Research Article
Evaluation of Loess Collapsibility Based on Random Field Theory in Xi’an, China

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The engineering properties of collapsible loess have significant uncertainty. Accurate prediction of collapsible deformation is crucial for the safety of engineering construction in loess areas. Taking the typical collapsible loess stratum as the research object in Xi’an, based on the random field theory, combined with the Monte Carlo strategy and modulus reduction method, the stochastic finite element analysis of loess self-weight collapsibility is carried out to study the influence of the spatial variability of compression modulus on the self-weight collapsibility of loess. The results show that the loess tends to be stratified and average along the depth direction with the increase of transverse correlation distance. The random field result of self-weight collapsibility considering the spatial variability of compression modulus is significantly greater than the deterministic result of layered average and the calculated value of loess code. Considering the low compression modulus dominance effect of compression modulus with positive skewed distribution of random field, the equivalent characteristic value of the compression modulus calculated by the layered average modeling for the collapsibility evaluation of typical loess strata in Xi’an area is proposed.

1. Introduction

Loess is a kind of porous, underconsolidated, and friable sediments formed in the Quaternary period. Despite being generally distributed worldwide, China takes the largest portion by owning the largest Loess Plateau and Loess Plain in the world [1, 2]. These two combined account for 7% of the land territory of China [3, 4]. Under conditions of additional loading and, or wetting, it will collapse [5, 6]. This severe collapsibility results in costly and potentially dangerous problems of hydroconsolidation and engineering geological disasters [7–9].

Currently, there are two types of tests used to determine the collapsibility of loess sites and foundations [10]. One test is the oedometer test (indoor test). The other test is the field immersion test (field test). However, the results of indoor tests are not consistent with those of field tests for the same loess site compared to indoor and field test results of loess sites in China. There is a large difference between the collapse value under overburden pressure obtained in the indoor test and that obtained in the field for the same site [11]. There is still a large difference between the values of loess collapsibility calculated from the recommended formula of the current code and the actual values [12], and the relationship between the two values for a given site is uncertain. The collapsibility evaluation of loess developed within the collapsibility theory framework of traditional saturated loess cannot meet the requirements of current engineering construction [12].

In the long geological time, the soil has experienced long-term and multicycle geological processes, which makes the soil parameters have significant spatial variability. In the past, loess collapsibility was basically evaluated as homogeneous material, and soil parameters were stratified and averaged along the depth direction, ignoring the spatial uncertainty of soil parameters.

Based on the concept of spatial variability proposed by Vanmarcke [13] and Lumb [14], the spatial variability...
random field model of rock and soil mass is established. Based on a large number of indoor experiments, field tests, and literature, a modified Bartlett’s test was proposed \cite{15,16}. In recent years, more attention has been paid to the spatial variability of soil parameters in geotechnical engineering. With the help of this random field model, relevant scholars have studied the influence of shield tunnel surface deformation \cite{17,18}, excavation surface stability \cite{19}, foundation settlement and liquefaction \cite{20,21}, slope stability \cite{22–24}, and other problems. The research results show that there is a great difference between random field theory and random variable theory. Most of the research results are based on finite element method simulation. The computation is very time consuming when the model dimension is very large. The modified finite element method can improve the simulation efficiency \cite{25,26}, and it may be able to provide effective guidance for relevant calculation.

At present, studies on loess collapsibility are based on stratified average random variable theory without considering the spatial correlation and variability of loess soil property distribution. Therefore, based on the random field theory and Cholesky decomposition method, Monte Carlo simulation was used to analyze the randomness of loess dead weight subsidence based on typical collapsible loess strata in Xi’an, China and to study the influence of spatial variability of compression modulus on deadweight subsidence. The relation between the indeterminate results of spatial variability of soil parameters and the deterministic results of stratified average is established, and the equivalent characteristic value of compression modulus calculated by stratified average modeling is proposed for evaluating the collapsibility of typical loess strata in Xi’an.

2. Random Field Theory

For natural loess, the values of the compression modulus are shown in Table 1. Since the compressive modulus \(S(P_i)\) is non-negative, as shown in Figure 1, its logarithmic value basically conforms to the normal distribution. According to the S-W (Shapiro–Wilk) test, the \(P\) value is 0.153, which is greater than 0.050, accepting the null hypothesis of the log-normal distribution of the compressive modulus.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Water content (%)</th>
<th>Unit weight (kN/m³)</th>
<th>Void ratio</th>
<th>Cohesion (kPa)</th>
<th>Friction angle (°)</th>
<th>Compression modulus (MPa)</th>
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<td>0.967</td>
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<td>17.4</td>
<td>0.921</td>
<td>14.78</td>
<td>62</td>
<td>21.28</td>
</tr>
</tbody>
</table>
As shown in Figure 2, random field theory is used to simulate the variability of the spatial distribution of compression modulus \( S(P_i) \). The autocorrelation function of the logarithm of compression modulus \( \ln(S(P_i)) \) and \( \ln(S(P_j)) \) at any two points \( P_i \) and \( P_j \) in the soil layer is as follows:

\[
R_{jk}(\tau_x, \tau_z) = \exp \left[ -2 \left( \frac{\tau_x}{\delta_x} + \frac{\tau_z}{\delta_z} \right) \right],
\]

(1)

where \( \tau_x \) and \( \tau_z \) are the horizontal and vertical spacing of \( P_j \) and \( P_k \), respectively. \( \delta_x \) and \( \delta_z \) are the horizontal and vertical correlation distances of compression modulus, respectively.

Since the random finite element modeling method is adopted in this paper, the Cholesky decomposition method has good adaptability to the generation of anisotropic random fields and can realize one-to-one mapping between discrete values of random fields' compression modulus and numerical model elements. Therefore, this paper adopts the Cholesky decomposition method as the discrete method of the random field model of compression modulus.

According to the basic idea of constructing a probabilistic process, random sampling, and establishing an estimator of the Monte Carlo method, the statistical results of the random field considering the spatial variability of the compression modulus can be considered as the unbiased estimator of the loess wetting under a sufficient number of model tests.

3. Evaluation of Loess Collapsibility considering Spatial Variability of Soil Parameters

3.1. Engineering Geology Overview. In this paper, the typical collapsible loess strata in Xi'an area is taken as the research object. Four exploratory wells are manually excavated with excavation depth of 24.5 m, 26.2 m, 25.0 m, and 24.5 m, respectively. The sampling interval of geotechnical test is 1 m. Engineering properties of each soil layer are as follows:

(i) \( Q_4 \) cultivated soil: dark brown in color, slightly wet, with a large number of plant roots. The soil bottom depth is 0.20–0.30 m, with an average of 0.28 m. The soil thickness is 0.30 m.

(ii) \( Q_4 \) black loessial soil: brown in color, hard plastic, block-like structure, and well-developed pores. The bottom depth of soil layer is 0.80–1.20 m, with an average of 1.05 m. The soil thickness is 0.60–0.90 m, with an average of 0.78 m.

(iii) \( Q_3 \) neo-loess: brownish-yellow in color, loose, mainly cohesive soil, with well-developed pores. The depth of soil bottom is 7.60–8.70 m, with an average value of 8.13 m. The thickness of the soil layer is 6.60–7.50 m, with an average value of 7.08 m.

(iv) \( Q_2 \) fossil soil: brown-red in color, hard plastic, with well-developed needle-like pores. The depth of soil bottom is 10.60–11.60 m, with an average value of 11.33 m. The thickness of the soil layer is 2.90–3.80 m, with an average value of 3.2 m.

(v) \( Q_1 \) old loess: the color is yellowish-brown, plastic, needle-shaped pores are developed, and the soil quality is uniform. The depth of soil bottom is 19.60–21.50 m, with an average value of 20.73 m. The thickness of the soil layer is 8.70–10.00 m, with an average value of 9.40 m.

(vi) \( Q_1 \) fossil soil: brownish-red in color, hard plastic, and a block structure. The depth of soil bottom is 24.80–26.20 m, with an average of 25.25 m. The thickness of the soil layer is 3.30–5.40 m, with an average of 4.53 m.

3.2. Self-Weight Collapse Deformation Calculation Method per GB 50025-2018. The self-weight collapsibility coefficient is determined using (2), per PRC MOHURD, with code for building construction in collapsible loess regions, GB 50025-2018 [10]:

\[
\delta_{zs} = \frac{h_z - h'_z}{h_0},
\]

(2)

where \( \delta_{zs} \) is the self-weight collapsibility coefficient of the loess, and \( h_z \) is the specimen height after the sample was loaded to its self-weight in mm. \( h'_z \) is the specimen height when it was saturated after the sample was loaded to its self-weight in mm. \( h_0 \) is the initial specimen height in mm.

When \( \delta_{zs} \) is greater than 0.015, it is defined as self-weight collapse loess, and when \( \delta_{zs} \) is less than 0.015, it is defined as nonself-weight collapse loess.

The meaning of \( \delta_{zs} \) is the same as that of the collapse potential \( I_c \) [27], and their calculation methods are basically the same, except that the result of \( \delta_{zs} \) is expressed as a decimal number, while that of \( I_c \) is expressed as a percentage.

According to the \( \delta_{zs} \) of every loess layer in the actual site obtained, the amount of self-weight collapse deformation is calculated using

\[
\Delta_{zs} = \sum_{i=1}^{n} \delta_{zs_i} h_i,
\]

(3)

where \( \delta_{zs} \) is the self-weight collapsibility coefficient of every loess layer at different depths, \( h_i \) is the thickness of the \( i \)th layer soil, and \( \Delta_{zs} \) is the self-weight collapse deformation.
3.3 Compression Modulus Random Field Model. Let $\delta_r = n \cdot \delta_z$ ($n = 1, 10, 20, 60, 100, 1000$), respectively, $n$ is the horizontal and vertical correlation distance ratio; with the increase of the ratio $n$, the simulated value of the random field of the compressive modulus changes more and more smoothly along the horizontal direction, and the same-color areas increase, and the soil layer tends to be uniform. Moreover, with the variability of compression modulus, each soil layer decreases gradually with the increase of $n$.

The results of random field simulation of compression modulus are shown in Figure 3. As shown in Figure 3(f), when $n = 1000$, it can be considered that the lateral correlation distance is sufficiently large compared with the site range, and there is a significant autocorrelation between the random field simulation values of the compressive modulus in each soil layer at different depths. It can also be seen from the figure that the simulated value of compressive modulus has been obviously layered and averaged in the depth direction, and no longer has spatial variability. At this time, it degenerates into a random variable and considers that the soil is stratified evenly along the depth direction, and the soil parameter compression modulus is simulated as a random variable. The sampling distribution has nothing to do with the spatial position of the soil sample, and there is no difference in sampling at any point within the depth layer. Sampling at any position in the same depth layer can be

![Figure 3: Random field simulation results of compression modulus at different (n) (unit: MPa).](image-url)
regarded as an independent test sequence model of the stratification at that depth. It should be noted that each figure only shows the single simulation results of compression modulus in the random field, and the discrete parameter values of each unit have randomness that cannot be copied, but the overall trend of random field is roughly the same.

The lateral variation coefficient of compression modulus stratified by depth coordinate at different \( n \) values is shown in Figure 4. When \( n = (1, 5, 10, 15, 20, 30, 60, 80, 100, 1000) \), the average coefficient of variation of soil compression modulus = (31%, 28%, 24%, 25%, 21%, 19%, 16%, 14%, 10%, 2%). It can be seen that with the increase of \( n \), the compression modulus variability of each soil layer decreases gradually, and there is a nonlinear negative correlation between them. However, the coefficient of variation at smaller depths (depth \( \leq 5 \) m) is relatively large, and even when \( n = 60, 80, \) and 100, it can still reach 20% and above. Until \( n = 1000 \), the surface coefficient of variation is less than 5%, which can be considered as close to no variation. The reason is that the average value of the random field depth of the compressive modulus is relatively small, and a tiny disturbance will have a greater impact on the coefficient of variation, and when \( n \) is large enough, each point loess in the horizontal range almost completes autocorrelation so that the compressive moduli of each point tend to be nearly identical, and the variation coefficient is no longer disturbed by the smaller mean value.

3.4. Numerical Calculation Model. This paper combines the random field model and ABAQUS finite element software to carry out the random finite element analysis of loess self-weight collapse. As shown in Figures 5 and 6, the size of the site in the model is 70 m (long) \( \times 70 \) m (wide) \( \times 30 \) m (high), and the collapsible area is a square grid with a diameter of 25 m at the upper bottom, 55 m in diameter at the lower base, and a height of 24 m. The total number of nodes is 163,904, and the total number of elements is 33,687. The site model is linear hexahedral element C3D8R for the non-collapsible area and linear tetrahedral element C3D4 for the collapsible area.

The XZ plane is considered to generate \( 30 \times 30 \) random values of compression modulus using Cholesky decomposition. A one-to-one element mapping of the generated 900 parameters to the ABAQUS finite element model mesh is established. The random field model is converted into a numerical simulation and analysis model. The XY direction displacements are constrained around the site, and the XYZ displacements are constrained at the bottom.

Loess compressive modulus has a very important influence on the self-weight collapse of loess, so this paper mainly considers the spatial variability of the compressive modulus, and the values of other physical and mechanical properties are shown in Table 1.

The stochastic finite element modeling and analysis process of loess self-weight collapse is as follows:

1. The Cholesky decomposition method is used to generate a random field model of uncertainty compressive modulus.
2. Establish a one-to-one element mapping between the random field model and the finite element model grid, and convert the random field model into a numerical simulation analysis model.
3. By means of the Monte Carlo simulation of probability analysis, repeat steps (1) and (2), and combine the modulus reduction method to establish a finite element model of loess self-weight collapse, and conduct stochastic analysis of loess self-weight collapse. The self-weight collapsibility of each random finite

Figure 4: Variation coefficient of compression modulus with different \( n \) and different depth.

Figure 5: Geometric model.
element model is extracted, and the collapsibility evaluation of loess considering the spatial variability of soil parameters is carried out.

4. Result Analysis

The lateral correlation distance of loess soil parameters is mostly greater than 25 m [28], and the depthward correlation distance of compressive modulus is 2.05 m. Therefore, let \( n = 15 \); that is, the horizontal correlation distance is 15 times of the vertical correlation distance, and 100 groups of random field discrete values are generated. The variation of the average compressive modulus with the number of simulations is shown in Figure 7. It can be seen from Figure 7 that when the number of simulations is greater than or equal to 80 times, the average compressive modulus no longer changes drastically and basically oscillates slightly up and down around a constant. The variation range is (14.20, 14.25), and the variation range is (−0.09%, 0.09%), approaching convergence.

Therefore, 100 groups of compressive modulus random field model samples are selected, and by modifying the inp format file, the discrete values of each group of compressive modulus parameters are imported into the finite element model, and the loess self-weight collapse finite element model is established based on the modulus reduction method for numerical simulation calculation. Figure 8 shows the average value of self-weight collapsibility at the center point, \( X = −12.5 \) m, \( X = 12.5 \) m, \( Y = −12.5 \) m, and \( Y = 12.5 \) m with the number of simulations. It can be seen from Figure 7 that when the number of simulations is greater than or equal to 90 times, the average value of self-weight collapsibility no longer changes drastically with the increase of the number of simulations and basically oscillates slightly up and down around a constant. The variation ranges at the center point, \( X = −12.5 \) m, \( X = 12.5 \) m, \( Y = −12.5 \) m, and \( Y = 12.5 \) m are (−0.11%, 0.23%), (−0.11%, 0.13%), (−0.21%, 0.18%), (−0.10%, 0.19%), and (−0.10%, 0.19%), and it can be seen that the 100-sample capacity has satisfied the convergence of the loess self-weight collapse calculation model.

The statistical results of the maximum self-weight collapsibility at the center points \( X = −12.5 \) m, \( X = 12.5 \) m, \( Y = −12.5 \) m, and \( Y = 12.5 \) m are shown in Figure 9. Black dots represent deterministic results of layered average maximum self-weight collapsibility without considering spatial variability of compressive modulus. The statistical characteristics are shown in Table 2. It can be seen from Figure 8 that the results of the maximum self-weight collapsibility at the five positions basically show a normal distribution, and the \( P \) values of S-W test are 0.344, 0.656, 0.317, 0.438, and 0.504, all of which are greater than 0.05, accept the null hypothesis that the maximum self-weight collapsibility follows a normal distribution. Compared with the maximum self-weight collapsibility of 176 mm, 138 mm, 145 mm, 141 mm, and 142 mm at the stratified average of five locations, the maximum self-weight collapsibility at the five points after considering the spatial variability of compression modulus (unit: mm) range is (137, 265), (114, 201), (109, 206), and (109, 209), and the calculated results are 81%, 85%, 78%, and 78%, respectively, which are greater than the calculated values of stratified average numerical simulation. The reason is the asymmetry of lognormal distribution model.

It can be seen from Table 2 that the 95% confidence intervals of the average maximum self-weight collapsibility at the five locations are 189 ∼ 198 mm, 152 ∼ 159 mm, 151 ∼ 157 mm, 150 ∼ 157 mm, 150 ∼ 157 mm, respectively. The deterministic results of the stratified average at any position did not fall within the 95% confidence interval; that is, the maximum probability deviates from the true value of the loess self-weight collapsibility.

Figure 10(a) shows the results of self-weight collapsibility with depth calculated by stochastic finite element modeling, layered average numerical simulation, and loess code calculation considering the spatial variability of compressive modulus. It can be seen from Figure 10(a) that the standard method calculates the self-weight collapsibility of loess according to the self-weight collapsibility coefficient of depth stratification. Collapse occurs only when the self-weight collapsibility coefficient is greater than 0.015, and the self-weight collapsibility above 15 m is essentially the compression settlement caused by the dead weight collapsibility of soil.
within the range of 12–15 m. When the depth is greater or equal to 15 m, it is considered that the self-weight collapsibility will no longer occur. This is inconsistent with the collapsible loess of the site with a thickness of 24 m. Therefore, the variation curve of self-weight collapsibility with depth in the standard method is distorted, and only the maximum self-weight collapsibility can be used as a reference. The stochastic finite element uncertainty result shows...
that the range of self-weight collapsibility at 15 m (unit: mm) is (78, 176), the median is 119 mm, and the average is 123 mm. It can be seen that the deterministic layer-average numerical simulation result is only a case of the self-weight collapsibility set considering the spatial variability of soil parameters and may not be the true value of the self-weight collapsibility.

The maximum self-weight collapsibility of different methods is shown in Figure 10(b). Combining Figure 10(b)
and Table 2, it can be seen that the deterministic results of layered average numerical simulation and the calculated values of standard method have 81% and 100% probability of underestimating the maximum self-weight collapsibility of loess, respectively, compared with the random results of 100 times considering the spatial variability of compression modulus. Considering the spatial variability of compression modulus, the average value of the maximum self-weight collapsibility is 193mm, which is 10% and 71% higher than that of 176mm based on the deterministic stratified average and 113mm based on PRC MOHURD, respectively. The 95th percentile of random calculation results is relatively stable and can be used as the representative value of random results of self-weight collapsibility. The value is 229 mm, which is 30% and 103% higher than the calculated value of stratified average deterministic result and the standard calculated value of self-weight weight collapsibility of loess, respectively. The reason is that the log-normal distribution is the limit distribution form of the product of many uncertain factors, which is consistent with the formation process of loess undergoing long-term and multicycle geological action in a long geological age, and the positive skewed distribution of the random field of compressive modulus leads to the predominance of low modulus, so that the uncertainty results of loess self-weight collapse considering spatial variability are mostly larger than the deterministic results of layered average.

Although the self-weight collapse model based on random field theory is more suitable for the spatial distribution of actual soil parameters, the deterministic calculation method of layered average is relatively simple and easy to apply. Therefore, it is necessary to link the uncertain results considering the spatial variability of soil parameters with the deterministic results of layered averaging to determine reasonable soil parameter eigenvalues. Figure 11 shows the relationship between the self-weight collapsibility and the shrinkage coefficient obtained by deducting the compressive modulus and performing a layered average deterministic analysis. It can be seen that the reduction coefficient of compressive modulus and the amount of self-weight collapse are linearly negatively correlated. When the compressive modulus reduction factor is reduced to 0.80, the deterministic result of the stratified average of 230mm is basically consistent with the 95th percentile of 229 mm of the random result considering the spatial variability of the compressive modulus. Therefore, it is suggested to take 0.80 times the compressive modulus as the equivalent eigenvalue of the deterministic calculation method for the collapsibility evaluation of typical loess strata in Xi’an.

### Table 2: Statistical characteristics of maximum collapse value under overburden pressure at different positions (unit: mm).

<table>
<thead>
<tr>
<th>Location</th>
<th>Average value</th>
<th>Standard deviation</th>
<th>Median</th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>95th percentile</th>
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<td>21</td>
<td>190</td>
<td>137</td>
<td>265</td>
<td>229</td>
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<td>X = −12.5 m</td>
<td>155</td>
<td>18</td>
<td>156.5</td>
<td>114</td>
<td>201</td>
<td>188</td>
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<tr>
<td>X = 12.5 m</td>
<td>154</td>
<td>17</td>
<td>153</td>
<td>109</td>
<td>206</td>
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<td>Y = −12.5 m</td>
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<td>152.5</td>
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<tr>
<td>Y = 12.5 m</td>
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<td>152.5</td>
<td>109</td>
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Conflicts of Interest
The author declares that there are no conflicts of interest.

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