

Study on Failure Plane of Bulk Solid in Squat Silos

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Abstract: With the increasing volume demand of silos, squat silo diameters are bigger and bigger. However, present wall pressure computation methods are mostly based on small diameter silos. To solve this problem, systematical research on the wall pressure in squat silos is of great importance. For now, in the Chinese code the wall pressure computation methods are based on the limit equilibrium theory to be calculated, which define the orientation of the failure plane in the bulk solid within the silo. The rupture angle is a key parameter to silos' wall pressure. Therefore the value and direction of rupture angle are researched by theoretical method in this paper, which has heavy significance and provide an important basis for the large diameter silo design.

Keywords: Failure Plane, Bulk Solid, Squat Silo, Wall Pressure

1. INTRODUCTION

Silos are structures that have always concerned mankind due to their capacity to store bulk solid, such as grain, coal, cement and so on. With the increasing production demand, the demand of silo volume increases continuously. Diameters of squat silos are bigger and bigger. The maximum diameter of present silos exceeds 100 meters [1].

With the passing of time, knowledge about silos has been further developed. However, this knowledge is mostly based on small silos whose diameter is smaller than 20 meters. There is little system research on large diameter silos whose diameter is larger than 20 meters. Scale effect is considered to particularly important to silos [2]. Therefore, it is meaningful to study on larger diameter silos.

Many scholars studied on silo pressure with theoretical analysis, such as Janssen (1895), Airy (1897), Reimbert M and Reimbert A [3], Walker, Walkers, Coulomb, Rankine, Jenike, Liu, Yuan etc [1-8]. Most of this research applied to small diameter silo. Only little system research directed to large diameter silos. Yuan (2004) studied static wall pressure on large diameter silos used limit equilibrium method in her PhD thesis. Part of her research was adopted in China Code for design of reinforced concrete silos (GB50077-2003) [9].

Wall pressure is a key parameter to silos' design. It has an important effect on the safety and efficiency of silos. At present, the wall pressure calculation method in the Chinese code are based on the limit equilibrium theory, which define the orientation of the failure plane in the bulk solid within the silo.

In this paper, the angles of failure plane in the bulk solid within squat silos are discussed.

2. THE RUPTURE ANGLE IN CHINA'S CODE

In China's code [9], the Rankine active earth pressure formula is adopted in the calculation of wall pressure in squat silos. But when the top of the stored bulk materials is a conical pile, the Rankine formula does not work, because the Rankine theory must be based on the assumptions that the interface between the retaining wall and the soil is erect and smooth, and that the top plane of the bulk materials behind the retaining wall is horizontal. Consequently, the Appendix C in China's Code (GB50077-2003) [9] indicate the effect of conical pile must be taken into account to calculate the wall pressure of large diameter silos ($d_n \geq 24\text{m}$) with the following formula by different rupture angle.

A circular silo with stored-bulk-solid is taken into consideration and shown in Fig. (1). The top of the bulk solid in Fig. (1) has a conical shape, and the angle of the top cone is denoted by β , which is always regarded as the surcharge angle of the bulk solid. The central line of the silo is O_1O_2 . The line AC is the failure plane with an angle θ to the vertical. The planes from the rupture point A to the cone tip O_1 in Fig. (2) have angle θ_0 , which can be calculated by

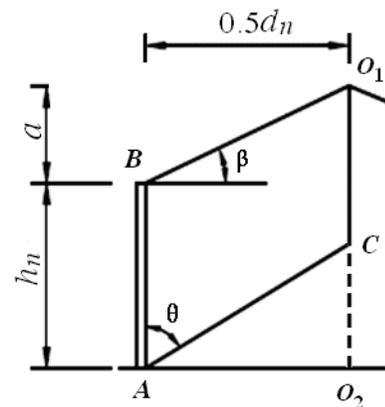


Fig. (1). The failure plane cuts the central line of the silo.

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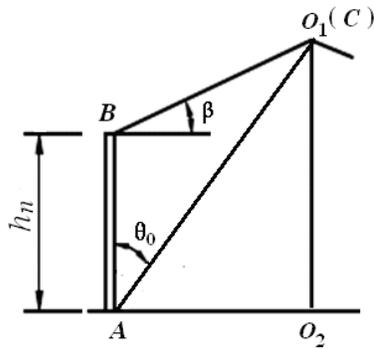


Fig. (2). Angles of failure plane $\theta=\theta_0$.

$$\cot \theta_0 = 2\delta + \tan \beta \quad (1)$$

$$\delta = h_n / d_n \quad (2)$$

According to the Appendix C in China's Code, when the rupture angle θ is greater than θ_0 which is shown in Fig. (2), in this case the pressure can be computed by Eq. 3-5.

$$\cot \theta = -\cot \varphi + \frac{\sqrt{2[1 + \cos 2\varphi + \sin 2\varphi(\tan \beta + 6\delta)]}}{\sin 2\varphi} \quad (3)$$

$$\lambda_{k1} = \frac{1}{12\delta^2} (6\delta + \tan \beta - \cot \theta) \cot(\theta + \varphi) \quad (4)$$

$$p_h = \lambda_{k1} \gamma h_n \quad (5)$$

where φ is the internal friction angle, λ_{k1} is the lateral pressure coefficient, p_h is the lateral pressure, and γ is the density of the bulk materials.

In another case the rupture angle θ is less than or equal to θ_0 which is shown in Fig. (3), the pressure can be computed by Eq. 6-10.

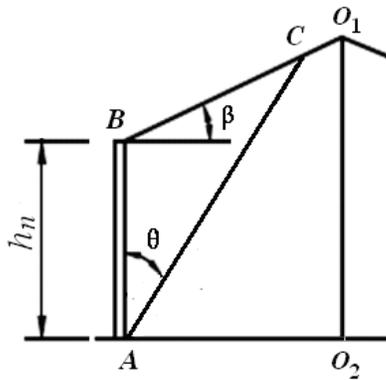


Fig. (3). Angles of failure plane $\theta < \theta_0$.

$$\tan(\theta + \beta) = -\tan \psi + \sqrt{(\tan \psi + \cot \psi)(\tan \psi + \tan \beta)} \quad (6)$$

$$\psi = \varphi - \beta (\varphi \neq \beta) \quad (7)$$

$$\lambda_{k2} = \frac{\cos^2 \varphi}{1 + \sqrt{\frac{\sin(\varphi - \beta) \sin \varphi}{\cos \beta}}} \quad (8)$$

$$\eta = 1 - \frac{1}{3} (2\delta + \tan \beta) \tan \theta \quad (9)$$

$$p_h = \gamma h_n \lambda_{k2} \eta \quad (10)$$

where λ_{k2} is the lateral pressure coefficient and η is the correction factor.

3. ANALYSIS OF THE ORIENTATION ON FAILURE PLANE

3.1. First Case

According to the Appendix B in China's Code [9], the internal friction angle of bulk solid is range between 22° and 40° . Following the parameters θ_0 and θ calculated by Eq. 1 and Eq. 3, respectively, which present whether the first case shown by Fig. (1) is reasonable.

From Fig. (4-9), we can see that when $0 \leq \delta \leq 1$, $\theta < \theta_0$. And further, the parameter θ is calculated on the basis of different internal friction angle and aspect ratio δ , which is always less

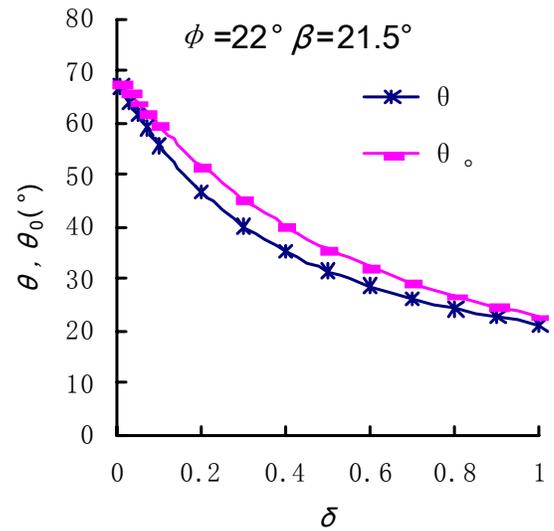


Fig. (4). Rupture angle calculated by Eq. 3 with $\varphi = 22^\circ$.

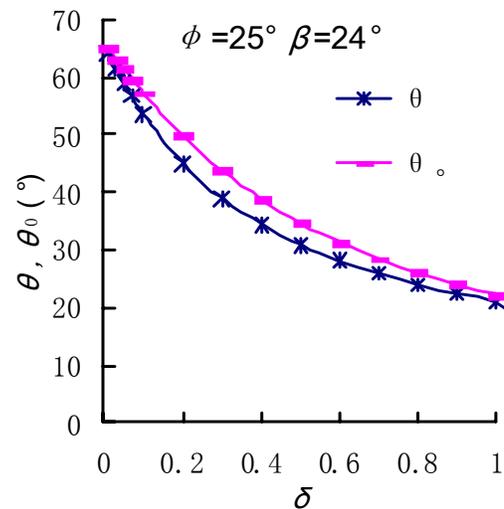


Fig. (5). Rupture angle calculated by Eq. 3 with $\varphi = 25^\circ$.

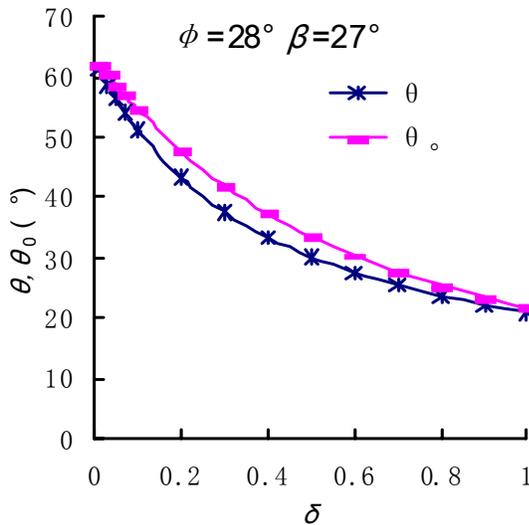


Fig. (6). Rupture angle calculated by Eq. 3 with $\phi = 28^\circ$.

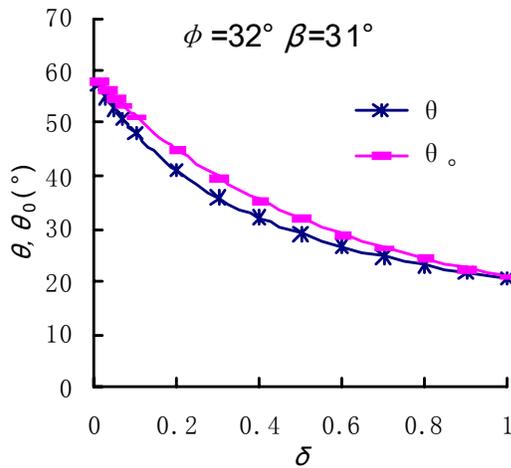


Fig. (7). Rupture angle calculated by Eq. 3 with $\phi = 32^\circ$.

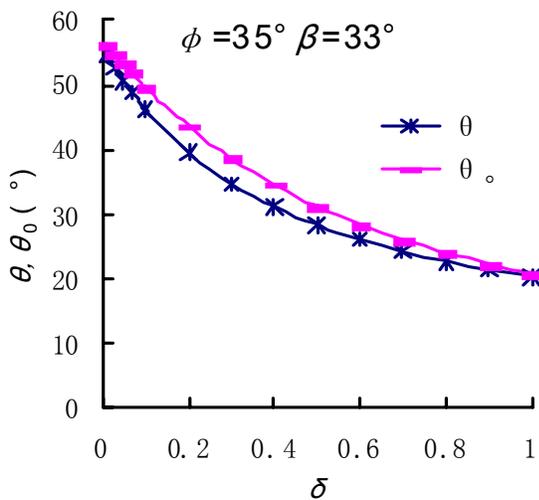


Fig. (8). Rupture angle calculated by Eq. 3 with $\phi = 35^\circ$.

than the parameter θ_0 . Thus, in the proposed method, the parameter θ calculated by Eq. 3 apparently contradict the hypothesis that the failure plane cuts the central line of the silo.

3.2. Second Case

In another case the rupture angle θ is less than or equal to θ_0 which is shown in Fig. (3) and calculated by Eq. 6.

Fig. (10-15) shows that the parameter θ is greater than θ_0 for the most part. And further, the parameter θ is calculated

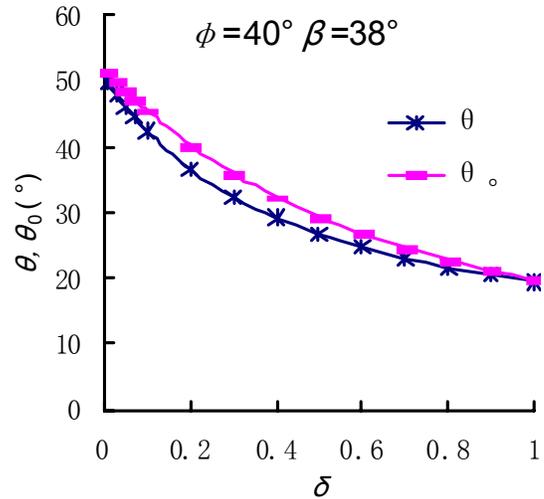


Fig. (9). Rupture angle calculated by Eq. 3 with $\phi = 40^\circ$.

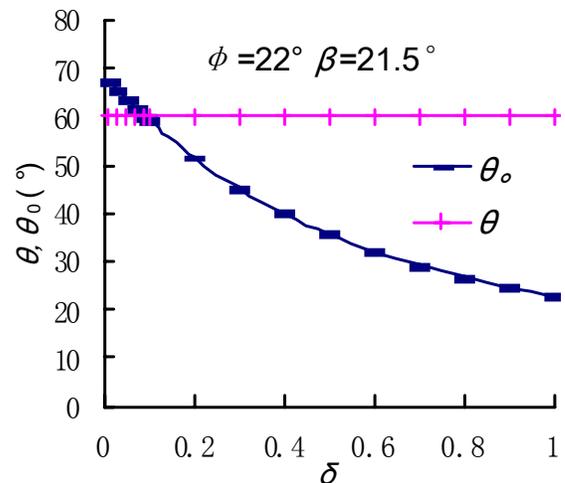


Fig. (10). Rupture angle calculated by Eq. 6 with $\phi = 22^\circ$.

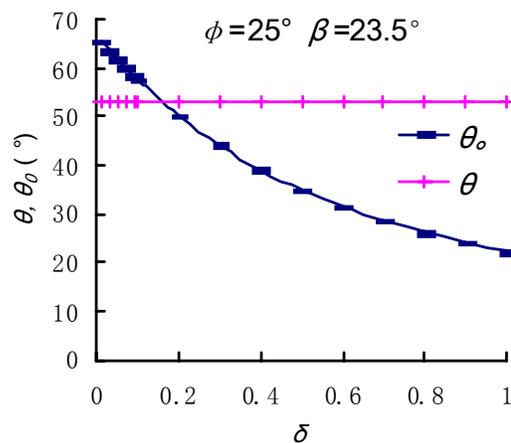


Fig. (11). Rupture angle calculated by Eq. 6 with $\phi = 25^\circ$.

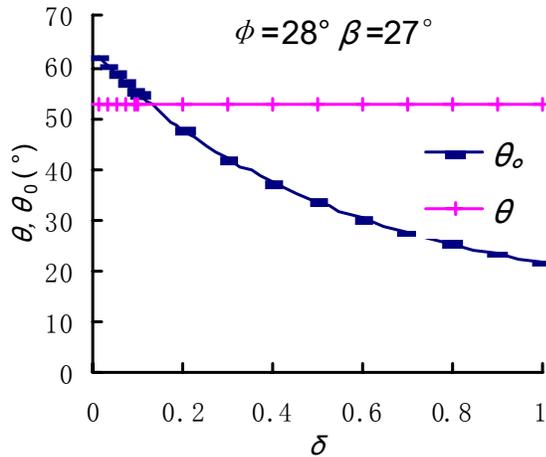


Fig. (12). Rupture angle calculated by Eq. 6 with $\phi = 28^\circ$.

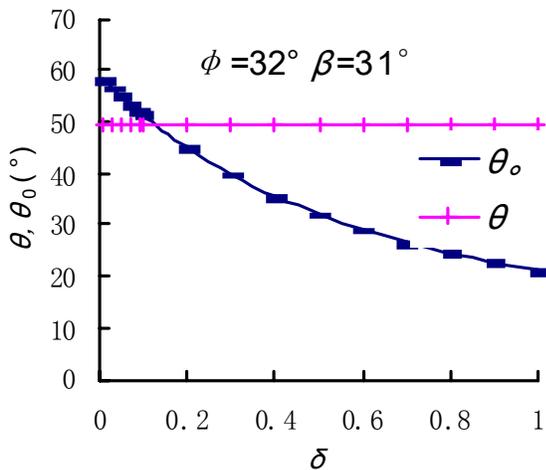


Fig. (13). Rupture angle calculated by Eq. 6 with $\phi = 32^\circ$.

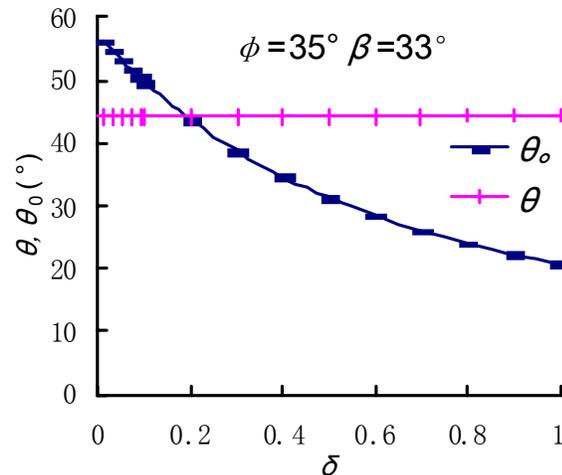


Fig. (14). Rupture angle calculated by Eq. 6 with $\phi = 35^\circ$.

on the basis of different internal friction angle and aspect ratio δ , which is mostly greater than the parameter θ_0 . In practice, the aspect ratio of squat silos is about 0.2 to 1.0. Thus, in the second case, the parameter θ calculated by Eq. 6 obviously disagree with the assumption that the rupture plane reaches the top surface of the storage.

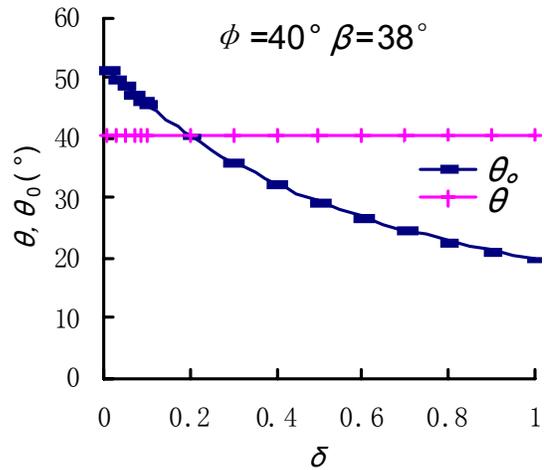


Fig. (15). Rupture angle calculated by Eq. 6 with $\phi = 40^\circ$.

3.3. Analysis and Synthesis

The rupture angles calculated by Eq. 3 and Eq. 6 appear to contradict assumptions those the orientations were shown in Figs. (1 and 3). In the second case the rupture angle θ is mostly greater than or equal to θ_0 , then let θ equal to θ_0 , we obtain .When correction factor is constant, Eq. 10 just a reducible Coulomb formula [1]. By more calculation even θ less than θ_0 , we also get. To compute wall pressure of large diameter squat silos, the reducible Coulomb formula is suitable according to the research results of Yuan [1]. If Eq. 10 is select to calculate the wall pressure, we must make it clear that the parameter θ is not always less than θ_0 .

4. CONCLUSIONS

Through theoretical and empirical analysis, this thesis reached the following conclusions.

In general, the failure plane of stored-bulk-solid can not cut the central line of silo. Thus, the Eq. 5 disagrees with the wall pressure in the squat silos.

Only when the aspect ratio δ is very small numbers to nearly 0, the failure plane can meet the top of the stored bulk materials.

To compute wall pressure of squat silos, the reducible Coulomb formula is reasonable. But the parameter θ is often greater than θ_0 .

CONFLICT OF INTEREST

Declared none.

ACKNOWLEDGEMENTS

This research was supported by The Anhui Provincial Key Science Research Project in Colleges and Universities (N0. KJ2010A294).

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Received: November 23, 2011

Revised: November 30, 2011

Accepted: December 20, 2011

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