ABSTRACT: In this paper, aiming at the main problems existing in the carriage of the mining dump truck in service, the longitudinal section curve configuration of the carriage is studied in combination with three factors: material performance, rated volume of the carriage and smoothness of unloading. The discrete element method is used to simulate the movement of the material and the interaction between the material and the bottom plate at the rear of the carriage. At the same time, the unloading experiment is carried out under the condition of full load. The experimental analysis is consistent with the theoretical and numerical simulation results. The results show that the longitudinal section of the carriage is the best when it is "arc + polynomial curve + straight line + arc".

KEYWORDS: truck carriage, longitudinal section curve, numerical simulation, structure optimization.

1 INTRODUCTION

The carriage is one of the major large structural components of heavy mining dump trucks. It is usually loaded by large electric shovel or hydraulic shovel, and goes back and forth to the excavation point and discharge point (Guo Shanshan, 2019; Demirel N et al., 2018). It is also known as off highway dump truck because of its super wide shape and over capacity of total mass, so it is not allowed to drive on the road. At present, it has beared 40% of the world's coal and 90% of the world's iron ore mining transportation (Kansake B A, Frimpong S and Ali D, 2019; Yadav P K, Gupta S and Kumar D, 2020). Carriage is one of the main large-scale structural parts of heavy-duty mining dump truck. It bears the burden of transporting ore directly. The stability of quality directly affects the efficiency of mining transportation. However, due to the heavy load, poor operating environment and complex working conditions, the service life is seriously shortened, and even some trucks are completely scrapped in about 10-16 months of operation (Wei F, Shen Y and Xu T, 2016; Shi Mingming, Wang Changguan, 2019; Yadav P K, Gupta S and Kumar D, 2020; Aben K, Orazaliyev Y and Suorineni F T, 2019). The shape of the longitudinal section curve of the truck carriage should be determined by the requirements of the dump truck for the whole car. Loading requires that the carriage can achieve impact resistance, wear resistance, etc. during the operation, impact resistance, scattering phenomenon minimization, etc. unloading requires that the truck wear minimization, etc (Octaviania B P, Hartono A, 2020). In addition, the processing technology, welding technology and site use requirements of the carriage shall be considered. Based on the project of Qingdao Walker mining equipment Co., Ltd, "Research on the carriage of heavy mining dump truck with capacity of over 220t", this project has carried out in-depth
research on the design of the carriage based on extensive collection and analysis of relevant research results of heavy mining dump truck at home and abroad (Zhang Fenghou, 2019; Yamada K et al., 2020; Tapia E et al., 2020; Ali D, Frimpong S, 2018; Li Yong, 2018; Yang Weiwei et al., 2019).

2 ANALYSIS OF CARRIAGE MECHANICAL STRUCTURAL

2.1 Profile of longitudinal section of carriage

![Figure 1: Truck carriage](image1)

Figure 1 shows the typical carriage in service. The main problems of the typical cars in service include: (1) the rear of the bottom plate is open, the materials are easy to be scattered from the rear, resulting in low transportation efficiency of the truck, and the scattered materials are easy to break the tires, reducing the life of the dump truck; (2) the end of the car is too close to the ground when unloading, and the bulldozer is required to clean up the material yard after unloading, which increases the maintenance cost; (3) the wear of the bottom plate and side plate is serious, which reduces the service life of the carriage; (4) in the dead angle that the front plate is connected with the bottom plate, the side plate and the bottom plate, the phenomenon of material stagnation is common, which results in the reduction of the payload of the carriage.

![Figure 2: The configuration of the carriage](image2)

2.2 Streamline front plate

In bionics, the fantastic eggshell structure shows us that we can create the largest space with the least materials and bear the force hundreds of times of its own weight without being crushed. It embodies the most natural, reasonable, economic and effective natural masterpiece of nature. The arched external convex structure of the front plate of the carriage is the arched thin-walled structure of the egg. The arched surface sits directly on the main beam, increasing the contact area between the main beam and the front plate, so that the impact force is directly transmitted to the main beam, rather than all borne by the front plate. In this way, it can not only buffer the impact force of the material to a certain extent, but also increase the effective load of the carriage.

2.3 Analysis of transition curve configuration of front plate and bottom plate

The curved surface connection between the front plate and the bottom plate of the carriage can not only reduce the stress concentration, but also reduce the problem of material adhesion at the right angle of the carriage. The main influencing factors of the transition surface at the joint are the performance of the curve material, the rated volume of the car and the smoothness of unloading.
3 ANALYSES OF THE FACTORS AFFECTING TRANSITION SURFACES AT JOINTS

3.1 Influence of material properties on transition curve formation

The minimum relative bending radius can be used to describe the ultimate deformation of sheet metal. The minimum relative bending radius refers to the ratio of the minimum fillet radius that can be bent into the inner surface of the bending part to the thickness of the blank under the condition that the outer surface does not crack when the blank is bent.

Which is expressed by \( \frac{r_{\text{min}}}{t} \). The smaller the value, the better the bending performance of the sheet metal.

The factors that affect the minimum bending radius are: mechanical properties of materials, angle of bending parts \( \alpha \), heat treatment state of sheet metal, edge and surface state of sheet metal, bending direction, etc.

The minimum relative bending radius under the condition of allowable elongation is:

\[
\frac{r_{\text{min}}}{t} = \frac{1}{2} \left( \frac{1}{\delta_{\text{max}}} - 1 \right)
\]

(1)

\( \delta_{\text{max}} \): allowable elongation of material.

It can be seen from formula (1) that the larger the allowable elongation of the sheet metal \( \delta_{\text{max}} \), the smaller the minimum relative bending radius \( \frac{r_{\text{min}}}{t} \), and the greater the limit deformation degree is.

3.2 Impact of the design volume

The shape and curvature radius of transition curve must meet the requirements of rated volume. The solid works model is used to simulate the overall shape of the material and make it separate from the car to calculate the volume of the car (Wang Xin, 2019; Kim I H, Lim D W and Jung J W, 2019).

Because the shape and radius of curvature of the transition curve between the bottom plate and the front plate directly affect the volume of materials loaded in the car. If the transition section is made of HARDOX steel 450, under the condition that the radius of transition curve is greater than the minimum relative bending radius of HARDOX steel 450, Solid Works is used to build the material block model of different transition curves, then the evaluation function is used to calculate the volume of the material block, give the density of the material block, and calculate the car load, so as to determine the shape and curvature of the transition curve.

3.3 Impact of the unloading smoothness

It is a serious problem in the field use of the heavy dump truck that the bottom plate of the truck is stuck, which makes it difficult to unload and causes too much surplus material in the truck body, which seriously affects the transportation efficiency. According to statistics, the average sticking rate of coal mines in China is about 15%, and that of metal and non-metal mines is 15% - 30%. Relevant statistical data show that the energy consumption increase caused by coal sticking is as high as 30%. The transition curve between the front plate and the bottom plate of the carriage can be "arc", "cubic curve" and "bionic polynomial curve". The "bionic polynomial curve" type adopts the inner contour of the middle toe of the right front paw of the vole studied in.

In the long-term living process of soil environment, voles' claws and toes have evolved for hundreds of millions of years, gradually forming the optimized geometry and excellent biomechanical properties, which can produce the lowest cutting resistance in the process of excavation, which provides the basis for bionic research on the optimization of geometry and mechanical properties of equipment in construction machinery, such as carriage, carriage, etc. The 4-degree polynomial fitting equation of the inner contour of vole's claw toe is as follows:

\[
y = 0.000005x^4 - 0.0005x^3 + 0.22x^2 - 0.6813x - 16.84
\]

(2)

(Kushwaha R L, Shen J, 1995).
4 CONFORMATION ANALYSES OF BASE PLATE CURVES

4.1 Straight Circular upward curved base plate

For the dump truck with tail opening and no rear guard board, in order to bear the material, the bottom plate of the carriage generally inclines upward at a certain angle, and the external contour is "V" shape when viewed from the side, as shown in Figure 1. However, this kind of carriage has a large amount of tail wear and is easy to spread materials. In order to enhance the bearing capacity and protect the tires, the tail of the new carriage adopts the duck tail structure, as shown in Figure 2, the bottom plate upwarping section 4, that is, the rear of the carriage bottom plate inclines upward at a larger angle. Generally, the upwarping part accounts for about 1/5 to 1/3 of the floor.

The advantages of the upwarping structure at the rear of the carriage are mainly reflected in the following aspects: (1) The wear of the bottom plate is less; (2) the loading load is increased to reduce the scattering of materials during transportation; (3) the material is ejected far away during unloading to reduce the cost of bulldozer clearing.

4.2 Structural parameters of the straight + rounded warped base plate

The new body bottom plate is composed of two parts, i.e. flat plate and upwarping structure. The length of the base plate is composed of the length L of the flat plate and the length L₂ of the streamline upwarping structure. The angle of the upwarping structure base plate to the flat plate is δ. When the load capacity is fixed, the body volume is determined, and the values of L and L₁ are fixed; At the same time, s = L + L₁ + L₂ is determined by the space of the frame, where L and L₁ are determined by the assembly size of the frame, which are fixed and constant quantitative. As shown in Figure 3.

When the body load is fixed, δ is mainly determined by three factors. The first is the actual length L₂ of the body tail upwarping structure; the second is the loading condition of the bottom plate and the efficiency of unloading. The third is that the upwarping structure can prevent the material from scattering.

When unloading, in order to facilitate unloading and avoid material accumulation at the rear of the body, it is generally required that the lowest part of the body rear shall not be lower than the height r of the tire radius, as shown in Figure 4. At this time, the upwarping angle of the tail structure is δ, and the streamline arc section of the upwarping part of the bottom plate can be approximately a straight line. From geometry knowledge:

$$\frac{R}{\sin(90 - \beta)} = \frac{L_2}{\cos \delta \sin(\beta - \delta)}$$

(3)

Figure 3: the upturned structure of new carriage

Figure 4: the unloading schematic of new carriage

4.3 Analysis of the angle of rear-end warpage

Simplify the model of the car floor, apply PFC2D software, and use the discrete element method to simulate the movement of particle media and the interaction with the car floor at the end of unloading (Saadat M, Taheri A, 2020).

The idealized assumption is made for the bottom plate of the material car body. The following assumptions are made during particle flow simulation during material unloading: (1) The
material particle unit is rigid; (2) the contact occurs in a very small range, that is, point contact; (3) the contact characteristic is elastic contact, and there is a certain amount of "overlap" at the contact; (4) the contact has a special connection strength; (5) the material block is simplified as a spherical particle unit.

Assign the properties to the particle sphere, the density is 1000kg/m³, the rigidity is 108N/m, the acceleration of gravity is 9.81m/s²; assign the normal rigidity 108N/m, the tangential rigidity 108N/m to the rigidity of the model wall of the bottom plate; the friction coefficient between the sphere and the sphere is fric = 1.0. Two variables are monitored, one is the velocity of the ball in Y direction near the (30, 5) upwarped structural coordinate of the bottom plate model wall, the other is the diagnosis of mean unbalanced force (muf) of the bottom plate. The total time step is N=20000. Monitor the change of variables every 5 steps, so as to store the changed data into an array and display it. Based on the empirical value, the floor model walls with 4°, 6° and 8° upwarping angles are respectively established. The monitoring results of the floor model contact force and variables are as showed in Fig.5.

4.3.1 Bottom plate tail upwarping angle is 4°

When the ore car car unloads materials, the schematic diagram of the contact force, displacement direction and speed direction between the base plate model wall and particles is shown in Figure 5(a). When the ore car car unloads the materials, the structural coordinate of warping up at the end of the base plate model wall is the speed of the ball in Y direction near (30, 5), and the monitoring results are shown in Figure 6(a). The average contact force between the tail of the bottom plate model wall and the material particles, as shown in Figure 6(b).

Figure 5: PFC2D model diagram, (a) Model with base plate tail up angle of 4°, (b) Model with base plate tail up angle of 6°, (c): Model with base plate tail up angle of 8°.

Figure 6: Falling properties of materials at an angle is 4°: (a) Velocity of material particles in the Y direction (b) Average contact force of the plate with the material particles
4.3.2 The upwarping angle of the bottom plate tail is 6°

When unloading, the contact force, displacement direction and velocity direction between the base plate model wall and particles are shown in Figure 5(b). When unloading materials from the carriage, the speed of the ball in the Y direction near (30, 5) of the structural coordinate at the end of the base plate model wall is upwarped, and the monitoring results are shown in Figure 7(a). The average contact force between the tail and the particles of the materials, as shown in Figure 7(b).

4.3.3 The upwarping angle of the bottom plate tail is 8°

When the ore car unloads materials, the contact force, displacement direction and speed direction between the base plate model wall and particles are shown in Figure 5(c). When the ore car car unloads the materials, the structural coordinate of warping up at the end of the base plate model wall is the speed of the ball in Y direction near (30, 5). The monitoring results are shown in Figure 8(a). The average contact force between the tail and the particles of the materials, as shown in Figure 8(b).

When the upwarping angle is 6°, the material particles on the base plate model wall will unload fastest under the action of self-weight; the next is 4°, and the slowest is 8°. When the angle is 6°, the force exerted by the material on the bottom plate is the smallest and the distribution is the most uniform; when 8°, the average force exerted by the material on the bottom plate is approximately twice that of 6°, and the fluctuation of the force is large, which indicates that the impact of the material on the bottom plate is frequent and easy to cause damage to the carriage; when the upwarping angle is 4°, the force magnitude and distribution are between 6° and 8°. Therefore, considering the unloading
speed of the materials, the magnitude and distribution of the force exerted by the materials on the bottom plate, the upwarping angle should be designed to 6°.

5 EXPERIMENTAL ANALYSIS OF IDEAL UNLOADING CURVE OF LONGITUDINAL SECTION

Considering the comprehensive factors such as processing technology and processing cost, the front plate of the new carriage is mainly analyzed as "straight line type" and "circular arc type"; the transition curve is mainly analyzed as "circular arc type", "cubic curve type" and "bionic polynomial curve type"; the bottom plate is "straight line + tail up warping", in which the tail up warping curve is analyzed as 6° from the above section; the front plate is analyzed as "straight line + tail up warping" remains unchanged. The front plate curve is defined as section A, the front plate and the bottom plate curve as section B, the front straight line section of the bottom plate as section C, and the upwarping section of the bottom plate tail as section D. Then the functions of the ideal curves of the four longitudinal sections are Table 1-4:

(1) Straight line + straight line + straight line;
(2) Arc + arc + straight line + straight line;
(3) Arc + cubic curve + straight line + straight line;
(4) Arc + bionic polynomial curve + straight line + straight line.

Table 1 Parameters of the first curve

<table>
<thead>
<tr>
<th>Section</th>
<th>y = ax + b</th>
<th>x ∈ [0,2100]</th>
<th>a₁ = -1.3952</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section A</td>
<td>y = ax</td>
<td>x ∈ [2100,6668]</td>
<td>a₂ = 0.1603, b₂ = -3516.0715</td>
</tr>
<tr>
<td>Section B</td>
<td>y = ax + b₃</td>
<td>x ∈ [6668,9643]</td>
<td>a₃ = 0.2582, b₃ = -4172.3526</td>
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</tbody>
</table>

Table 2 Parameters of the second curve

<table>
<thead>
<tr>
<th>Section</th>
<th>(x + a₁)² + (y + b₁)² = R²</th>
<th>x ∈ [0,2100]</th>
<th>a₁ = -4132, b₁ = -2815, R = 5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section A</td>
<td>(x + a₁)² + (y + b₂)² = R²</td>
<td>x ∈ [2100,2658]</td>
<td>a₂ = -2288, b₂ = 2138, R = 800</td>
</tr>
<tr>
<td>Section B</td>
<td>y = ax + b₃</td>
<td>x ∈ [2658,6668]</td>
<td>a₃ = 0.160, b₃ = -3156</td>
</tr>
<tr>
<td>Section C</td>
<td>y = ax + b₄</td>
<td>x ∈ [6668,9643]</td>
<td>a₄ = 0.258, b₄ = -4172</td>
</tr>
</tbody>
</table>

Table 3 Parameters of the third curve

<table>
<thead>
<tr>
<th>Section</th>
<th>(x + a₁)² + (y + b₁)² = R²</th>
<th>x ∈ [0,2100]</th>
<th>a₁ = -4132, b₁ = -2815, R = 5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section A</td>
<td>(x + a₁)² + (y + b₂)² = R²</td>
<td>x ∈ [2100,2658]</td>
<td>a₂ = -2288, b₂ = 2138, d₂ = -1888</td>
</tr>
<tr>
<td>Section B</td>
<td>y = ax + b₃</td>
<td>x ∈ [2658,6668]</td>
<td>a₃ = 0.160, b₃ = -3156</td>
</tr>
<tr>
<td>Section C</td>
<td>y = ax + b₄</td>
<td>x ∈ [6668,9643]</td>
<td>a₄ = 0.258, b₄ = -4172</td>
</tr>
</tbody>
</table>

Table 4 Parameters of the fourth curve

<table>
<thead>
<tr>
<th>Section</th>
<th>(x + a₁)² + (y + b₁)² = R²</th>
<th>x ∈ [0,2100]</th>
<th>a₁ = -4132, b₁ = -2815, R = 5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section A</td>
<td>(x + a₁)² + (y + b₂)² = R²</td>
<td>x ∈ [2100,2658]</td>
<td>a₂ = 5 × 10⁻⁶, b₂ = -5 × 10⁻⁴, e₂ = -16.84, c₂ = 0.22</td>
</tr>
<tr>
<td>Section B</td>
<td>y = ax + b₃</td>
<td>x ∈ [2658,6668]</td>
<td>a₃ = 0.160, b₃ = -3156</td>
</tr>
<tr>
<td>Section C</td>
<td>y = ax + b₄</td>
<td>x ∈ [6668,9643]</td>
<td>a₄ = 0.258, b₄ = -4172</td>
</tr>
</tbody>
</table>

According to the above four longitudinal section curves, the car model is made, and the
unloading experiment is carried out under the full load state. The unloading is shown in Figure 9. The four types of carriages are weighed in each state of unloading. The measured load after unloading is kg, as shown in Table 1. The relation curve between the unloading angle and the load capacity of the car after unloading is shown in Figure 10.

![Figure 9: The carriage unloading state diagram](image)

![Figure 10: Relationship between angle and loads](image)

According to the analysis of unloading curve trend chart 1, when four series of curves are unloaded under the same load, "arc + bionic polynomial curve + straight line + straight line" is the fastest, others are "arc + cubic curve + straight line + straight line", "arc + arc + straight line + straight line", and the worst is "straight line + arc + straight line + straight line". When the unloading angle is about 35°, the longitudinal section curve of arc + bionic polynomial curve + straight line + straight line has basically been completely unloaded, while the other three types of curves all retain some materials. Therefore, it can be judged that when the transition curve between the bottom plate and the front plate is a multiple curve imitating the inner contour of the vole claw toe, the friction force on the carriage is small, the unloading speed is fast, and the unloading track is relatively ideal.

6 CONCLUSIONS

The influence of unloading height on the upwarping structure of the rear part is analyzed. According to the design requirement that the lowest part of the rear part of the body should not be lower than the height of the tire radius, the relationship between the length $L_2$ of the upwarping structure and the upwarping angle is obtained.
Based on the PFC2D particle flow software, the discrete element method is used to simulate the movement of the particles and the interaction between the particles and the rear floor of the body. Based on the analysis of the contact force and variable monitoring results, it is determined that when the angle of upwarping is 6°, the material particles on the model wall unload quickly and the contact force is distributed evenly on the model wall.

It is pointed out that the main influencing factors of the curve connection between the front plate and the bottom plate of the car body are the performance of the curve section material, the set volume of the car body and the smoothness of unloading.

Four kinds of assumed longitudinal section curves, namely "line + line + line", "arc + arc + line + line", "arc + cubic curve + line + line", "arc + bionic polynomial curve + line + line" are studied, the relationship between the lift angle of oil cylinder and the material surplus in the car body after unloading is obtained through unloading test of the car body model made by four kinds of curves. The results show that the unloading trajectory of "arc + bionic polynomial curve + straight line + straight line" is the best. Among them, the bionic polynomial curve is the internal contour curve of vole’s claw toe.

ACKNOWLEDGMENTS

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REFERENCE