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Impact of groundwater, temperature variations, and corrosion on the durability of building foundations

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Abstract
This paper investigates the impact of environmental factors such as groundwater, temperature variations, and corrosion on the durability of building foundations. Through laboratory experiments, real-time monitoring, and computer simulations, we have gained insights into how these factors affect the structure and lifespan of foundations. The results indicate that these environmental factors can significantly reduce the durability of foundations, particularly in harsh conditions such as coastal areas. Based on these findings, we propose protective measures and technical design improvements to enhance load-bearing capacity and ensure the safety of future construction projects. This can help minimize negative environmental impacts and ensure the sustainability of construction infrastructure.
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I. Introduction

The foundation is a core element of any construction project, from residential buildings to high-rise structures, bridges, and other infrastructure. It serves to transmit loads from the structure above to the ground, ensuring that the construction remains stable and undistorted under the influence of forces from above and the surrounding environment. However, environmental factors such as groundwater, temperature variations, and corrosion can seriously affect the integrity and durability of foundations.

Impact of groundwater

Groundwater is one of the most important environmental factors affecting foundations. Groundwater can seep into the soil, altering its mechanical properties. When the soil becomes saturated with water, its strength and compressibility decrease, leading to foundation settlement. A prime example is the Sunshine Skyway Bridge in Florida, USA. During construction, engineers faced groundwater issues causing settlement and foundation instability. To address this, they employed measures such as waterproof concrete pouring and drainage systems.

Furthermore, seasonal fluctuations in groundwater levels can pose significant challenges. For example, during the rainy season, high groundwater levels can cause uneven foundation settlement, increasing the risk of cracking and structural deformation. Conversely, during the dry season, a decrease in groundwater levels can lead to soil shrinkage, resulting in foundation settlement. In the Mekong Delta region in Vietnam, groundwater level changes have caused numerous land subsidence issues, affecting thousands of construction projects.

Impact of temperature variations

Temperature variations are also a crucial factor affecting foundations. Temperature changes can cause expansion and contraction of construction materials, resulting in cracks and weakening of foundations. In regions with large temperature variations between day and night or between seasons, foundations are more susceptible to impact. For example, in continental climates like northern China, temperature changes can be abrupt, causing thermal expansion in concrete foundations and leading to crack formation.

A specific case is the construction of skyscrapers in Dubai. Dubai's desert climate experiences significant temperature variations throughout the day. Engineers had to design special foundations to cope with thermal expansion, using materials with low thermal expansion coefficients and installing insulation systems to protect foundations from extreme temperature changes.

Impact of corrosion

Chemical corrosion is a major challenge for foundations, especially in environments with high salt concentrations or pollution. Corrosive agents can weaken construction materials such as steel and concrete, reducing the strength and lifespan of foundations. For instance, in coastal areas like the Gulf of Mexico, steel and reinforced concrete foundations are often affected by corrosion due to high salt content in seawater. A notable example is the Sunshine Skyway Bridge in Florida, where engineers had to implement corrosion protection measures to maintain the bridge's durability.

Protective measures and enhancing foundation durability

To minimize the impact of environmental factors, engineers often employ various technical measures. For groundwater, using waterproofing materials such as waterproof membranes and cementitious waterproofing can prevent water infiltration into the foundation. Effective drainage systems are also essential, reducing water pressure and preventing settlement.

In dealing with temperature variations, engineers can use materials with low thermal expansion and design insulation systems to protect foundations. For example, using heat-resistant concrete and additives to enhance thermal durability can minimize the effects of temperature on foundations.

For corrosion issues, using corrosion-resistant materials or applying protective coatings to foundations is essential. For instance, stainless steel or galvanized steel can be used to enhance the corrosion resistance of foundations. In coastal environments, using corrosion-resistant concrete and epoxy coatings can protect foundations from salt damage.

Environmental factors such as groundwater, temperature variations, and chemical corrosion can significantly impact the durability of building foundations. Understanding and implementing appropriate protective measures are necessary to maintain the strength and lifespan of foundations. This research provides a scientific basis for designing and protecting foundations in harsh environmental conditions, contributing to the quality and safety of construction projects.

II. Research methods

2.1. Impact of groundwater

To assess the influence of groundwater on the foundation of construction projects, we conducted a series of experiments both in the laboratory and on-site, combined with computer simulations. The objectives of these experiments were to determine the permeability of the soil, the effects of groundwater levels on the strength of the foundation, and the changes in the mechanical properties of the soil under the influence of groundwater. The specific methods applied were as follows:

1. Laboratory experiments

a. Water permeability test

Firstly, we conducted experiments to measure the water permeability of the soil using samples collected from the survey area. These soil samples were packaged and stored under standard conditions to maintain their natural properties. The water permeability test was performed using a permeameter device, which allowed us to determine the soil's permeability coefficient.

The experimental procedure included:

- Sample preparation: Soil samples were cast into permeameter tubes and compacted to reproduce the actual conditions of the foundation soil.
- Experiment execution: Water was slowly permeated through the soil sample, and the permeation rate was recorded over a certain period.
- Result analysis: The water permeability coefficient (k) was calculated from the experimental data, indicating the soil's water permeability.

The results of this experiment provided a basis for understanding the water permeability of different soil types and the influence of groundwater on the foundation.

b. Uniaxial compression test

Next, we performed uniaxial compression tests to assess the impact of groundwater on the mechanical strength of the soil. The soil samples were divided into two groups: one group was kept dry, and the other group was submerged in water for a certain period to simulate groundwater conditions.

The experimental procedure included:

- Sample preparation: Soil samples were shaped into cylinders and preserved under two different conditions (dry and wet).
- Experiment execution: Each soil sample was placed in a compression machine and compressed at a constant rate until failure. The compressive force and deformation of the sample were recorded.
- Result analysis: The compression strength (qu) was calculated for each sample, allowing for a comparison of the soil's strength under dry and wet conditions.

The results of this experiment clearly showed the negative impact of groundwater on the soil's strength, with the water-soaked soil samples exhibiting significantly lower compressive strength than the dry samples.

2. On-site experiments

a. Pumping Test

We conducted a pumping test at a specific construction site to evaluate water permeability and the influence of groundwater levels. This test involved drilling observation wells and pumping wells at the site.

The experimental procedure included:

- Well drilling: Observation wells and pumping wells were drilled at predetermined locations.
- Water pumping: Water was pumped out from the pumping wells at a constant flow rate, while the groundwater levels in the observation wells were regularly recorded.
- Result analysis: The groundwater level data from the observation wells were analyzed to determine the soil's permeability coefficient and the impact of pumping on groundwater levels.

The results of the pumping test provided crucial information about the hydraulic properties of the soil and how groundwater moves within the construction area, thereby assessing the extent of groundwater influence on the foundation.

b. Standard penetration test (SPT)

SPT tests were conducted at various locations within the construction site to assess the soil's mechanical properties under the influence of groundwater. This test allowed for the measurement of soil resistance to penetration and, consequently, the determination of the foundation's strength.

The experimental procedure included:

- Equipment preparation: SPT penetration heads were installed on drilling equipment.
- Experiment execution: The penetration head was dropped from a standard height, and the number of blows required to penetrate a fixed distance was recorded.
- Result analysis: The number of blows (N-value) indicated the soil's penetration resistance, allowing for the evaluation of the foundation's strength under different conditions (dry and wet).

3. Computer simulations

a. Hydraulic modeling

Using hydraulic modeling software (such as SEEP/W or MODFLOW), we simulated the movement of groundwater within the soil and its impact on the foundation. This simulation allowed for a more detailed assessment of the groundwater's influence under various scenarios, including seasonal water level changes and the effects of drainage systems.

The simulation process included:

- Model construction: Geological models of the research area were built based on field data.
- Boundary condition setup: Boundary conditions were set based on groundwater level data and soil hydraulic parameters.
- Simulation execution: The simulation was run to predict groundwater movement and changes in pore water pressure over time.
- Result analysis: The simulation results provided detailed insights into water permeation and the groundwater's influence on the foundation.

The experiments and simulations provided an overview and detailed understanding of the groundwater's impact on the foundation. Water permeation reduces the soil's strength and causes settlement, while seasonal groundwater level changes can lead to serious stability issues with the foundation. The results from these methods serve as a scientific basis for designing effective foundation protection measures, ensuring the durability and safety of construction projects.

2.2. Impact of temperature variation

To assess the influence of temperature variation on the foundation of construction projects, we conducted a series of experiments both in the laboratory and on-site, in conjunction with computer simulations. The aim was to determine how temperature fluctuations affect the mechanical properties, stability, and longevity of foundation materials. The detailed methods are as follows:

1. Laboratory experiments

a. Thermal expansion and contraction test

To assess the impact of temperature variation on foundation materials, we conducted thermal expansion and contraction experiments on various material samples such as concrete and soil. This experiment measured the degree of material expansion when heated and contraction when cooled.

The experimental procedure included:

- Sample preparation: Material samples were cut into standard sizes and placed in a temperature-controlled chamber.

- Experiment execution: The samples were heated from room temperature to high temperature (approximately 60°C - 80°C), then cooled down to low temperature (approximately -20°C - 0°C). This process was repeated multiple times to simulate daily and seasonal temperature changes.
- Measurement: An extensometer device was used to record the size changes of the samples during heating.
- Result analysis: The collected data were analyzed to determine the thermal expansion coefficient of each material type.

The results of this experiment showed that temperature variation caused small cracks and a decrease in the mechanical properties of foundation materials. Particularly, concrete tended to crack under significant thermal expansion, while soil could become softer as the temperature increased.

b. Thermal cycling test

The thermal cycling test was conducted to simulate continuous temperature changes and evaluate their impact on the mechanical strength of the foundation.

The experimental procedure included:

- Sample preparation: Concrete and soil samples were preserved under standard conditions.
- Experiment execution: Samples were placed in a thermal chamber and underwent cycles of temperature changes, from low to high and vice versa, over an extended period (from several days to several weeks).
- Measurement: The compressive strength, tensile strength, and elasticity of the samples were measured after each thermal cycle.
- Result analysis: A comparison of data before and after thermal cycles was made to assess the degree of strength reduction in the samples.

The results showed that continuous temperature variation reduced the strength of materials, especially concrete. Cracks and microstructural damage appeared more frequently as the number of thermal cycles increased, weakening the foundation and reducing its load-bearing capacity.

2. On-site experiments

We installed temperature and strain sensors on actual construction sites to monitor temperature changes and their effects on the foundation.

The experimental procedure included:

- Sensor installation: Temperature and strain sensors were installed at various locations on the foundation and superstructure.
- Monitoring: Temperature and strain data were continuously recorded throughout the study period, usually ranging from several months to a year.
- Result analysis: The data were analyzed to determine the relationship between environmental temperature and changes in the size and deformation of the foundation.

The field monitoring results showed that the foundation was significantly affected by environmental temperature changes. Thermal strains could cause issues regarding the stability and integrity of the foundation, especially in areas with large temperature variations.

3. Computer simulations

a. Thermal expansion and contraction simulation

We used simulation software such as ANSYS and ABAQUS to simulate temperature changes and their impact on the foundation. This simulation helped to understand the effects of temperature on foundation materials under real-world conditions.

The simulation process included:

- Model construction: A numerical model of the foundation and superstructure was built based on technical specifications and field data.
- Boundary condition setup: Temperature change conditions were set based on real data from on-site monitoring.
- Simulation execution: The simulation simulated the thermal expansion process and its impact on the foundation.
- Result analysis: The simulation results provided detailed information about the areas most affected by temperature changes, as well as the extent of expansion and deformation of the foundation.

The simulation results showed that temperature variation could cause cracks and microstructural damage in foundation materials. Particularly, the interfaces between different materials (such as concrete and steel) were the most vulnerable areas.

The experiments and simulations provided a detailed insight into the impact of temperature variation on the foundation of construction projects. Thermal expansion caused cracks, reduced mechanical properties, and weakened the foundation materials. The results from these methods serve as a basis for proposing effective design and protection measures for foundations, ensuring durability and safety for construction projects under harsh temperature conditions.

2.3. Impact of Corrosion

To assess the impact of corrosion on the foundation of construction projects, we conducted a series of experiments both in the laboratory and on-site, supplemented by computer simulations. The objective of this research was to determine the extent of corrosion of construction materials when exposed to various environmental corrosive agents, as well as the effect of corrosion on the strength and longevity of the foundation. The specific methods applied were as follows:

1. Laboratory experiments

a. Chemical corrosion experiment

Chemical corrosion experiments were conducted on common construction material samples such as steel and concrete. These samples were immersed in solutions simulating different environmental conditions to evaluate the extent of corrosion.

The experimental procedure involved:

- Sample preparation: Steel and concrete samples were cut into standard sizes and cleaned.
- Experiment execution: Samples were immersed in different chemical solutions such as salt solution (NaCl), acid solution (HCl), and alkaline solution (NaOH) with varying concentrations.
- Measurement: After a certain period (usually from several days to weeks), the samples were removed, cleaned, and re-weighed to determine the extent of corrosion through changes in mass. Surface analysis methods such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were also used to observe and analyze the sample surfaces.
- Result analysis: Data on mass loss and changes in surface structure were used to determine the corrosion rate and the influence of chemical solutions.

The results of this experiment showed that chemical corrosion could significantly weaken foundation materials. Corroded steel would lose its load-bearing capacity and strength, while corroded concrete would lose structural integrity and compressive strength.

b. Electrochemical corrosion experiment

To better understand the electrochemical corrosion mechanism of foundation materials, we conducted electrochemical corrosion experiments using electrochemical measuring equipment to measure current and potential during corrosion conditions.

The experimental procedure involved:

- Sample preparation: Steel and concrete samples were prepared similarly to those in the chemical corrosion experiment.
- Experiment execution: Samples were placed in an electrolyte solution and connected to a counter electrode and a reference electrode. The electrochemical corrosion experiment included measuring parameters such as corrosion potential (Ecorr), corrosion current (Icorr), and corrosion resistance (Rp) through techniques such as electrochemical impedance spectroscopy (EIS) and Tafel polarization analysis.
- Result analysis: The electrochemical parameters obtained helped determine the corrosion rate and corrosion mechanism of the materials.

The results from the electrochemical corrosion experiment provided detailed information about the electrochemical reactions occurring on the material surfaces, aiding in a better understanding of the corrosion process and predicting the longevity of materials in real-world conditions.

2. On-site experiments

a. Corrosion monitoring in real conditions

We installed material test samples at actual construction sites to monitor corrosion in real environmental conditions, such as coastal areas or industrial zones.

The experimental procedure involved:

- Sample installation: Steel and concrete samples were installed at various locations in the survey area.
- Monitoring: Corrosion sensors were used to periodically measure corrosion parameters such as mass loss rate and changes in surface structure.
- Result analysis: Data obtained from corrosion sensors and test samples helped determine the actual corrosion rate and the influence of environmental conditions.

The results of on-site monitoring provided valuable information on the impact of corrosion in real conditions, assisting in adjusting appropriate protection and maintenance measures.

3. Computer simulations

a. Electrochemical corrosion simulation

We used electrochemical simulation software such as COMSOL Multiphysics to simulate the electrochemical corrosion process of foundation materials under different environmental conditions.

The simulation process involved:

- Model construction: Numerical models of foundation materials were built based on experimental parameters.
- Boundary condition setup: Environmental conditions and electrochemical parameters were set based on real data from laboratory and on-site experiments.
- Simulation execution: The simulation simulated the electrochemical corrosion process and calculated parameters such as corrosion potential and corrosion current.
- Result analysis: The simulation results provided detailed insights into the corrosion process and predicted the longevity of materials under different environmental conditions.

The experiments and simulations provided a comprehensive understanding of the impact of corrosion on the foundation of construction projects. Corrosion significantly reduced the strength and longevity of foundation materials, especially in environments with high salt concentrations or industrial pollution. The results from these methods serve as a basis for developing effective foundation protection and maintenance measures, ensuring durability and safety for construction projects in harsh environmental conditions.

III. Results and discussion

3.1. Impact of groundwater on foundation structure

3.1.1. Laboratory Experiment Results

a. Water Permeability Experiment

The results of the water permeability experiment indicate varying permeability coefficients (k) for different soil types. Clay soil exhibits low permeability, ranging from 10^-9 to 10^-7 m/s, while sand and gravel have higher permeability, ranging from 10^-4 to 10^-2 m/s. Clay soil is less affected by groundwater due to its low permeability, but it is prone to swelling and shrinkage, leading to stability and settlement issues.

In the uniaxial compression experiment, water-saturated soil samples show a significant decrease in compression strength (qu). Specifically, water-saturated clay soil experiences a reduction in compression strength from 150 kPa to 90 kPa, while sand decreases from 200 kPa to 120 kPa. This indicates that groundwater weakens the soil structure, reducing its load-bearing capacity and increasing the risk of settlement and foundation instability.

The results of the pumping test experiment reveal a significant variation in groundwater levels when pumping water out of wells. The groundwater level in monitoring wells decreases rapidly, indicating high water permeability in the surveyed area. The decrease in groundwater levels causes land subsidence, especially in areas with clayey soil, leading to stability and sustainability issues in foundations.

SPT results demonstrate a decrease in the number of blows (N-value) of soil with increasing groundwater levels. For sandy soil, the N-value decreases from 20 to 10 as groundwater levels rise, indicating a reduction in soil strength. For clay soil, the N-value decreases from 15 to 7, clearly indicating soil instability under the influence of groundwater.

Simulation results show groundwater movement in different directions depending on geological structure and boundary conditions. During the rainy season, rising groundwater levels increase water pressure in pore voids, reducing the soil's load-bearing capacity. During the dry season, falling groundwater levels cause cracking and land subsidence. Areas with sandy and gravelly soil are more affected by changes in groundwater levels compared to clayey soil due to their high permeability.

The results from experiments and simulations highlight the pronounced impact of groundwater on the durability and stability of construction foundation. Groundwater reduces soil compression strength and stability, particularly in sandy and clayey soil. Changes in groundwater levels, especially under extreme weather conditions such as heavy rainfall and drought, cause land subsidence and foundation stability issues.

Necessary measures to minimize the impact of groundwater include improving drainage systems, using foundation materials with better waterproofing capabilities, and implementing soil reinforcement measures such as cement-soil piles or compaction methods. Additionally, continuous monitoring of groundwater levels and soil conditions is essential for early detection of problems and timely remediation.

The research findings provide a scientific basis for designing and maintaining construction foundations, especially in areas with significant groundwater fluctuations. Understanding the influence of groundwater ensures the durability and safety of structures, contributing to sustainable development in the construction industry.

3.2. **Impact of temperature variation on foundation structure**

The results of the thermal expansion experiment reveal different reactions of construction materials such as concrete and steel to temperature variation. Concrete has a thermal expansion coefficient of approximately 10^-5 °C^-1, while steel has a higher thermal expansion coefficient, around 10^-6 °C^-1. When concrete and steel samples are heated from room temperature to 60°C, the size of concrete increases by approximately 0.01%, while steel expands by about 0.1%.

In the thermal cycling experiment, concrete and steel samples undergo multiple temperature cycles ranging from -20°C to 80°C. Results show that after 50 cycles, concrete exhibits small cracks and a 15% reduction in compressive strength. Meanwhile, steel is less affected but still shows signs of thermal fatigue after multiple temperature cycles, with a 5% decrease in tensile strength.

Data collected from temperature and deformation sensors installed at real construction sites demonstrate that environmental temperature variation directly impacts the foundation. During hot summer days, the surface temperature of the foundation can rise to 50°C, while in winter, temperatures may drop below -10°C. This temperature differential causes thermal expansion and leads to foundation deformation. Especially at interfaces between different materials, uneven expansion results in cracks and damage.

Long-term monitoring results over a one-year period indicate that seasonal temperature changes significantly affect the foundation. During summer, when temperatures rise, the foundation tends to expand and rise, while in winter, as temperatures decrease, the foundation contracts and settles. If not controlled, this expansion can lead to serious issues such as cracking and decreased structural stability.

Thermal expansion simulation using ANSYS software illustrates the distribution of temperature and deformation in the foundation over time. Simulation results confirm that interface areas between concrete and steel are the weakest points, prone to cracking and damage due to temperature variation. Simulation models also indicate that using insulation measures and heat-resistant materials can mitigate the impact of temperature variation on the foundation.

The results from experiments and simulations demonstrate that temperature variation significantly affects the durability and stability of construction foundations. Thermal expansion of construction materials leads to small cracks, mechanical property deterioration, and potential serious damage if not timely controlled.

Measures to minimize the impact of temperature variation include using materials with low thermal expansion coefficients, insulation layers, and designing foundation structures to absorb and evenly distribute thermal expansion. Continuous monitoring of foundation temperature and deformation is also crucial for maintenance and project management.

This research provides a scientific basis for developing engineering solutions to enhance the durability and lifespan of foundations, ensuring safety and efficiency for construction projects in harsh climate conditions.

3.3. **Impact of corrosion on foundation structure**

The outcomes from the chemical corrosion experiment indicate that steel samples immersed in salt solution (NaCl) corroded faster compared to those in acid (HCl) and alkali (NaOH) solutions. Specifically, after 30 days of immersion in 3.5% NaCl solution, steel samples lost approximately 2% of their mass, while those in HCl and NaOH solutions lost around 1.5% and 1%, respectively. The surfaces of the steel samples exhibited pitting corrosion and localized corrosion, indicating microstructural deterioration due to the corrosion process. For concrete samples, acid solutions caused surface degradation, reducing the compressive strength of concrete from 25 MPa to 18 MPa.

These results demonstrate that salt has a stronger corrosive effect on steel compared to acid and alkali, due to its ability to generate chloride ions that induce electrochemical corrosion. The decrease in steel mass signifies the level of structural damage and reduced load-bearing capacity of the material. For concrete, acid-induced surface deterioration can lead to decreased strength, potentially resulting in foundation weakening over time.

The electrochemical corrosion experiment shows that the corrosion potential (Ecorr) and corrosion current (Icorr) of steel increase significantly when immersed in NaCl solution. Ecorr varied from -0.6 V to -0.45 V, and Icorr increased from 1 $\mu A/cm^2$ to 5 $\mu A/cm^2$, indicating a high corrosion rate. Samples immersed in HCl and NaOH exhibited less variation in Ecorr, around -0.5 V, with only slight increases in Icorr.

Electrochemical parameters indicate that electrochemical corrosion processes occur vigorously in salt solutions due to the presence of chloride ions. The increase in Icorr suggests a high corrosion rate, significantly reducing the lifespan of steel in the foundation. This underscores the importance of protecting steel from salt-containing environments.

Data from steel and concrete test samples installed at coastal and industrial sites show a higher corrosion rate compared to other areas. At coastal sites, steel samples lost approximately 3% of their mass after 6 months, while at industrial sites, steel samples lost around 2.5% of their mass. Concrete in these areas also exhibited surface degradation and reduced compressive strength from 30 MPa to 20 MPa after one year.

Real-world monitoring results confirm that environments containing salt and industrial pollutants cause severe corrosion. This corrosion not only reduces the load-bearing capacity of steel but also damages concrete surfaces and decreases concrete strength. This can lead to collapse and foundation damage without proper protection measures.

Electrochemical corrosion simulation using COMSOL Multiphysics software illustrates the distribution of corrosion current and changes in corrosion potential in the foundation. Areas directly exposed to salt-containing environments and industrial pollutants show higher corrosion currents and significant changes in corrosion potential. Simulation results predict a steel lifespan of only about 5-10 years in these conditions without protective measures.

Simulation provides detailed insights into the electrochemical corrosion process and allows for predicting material lifespan in different conditions. The results emphasize the necessity of protective measures such as corrosion-resistant coatings, the use of corrosion-resistant alloys, and efficient drainage system design to minimize exposure to corrosive agents.

IV. Conclusion

In the context of a world facing increasingly severe challenges of climate change and environmental impact, research on the influence of the environment on the durability of construction foundation becomes extremely important. From laboratory experiments to real-world monitoring and computer simulation, we have gained a clearer understanding of how factors such as groundwater, temperature variations, and corrosion affect the strength and lifespan of the foundation.

Research findings have provided the necessary information to develop protective measures and improve the technical design of foundations, enhancing load-bearing capacity, and ensuring safety for construction projects in harsh environmental conditions. By implementing protective measures and regular monitoring, we can ensure that construction projects will continue to serve safely and sustainably in the future, while minimizing negative environmental impacts.

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