Collapsibility and Collapse Assessment of Loess Under Unloading Effect of Malan Loess in Longdong

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Abstract: Unloading collapsible conditions are common in self-weight collapsible loess sites. But loess collapse settlement is generally evaluated without considering the influence of unloading. So, Malan loess in Longdong as the object of study, unloading collapsible tests under different pressures were set up, after derivation, the expression of loess collapsibility coefficient under unloading condition is established. The results showed that:(1) With the increase of unloading amounts, the collapsibility coefficient of loess gradually decreases. (2) The calculation formula of unloading collapsibility coefficient expressed by collapsible completion ratio, unloading stress ratio and unloading collapsible attenuation coefficient can make the calculation result of unloading collapse settlement more accurately. (3) Based on the experimental control group, the formula is further improved, and the parameter values in the expression are corrected. The formula can be used to calculate the unloading collapsibility coefficient of Longdong Malan loess (Q_3) under different initial pressures under any collapsible completion ratio and unloading stress ratio. By comparing the experimental values with the calculated values, the rationality and accuracy of the derived expression are verified. The method for determining the influence coefficient of loess collapsibility considering unloading effect is obtained , and the evaluation system of collapsibility is further supplemented and verified.

Keyword: Malan loess; collapse settlement; collapsibility coefficient; collapse assessment

1 Introduction

At present, the research on the determination of loess collapsibility is based on two general directions. On the one hand, the field experiment is carried out. A large area of foundation pit is immersed in water at the construction site [1] ; On the other hand, the indoor experimental research is carried out by simulating the field test [2] , which is generally the basic geotechnical experiment or the humidification and dehumidification experiment [3] .The measured loess collapsibility is the first step in the evaluation of collapsibility [4] . Some scholars use the basic physical index parameters of loess as the standard to evaluate the collapsibility of loess [5] . Another part of the scholars through data mining for multivariate analysis [6] , by optimizing the correction coefficient to improve the correctness and applicability of the evaluation formula [7] .

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The above research on loess collapsibility is the self-weight collapsibility and total collapsibility obtained under the action of specified pressure or saturated self-weight pressure of overlying loess [8] . However, due to the complexity of loess collapsibility, the existing evaluation method of loess collapsibility [9] is not suitable for unloading collapsible conditions. Therefore, it is urgent to study the collapsibility of loess under unloading, and only Jin Xin [10] and others have no other research on the collapsibility characteristics under unloading based on the research of a project in Shaanxi Province. Based on the results of indoor loess unloading collapsibility test under different conditions, this paper studies the law of loess collapsibility and its deformation characteristics under unloading. It provides a basis for the evaluation method of collapsibility of loess foundation under unloading, new measures of foundation treatment and technical standards.

2 Experimental design arrangement

2.1 Basic physical and mechanical indexes of experimental loess

Q_3 loess is widely distributed in the northwest of China and most of them have obvious collapsibility. The test loess samples are taken from the construction section of Daqing Expressway in Qing yang, Gansu Province, which belongs to the typical Q_3 of Malan loess in Longdong. a total of 45 exploration wells were set up by artificial exploration wells, and the loess depth was 1.0～8.5 m. The indoor test of loess is shown in Figure. 1 . The indoor compaction, compression, collapsibility and other experiments were carried out in turn to measure the loess characteristics of Malan loess in this area. The basic physical properties parameters are shown in Table. 1.

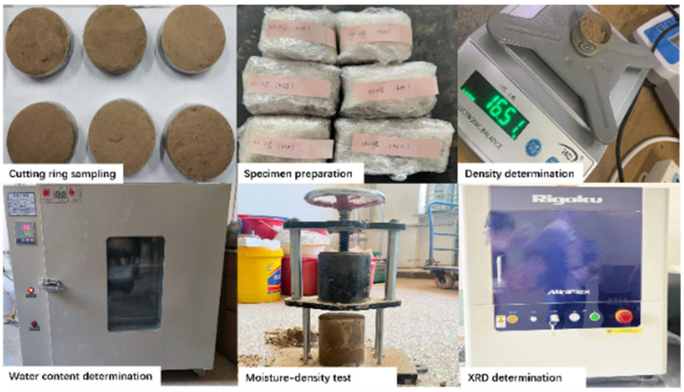


Figure. 1 Sampling loess indoor test

Table. 1 Basic physical and mechanical properties of experimental loess samples

	Water content/w/%	Density / ρd / g·cm³	Saturation /Sr/%	void ratio/e	Liquid limit WL/%	Plasticity Index/I
range value	8.1 ~ 30.2	1.2 ~ 1.49	20 ~ 95.30	0.66 ~ 1.27	24.6 ~ 31.4	8.9 ~ 18
average value	17.09	1.30	44.0	1.08	26.8	13.25

Malan loess in Longdong (Q_3) has low sand content, high silt and grain content. The loess is moist and compact, low disintegration speed, weak permeability, easy to compress, and the shear resistance of the loess is easily affected by water. It is collapsible loess and the collapsibility is medium to strong.

2.2 Experimental scheme

In order to study the collapsibility of loess under unloading,the conventional loess collapsibility test was carried out as a comparison.

(1) According to the provisions of the<Standard for building construction in collapsible loess regious> [11] on the collapsible loading pressure, the loess layer within 10 m is taken as 200 kPa, and the saturated self-weight pressure of the overlying loess is taken below 10 m. In this experiment, the inner diameter of the ring knife is 61.8 mm and the height is 20 mm. According to the actual unloading collapsible condition, because the foundation loess is in a natural stable state, the self-weight pressure of the overlying loess is applied to the sample first(Same as the conventional geotechnical test method, the step-by-step loading method is adopted, and the pressure is 100 kPa, 150 kPa, 200 kPa, 250 kPa, 300 kPa and 350 kPa), after the deformation is stable, the vertical unloading treatment is carried out (Step by step unloading) ,to simulate the unloading of foundation stress reduction after foundation pit excavation.

(2) Under the comparison of loess collapsible experiments under constant pressure, unloading collapsible experiments were carried out. Using a ring knife to take loess, and the depth direction was taken at 1, 2, 3, and 4 m respectively. Considering that the main influencing factors of collapsibility ar e the influence of different pressure and constant pressure on loess collapsibility, the test plan is as follows in Table. 2:

Table. 2 Collapsibility coefficient test under unloading

Depth (m)	Unloading volume (kPa)	Pressure under constant self-weight	Water content (%)	Number of specimens prepared (pcs)
1	25, 50, 75, 100, 200	1γ	6,12,18	9
2		2γ	6,12,18	9
3		3γ	6,12,18	9
4		4γ	6,12,18	9

Summarize the data law, and the collapse coefficient and pressure curves of loess with different buried depths are drawn. It is found that the initial pressure of loess collapse is closely related to the buried depth, and increases with the increase of loess density. Because the collapsibility is related to the physical properties of the loess itself, the greater the buried depth, the greater the density of the loess, the lower the compressibility, so the collapsibility is weakened.

3 Collapsible characteristics of loess under unloading

The collapsible deformation of loess is the result of the combined action of water and pressure. Under the condition of initial pressure, the loess particles are closely arranged, the structural compactness is high, and the loess structure is in a stable state. After the unloading occurs, the stable structure is destroyed. When the loess is immersed in water, the pressure on the loess is less than the pre-equilibrium state pressure, and the force that causes the structure to be destroyed cannot be achieved. Although the loess will continue to produce some additional deformation or collapsibility under the action of pressure after unloading, the deformation will decrease, and even there will be a change from collapsibility to non-collapsibility, The test diagram is shown in Figure. 2 .

Figure. 2 Unloading collapsible test under different unloading amount

3.1 Relationship between collapsibility coefficient and pressure under different unloading amounts

Through indoor experiments and statistical experimental data, the relationship diagram of the collapsibility coefficient under unloading is drawn, and its variation law is studied. The unloading level is set according to the step-by-step load reduction method, and the decrease of each level within 100 kPa is 25 kPa. Figure. 3 is the change of collapsibility coefficient of loess at different depths under different unloading levels.

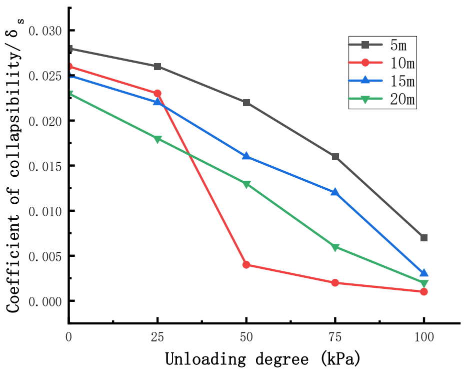


Figure. 3 The relationship curve between collapsibility coefficient and unloading amount

From the graph analysis: with the gradual increase of unloading amount, the collapsibility coefficient of loess gradually decreases. The same trend of the four curves of 5m, 10m, 15m and 20m is decreasing, indicating that the collapsibility coefficient of loess with different buried depths decreases with the increase of unloading amount, and the collapsibility coefficient is the largest when the upper pressure is constant.

It can be seen from the figure that the curve reduction caused by different unloading amounts in the process of loess unloading and collapsibility is much larger than the curve reduction caused by different buried depths, indicating that the collapsibility of loess under unloading is highly sensitive to the change of upper pressure, and the unloading amount is the main influencing factor.

3.2 The variation law of loess collapsibility coefficient and upper pressure under unloading

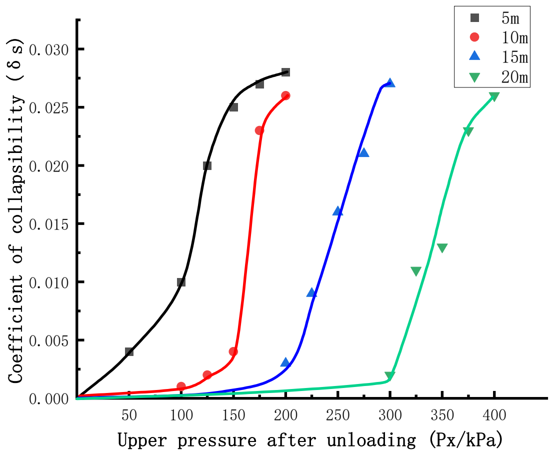


Figure. 4 Change law of loess collapsibility coefficient and upper pressure under unloading

From the Figure. 4 analysis, it can be concluded that the overall change trend of the collapsibility coefficient of 5m, 10m, 15m and 20m loess with the change of the upper pressure after unloading is the same. Comparing the four curves, it can be seen that the development trend of loess unloading collapsibility with larger buried depth is slower than that of shallow buried loess, and the collapsibility is weak.The variation of loess collapsibility coefficient and upper pressure $\delta_s - P_X$ curve under unloading conforms to the trend of constant pressure collapsibility, which can be divided into two stages, compaction stage and unloading collapsibility stage.

There is a correlation between loess collapsibility and buried depth under unloading. The larger the buried depth, the slower the unloading collapsible deformation of loess, the more lagging the development of the corresponding $\delta_s - P_X$ curve, and the later the peak value of collapsibility coefficient. The buried depth determines the strength of loess compressibility. The larger the buried depth is, the smaller the void ratio is, the denser the particle arrangement is, and the weaker the collapsibility is. The unloading collapsible process of 5 m loess is the most complete with the change of pressure, and the upper pressure range of the compaction stage is the smallest, which is 0 ~ 75 kPa. After that, collapsible occurs, but when the pressure reaches the initial pressure, the curve is stable, and the loess reaches the secondary stability; the pressure range of the 10 m loess compaction section is 0 ~ 150 kPa ; at the end of the 15 m loess compaction section, the upper pressure is 200 kPa, and the initial pressure of collapsibility is 246.5 kPa. The 20 m loess compaction stage is the longest, the collapsibility is the weakest, and the unloading collapsibility development process is the slowest. Although the loess deformation of the latter three is slowed down at the initial pressure, it is still in an increasing state and not completely stable.

4 The proposal and correction of unloading collapsibility coefficient

The process of loess collapsibility under the influence of unloading mainly considers two factors : the degree of completion of loess collapsibility when unloading occurs , the size of the unloading amount during unloading. At present, the self-weight collapsibility coefficient or collapsibility coefficient is still used in the evaluation of collapsibility and the calculation of collapsibility. According to this, the calculation of collapsibility is poor with the actual situation, and the researchers reduce the corresponding error by modifying the parameters, as shown in Table. 3.

Table. 3 Determination and correction of collapsibility coefficient by different researchers

source	correction method	Collapsible amount calculation Δs
Specification [12]	Force, loess and other correction coefficients β	$\Delta s=\sum_{i=1}^{n}\beta\delta_{si}h_i$
Standard [11]	Immersion probability coefficient α	$\Delta s=\sum_{i=1}^{n}\alpha\beta\delta_{si}h_i$
Zheng J, et al [13]	Discontinuous distribution coefficient of collapsible loess k	$\Delta s=k\sum_{i=1}^{n}\alpha\beta\delta_{si}h_i$
Huang X, et al [14]	Collapsible lower limit depth evaluation coefficient ς	$\Delta s=\varsigma\sum_{i=1}^{n}\alpha\beta\delta_{si}h_i$
Jin X, et al [10]	Considering the unloading collapsibility coefficient under unloading effect δ_{us}	$\Delta s=\sum_{i=1}^{n}\alpha\beta\delta_{usi}h_i$

In order to reflect the special collapsibility of unloading effect, it is necessary to consider the necessity of unloading effect when calculating the collapsibility of loess. The undisturbed loess in the field test site in Table 1 is taken respectively. The above formulas are used to calculate the loess unloading collapsible amount corresponding to the above-mentioned field test site, and the corresponding calculation results are shown in Figure. 5 .

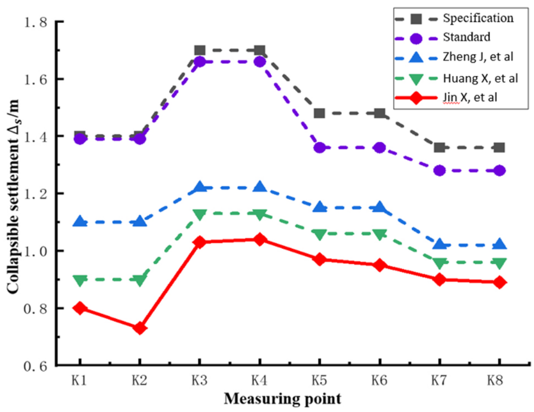


Figure. 5 Loess collapsibility under different calculation methods

In the (K1-K8) measuring point, in the face of the same thickness of collapsible loess layer, if the collapsibility coefficient δ_s under dead load condition is used mechanically according to the calculation method in table 3, the calculated value of collapsible amount is the same. If it is blindly applied to other modified algorithms for collapsible deformation calculation, the actual value is not much different from the calculated value. However, in the face of unloading collapsible conditions, if the collapsible amount is mechanically adjusted according to various empirical coefficients, it is still impossible to quantify the specific impact of unloading on the collapsible deformation of loess during the collapsible process. Therefore, it is necessary to use the characteristics of the reduction of deformation modulus when the loess is immersed in water and the unloading collapsibility coefficient δ_s to explore the evaluation method of collapsibility under unloading, so that the calculation of loess collapsibility under the influence of unloading collapsibility has a method to follow. Therefore, an evaluation method of loess collapsibility coefficient considering unloading effect is proposed.

5 Evaluation method of loess collapsibility based on unloading conditions

The research process of unloading collapsibility coefficient proposed by Jin Xin[10]is as follows: Firstly, the collapse completion ratio and unloading stress ratio are defined to characterize the completion degree of loess collapse before unloading and the unloading amount when unloading occurs. Secondly, the calculation formula of unloading collapse coefficient is deduced by using the collapse completion ratio and unloading stress ratio. The derivation principle is as follows Figure. 6 .

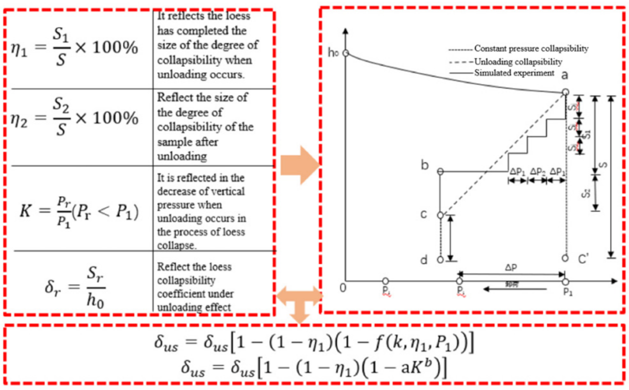


Figure. 6 Reasoning of the influence formula of collapsibility coefficient under unloading

Here $f(K) = aK^b$ is the expression of the fitting analysis results of the relationship between K and $\eta_2/(1-\eta_1)$ through various functions : Considering that the unloading collapsibility process is affected by three factors, that is, the initial pressure P_1 of the sample at the beginning of collapsibility ; the completed degree of loess collapsibility before unloading is the collapsibility completion ratio η_1 ; the magnitude of the unloading amount when the unloading effect occurs is the unloading stress ratio K. According to the range size reflecting the degree of influence of the factors, the primary and secondary relationship of the influence degree of K, η_1, P_1 is determined as $K \rightarrow \eta_1 \rightarrow P_1$. The results show that the unloading stress ratio plays a controlling role in the value of $\eta_2/(1-\eta_1)$, and the initial pressure has the least influence on the collapsible deformation of loess after unloading. Therefore, in the expression of determining the collapsibility coefficient, K is taken as the main consideration in the fitting analysis. The data regression analysis is as follows Table. 4.

Table. 4 The fitting relationship table of $\boldsymbol{f(K, \eta_1, P_1)}$ under different conditions

P1/kPa	η_1/%	a	b	R^2	P1/kPa	η_1/%	a	b	R^2
200	20	1.212	2.567	0.995	250	20	1.214	1.864	0.986
	40	1.331	2.862	0.989		40	1.256	1.998	0.964
	60	1.298	3.451	0.982		60	1.072	2.986	0.976
	80	1.315	3.226	0.991		80	1.101	2.563	0.867
300	20	1.096	1.256	0.946	350	20	0.998	0.897	0.976
	40	1.086	1.246	0.956		40	0.956	0.659	0.984
	60	1.089	1.356	0.976		60	0.926	0.792	0.956
	80	1.078	1.589	0.938		80	0.931	0.865	0.978
400	20	1.069	0.956	0.984	400	60	1.058	0.976	0.983
	40	1.038	0.946	0.962		80	0.998	0.974	0.962

It can be seen from the table that the correlation coefficient between K and $\eta_2/(1-\eta_1)$ is above 0.9 under different pressure(P_1) and different unloading collapsible ratio(η_1) . From the nature of the function itself, the power function can also qualitatively reflect the change law of the unloading amount and the collapsible deformation of the loess after unloading, Since the values of parameters a and b are close under different P_1 and η_1 conditions, the mean value of a and b can be used to further simplify the expression of $f(K)$.

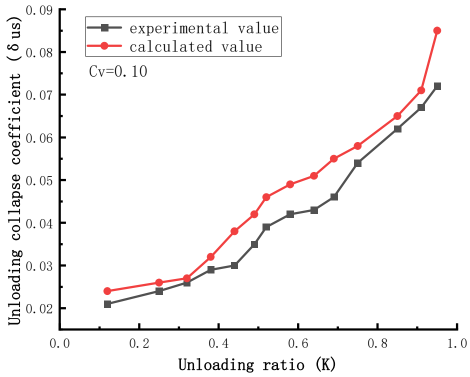
$$\begin{cases} a = 1.059 \\ b = 1.698 \end{cases} \quad (1)$$

6 Expression and verification of collapsibility coefficient under unloading effect

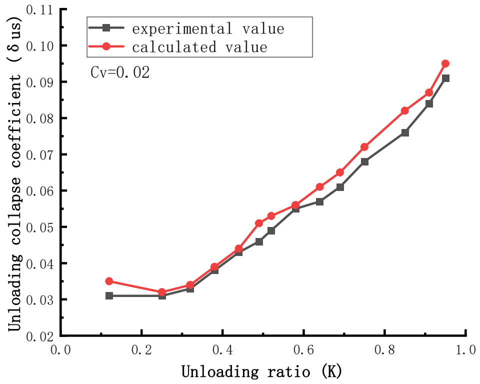
By substituting the average values of parameters a and b into $f(K)$, the expression of unloading collapsibility coefficient considering unloading effect in the process of loess collapsibility is obtained . Substitute into :

$$\delta_{us} = \delta_{us}[1 - (1 - \eta_1)(1 - 1.059K^{1.698})] \quad (2)$$

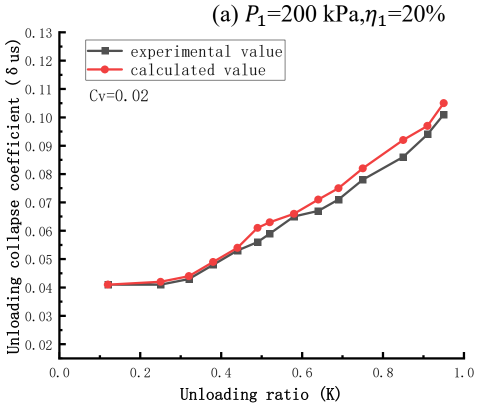
Through the correlation analysis of the calculation results of δ_{us} and the measured results, the coefficient of variation Cv and some comparison curves between the two are obtained, as shown Figure. 7.



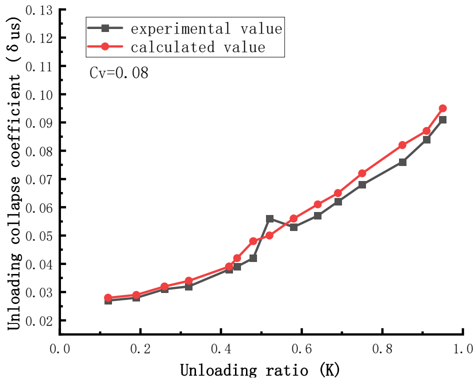
(a) P_1=200 kPa,η_1=20%



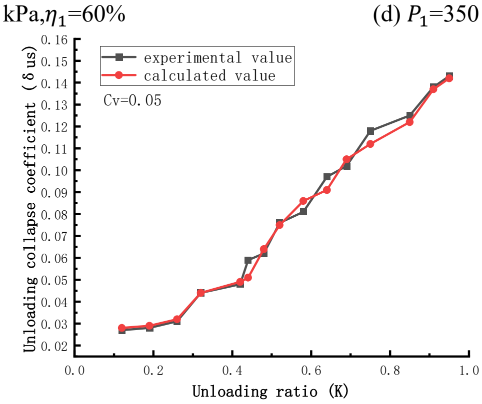
(b) P_1=250 kPa,η_1=40%



(c) P_1=300 kPa,η_1=60%



(d) P_1=350 kPa,η_1=40%



(e) P_1=400 kPa,η_1=20%

Figure. 7 The relationship between unloading ratio and unloading collapsibility coefficient under different conditions

It can be seen from Figure. 7 and Table 5 that the experimental values are in good agreement with the calculated values, and the overall law is consistent, and the coefficient of variation between the two [15]is less than 0.15. It shows that it is reasonable to ignore the influence of factors P_1 and η_1 and simplify the parameters in $f(K)$ when regressing the expression of $f(K, \eta_1, P_1)$, it shows that the results of loess unloading collapsible deformation calculated according to formula (2) have certain reliability. It can be used to calculate the collapsible deformation of Longdong Malan loess under different initial pressures, different unloading and collapsible completion degrees, so as to scientifically evaluate the collapsibility of loess under the influence of unloading.

7 Conclusions

Malan loess in Longdong (Q_3) has low sand content, high silt and grain content. The loess is moist and compact , and the shear resistance of the loess is easily affected by water. It is collapsible loess and the collapsibility is medium to strong. The collapsible characteristics of loess under unloading can not be ignored in its construction project. Through the indoor and outdoor unloading constant pressure comparison experiment of this kind of loess, the variation law of its collapsibility coefficient and its influence relationship is explored, and the following conclusions are drawn.

(1) The collapsible deformation of loess is the result of the combined action of water and pressure. Under the initial pressure, the loess is compressed to make the structure dense after the particles are rearranged. In the test, the collapsibility coefficient of loess with different buried depths is the largest under the condition of constant upper pressure, but with the gradual increase of unloading amount, the collapsibility coefficient decreases.

(2) In the process of loess unloading and collapsibility, the decrease of the curve caused by different unloading amounts is much larger than that caused by different buried depths, indicating that the collapsibility of loess under unloading is highly sensitive to the change of upper pressure, and the unloading amount is the main influencing factor.

(3) The formula for evaluating the collapsibility of Longdong Malan loess under unloading is obtained, $\delta_{us} = \delta_{us}[1 - (1 - \eta_1)(1 - 1.059K^{1.698})]$,the difference between the calculated value and the actual value of the formula is very small, which is accurate and reasonable. It is suitable for the evaluation and prediction of the collapsibility of Longdong Malan loess (Q_3), and has certain reference value in engineering practice.

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