The Mechanical Research of Vertical Screw Conveyor Particle Group Based on the Radial Change of Material Speed

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Abstract. This paper establishes a granular mechanics model for the stable movement of the material particle group in the vertical screw unloader with the granular mechanics, continuum mechanics and particle group theory and innovatively proposed the hypothesis that the speed of the material particle group changes radially in the spiral groove. Through the analysis of the material movement, the movement characteristic parameters of the material are determined. The study found that the material free surface type of the longitudinal section of the conveyor and its identification and solution methods and the pressure distribution law of the material particle group on the conveying pipe wall and spiral surface. In this paper, the granular mechanics, continuum mechanics and particle group theory are used to establish a granular mechanics model for the stable movement of the material particle group in the vertical screw unloader. We innovatively proposed the hypothesis that the speed of the material particle group changes radially in the spiral groove and determined the material movement characteristic parameters through the analysis of the material movement.

Keywords: Granule mechanics, Particle group theory, Radial speed change, Vertical screw conveyor.

1. Introduction
The screw ship unloader is a high-efficiency continuous bulk unloading machine. Its structure and material transportation principle are relatively simple, but the mechanical analysis of its transportation process is very complicated. Due to the complex mechanical properties of bulk materials and the complex movement of bulk materials during the vertical spiral conveying process, the single particle theory originally used to calculate the vertical screw conveyor ignores the distribution characteristics of the material in the longitudinal section and the pipe wall and spiral surface. The pressure distribution characteristics on the above, no longer meet the actual situation of high filling rate vertical screw conveyor [1]-[5]. The particle swarm theory currently studied assumes that the angular velocity of the particles in the direction of the spiral diameter remains constant, which is also different from the movement of the particles in the vertical spiral conveying with a high filling rate. In order to design a vertical screw ship unloader with high filling rate and high ergonomics, it is necessary to study the mechanism of vertical screw transportation more deeply and establish a better mechanical model.
2. Movement analysis of bulk materials on spiral surface

During the material conveying process of the vertical screw conveyor, when the screw shaft rotates at an appropriate speed, the material on the screw surface is driven to rotate together. The rotation of the material generates centrifugal force, so that the material is in close contact with the spiral tube wall and the spiral leaf surface. Its own gravity generates pressure on the spiral tube wall and spiral blade surface, which in turn causes friction. When the friction force exceeds a certain value, the material and the screw will be prevented from rotating together, that is, relative movement between the material and the screw, so that the material can obtain an upward movement component, and the material can move upward for vertical transportation.

The assumption for the movement analysis of the material particle group during the work of the vertical screw conveyor is:

1) The movement of materials in the conveying section is stable;
2) The material has no radial movement, that is, the material in the radius makes the same movement in the cylindrical surface;
3) The radial speed of the material is different from the radial speed of the spiral. The radial speed of the material decreases with the increase of the radius, that is, the closer to the spiral tube wall, the slower the speed of the material. Through experimental observation, it can be found that the speed of the material has such a law: the radial speed of the material on the outer side is less than the radial speed of the inner material, but the axial speed of the outer material is greater than that of the inner material. If it is assumed that the material speed is the same as the spiral speed, it is obviously different from the experiment. Therefore, the method adopted in this article is to assume that the speed of the material is different from the speed of the screw ($\omega = ar^2 + b$).

The motion analysis of the material particle group in the work of the vertical screw conveyor is based on the spiral speed $\omega_s$ greater than the critical speed. Take the micro unit at radius $r$ for analysis. Figure 1 shows the velocity analysis diagram of the unit. It is easy to get that the actual movement of this micro unit body is a combination of the following movements: ①The rotary movement around the screw axis is its traction movement; ②The spiral line is expanded and the relative movement between the spiral leaf surface in this direction. After decomposing the absolute speed of the material, the circular motion speed $V_B$ and the upward motion speed $V_z$ of the material can be obtained, and the spiral lift angle of the material motion is $\psi$.

![Figure 1. Material speed analysis diagram](image)

From Figure 1, it can be concluded that the relationship between the vertical upward motion component of the material and the speed of the material rotating around the screw axis can be expressed as:

$$v_z = (v_s - v_B) \tan \alpha = (\omega_s r - \omega r) \frac{H}{2\pi r} = (\omega_s - \omega) \frac{H}{2\pi}$$

(1)
When the boundary condition \( r = 0, \omega = \omega_1 \); when \( r = R, \omega = \omega_R \) is brought into \( \omega = \omega_1 r^2 + b \), and the material speed is solved as:

\[
\omega = -\frac{\omega_1 - \omega_R}{R^2} r^2 + \omega_1
\]  

(2)

3. Screw critical speed

When the material rotates at the critical speed, there is no relative sliding between the material particles and the spiral blade surface, so the material particles rotate with it. The material closely adheres to the spiral tube wall under the action of the centrifugal force generated by the rotation. At this time, the force of the spiral tube wall acting on the material particles is \( F_i = m\omega_1^2 R \). Then the friction force generated by the pipe wall to the material is \( f_2 F_i \). This friction force is not enough to prevent the material particles from rotating together with the spiral, so there is no slippage between the material and the spiral blade surface, but rotates around the spiral axis together with the spiral blade surface. Because there is no vertical upward motion component, the material particles still do not send upwards. (Where \( f_2 \) is the friction coefficient between the material particles and the spiral tube wall)

Figure 2. Material stress analysis under critical conditions

Expand a certain spiral leaf surface into a plane in a spiral manner, and the material is on this plane, and the material is analysed and calculated, as shown in Figure 2(b). When the spiral speed just reaches the critical speed, the friction force provided by the spiral tube wall to the material is not large enough to cause relative sliding between the material and the spiral blade surface, then the material still does not have an upward velocity component, due to the friction is the source power that provides the upward movement component of the material. According to the relationship between force and speed, it can be obtained that the friction force of the pipe wall against the material must be in the horizontal plane. In the plane of the spiral line, the material is in equilibrium under the combined action of the following three forces: The gravity of the material itself \( mg \); The resultant force \( F_s \) of the pressure perpendicular to the expansion line and the friction force caused by this pressure, \( F_s \) deviates
from the normal direction by a friction angle $\varphi_s$, The normal reaction force $F_t$ and friction force $f_2F_t$ of the pipe wall acting on the material [10][15].

As shown in Figure 2(c), the polygon method based on force is:

$$n_k = \frac{30}{\pi} \sqrt{\frac{g}{R\mu}} \tan(\alpha + \varphi_s)$$

(3)

4. Free surface of bulk material

For ship unloaders with high filling rate, the distribution of materials in the longitudinal section is an important factor affecting screw conveying. When the material rises in the screw conveyor, under the action of centrifugal force, a free boundary of a certain shape is gradually formed, that is, the interface with the air. Take the micro-units adjacent to the free surface for analysis. If there is a certain relative sliding between adjacent materials in the horizontal direction, the materials will reach a limit equilibrium state along the circumferential direction in a plane perpendicular to the radial direction. Description The limit state of the material is determined by the Moore stress circle where the stress state in the $\tau - \theta$ plane is similar to the limit shear stress curve [6-8], As shown in Figure 3.

![Figure 3](image)

**Figure 3.** Analysis of ultimate stress state of micro-unit materials

Take the triangular micro-blocks at the free surface and list the equilibrium conditions to obtain the surface curve equation:

$$z = \frac{\lambda_s}{6ga}(ar^2 + b)^3 + c$$

(4)

$$\lambda_s = \frac{1 - \sin \varphi}{\cos^2 \varphi}$$

(5)

The integral constant depends on the filling rate $\phi$ and the material speed $\omega$, which can be determined by the definition of the filling rate.

$$\phi \pi h(R - R_0^2) = \int \int 2\pi r dr dz$$

(6)

Corresponding to different material filling rate and rotation speed $\omega$, 4 types of free surface curves can be formed as shown in Figure 4.
In the figure, is half the pitch of the spiral (That is $h = \frac{H}{2}$, this article discusses the spiral as a double-ended spiral), $h_1$ is the intercept of the free surface on the spiral axis, $h$ is the intercept of the free surface on the pipe wall, is the intercept of the free surface curve on the lower helix, $h_2$ is the intercept of the free surface curve on the upper helix, $R_1$ is the radius of the spiral axis, and $R_2$ is the radius of the spiral.

According to equations (6) and (8), combined with Figure 4, the curve equations of the four types of free surfaces can be obtained as follows:

The first type of free surface curve equation (Figure 4-a):

$$
\phi \pi h (R - R_1^2) = \int_\Omega 2\pi rrdz
$$

By analogy, the other three free surface curve equations can be obtained respectively.

5. Stress distribution on the boundary

After the material is stably conveyed in the spiral conveying pipe and forms a free surface state, the centrifugal force generated by the high-speed rotation of the material and the gravity exerted on it will form pressure on the spiral shaft, upper and lower spiral surfaces, and the inner wall of the spiral pipe. The practice of a large number of vertical spiral ship unloaders shows, the pressure of the material on the screw shaft and the pressure of the upper helix is smaller than the other two parts. In order to simplify the model, generally ignore this part of the pressure [9]-[10].

In order to accurately reveal the characteristics of material transportation, a mathematical model that is closer to the actual situation must be made for the pressure distribution of the material on the spiral surface, screw shaft and conveying pipe. The stress on the free surface boundary is 0; On the vertical boundary where the material contacts the screw shaft, there is relative sliding between the material and the screw shaft and is in a state of limit equilibrium; On the boundary of the spiral surface, the material is conveyed upward due to relative sliding on the spiral surface. The pressure and friction of the material on the pipe wall and on the lower helix form a dynamic balance force system, thereby determining the movement of the material and the stress distribution on the boundary.

5.1. The pressure distribution of the material on the spiral pipe wall

For the first type of free surface (as shown in Figure 4-a), combined with the curve equation of the first type of free surface (Equation 9) and as shown in Figure 5, when in this type of free surface state, the pressure of the material on the spiral tube is caused by centrifugal force and is divided into two parts, $0 \leq z \leq h_1$ and $h_1 \leq z \leq h_2$. 

![Figure 4. 4 types of free surface curves](image-url)
Figure 5. The first type of free surface micro-units

(1) When $h_1 \leq z \leq h_2$, as shown in Figure 5(a), take a micro-material element in this interval, and its centrifugal force is:

$$\sigma_z R d\theta d\varphi = \int_r^h \rho dr dz rd\theta r \omega^2$$

Then the $z$ function of centrifugal force of the material on the pressure of the spiral tube wall is:

$$\sigma_z = \frac{\rho c_1 \omega^2}{3R} (R^3 - r^3) + \frac{\rho c_2 \omega^2}{2} (R^2 - r^2)$$

(2) When $0 \leq z \leq h_1$, as shown in Figure 5(b), take a micro-material element and its centrifugal force is:

$$\sigma_z R d\theta d\varphi = \int_{R_0}^h \rho dr dz rd\theta r \omega^2$$

Then the $z$ function of centrifugal force of the material on the pressure of the spiral tube wall is:

$$\sigma_z = \frac{\rho c_1 \omega^2}{3R} (R^3 - R_0^3) + \frac{\rho c_2 \omega^2}{2} (R^2 - R_0^2)$$

By analogy, the other three free surface curve equations can be obtained respectively.

5.2. Material pressure on the spiral leaf

For the first type of free surface (as shown in Figure 4-a), combining the curve equation of the first type of free surface and as shown in Figure 5, take a micro-material element and perform stress balance analysis on it. The material element is in a state of stress balance, including:

$$g \rho f_1 (r) dr * r * d\theta + \tau_{r} r d\theta \frac{dr}{cos \varphi} \sin \varphi - \sigma_{r} r d\theta \frac{dr}{cos \varphi} \cos \varphi = 0$$

$$g \rho f_1 (r) + \tau_{n} r g \varphi - \sigma_{n} = 0$$

$$g \rho f_1 (r) + f_1 \sigma_{n} r g \varphi - \sigma_{n} = 0$$

Then the compressive stress $\sigma_n$ of the material to the spiral blade is:
\[ \sigma_n = \frac{\rho g f_1(r)}{1 - f_1 \tan \theta} = \frac{\rho g \left[ \frac{\lambda \omega_s}{2 g c_1} (c_1 r + c_2 R)^2 + C_0 \right]}{1 - f_1 \frac{H}{2 \pi r}} \]

(12)

By analogy, the other three free surface curve equations can be obtained respectively.

5.3. Pressure distribution curve at the boundary of particle group on spiral surface
Given spiral radius \( R \), spiral shaft radius \( R_0 \), pitch \( H \), filling rate \( \phi \), spiral speed \( \omega_s \), material density \( \rho \), gravitational acceleration \( g \), internal friction coefficient \( f \), friction coefficient \( f_1 \) between the material and the spiral surface and pipe wall.

![Figure 6. Pressure distribution on the particle boundary on the spiral surface](image)

After the free surface type is determined, the pressure distribution equation of the material on the spiral tube wall and spiral surface can be numerically solved according to the free surface type, and the pressure distribution under the four free surface states can be obtained, as shown in Figure 6.

6. Conclusion
This paper applies granular mechanics, continuum mechanics and particle group theory to theoretically model and analyze the mechanism of multi-head vertical screw conveying, and establishes a granular mechanics model for the stable movement of material particles in the vertical screw ship unloader.

Firstly, the assumption of radial variation of the rotational speed of the material particles in the spiral groove is made. On this basis, the material movement characteristic parameters are established through the analysis of the material movement, and then the material free surface type of the longitudinal section of the conveyor and the method of its discrimination and solution are determined by the study. This research has determined the pressure distribution law of the material particle group on the wall of the conveying pipe and the spiral surface, which provides a theoretical basis for the final
establishment of the calculation model of the material movement characteristic parameters, productivity and screw shaft drive power.

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