Study on Simplified Calculation Method of Lateral Soil Pressure of Viscous Aggregate

Hu Xinyi, Feng Xiaojing

Abstract*— *In engineering,the Coulomb theory is widely used to calculate the earth pressure in various codes and standards,but the theory is more cumbersome in solving the earth pressure in cohesive soil.Especially in the early stage of the project,in order to simplify the calculation,some scholars propose to increase the friction angle in the cohesive soil by 2~3°,which is equivalent to the calculation of the non-cohesive soil. In this paper,the improved Kuhlman diagram method is used to discuss the effectiveness of this simplified method based on the principle of shear strength equivalence,and the sensitivity degree of the influencing factors is obtained by using orthogonal experiments.Then, the influence trend of the main influencing factors on the equivalent results is discussed,and the comprehensive influencing factors are proposed,and the corresponding relationship between the internal friction angle and the equivalent internal friction angle at different levels is given.Finally, according to the above analysis rules,this paper proposes the value method of the equivalent internal friction angle at different levels,and the case analysis results show that the calculation results of the method are more accurate,meet the error requirements of the project,and provide a basis for the scheme design in the early stage of the project.

Index Terms*—*cohesive soils；soil pressure；Kulhmann diagram method；equivalent internal friction angle

I. Introduction

Earth pressure calculations are extremely important in the design of structures such as retaining structures in civil engineering, open wagons in vehicle engineering and silos. Accurate earth pressure calculation can ensure the safety,stability and durability of these structures. At present, the classical earth pressure calculation is dominated by Rankine theory and Cullen theory,which starts from the limit equilibrium of a point within the earth and studies the distribution of earth pressure under the active and passive limit states;and the Cullen theory deduces the earth pressure on the back of the wall according to the overall equilibrium of the earth wedge behind the wall.

In terms of theoretical research,on the basis of the above, scholars at home and abroad have also studied the distribution of earth pressure under complex working conditions and different load forms;Bang[1] studied the formula for calculating the earth pressure of sandy soil behind the wall by considering the displacement of the wall;and Li Juwen[2] derived the formula for calculating the active earth pressure of the ground continuous homogeneous load q that acted at a certain distance d from the back of the wall based on the conditions of static equilibrium. For the shape of the rupture surface of the slip fracture body,Li Xinggao[3],Cao Zhenmin[4],and Wang Kuihua[5] derived the formula for soil pressure based on the plane or logarithmic helix slip fracture surface,and Wang Hongxing[6] combined with the theory of variational partitioning to derive the formula for the active soil pressure of clayey soil under several different slip fracture surfaces. For the layer splitting method,Ke Caitong[7] used oblique layer splitting method to derive the active soil pressure formula for complex cases,Cao Xiong[8] obtained the active and passive soil pressure formula for homogeneous overload conditions based on Bishop strip splitting method and using equilibrium equations,and Wang Jiayu[9] obtained a new method for the active soil pressure analysis by dividing the curved thin layer based on the circular arc principal stress trace. However, the calculation of viscous soil pressure still needs further in-depth study.Lu Tinghao[10] derived the active earth pressure calculation formula considering cohesion and adhesion on the back of the wall;Hu Xiaojun[11] proposed an improvement to the exact solution of the Coulomb active earth pressure for cohesive soil;Huang Wang[12] proposed a method to solve the most unfavorable angle and used the interpolation method to find the coefficient of cohesive earth pressure and extreme value of the rupture angle;Gu Yuci[13] derived the exact and approximate solutions of the Coulomb earth pressure for cohesive soil based on the assumption of the slip surface as a plane.The exact and approximate solutions of

In engineering applications, especially in the pre-project stage,the simplicity and practicability of the calculation methods are more important,the above theoretical studies have their scientific significance,but the engineering applications are slightly complicated,the literature[14] proposes to increase the angle of internal friction of cohesive soils by 2°~3° for the equivalence, however,there are many factors affecting this simplification,and such a simplification is debatable.In this paper,using the improved Kuhlmann diagram solving method,based on the principle of shear strength equivalence,based on the comparative analysis of the effectiveness of the above simplification methods and influencing factors,we propose a more specific simplified calculation method of active soil pressure of cohesive soils,get the range of values of the equivalent internal friction angle,and validate the effectiveness of the present method through data.

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II. MODELS FOR CALCULATING SOIL PRESSURE IN CLAYEY SOILS

At present, whether in the field of civil engineering or vehicle engineering, various types of specifications and standards in the general use of Cullen's theory to calculate the active soil pressure, while the soil pressure of cohesive soils is generally solved through the Kuhlmann diagramming method, the improved Kuhlmann diagramming method makes use of geometrical relations to transform the plotting solution into a formulaic solution, and this paper makes use of the method, based on the principle of shear strength equivalence, to study and analyze the equivalence of the calculation model of the soil pressure of a cohesive soil to the one without the The way of clayey soil is as follows:

A. Improved Kuhlmann graphical solution

The improved Kuhlmann's graphical solution method[15] computational model is as follows, as shown in Fig. 1, AB is the back of the retaining wall wall, AD is the fill surface behind the wall,the wall height H,θ is the angle of the slip fracture surface, φ is the angle of internal friction, α is the inclination angle of the back of the wall, β is the inclination angle of the fill surface behind the wall, δ is the friction angle between the back of the wall and the fill surface, G is the gravitational force,E_a is the active earth pressure, R is the earth support force outside the slide surface, Ψ is and the angle between the gravitational force and the active earth pressure, ABC is the slip fracture body, and BC is the the rear soil slide crack surface. Make a parallel line of AB through point C and intersect BD with point E. The weight of the sliding wedge ABC is:

$$G_{ABC} = \gamma \cdot S_{\Delta ABC} = \gamma \cdot S_{\Delta ABE} == \gamma \frac{1}{2} \overline{AB} \cdot \cos(\varphi - \alpha) \cdot \overline{BE} \quad (1)$$

where: $k = \frac{1}{2} \overline{AB} \cos(\varphi - \alpha)$ is a constant independent of the imaginary surface,

$$G = k \cdot \overline{BE} \quad (2)$$

By the above equation, we can see that the value of gravity is related to the length of BE. Make a parallel line of BN through point E to intersect BC at point F. EF//BN. From the geometric relationship: the vector triangle formed by E R W, is similar to △ BEF, obtained:

$$\frac{E}{G} = \frac{\overline{EF}}{\overline{BE}} \quad (3)$$

An expression for Ea is obtained:

$$E_a = k \cdot \overline{EF} \quad (4)$$

B. Equivalence principle

Both Rankine's theory and Cullen's theory show that the magnitude of earth pressure is closely related to the shear strength of the rear soil body, and a high shear strength of the soil body will result in a small earth pressure, therefore, according to the principle of equal shear strength, the cohesive soil is equated to a cohesionless soil and the earth pressure is solved.

If the cohesion of a clayey soil is c and the angle of internal friction is φ, then its shear strength is: $\tau_f = \sigma \tan\varphi + c$,

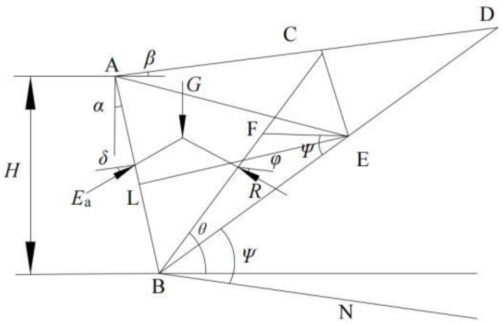

Fig1 Improved Kuhlmann graphical solution

Let $\tau_{feq} = \tau_f$, then, it can be deduced:

$$\varphi_{eq} = \arctan\left(\tan\varphi + \frac{c}{\sigma}\right) \quad (5)$$

Where: σ - is the soil shear surface positive stresses

φ_{eq} - is the equivalent internal friction angle of the soil

From (5) equation can be seen, the equivalent internal friction angle changes with the change of positive stress, each point of positive stress is related to the depth of the overburden, set the depth of a certain point is h_i, can be obtained at the point of the self-weight stress σ_{cz}, the positive stress on the shear surface $\sigma \neq \sigma_{cz}$, but the two are closely related, and the slip crack surface is a straight line, it can be roughly considered that the relationship between these two values at the point of the linear relationship, expressed as:

$$\sigma_i = m\sigma_{czi} = m\gamma h_i \quad (6)$$

Where: γ - Soil gravity (kN/m^3)

m- constant

As shown in Fig. 2, the h_{BC} expression can be obtained from the sine theorem:

$$\frac{AB}{\sin\angle ACB} = \frac{BC}{\sin\angle CAB} \quad (7)$$

$$BC = \frac{H\cos(\alpha-\theta)}{\cos\alpha\sin(\theta-\beta)} \quad (8)$$

$$h_{BC} = BC \cdot \sin\theta = \frac{H\sin\theta\cos(\alpha-\theta)}{\cos\alpha\sin(\theta-\beta)} \quad (9)$$

Assume that point i is at n times the total height of the slip surface:

$$h_i = nh_{BC} = \frac{nH\sin\theta\cos(\alpha-\theta)}{\cos\alpha\sin(\theta-\beta)} \quad (10)$$

Where: n-equivalent height factor

Bringing (10) into equation (5), we get:

$$\varphi_{eq} = \arctan\left(\tan\varphi + \frac{c\cos\alpha\sin(\theta-\beta)}{\gamma nH\sin\theta\cos(\alpha-\theta)}\right) \quad (11)$$

Bringing (11) to k yields:

$$k = \frac{1}{2}\overline{AB}\cos\left(\varphi_{ed} - \alpha\right) = \frac{1}{2}\overline{AB}\cos\left(\arctan\left(\tan\varphi + \frac{c\cos\alpha\sin\left(\theta-\beta\right)}{\gamma n H\sin\theta\cos\left(\alpha-\theta\right)}\right) - \alpha\right) \quad (12)$$

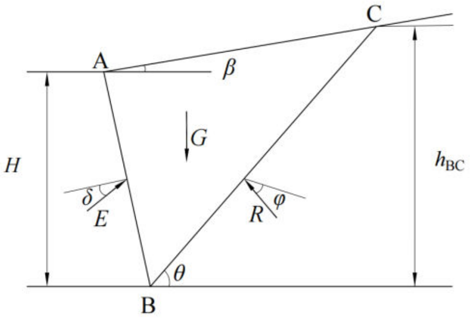

Fig2 h_{BC} schema

Bringing (12) into (4) yields the value of E_a for the improved Kuhlmann diagram solution after equivalence.

MATLAB software is used for programming to find the maximum value of *EF*, and the best equivalent height and hence the best equivalent angle of internal friction is obtained by using the method of theoretical solution of clayey soils [16] which is equivalent to the solution of this paper.

III. Analysis of Influencing Factors

If you are using *Word,* use either the Microsoft Equation Editor or the *Math Type* add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation *or* Math Type Equation). "Float over text" should *not* be selected.

From the Coulomb earth pressure formula, it can be seen that the main factors affecting the earth pressure are: wall height, angle of internal friction, cohesion, inclination of the back of the wall, inclination of the face of the fill behind the wall, weight of the fill behind the wall, and friction angle between the back of the wall and the fill. The correlation test for these seven factors yielded a correlation of 0 between each factor.

The sensitivity of each factor to the equivalent results can be realized by designing orthogonal tests. Taking the above seven influencing factors, three levels were selected for each factor according to common parameters and arranged them in an orthogonal table as shown in Table 1 below:

Table 1 Table of orthogonal tests

number	α /°	β /°	φ /°	δ /°	γ / kN /m^3	c /kPa	H / m	E_a / kN/ m theoretic	E_a / kN/ m this paper	inaccuracies/ %
1	0	0	5	5	16	5	5	98.9	97.1	1.8
2	0	0	10	10	20	15	10	74.1	74.6	0.7
3	0	5	5	15	20	10	15	357.1	349.6	2.1
4	0	5	15	5	18	15	5	133.7	128.6	3.8
5	0	8	10	15	18	5	10	232.5	233.7	0.5
6	0	8	15	10	16	10	15	37.2	38.3	2.9
7	5	0	5	15	18	15	15	96.3	95.2	1.1
8	5	0	15	5	20	10	10	59.6	58.9	1.2
9	5	5	10	10	18	10	5	14.6	15.1	3.5
10	5	5	15	15	16	5	10	143.1	142.7	0.3
11	5	8	5	10	20	5	5	157.8	160.2	1.5
12	5	8	10	5	16	15	15	48.9	51.2	4.8
13	10	0	10	15	16	10	5	12.4	13	5
14	10	0	15	10	18	5	15	302.5	296.5	2
15	10	5	5	10	16	15	10	24.1	24.7	2.6
16	10	5	10	5	20	5	15	532.8	524.3	1.6
17	10	8	5	5	18	10	10	229.6	233.5	1.7
18	10	8	15	15	20	15	5	84.6	88.7	5

Table 2 Extreme variance analysis of each parameter

level	α / °	β / °	φ / °	δ / °	γ / kN / m^3	c / kPa	H / m
I	2.2	1.93	1.52	2.48	2.9	1.28	2.16
II	2.4	2.32	2.68	2.2	2.52	2.73	1.17
III	2.98	2.73	2.53	2.3	2.04	3	2.04
extremely poor	0.78	0.80	1.16	0.28	0.86	1.72	0.99

For the calculated error is analyzed by the polar deviation, if the polar deviation is larger, the greater the impact of the factor on the target, indicating that the factor is the main influencing factor. The results of the extreme variance calculation are shown in Table 2:

The degree of influence of the seven factors was ranked by polar analysis. The final order of influence factor sensitivity was obtained:

$$c > \varphi > H > \gamma > \beta > \alpha > \delta$$

IV. Equivalent Angle of Internal Friction

A. *Composite Impact Factor*

In order to obtain the equivalent internal friction angle, according to the above analysis results, the main influencing factors are selected respectively to explore their influence laws on the results. From Eqs. (11)-(13), the optimal equivalent height corresponds to the equivalent internal friction angle one to one, and for convenience, the influence of c,γ,H,on the optimal equivalent height is discussed here, respectively. The range of values of c,γ,H, is selected, other parameters are fixed, and the values of equivalent height heq are calculated under different values, and the results are shown in Table 3. plotted in Fig. 3, it can be seen that:c,γ,H, and the change of equivalent height show monotonicity.

As γ,H, increases, the optimal equivalent height increases, with a positive correlation; as c increases, the optimal equivalent height decreases, with a negative correlation.

Table 3 Optimal equivalent height analysis

Impact parameters	Range/Optimum Height					
c / kPa	range of values	10	15	20	30	35
	Optimal equivalent height position	0.278h	0.173h	0.134h	0.073h	0.028h

H / m	range of values	10	15	20	30	35
	Optimal equivalent height position	0.045h	0.097h	0.133h	0.207h	0.275h
γ / kN / m^3	range of values	10	15	20	30	35
	Optimal equivalent height position	0.4h	0.425h	0.438h	0.474h	0.497h

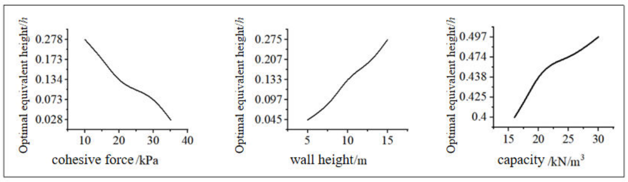

Fig. 3 Effect of c,γ,H,on the best equivalent altitude

Table 4 Relationship between η and optimal equivalent height

η level	Optimal equivalent height position
η = 0.033	0.118
η = 0.06	0.117
η = 0.1	0.116
η = 0.2	0.108
η = 0.3	0.062

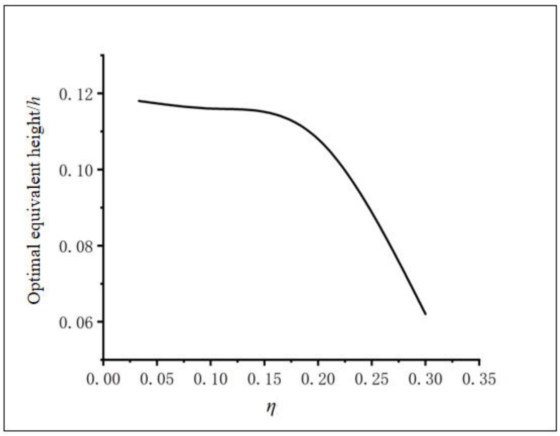

Fig. 4 Effect of combined influence factors on the best equivalent heights

Define $\eta = 2c/\gamma H$ is the integrated factor, then the effect of the factor on the best equivalent height is monotonically decreasing, through specific calculations to obtain the value of the best equivalent height under different values, see Table 4, plotted as a graph, as shown in Figure 4, from the figure can be seen η with the best equivalent height is negatively correlated when the η level of the lower level, the impact on the best equivalent height is small; when the η level of the higher level, the impact on the best equivalent height is more obvious.

B. Derivation of the equivalent angle of internal friction

According to the range of common c,γ,H, for geotechnical, the range of η values is obtained to be approximately $\eta = 0.033 - 0.3$. Taking the parameters of α , β , δ as fixed values: $\alpha = 5°$, $\beta = 10°$, $\delta = 10°$, and making changes to other parameters, the correspondence between the angle of internal friction and the best equivalent height can be calculated for different levels of η , and then the correspondence between the angle of internal friction and the equivalent angle of internal friction can be obtained, and the results of the calculations are shown in Table 5 below:

Table 5 Equivalent internal friction angles at different η levels

φ / η	0.033	0.1	0.15	0.2	0.22	0.25	0.3
5	6.9	8.2	9.1	10.3	11.9	12	13.7
8	10	11.4	12.9	14.8	16.7	22.5	25.1
11	12.8	14.7	16.3	18.7	20.2	27.5	31.7
13	15.2	17.7	19.9	23.1	25.1	35	40.6
15	17.2	19.9	22.4	26	28.3	40	47
18	20.2	23.2	26	30.2	33	48.3	58
21	23.2	26.4	29.5	34.5	37.9	58.2	71.8
24	26.2	29.6	33.1	39	41	70.8	87.7
27	29.3	32.9	36.8	43.8	49	87.4	88.6
30	32.3	36.1	40.6	48.9	55.7	88.4	-
33	35.4	39.5	44.5	54.7	63.7	-	-
36	38.4	42.8	48.6	61.5	73.9	-	-
39	41.5	46.3	52.9	69.6	76.6	-	-
42	44.6	48.6	57.1	80.2	88.7	-	-

Note: "-" indicates that the soil shear strength is high and the soil can be self-stabilized, potentially leading to zero or negative earth pressures, which are not discussed.

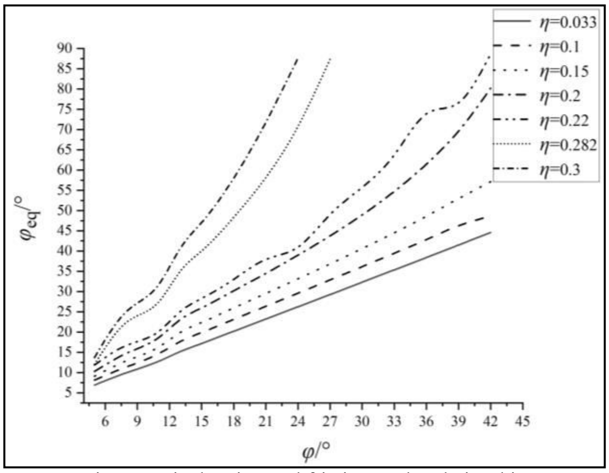

Fig. 5 Equivalent internal friction angle relationship

Table 6 η fitted straight lines for $\varphi_{ed} - \varphi$ at different levels

η numerical value	$\varphi_{ed} - \varphi$ fit a straight line
η = 0.033	$\varphi_{ed} = 1.0169\varphi + 1.8385$
η = 0.1	$\varphi_{ed} = 1.1051\varphi + 2.9474$
η = 0.15	$\varphi_{ed} = 1.2805\varphi + 2.6728$
η = 0.2	$\varphi_{ed} = 1.8359\varphi - 3.1051$
η = 0.22	$\varphi_{ed} = 2.0189\varphi - 2.032$
η = 0.282	$\varphi_{ed} = 3.2003\varphi - 6.04$
η = 0.3	$\varphi_{ed} = 4.5456\varphi - 25.072$

Taking φ as the horizontal axis and φ_{eq} as the vertical axis, the relationship can be obtained as shown in Fig. 5, which is basically a linear monotonically increasing relationship, and the slope of the line increases as the level of η increases. Linear fitting of the selected value of η, can be obtained when η takes different values of $\varphi_{ed} - \varphi$, has the following relationship,as Table 6:

Dividing n into three categories, when η is from 0 to 0.18, the slope is close to 1; when η is from 0.18 to 0.25, the slope is close to 2; and when η is from 0.25 to 0.30, the slope is close to 3 on average. based on the above law, in order to guarantee the sufficient safety, the interval is chosen as a low limit, and the safety factor is selected as 2. In the range of the internal friction angle of the common clayey soils, the equivalent ways for the given different levels of η are listed in the table 7 below:

Table 7 Equivalent internal friction angle of clayey soil

η level	φ_{eq}
$\eta = 0 \sim 0.18$	$\varphi_{eq} = \varphi + (0 \sim 10°)$
$\eta = 0.18 \sim 0.25$	$\varphi_{eq} = \varphi + (0 \sim 15°)$
$\eta = 0.25 \sim 0.30$	$\varphi_{eq} = \varphi + (4 \sim 25°)$

Explanation: 1. The interval is taken according to the linear interpolation between 0~40°.

Table 8 Comparison of numerical values of soil pressure for the calculation examples

η	α /°	β /°	φ /°	δ /°	γ / kN /m³	c /kPa	H / m	E_a / kN/ m theoretic	E_a / kN/ m this paper	inaccuracies/ %
0.05	0	0	24	21	14	1.5	4.4	40.0	41	2.60
0.1	5	8	5	10	20	5	5	198	193	0.49
0.15	0	0	10	10	20	15	10	401	403	0.25
0.2	10	5	5	10	16	15	9	467	466	0.21
0.25	10	0	10	15	16	10	5	69	69	1.50
0.3	10	8	15	15	20	15	5	62	62	1.60

V. CALCULUS

Calculation example: using the literature [16] in the cohesive soil Coulomb soil pressure formula to calculate the theoretical value, and with this paper's method of the equivalent angle of internal friction, calculate the equivalent numerical solution, the results of the calculations are shown in the table 8, compared to the findings: are satisfied with 5% engineering error, indicating that this paper's method is effective.

VI. REACH A VERDICT

(1) In this paper, the principle of equal shear strength is utilized, the equivalent height and equivalent internal friction angle are introduced to equate the cohesive soil to the cohesionless soil, and the improved Kuhlmann's graphical solving method is applied to calculate the value of the active earth pressure Ea, and the calculated value of the equivalent earth pressure meets the requirements of the engineering error.

(2) Through orthogonal test, the sensitivity analysis of seven factors affecting the equivalence results is carried out, and their influence degree is from the largest to the smallest.

(3) In this paper, we study the change rule of φ and φ_{eq} in the common range of values of the comprehensive influence factor η, and obtain the formula of $\varphi_{ed} - \varphi$ under different n levels, and give the method of internal friction angle φ_{eq} respectively.

(4) Through the calculation example analysis, the use of the equivalent method and the measured value is basically consistent, preliminary proof of the rationality of the method.

In this paper, although the simplified calculation method of active soil pressure of clayey soil is proposed through a series of analytical demonstration, it does not take into account the influence of other factors such as layered soil, uniform load, rear soil fissure, and the shape of slip surface, which is to be further studied.

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