recharge, runoff, and discharge [11–15].

For saturated aquifers, common recharge methods include precipitation infiltration through unsaturated aquifers and lateral runoff from external water sources. Common discharge methods include evaporation and human groundwater extraction.

For unsaturated aquifers, common recharge methods include precipitation recharge, evaporation from saturated aquifers below, and infiltration recharge. Groundwater runoff in unsaturated aquifers often involves rapid, free-flowing water caused by short-term intense rainfall, which can be destructive and lead to natural disasters. The most common discharge mechanism is the downward percolation of gravitational water following heavy rainfall, replenishing the saturated aquifer below and causing its water level to rise.

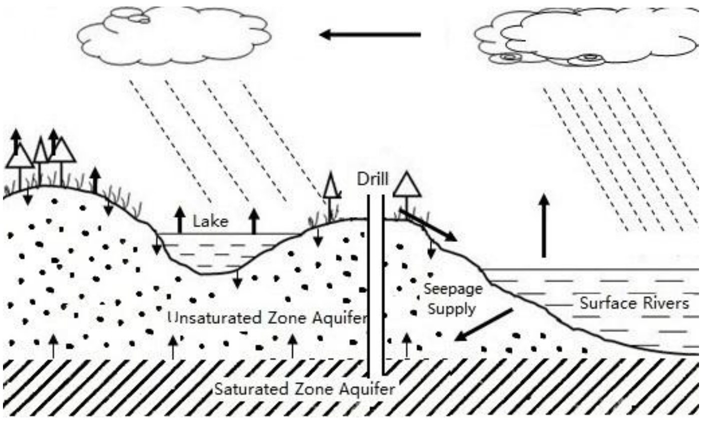

Figure 4: Schematic diagram of groundwater runoff

As shown in Figure 4, as the water level in saturated aquifers declines, surface river water infiltrates through the unsaturated aquifer to laterally replenish the saturated aquifer. Additionally, groundwater in aquifers can undergo recharge from precipitation infiltration and discharge through evaporation, as depicted in Figure 4.

After groundwater extraction from a saturated aquifer, its water level drops, as illustrated in Figure 5 (transition from panel (a) to panel (b)). Over-extraction of groundwater from saturated aquifers can cause the water level to decline further, reversing the direction of groundwater runoff and leading to seawater intrusion into the aquifer. In such cases, the saturated aquifer becomes recharged with high-mineralization seawater, a phenomenon known as seawater intrusion.

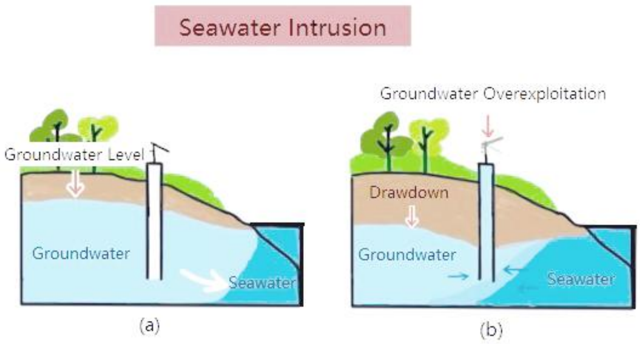

Figure 5: Diagram of seawater intrusion

As shown in Figure 6, after rainfall begins, the moisture content in the critical zone of the unsaturated aquifer rises rapidly until saturation is achieved. During this process, precipitation infiltrates, filling the voids between soil particles with gravitational water, expelling air, and saturating the upper portion of the unsaturated aquifer (Figure 6(b)). This transformation changes the unsaturated soil from a three-phase system (solid-liquid-gas) to a two-phase system (solid-liquid).

After rainfall ends, gravitational water in the critical zone percolates downward to replenish the saturated aquifer, causing its water level to rise. As the moisture content in the critical zone decreases (Figure 6(c)), the compressive strength of the critical zone reaches its highest level before rainfall, according to the optimal moisture content theory. However, after rainfall:

Increased moisture content softens the soil.

Buoyancy acting on soil particles increases.

Gravitational water reduces confining pressure on soil particles.

Adhesion forces between soil particles decrease due to changes in water bonding states.

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These factors collectively reduce the compressive strength of the critical zone [15–20]. If surface loads are applied to the critical zone during this period, surface subsidence or collapse is highly likely.

After the moisture content of the critical zone in the unsaturated aquifer reaches the state depicted in Figure 6(c), the water-soil bonding state of the groundwater fails to quickly restore equilibrium. The proportions of gravitational water and capillary water remain high, and the adhesive forces of bound water have not yet recovered. Consequently, the static adhesion between soil particles in the critical zone cannot be promptly reestablished. As a result, the compressive strength of the critical zone in the unsaturated aquifer cannot return to its pre-precipitation level.

If surface loads are applied to the critical zone under these conditions, the critical zone of the unsaturated aquifer remains highly susceptible to surface subsidence or collapse accidents.

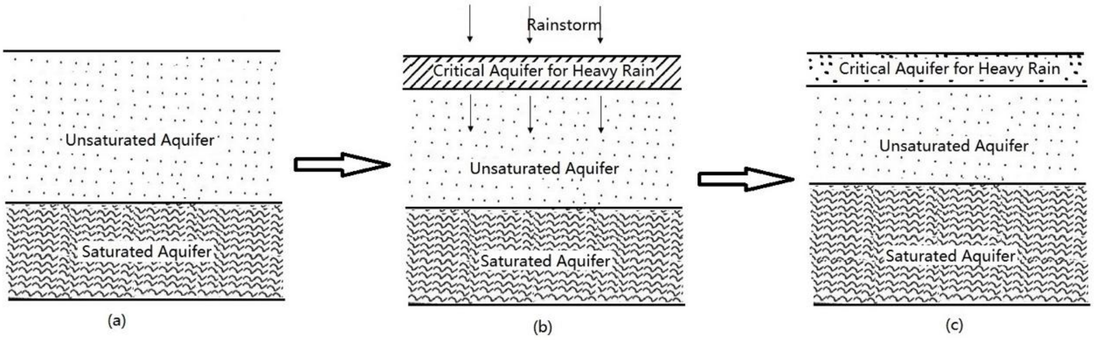

Figure 6: Schematic diagram of precipitation replenishment and soil softening

Using the Duncan-Chang model, the upward movement of groundwater fills gas voids in the unsaturated aquifer, reducing buoyancy and confining pressure on soil particles. As a result, the aquifer becomes more susceptible to collapse under the gravitational force of overlying objects. For instance, people walking on water-saturated swamplands often sink and become trapped, as depicted in Figure 7. Similarly, when soil beneath a structure suddenly becomes waterlogged, soil particles soften under gravitational water, causing structural subsidence, as shown in Figure 8 (road subsidence after heavy rainfall).

Figure 7: A girl is deeply trapped in a swamp

6. Analysis of common ground subsidence and collapse disasters in unsaturated aquifers

Case 1: Rapid Precipitation Causes Ground Subsidence in the Critical Zone of Unsaturated Aquifers

As illustrated in Figure 8, continuous heavy rainfall caused a highway surface collapse on May 1, 2024, at approximately 2:10 a.m., on the Meida Expressway in Guangdong, China. The disaster resulted in 48 fatalities and 23 vehicles falling into the collapse zone.

This incident can be explained using the two states of the critical zone in the unsaturated aquifer, as shown in Figure 6(b) and Figure 6(c). The rising moisture content in the critical zone softened

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the soil, reducing its compressive strength. When the weight of passing vehicles exerted pressure on this weakened zone, the critical zone experienced subsidence and collapse, leading to the highway surface failure and vehicle entrapment.

Figure 8: Collapse of meida expressway in Guangdong, China

Case 2: Sudden Groundwater Level Rise Reduces Supporting Pressure on Subsurface Rocks, Causing Structural Failure

In Figure 9, the collapse of a cement silo occurred in 1940 due to the soft soil foundation. This incident can similarly be explained using the moisture content theory of the critical zone in unsaturated aquifers (Figure 6). In this case, the surface load was not vehicles but the weight of the cement silo.

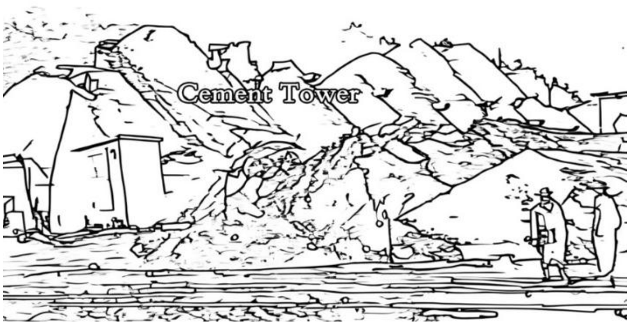

Figure 9: Cement silo collapse in 1940

Case 3: Groundwater Extraction Lowers the Saturated Aquifer Water Table, Altering Buoyant Forces on Soil Particles Due to Recharge with Low-Mineralization Water

Excessive groundwater extraction from saturated aquifers lowers the water table and creates a hydraulic gradient with adjacent water sources. For instance, when low-mineralization surface river water infiltrates the subsurface to replenish the saturated aquifer, it replaces the high-mineralization groundwater.

Existing theories of water-soil relationships fail to fully explain the effects of such mineralization changes on soil particles. Specifically:

If low-mineralization groundwater has a lower density than high-mineralization groundwater, buoyant forces on soil particles increase.

Conversely, if low-mineralization groundwater has a higher density, buoyant forces decrease.

These changes significantly impact soil particle behavior, soil skeleton stability, and rock mass integrity.

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Figure 4 illustrates the lateral infiltration of surface water, typically with lower mineralization levels than groundwater. This replacement alters the mineralization levels within the saturated aquifer, leading to changes in buoyant forces and potentially destabilizing the aquifer.

Case 4: Groundwater Extraction Lowers the Saturated Aquifer Water Table, Triggering Seawater Intrusion and Changes in Soil Buoyancy

In coastal regions, excessive groundwater extraction allows seawater to infiltrate and replenish the saturated aquifer, as shown in Figure 5. Seawater, typically with higher mineralization, replaces the low-mineralization groundwater, increasing the aquifer's mineralization level.

The buoyant forces on soil particles depend on the relative densities of the replacing and replaced groundwater:

When high-mineralization seawater replaces low-mineralization groundwater, the increased density reduces buoyant forces.

Conversely, the reverse scenario increases buoyant forces.

Furthermore, as the mineralization level of groundwater surrounding soil particles rises, the concentration of the groundwater solution increases. This can lead to dehydration and shrinkage of soil particles, reducing their volume and accelerating soil skeleton collapse. These effects can induce aquifer subsidence and ground failure.

To fully understand foundation settlement, it is crucial to explore how changes in groundwater mineralization levels affect the swelling and shrinkage behavior of soil particles.

7. Discussion and theoretical contributions

Previous research on water-soil relationships has not clearly distinguished between the saturation levels of groundwater aquifers (saturated vs. unsaturated) and their geographical distribution. This study examines groundwater recharge, runoff, and discharge, aquifer stratification (saturated and unsaturated zones), and ground subsidence disasters. The findings indicate that ground subsidence cannot be attributed solely to reduced groundwater volume from over-extraction; the change in groundwater mineralization must also be considered. Based on this, two theories—buoyancy theory and expansion theory—are proposed to address the effects on soil particles.

7.1. Buoyancy theory

When high-mineralization water in the saturated aquifer is replaced by low-mineralization water, the buoyant forces acting on soil particles change, disrupting the equilibrium of buoyancy. The loss of buoyant support can cause the soil skeleton to deform and compress under new gravitational forces.

As illustrated in Figure 10, water density is positively correlated with water mineralization. High-mineralization water has greater density, while low-mineralization water has lower density.

In Case 3, surface river water (low mineralization) recharges the saturated aquifer, reducing groundwater density and buoyancy on soil particles.

In Case 4, seawater (high mineralization) recharges the saturated aquifer, increasing groundwater density and buoyancy on soil particles.

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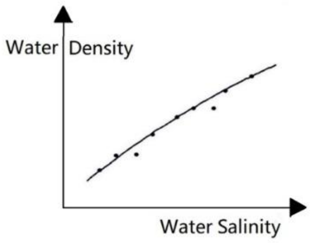

Figure 10: Correlation between water density and mineralization

7.2. Expansion theory

According to Higbie's permeation theory (1935), water molecules tend to migrate from low-concentration solutions to high-concentration solutions. When high-mineralization water in the saturated aquifer is replaced by low-mineralization water, the original water-soil equilibrium is disrupted.

Low-mineralization water, being a low-concentration solution, drives water molecules to migrate into soil particles, causing them to absorb water, soften, swell, and deform.

8. Conclusions

1. Before precipitation, the compressive strength of the critical zone in the unsaturated aquifer is at its maximum. After precipitation, the rising moisture content in this zone, coupled with changes in buoyant forces, soil particle softening, and reduced adhesion forces, significantly lowers its compressive strength. This creates a high risk of surface subsidence and collapse accidents.

2. When high-mineralization water surrounding soil particles is replaced by low-mineralization water, buoyant forces acting on soil particles are affected. This induces soil particle swelling, structural instability, water absorption, softening, and deformation. Over time, as groundwater slowly undergoes re-mineralization, its mineralization level gradually increases.

3. Ground subsidence cannot be solely attributed to the reduced groundwater volume from over-extraction. When low-mineralization water is replaced by high-mineralization water, the buoyant forces acting on soil particles are altered, causing them to shrink and destabilize the soil structure.

4. The critical zone of unsaturated aquifers, formed during sudden rainfall, significantly weakens the bearing capacity of soil foundations.

5. Bound water enhances the mechanical strength of soil-rock masses, whereas gravitational water diminishes it.

9. Recommendations

1. Enhance urban greening by increasing green spaces, using permeable hardened materials for ground surfaces, and improving urban drainage systems. Install additional drainage pipelines, ditches, and collection wells around buildings. Strengthen the collection and utilization of rainwater.

2. Reduce excessive groundwater extraction to maintain the stability and balance of water levels in saturated aquifers.

3. Future research on the relationship between groundwater discharge and ground subsidence should not overlook the effects of groundwater mineralization changes caused by groundwater replacement. These effects include:

Soil particle swelling and shrinkage behavior.

Soil bearing capacity.

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Groundwater re-evaporation rates.
Buoyancy changes on soil particles.
Groundwater re-mineralization processes.

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