Experimental and Numerical Investigation on the Stability of Loess Embankment Treated by Chemical Solution under Freezing-Thawing Conditions

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Research Article

Keywords: loess embankment, freezing-thawing cycle, chemical solutions, safety factor, limit equilibrium methods

Posted Date: March 15th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-286923/v1

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Re: Experimental and Numerical Investigation on the Stability of Loess Embankment Treated by Chemical Solution under Freezing-Thawing Conditions

I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while being considered by Natural Hazards. And the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. No data have been fabricated or manipulated (including images) to support our conclusions. No data, text, or theories by others are presented as if they were our own.

The submission has been received explicitly from all co-authors. And authors whose names appear on the submission have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results.

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I am sorry for any inconvenience that this may cause.

Yours sincerely,

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Conflict of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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List of notations

δ_s is collapsible coefficient (δ_s=0.015 is the evaluation criterion of collapsibility)

h_0 is initial height of the sample

h_1 is the stable height of the sample under a certain pressure

h_2 is the level stable height of the sample after immersion under the same pressure

N is the number of samples with safety factor less than 1

M is the total number of samples

β_s is RI

μ_s is average safety factor

σ_s is standard deviation of average safety factor

Abstract: In order to study the influence of chemical solution on the stability of loess embankment in seasonally frozen regions, the compression index, shear strength index and embankment safety factor of compacted loess fillings that were treated by different concentrations of chemical solution were analyzed through laboratory test and slope stability analysis program. The experimental results showed that the collapsible coefficients of remolded loess treated by different chemical solution will all increase which comparing the distilled water, and then will change again after freezing-thawing cycles (FTCs). The compression index of undisturbed loess will show regularity with the increase of chemical solution concentration. The shear strength of remolded loess also changed under the chemical solution and FTCs. Besides, simulation of the strength parameters by limit equilibrium methods showed that the safety factor of loess embankment with treatment of solution was significantly higher than that of untreated one, and the FTC would cause a further deterioration. The embankment stability improved after treated by chemical solution without considering seepage of rainwater. These results would provide a novel method to the problem of embankment stability related to environmental condition changes.

Key words: loess embankment; freezing-thawing cycle; chemical solutions; safety factor; limit equilibrium methods

1. Introduction

Since the British chemist (SMITHRA, 1872) first reported the concept of acid rain, which has become one of the most important atmospheric environmental issues around the world, has caused disaster to people's health, corrosion of cultural relics, and destruction of ecosystems. Economic development and urban expansion of China have caused air pollution like acid rain to be very prominent (Zhang et al., 2007; Ouang et al., 2008). With development of the loess regions, the frequency of acid rain has changed year by year, which has led to engineering problems. Because the loess is mostly distributed in the seasonal frozen region, this problem will be more complex under the influence of FTCs.

The Loess Plateau (34°00′-45°05′N, 101°00′-114°33′E) nearly covers a total area of 6.3×10^5 km^2 and is located in Northern China. The Loess Plateau is the largest loess area in the world, with an elevation of 200-3000 m and a sedimentary thickness of 30-80 m (sometimes 150-180 m) (Zhao et al., 2016). The typical loess is an Aeolian deposit with an open and meta-stable structure, characterized by high porosity, low density, and silt-dominated particle size arranged in an open fabric supported by cementation bonds. Due to these characteristics, the loess deposit can show an abrupt collapse due to wetting and overburden pressure which causes geological and geotechnical hazards such as landslides, ground subsidence, differential settlement, and surface cracks leading to the failure of man-made infrastructures built on deposits of loess soil (Li et al., 2015; Derbyshire et al., 1995). With approving of the 'National Expressway Network Plan' and 'Mid-to-Long Term Railway Network Plan' in 2005 and 2008 respectively, the high-speed railways and highways in China have experienced a major growth and expansion ever since (Ma et al., 2017). In Northern China, due to loess's advantages of abundant supply and low cost, it has been widely used as fillings or foundation soil of various infrastructures (Li et al., 2017). Therefore, the long-term exposure of loess embankment under natural environment was easily affected by change of temperature and humidity, and its engineering properties will change with time, which lead to various engineering problems. When a densely compacted loess is exposed to freezing, soil particles are separated by distinct ice lenses, causing macro-pores (5~20 μm) and fissures inside. Besides, when the ice melts, larger pores and fissures are left (Mu et al., 2011; Zhang et al., 2015). The fabric of loess is destroyed, leading to instability and collapse of the embankment after repeated FTCs (Qi et al., 2006). The shortcomings such as the collapsibility of loess and its own advantages should be fully considered as problems in use of the roadbed after backfilling (Qi et al., 2008; Li et al., 2017).

The impact of FTCs on seepage (Zimmie et al., 1990; Kim et al., 1992), porosity (Benson et al., 1993; Eigenbrod, 1996), liquid and plastic limit (Viklander et al., 2000; Zhang et al., 2015) of soil has already studied by a large number of engineers, scholars and research groups all over the world. In order to put the theory into practice, more scholars began to consider the impact of the FTCs on infrastructures. In the study of secondary subsidence or multiple collapse of embankment, many scholars have suggested that it is caused by repeated wetting-drying, freezing-thawing, and salinization-desalinization cycles in seasonally frozen regions (Eigenbrod, 2001; Houston et al., 2001; Li et al., 2010; Li et al., 2011; Malusis et al., 2011; Chang et al., 2013; Zhang et al., 2013; Li et al., 2018). Li et al (2015) studied the microstructure and engineering characteristics of recompacted loess after freeze-thaw, wet-dry, and salinization-desalinization cycles, they also analyzed the mechanism of multiple collapse of loess highway embankment. Özgan et al. (2015) compared and analyzed the physical indicators of soil samples before and after freezing and thawing. Besides, they used electron microscopy (SEM) tests and energy dispersion X-ray-EDX tests to observe the structure of samples, and performed triaxial compression tests on the soil samples to determine the mechanics of the soil samples. Meanwhile, these studies showed that the structure of some compacted loess was similar to that of undisturbed loess (Deng et al., 2010; Jiang et al., 2012; Liu et al., 2016). But in terms of the influence of acid rain on soil, most of studies focused on the impact on agriculture or environment. Some scholars have considered the stability of rock slope under acid rain. Zhao et al. (2009) simulated the formation of the sliding surface of the acid rain by testing the changes in the mineral composition and shear strength of the specimen after different soaking times. Their results showed not only the change of strength index but also the analysis of change in mineral composition. Finally, the chemical-mechanical model of clay was discussed. Zhao et al. (2019) taking the gabbro rock slope from a typical acid rain area in Ya'an city as an example, firstly designed a chemical-weathering simulation experiment for rocks affected by acid rain, and carried out research on the acid etching effect of gabbro structure with different penetration and acid rain duration. The direct shear test of the bulk structure and calculation of the slope stability were used to compare the slope stability under different acid rain duration conditions, and described the significant weakening effect of acid rain on the slope stability. However, engineering problems of loess such as slope stability or roadbed stability affected by external environment are still needed to be studied in seasonally frozen regions.

Previous studies on stability of soil embankment after freezing and thawing have yielded fruitful results, however, coupling the stability of embankment with chemical solution is a more complex issue. In order to study the effect of chemical solution on the stability of roadbed and embankment in seasonally frozen regions, the compressibility and shear strength of contaminated soil samples after freezing-thawing cycles were obtained. Moreover, the parameters obtained were used to simulate the stability of embankment, and to explore the roles which influence in the embankment under different conditions. This will provide a theoretical support for preventing embankment instability and collapse.

2. Experimental Materials and Procedure

2.1 Material properties

Fig.1 shows the chosen locations in the survey area. According to Specifications for Monitoring of Acid Rain (GB T 19117-2003), the average PH value of the rainfall in Lueyang is 5.48, being less than 5.6, so the rainfall is acidic in 2012-2017. The minimum PH value reaches 3.8. The average PH value of rainfall in Yan' an is 5.76, falling between 5.6 and 7.0, so the rainfall is neutral. The average PH of rainfall in Yulin is 7.34, being greater than 7, so the rainfall is alkaline. Its highest pH value reaches 9.3 (Fig. 2). This shows that the situation of rainfall with various pH value is very common in the survey area. This also provides a basis for the following experimental study.

Fig. 1 Survey map

Fig. 2 Rainfall and its pH value for typical areas in Shaanxi Province in 2012-2017

Loess samples was located at 34°16′ N 108°54′E, Shaanxi Province, Northwestern China. The reason for choosing this type of loess is that it has widely been used as highway or railway embankment. The loess was dried and sieved by a 2-mm sieve. The basic physical parameters of the sampled soil can be seen in Table 1. In this experiment, the procedures followed the specifications in the Chinese Geotechnical Test Method Standard (GBT50123-2019).

Table 1 Physical parameters and chemical composition of the loess and grain size distribution

2.2 Sample preparation

Sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH) are commonly used in industry, and were selected as the chemical solution in this experiment. The water content was controlled at 20%. The ring knife (inner diameter 61.8 mm, height 20 mm and inner diameter 79.8 mm, height 20 mm) was used to make the recompacted soil samples after the standard compaction test and the intact soil samples for compression test and shear test. Sulfuric acid and sodium hydroxide solutions with concentration of 5%, 10% and 15% were added respectively to the loess samples for collapsibility test and direct shear test. Sulfuric acid and sodium hydroxide solutions with molar concentration of 0.1 mol/L, 0.5 mol/L and 2 mol/L were added respectively to the soil for consolidation test. A group of soil samples moistened by distilled water was added for comparison of each samples.

2.3 Freeze-thaw procedure

The soil samples were frozen and thawed through the temperature test chamber. Each freeze-thaw cycle for freezing and thawing lasted for 8 hours (Fig. 3). The numbers of freeze-thaw cycle were 0, 1, 2, 5, 10, 15 and 20. According to the average temperature in the northwest region of China, the variation range of temperature was ±20 °C with an accuracy of ±0.1 °C (Zhang et al., 2020). In order to reduce random error, 4~8 tests were repeated.

Fig. 3 Temperature change in the temperature test chamber

3. Experiment Results

3.1 Compression characteristics

Because of the high porosity, the collapsibility becomes one of the most remarkable characteristics of loess. The collapsibility of remolded loess after compaction as backfill is not obvious, but under the influence of external environment including change of temperature and moisture transfer, compressibility changes over time. Fig.4 shows the change of the collapsible coefficient of the remolded loess treated by different chemical solution through freezing-thawing cycles at room temperature. After the freezing-thawing cycle, collapsible coefficient of the soil sample treated by acid-solution and the untreated soil sample become greater. The collapsible coefficient of soil sample treated by alkaline-solution becomes smaller. The collapsible coefficient can be obtained from Eq. (1).

$$\delta_s = \frac{h_1 - h_2}{h_0} \qquad (1)$$

Fig.5 and 6 show the change of compression of intact soil sample treated by different molar concentrations of acidic solution and alkaline solution. The smaller the compression of the soil, the higher the compressibility of the soil is.

Fig. 4 Collapsible coefficient of remolded loess under different conditions

Fig. 5 Constrained modulus of soil treated with H_2SO_4 solution

Fig. 6 Constrained modulus of soil treated with NaOH solution

It can be seen in Fig.5 that the compression of the soil samples treated with different molar concentration of acidic solution increases under alow pressure (200 kPa). As the pressure increases, the constrained of the soil samples decreases and then increases. The soil sample treated with 0.1 mol/L and 0.5 mol/L acidic solutions starts to decrease at 200 kPa and re-increases at 400 kPa. The soil sample treated with 2 mol/L acidic solution starts to decrease at 100 kPa and re-increases at 200 kPa. The soil sample treated without chemical solution starts to decrease at 50 kPa and re-increases at 100 kPa. Besides, the constrained of the soil sample increases with the decrease of the molar concentration of the acidic solution when the pressure is 12.5-800 kPa, but the phenomenon is opposite when the pressure is over 800 kPa.

The trend of compression of soil samples treated with alkaline solution is basically the same as that of acidic solution. It increases first, then decreases and increases finally with the increasing of the pressure. The compression of soil sample treated with 0.1 mol/L alkaline solution is very large when the pressure is less than 800 kPa. Followed by the soil sample without treated and soil sample treated with 0.5 mol/L alkaline solution. The constrained modulus of soil sample treated with 2 mol/L alkaline solution is the smallest, that is, the compressibility is the highest under this condition. The change in constrained modulus is exactly the opposite when pressure is greater than 800 kPa. The compressibility of the soil after treatment with chemical solution increases in the low-pressure zone (<800 kPa) with the increase of the molar concentration of the solution, while the compressibility decreases with the increase of the molar concentration of the solution in the high-pressure zone (>800 kPa).

3.2 Shear strength characteristics

The liquidity index of soil increases with the increase of concentration of solution (shown as Fig. 7). Besides, the liquidity index of soil sample treated with alkaline solution is greater than that of acidic solution at the same concentration. Moreover, the liquidity index of soil sample treated with chemical solution is significantly greater than that of the untreated one. The liquidity index of untreated soil is 0.176, and the liquidity index of the soil treated with acidic and alkaline solution at the concentration of 5% is 0.267 and 0.280, respectively. The soil liquidity index of soils treated with acidic and alkaline solutions at concentration of 10% is 0.317 and 0.355, respectively. In addition, they were 0.353 and 0.375 when the concentration is 15%.

Fig. 7 Relationship between liquidity index and concentration of solution

The main reason for this phenomenon is that the water generated by the chemical reactions between soil sample with acidic and alkaline solution are different. According to the chemical composition of soil sample measured in the test, only the SiO_2 and Al_2O_3, which account for about 72% of the total, eacted? with sodium hydroxide solution. When the concentration of the chemical solution is the same, more water generates at this time, and the water content varies with increase of chemical concentration (shown as Eq. (2) and (3)).

$$\begin{cases} 2NaOH+SiO_2=Na_2SiO_3+H_2O \\ 2NaOH+Al_2O_3=2Na_2AlO_3+H_2O \end{cases} \tag{2}$$

$$\begin{cases} H_2SO_4+CaO=CaSO_4+H_2O \\ 3H_2SO_4+Al_2O_3=Al_2(SO_4)_3+3H_2O \\ 3H_2SO_4+Fe_2O_3=Fe_2(SO_4)_3+3H_2O \\ H_2SO_4+MgO=MgSO_4+H_2O \end{cases} \tag{3}$$

The strength of the soil increases with concentration of the chemical solution. After the freeze-thaw cycle, it deteriorates remarkably. However, although the strength of the soil treated with chemical solution after the freeze-thaw cycle deteriorates, the final strength is still greater than that of the soil sample moistened by distilled water. Besides, the strength of the soil treated with alkaline solution is greater than that of the soil treated with the acidic solution. As shown in Table 2, when soil sample did not undergo the freeze-thaw cycle, the strength of soil sample moistened by distilled water is 143.71 kPa, and the strength after contamination with 15% acid and alkali solutions are 227.4 and 254.37 kPa, respectively. After 20 freeze-thaw cycles, the shear strength in the above three cases are reduced to 115.89, 212.71, and 171.52 kPa, respectively.

Table 2 Shear strength under different conditions, kPa

4. Stability on Loess Embankment Slopes

4.1 Numerical Model

An embankment along a highway in the loess area is selected as research object. The simulation model is obtained according to an instance of roadbed size and its stress. The model is divided into four layers, namely backfill, Q_4 loess, Q_3 loess and Q_2 loess. Dimensions and load conditions of the model are shown in Fig.8. The boundary conditions are horizontally constrained on the left and right sides. The bottom is fixed and the rest are free boundaries. According to the data obtained in the above lab experiment and analogous to the physical and mechanical parameters of other similar geotechnical engineering, the parameters in this simulation are determined, as shown in Table 3. According to rainfall and frozen soil in loess area, the depth of influence is selected as 1.5 m.

Fig. 8 The simulation model of loess embankment

Table 3 Mechanical parameters at different layers

4.2 Change in safety factor

Fig.9 shows the stability of embankment after freeze-thaw cycle. The slip surface with a safety factor less than 1 after screening is given. The smallest safety factor is only 0.859. Therefore, it can be found that after multiple freeze-thaw cycles, the stability of the embankment will seriously deteriorate and the strength will significantly reduce. This seriously jeopardizes the safety and stability of highway embankment in loess area.

Fig. 9 Safety factor of embankment after freeze-thaw cycle

The depth of infiltration in the loess area does not exceed 1.5 m. The infiltration depth of the large-porosity loess model is 1.3 m. (Tong et al., 2017). The strength of the soil after treated by acid or alkaline solution has changed significantly. The safety factor of acid-polluted embankment increased from 1 to 1.416 with an increase of 64.8%. The safety factor of alkali-polluted embankment increased from 1 to 1.569 with an increase of 82.7% (shown as Fig. 10). This shows that acid-alkaline solution has a positive effect on the stability of loess embankment. However, the problems in the real environment are very complicated. The influence of infiltration and the impact of erosion on slope stability have not been simulated. Overall, the multiple factors have greatly increased the uncertainty of the stability of embankment. Therefore, the analysis in this paper is only carried out under steady conditions.

(a) Acidic solution

(b) Alkaline solution

Fig. 10 Simulating slope safety factor after pollution

4.3 Results analysis

The safety factor (F_S) of the minimum slip surface is obtained from the analysis of slope stability. In addition to the F_S, another important parameter is the average safety factor, which is obtained through a probabilistic analysis of all slip surfaces. The probability of failure, i.e., *PF*, is obtained by Eq. (4).

$$PF = \frac{N}{M} \times 100\% \tag{4}$$

The reliability index (RI), not only characterizes the slope stability but also separates the average safety factor from the safety factor (shown as Eq. (5)). Detailed results under each condition are shown in Table 4.

Table 4 Summary of probabilistic analysis under different conditions

$$\beta_s = \frac{\mu_s \text{-} 1}{\sigma_s} \tag{5}$$

As shown in Fig.11, the gray columns indicate a safety factor of less than 1, and the rest is greater than 1. That is to say, only under the conditions of freezing and thawing cycles, the soil will theoretically have a large degree of slope instability, and the stability of the soil slope after treated by acidic or alkaline solution is enhanced. The safety factor has no slip surface less than 1, so the slope is relatively stable.

For the slope stability by the Simplified Bishop Method, "960/1000" indicates that 960 of the 1000 calculated samples have a safety factor less than 1, which is equivalent to a 96.5% probability of slope failure. Except for embankment under freeze-thaw cycle, the gray column does not appear under other conditions, so there is no need to take the *PF* into consideration when the embankment affected by acid or alkaline solution. The frequency of safety factor of embankment affected by acid or alkaline solution appears to be the same, reaching its maximum value between 1.4 and 1.6, while the safety factor of embankment after freezing and thawing reach its maximum value at about 0.9.

Fig. 11 The safety factor and its ralative frequency in different conditions

In general, convergence graph can illustrate the result of probability analysis and relatively stable value, such as the *PF* or the average safety factor. If the value is not stable in convergence graph, the number of samples needs to be increased. As shown in Fig.12, the convergence of average safety factor and *PF* under normal condition are analyzed. It can be clearly found that two of them distribute symmetrically. In general, the safety factor of embankment is all greater than 1. What's more, the safety factor decreases first, then increases and finally gets stable at around 25 with increase of samples. The trend of embankment of *PF* increases at first, then decreases and finally stabilizes at around 32% with increase of samples. It shows that the embankment has a good stability without external influence.

Fig. 12 Convergence graph of average safety factor and probability of failure of normal embankment

The convergence graph can be used to determine whether the probability analysis converges to a final answer and whether more samples are needed. As shown in Fig.12 and 13, the safety factors of embankment no longer fluctuate significantly after reaching a steady state when the number of samples is around 200. After reaching an all-time high, they decrease and eventually reach a steady state. The safety factor of the embankment after freeze-thaw cycles reaches its peak earlier, and the subsequent variation is not very obvious. The safety factor of embankment affected by acid or alkaline solution increases with increase of the number of samples and is greater than 1. This means that the embankment affected by acid or alkaline solution is more stable than that subjected to the freeze-thaw cycles.

Fig. 13 Convergence graph of safety factor of embankment under different conditions

Fig. 14 Convergence graph of *PF* of embankment under freeze-thaw cycles

It can be found in Fig.12 and 14 that the *PF* of normal embankment starts from 0 and increases first and then decreases with increase of sampling, and finally reaches a steady state at about 33%. After the freeze-thaw cycle, the *PF* of embankment, on the other hand, starts to decrease from 100% and then stabilizes at 96%.

Therefore, the influence of freeze-thaw cycle on the stability of embankment of backfilled roadbed affected by chemical solution can’t be ignored. It should be noted that the analysis of stability did not take the infiltration and erosion of water into consideration. The impact will only be improved in the case of analysis of the final state. Although the pH value of the rainfall is somewhat different from the solution used in the test, the impact of the long-term rainfall on the roadbed can’t be ignored.

5. Conclusion

In order to study the effect of chemical solution on stability of loess embankment in seasonally frozen regions, indoor compression test and strength test were used to investigate the remodeled and undisturbed loess treated by chemical solution after freeze-thaw cycle. The stability of embankment after the change of soil properties was simulated by the limit equilibrium method. The following conclusions are obtained:

1) The collapsible coefficient of remolded loess after treatment with chemical solution will increase. After freeze-

thaw cycle, the collapsible coefficient of soil samples without treated and treated with acidic solution will continue to increase, and the collapsible coefficient of soil sample treated with alkaline solution will decrease slightly.

2) The compression of the soil sample treated with chemical solution increases slightly then decreases with the increase of the molar concentration of solution when it is less than 800 kPa. When the pressure is greater than 800 kPa, the compression increases rapidly, and it increases with increase of molar concentration of solution. The soil untreated has a small constrained modulus at pressures less than 800 kPa and gradually reaches maximum as pressure increases.

3) Without considering the infiltration of water, chemical solution will increase the safety factor of the embankment. In areas where the embankment is unstable, due to long-term freeze-thaw cycles, it is conceivable to use chemical solution to improve the stability of the embankment of backfilling.

Acknowledgements

The research is supported by the National Natural Science Foundation of China (No. 51608436, No. 42071083), Shaanxi Natural Science Foundation (2019JQ756), Special Scientific Research Project of Shaanxi Education Department (19JK0452) and China Postdoctoral Science Foundation (2019M663648).

Conflict of Interest:

The authors declare that they have no conflict of interest.

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Figures

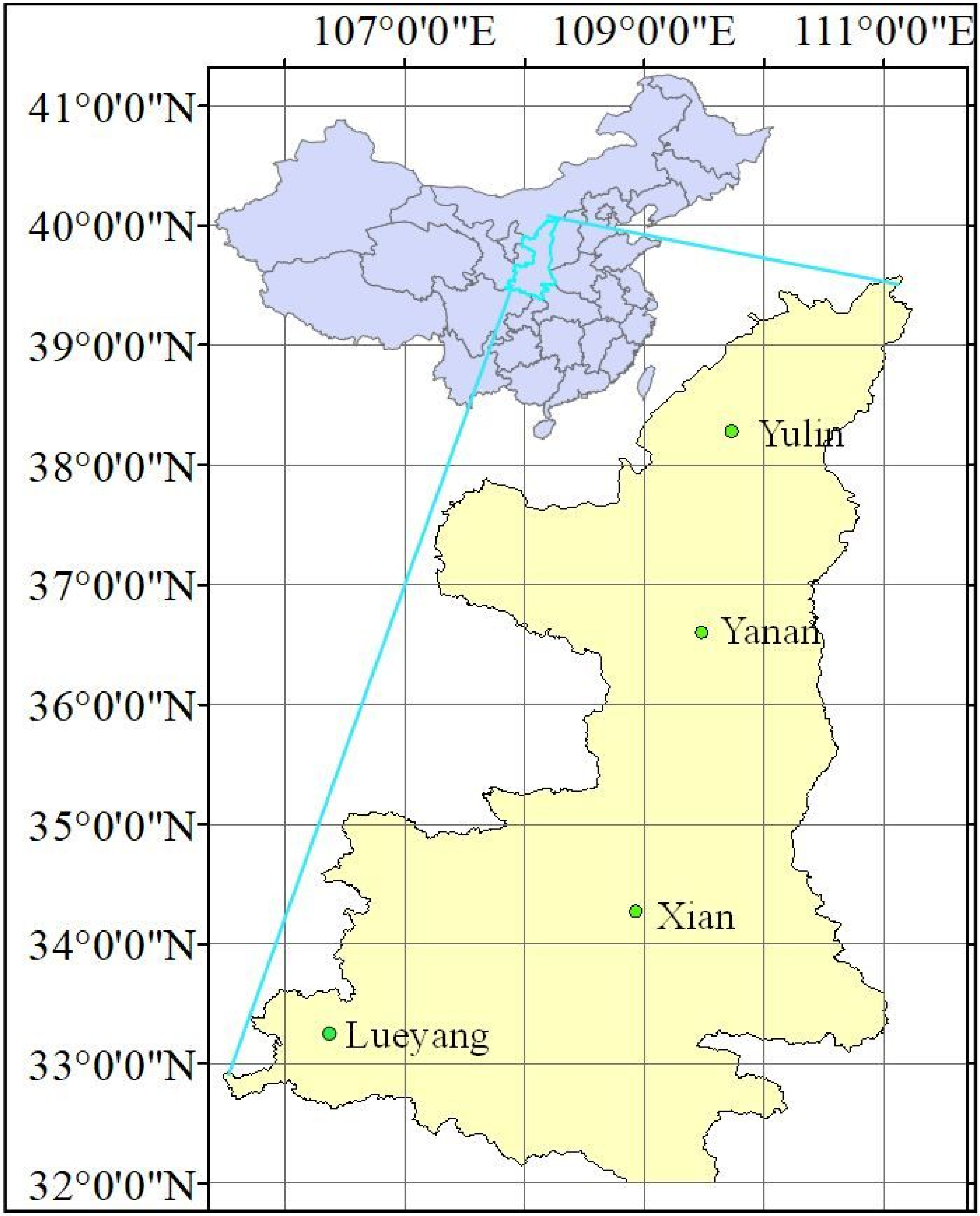

Figure 1

A map for the survey area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

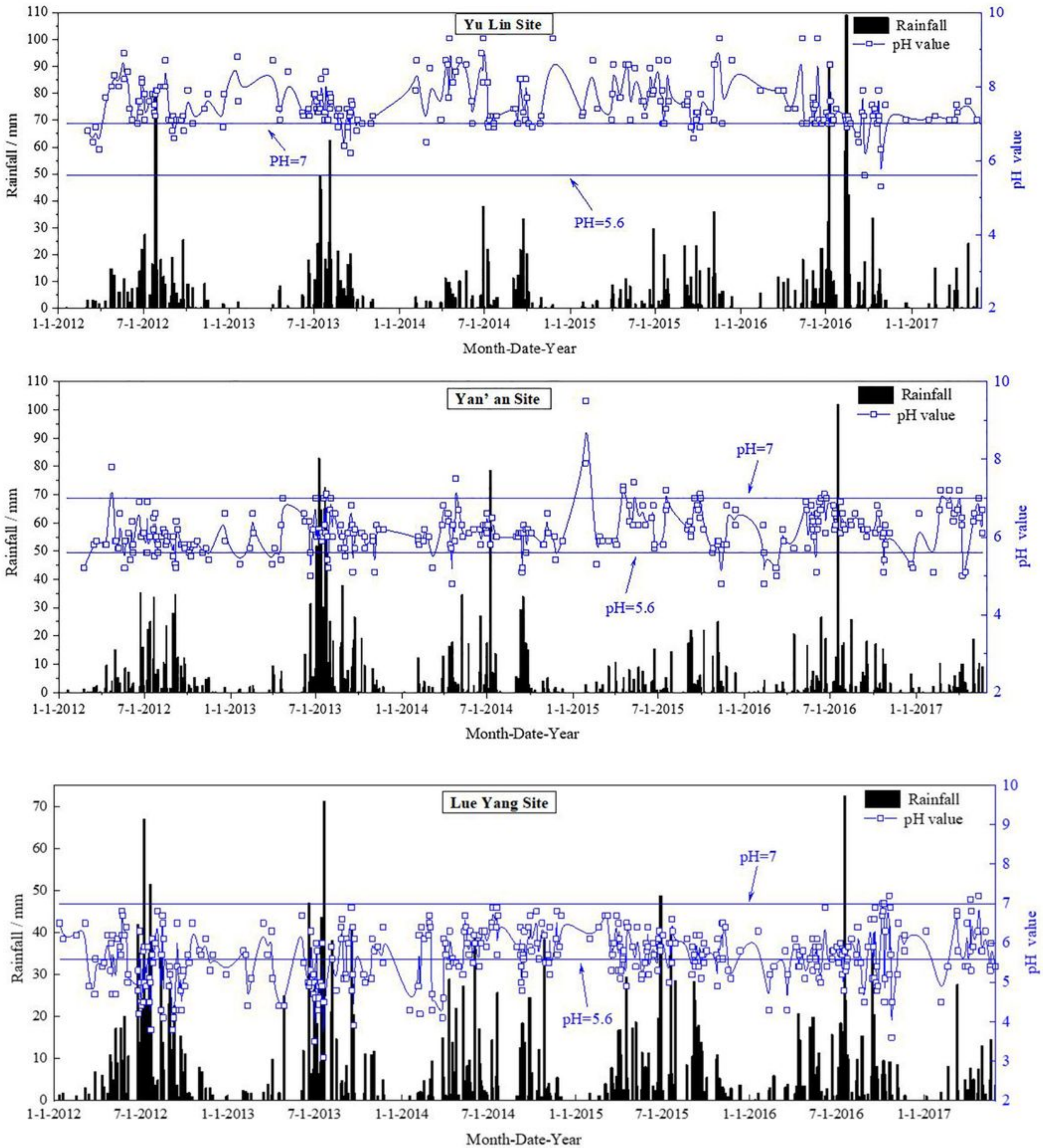

Figure 2

Rainfall and its pH value of typical areas in Shaanxi Province in 2012-2017

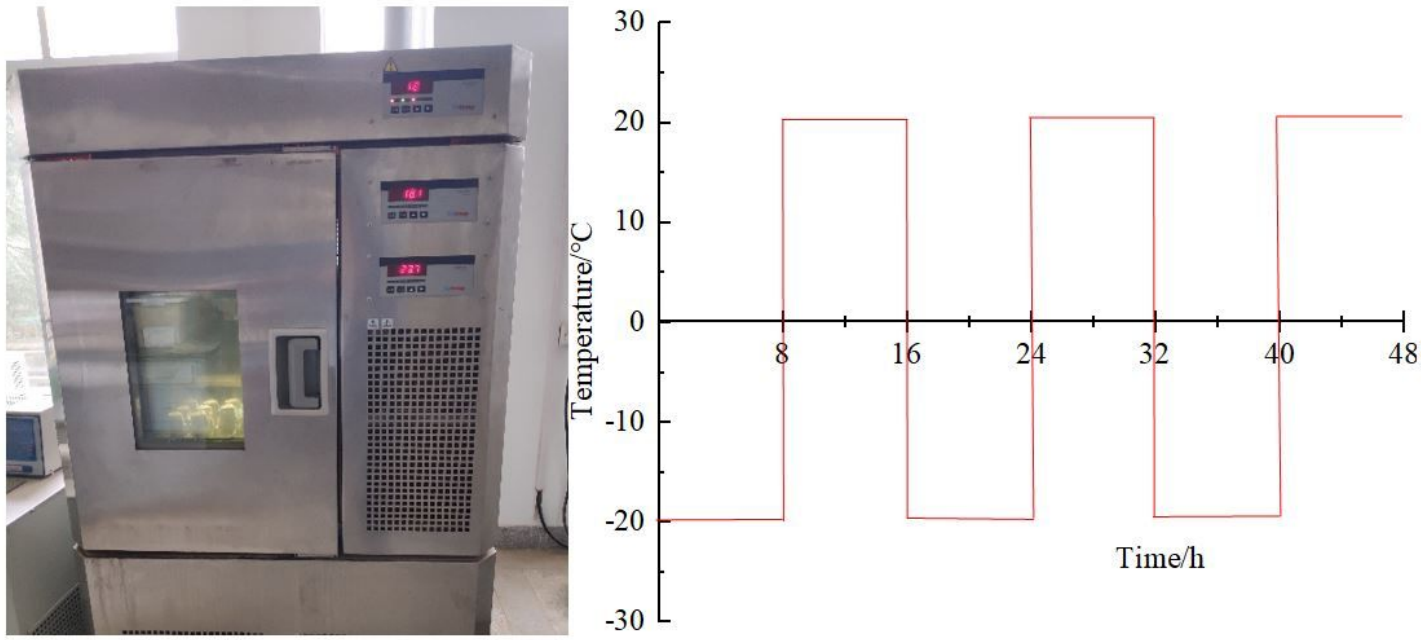

Figure 3

Temperature change in the temperature test chamber

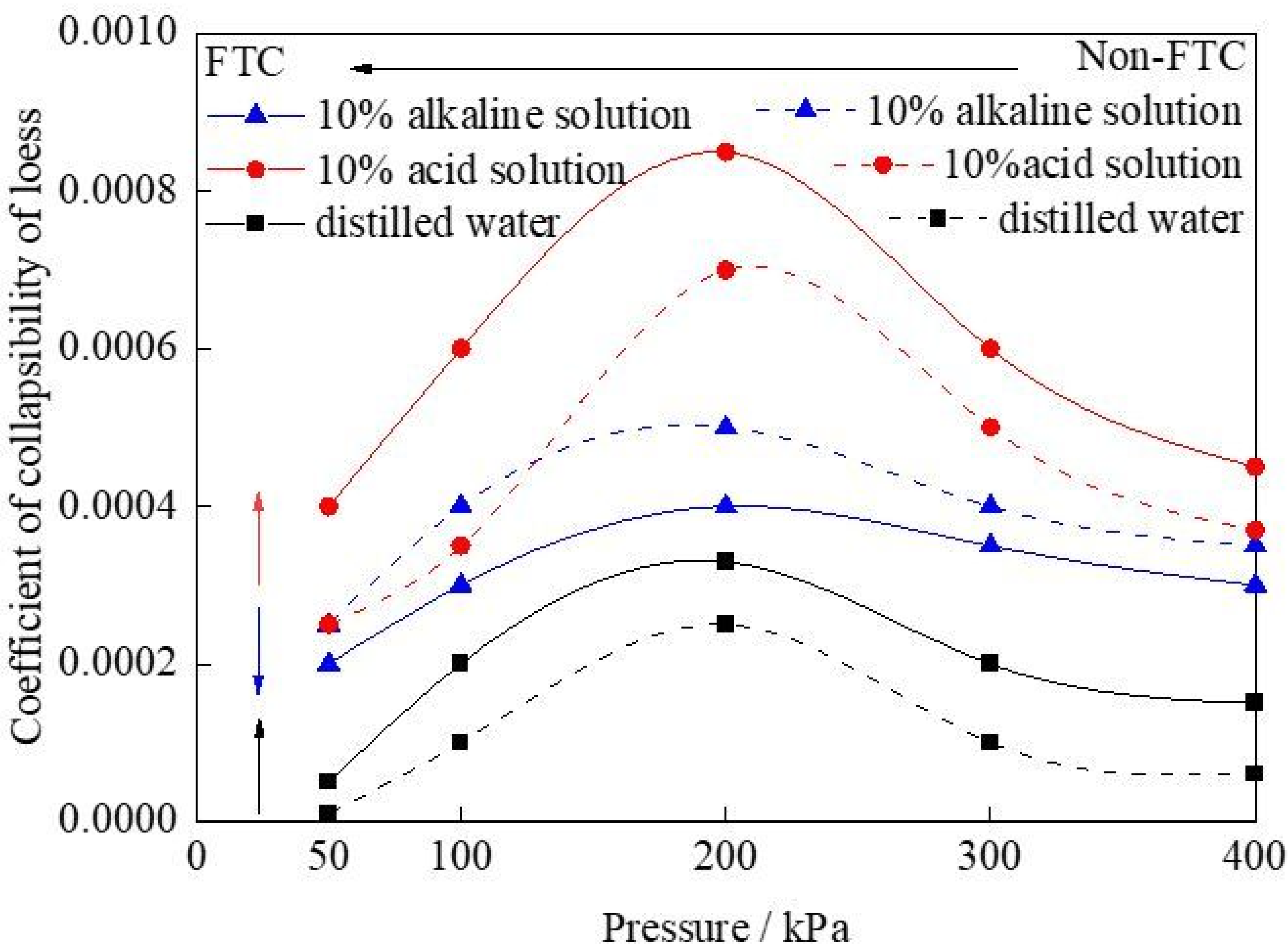

Figure 4

Collapsible coefficient of remolded loess under different conditions

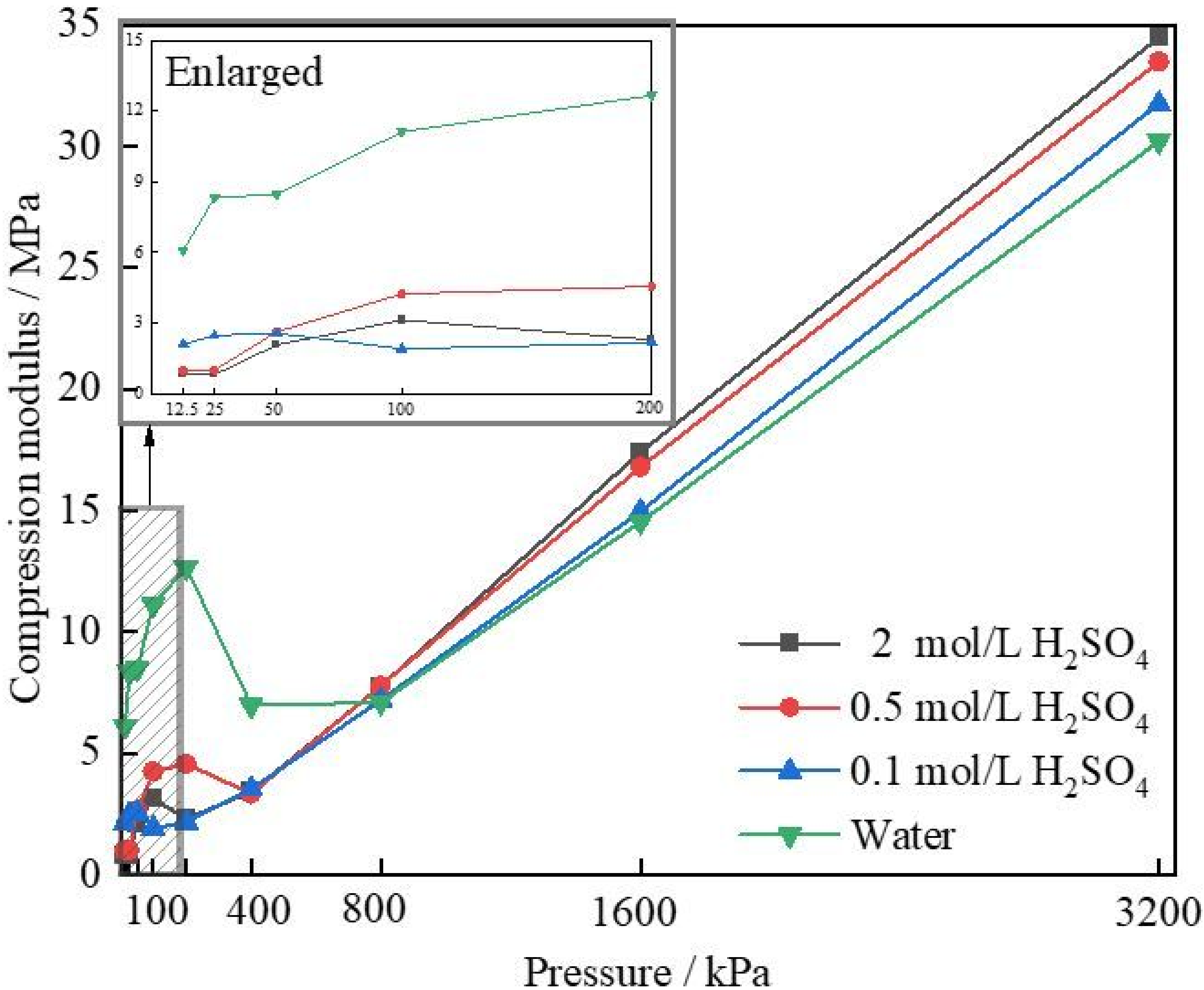

Figure 5

Constrained modulus of soil treated with H2SO4 solution

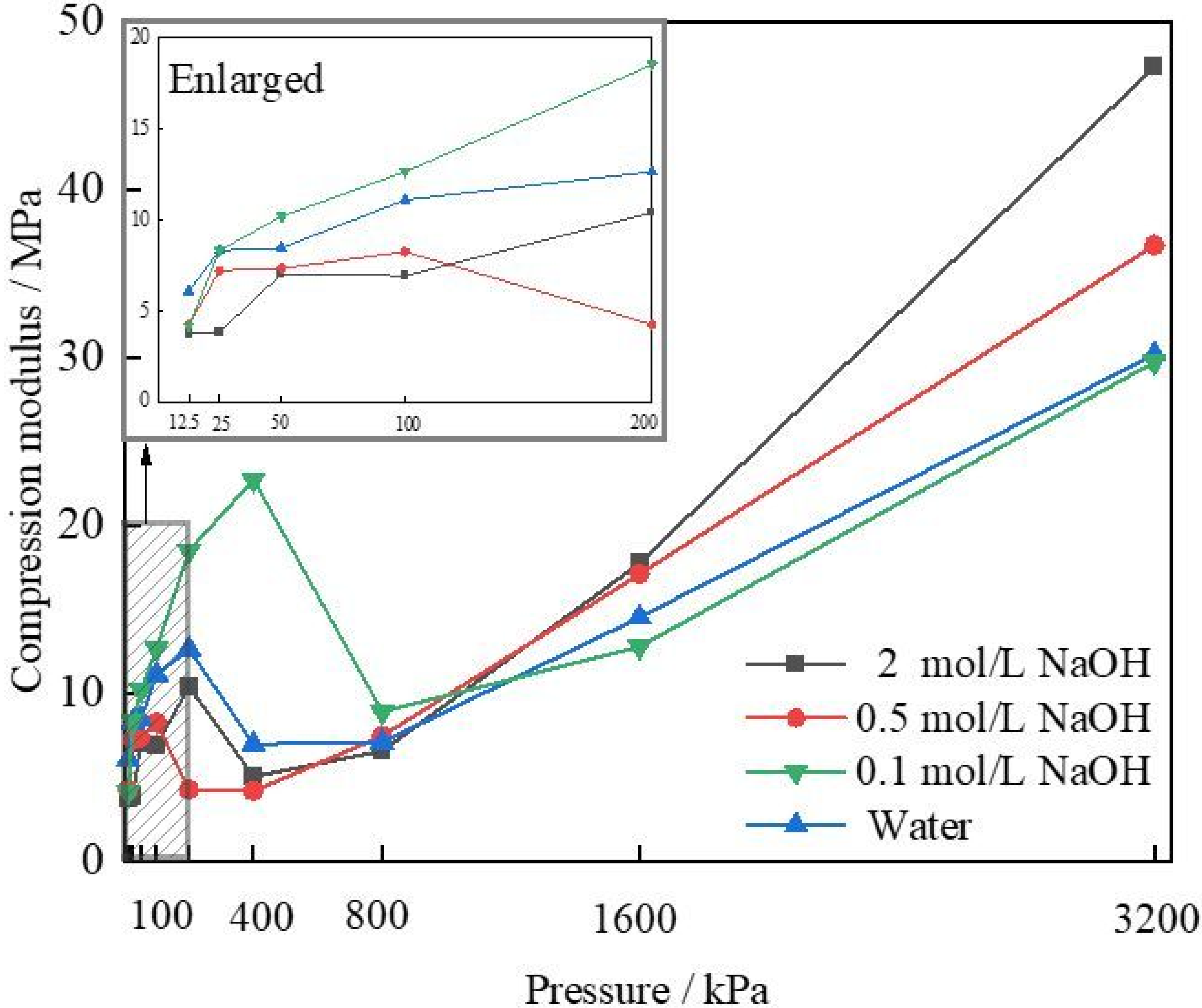

Figure 6

Constrained modulus of soil treated with NaOH solution

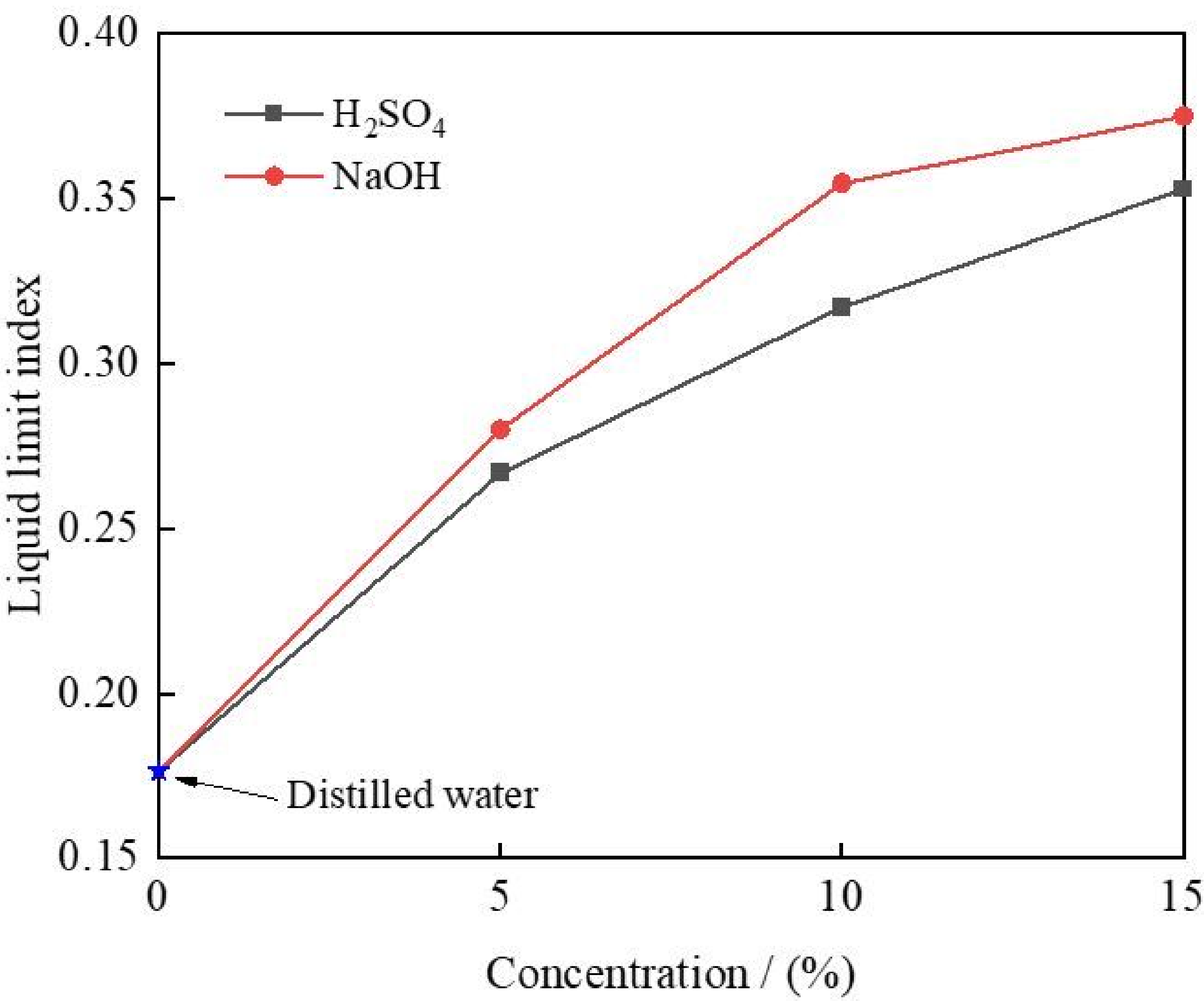

Figure 7

Relationship between liquidity index and concentration of solution

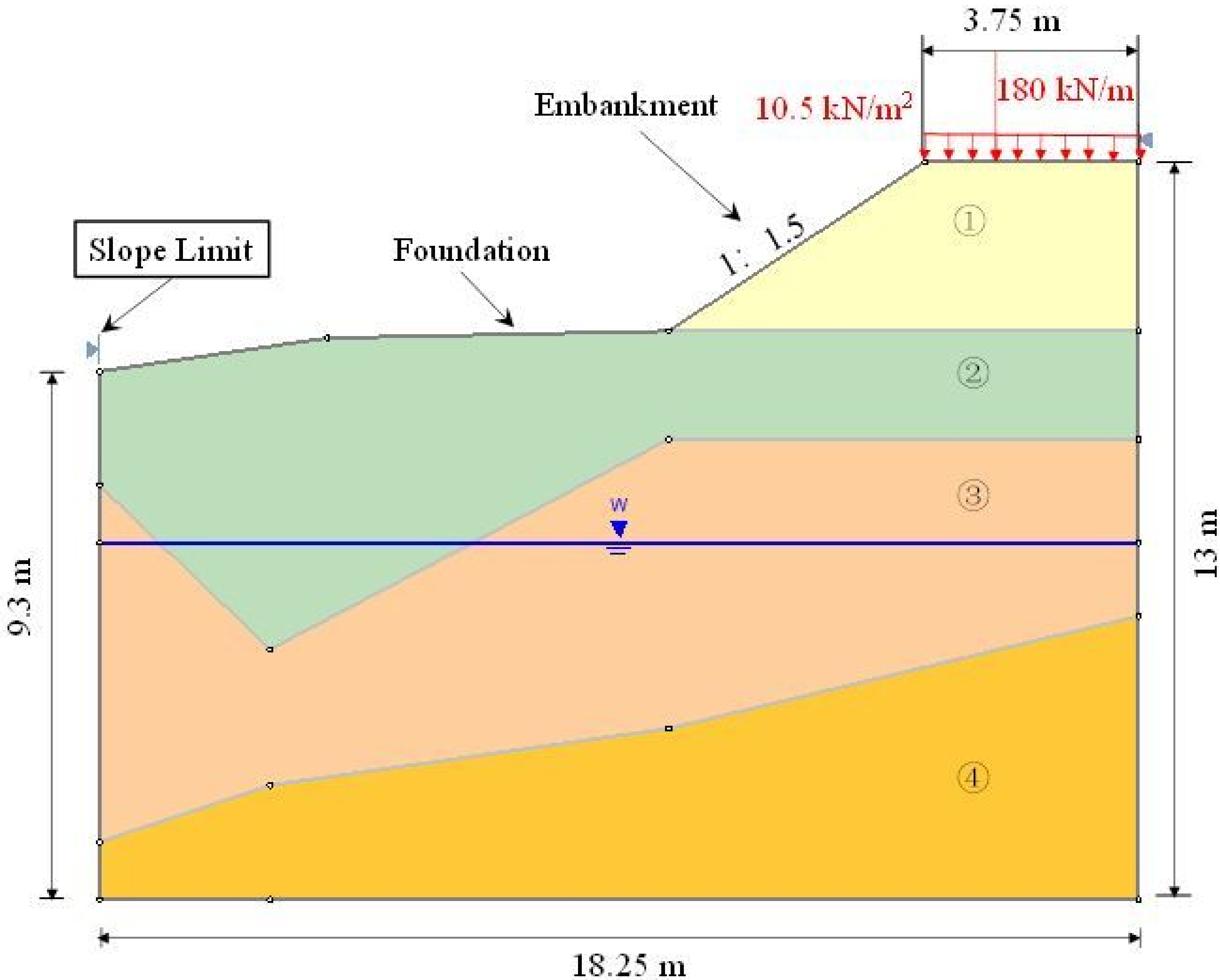

Figure 8

The simulation model of loess embankment

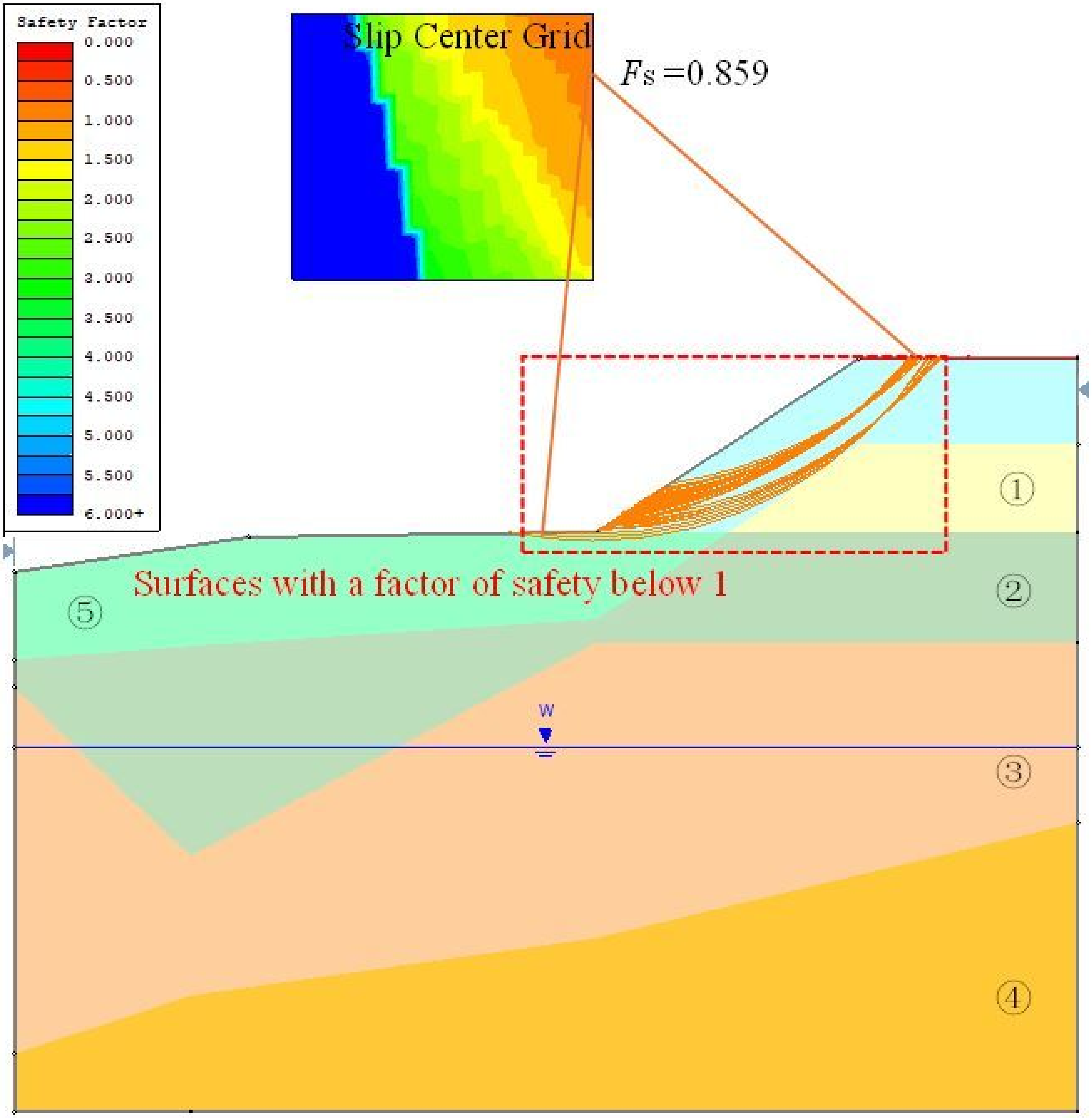

Figure 9

Safety factor of embankment after freeze-thaw cycle

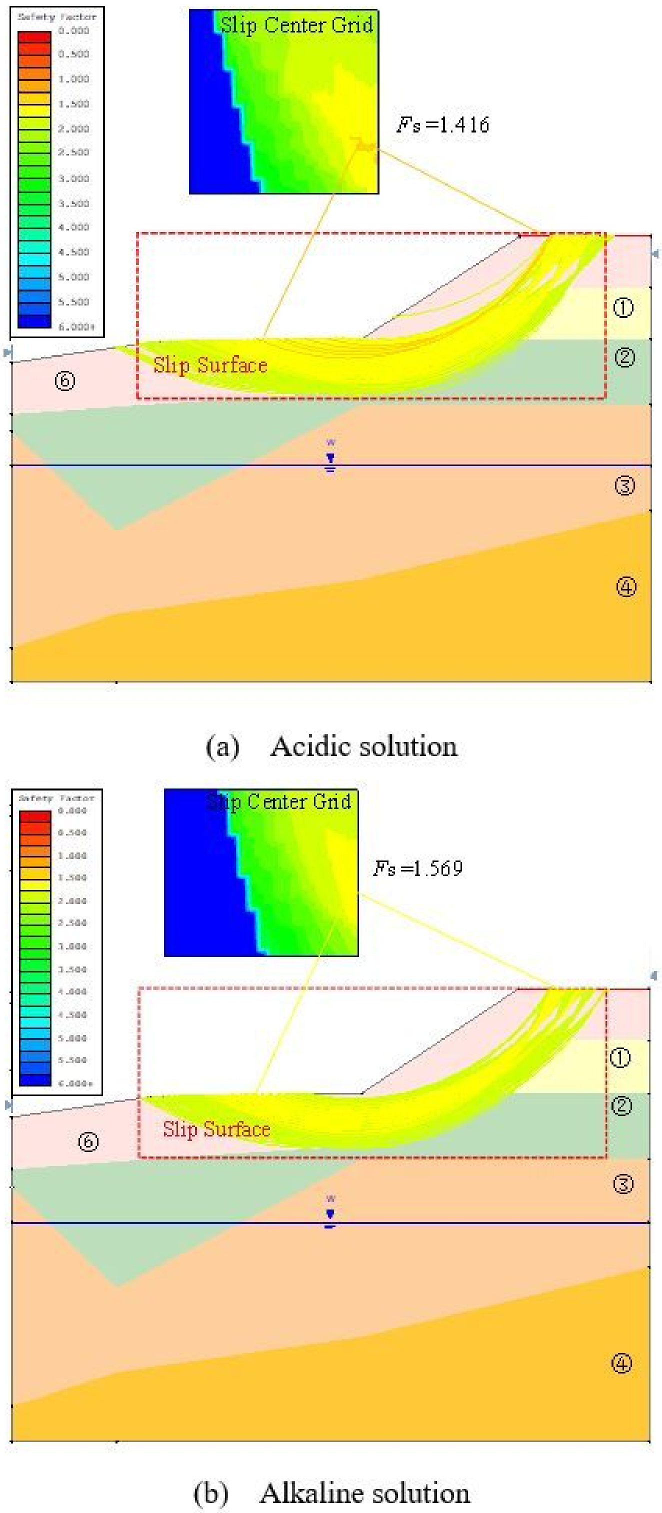

Figure 10

Simulating slope safety factor after pollution (a) Acidic solution (b) Alkaline solution

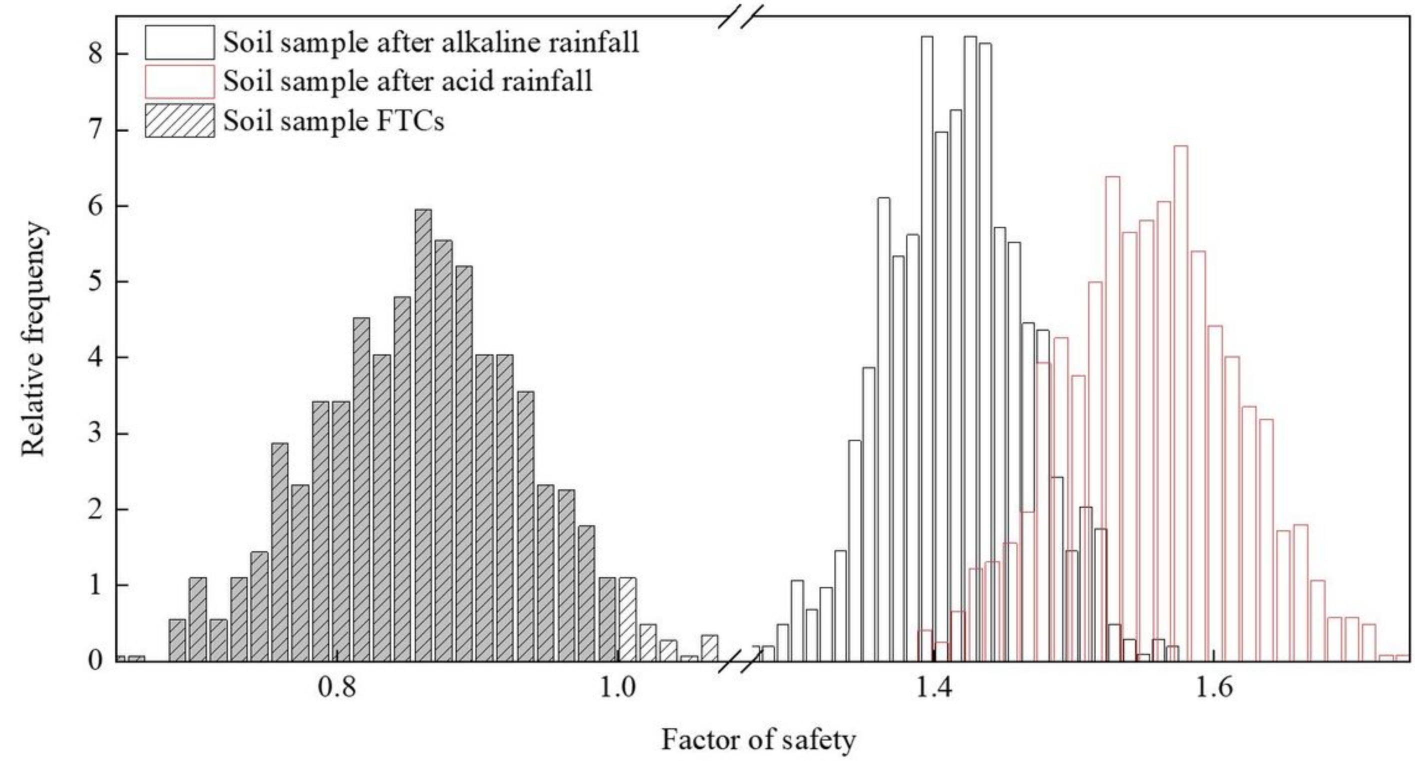

Figure 11

The safety factor and its relative frequency in different conditions

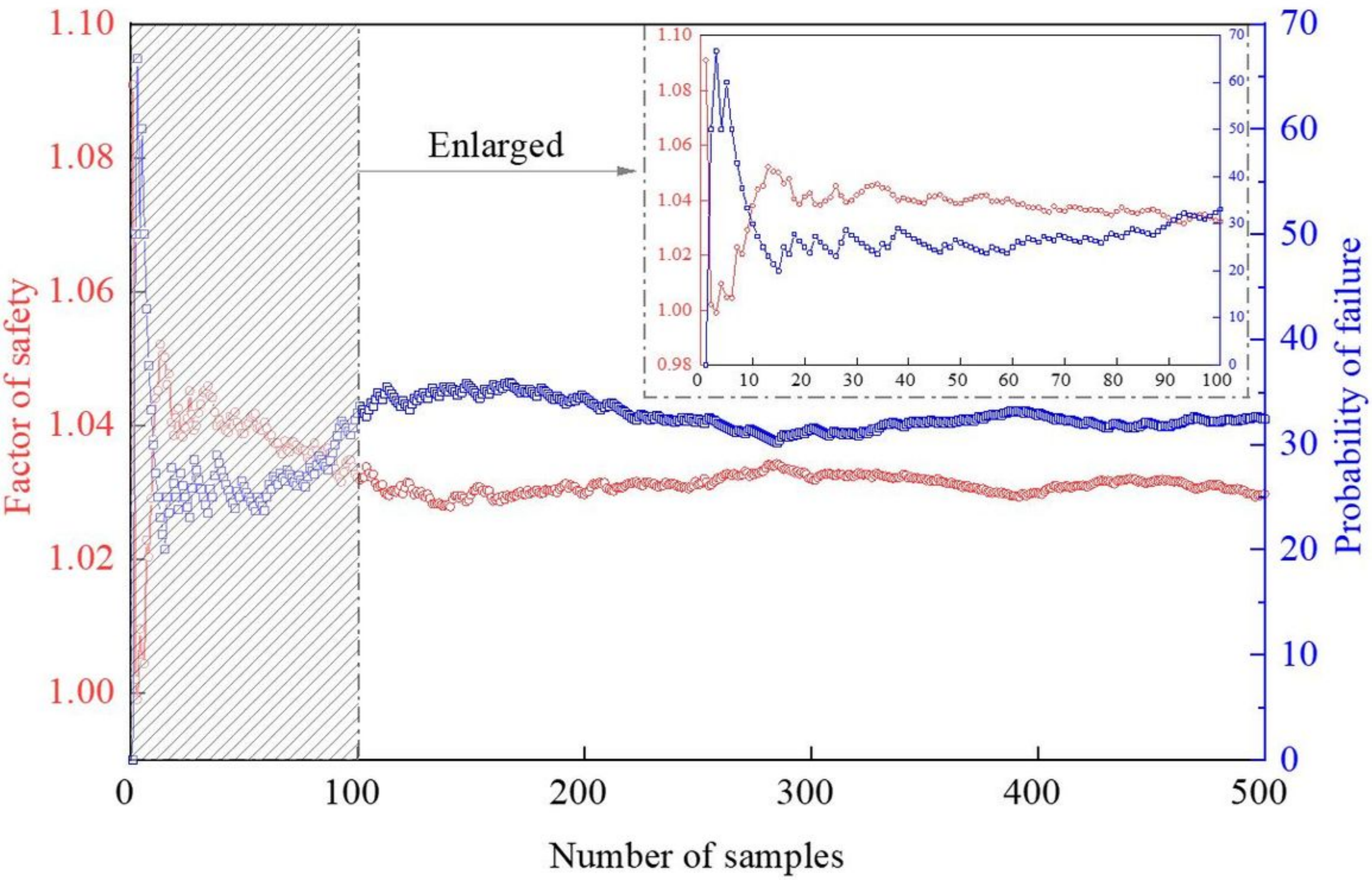

Figure 12

Convergence graph of average safety factor and probability of failure of normal embankment

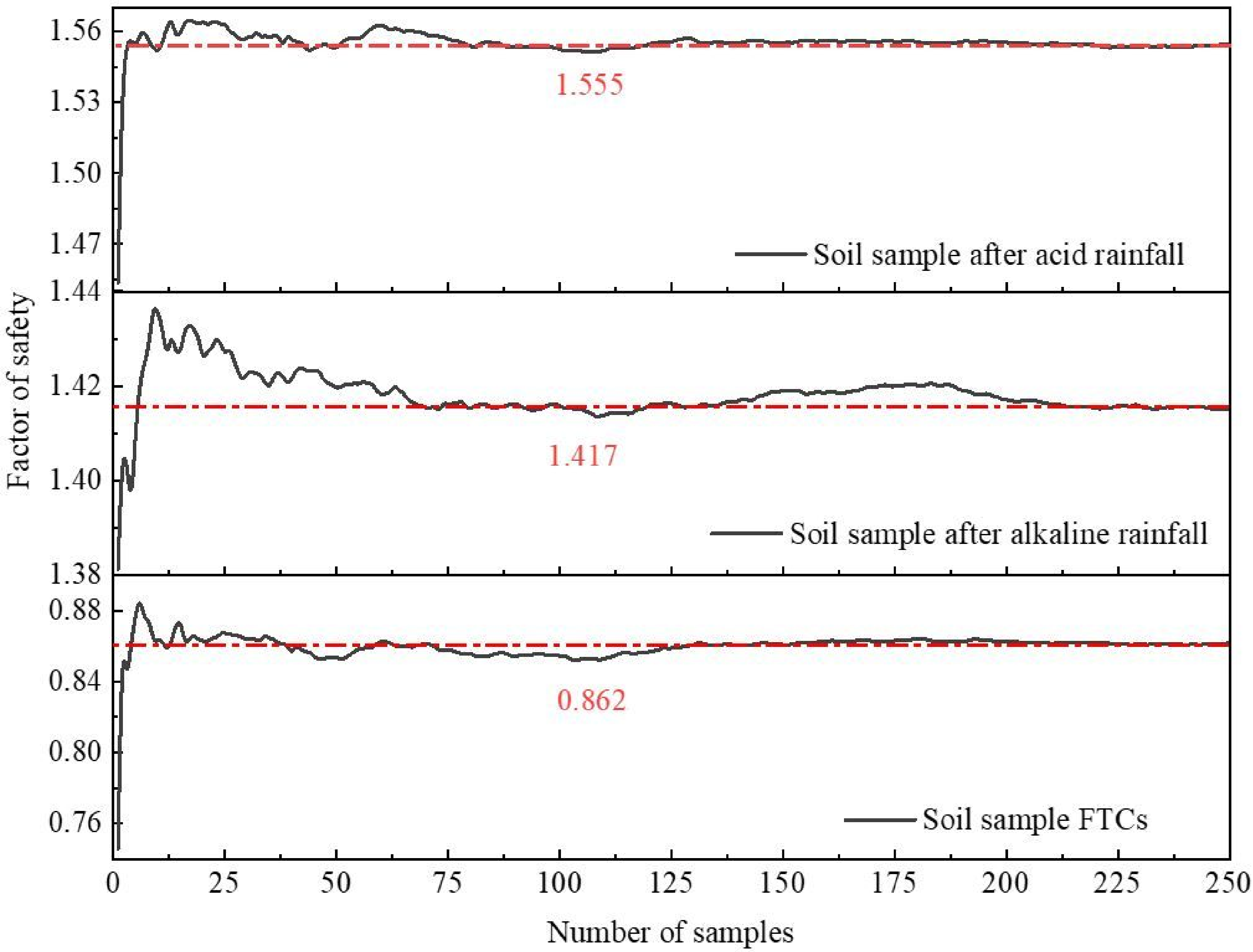

Figure 13

Convergence graph of safety factor of embankment under different conditions

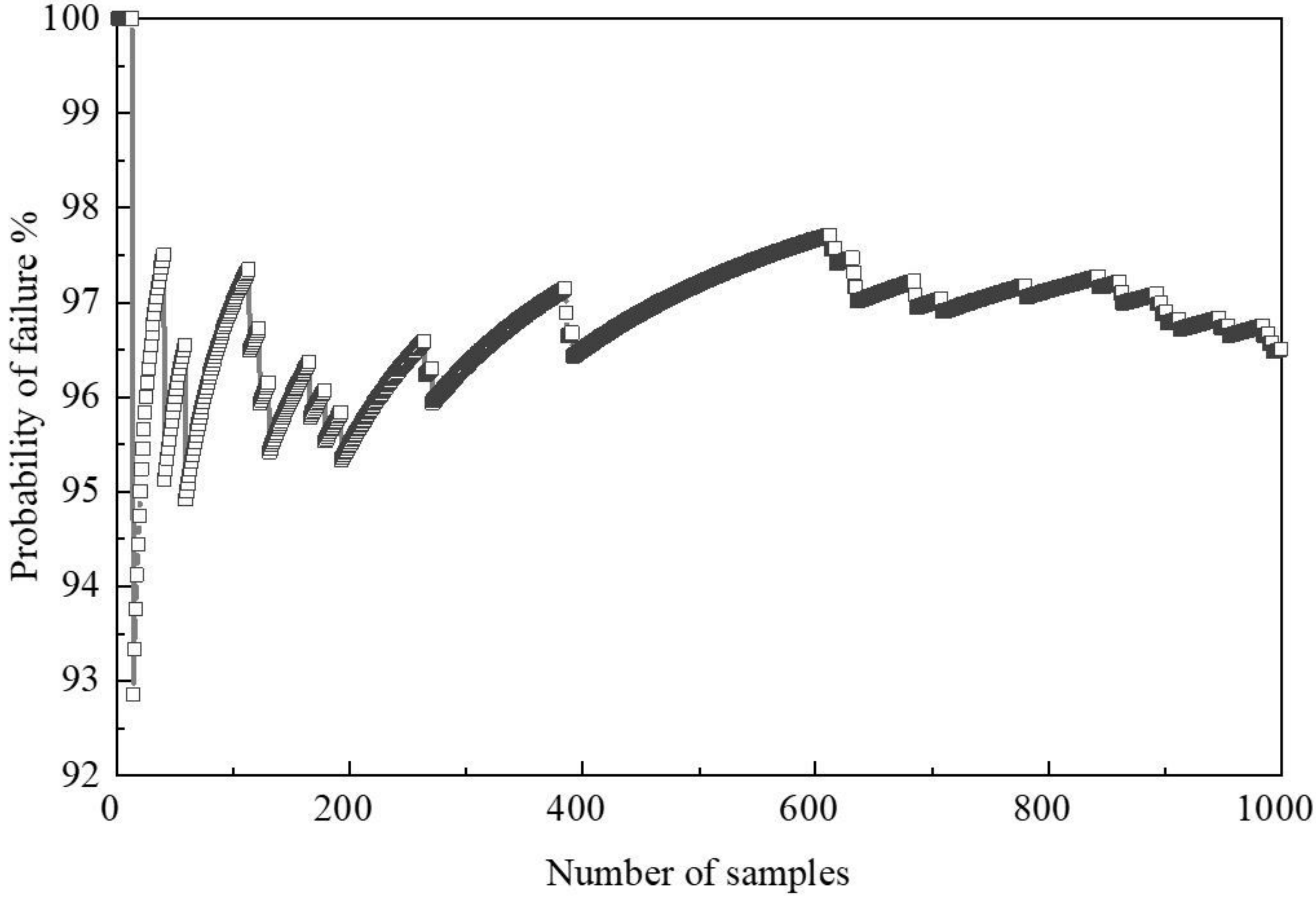

Figure 14

Convergence graph of PF of embankment under freeze-thaw cycles