Computer simulation of unloading a dump truck on an inclined platform.

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Abstract. The article deals with the problem of loss of stability of a dump truck when unloading on an inclined platform. The main task of the study is to determine the maximum permissible angle of inclination of the site. The analysis of modern methods of solving the problem is given. A mathematical model of a dump truck when unloading on a site with a longitudinal slope is developed. In the case of cargo sticking to the platform, an analytical formula is obtained for calculating the critical angle of inclination of the platform. When the cargo is moving, the procedure of step-by-step change of parameters is proposed. Based on the obtained ratios, a program for calculating the longitudinal stability of the dump truck is compiled. The results of assessing the longitudinal stability of two KAMAZ dump trucks are presented.

1. Introduction

Overturning of the car (loss of stability) can occur both in the longitudinal and transverse plane. In the longitudinal plane: when braking sharply on a steep descent, when driving on a steep ascent, when reversing into a ravine or river. In the transverse plane: when driving at high speed on sharp turns, when the side skid abruptly stops as a result of hitting an obstacle with the rear wheel, when the load is unevenly loaded or moved on a turn, etc. [1].

These cases are also found in the operation of dump trucks [2]. In addition, for this class of vehicles, there is a risk of overturning the vehicle when unloading. Overturning occurs during unloading on inclined platforms or when the rear wheels sink into the ground. In this regard, the main task in assessing the stability of the dump truck is to determine the maximum permissible (critical) angle of inclination of the unloading site.

2. Modern methods of assessing sustainability.

Traditionally, the critical angle of the site is determined when testing full-scale samples of cars on special stands. Our country has developed state standards that regulate such tests [3]. Similar tests are carried out abroad. For example, experimental studies of the stability of heavy-duty vehicles with a lateral (transverse) slope are performed at the company Fliegl Fahrzeugbau [4]. At the Schmitz Cargobull company, all dump semi-trailers are tested for rollover resistance both backward and sideways at the development stage with the help of a unique test bench [5]. However, this approach requires significant costs for conducting expensive tests and increases the time of finishing cars.

Another approach to solving this problem is based on the use of computational research methods. In particular, at the Chelyabinsk Polytechnic Institute, the critical angle of the unloading platform was calculated on a complete finite element model of the KAMAZ-6520 car [6]. The model took into account the suspension design, the non-linearity of the elastic suspension elements and tires, as well as the
possibility of plastic deformation of the bearing system during torsion. However, the development and debugging of such a model requires not only considerable time, but also the well-coordinated work of a whole team of highly qualified engineers. In addition, the results obtained require experimental verification and are the subject of serious scientific research.

At the same time, there is a need to develop a relatively simple, engineering method for calculating the critical slope angle of the site to assess the stability of the dump truck.

3. Longitudinal stability of the dump truck.

Consider the scheme of unloading a dump truck on a longitudinal slope (Fig. 1).

\[ \sum M_x(m_1 \vec{e}) + \sum M_x(R_1) + \sum M_x(\overline{\Theta}_x) = 0, \]

Let the load be a monolithic block, symmetrical with respect to the vertical plane of symmetry \(O_{xy}\) of the car. We bring all the inertia forces of the load (\(\overline{\Theta}_x\)) to its center of mass \(C\) in the form of the main vector \(\overline{R}_w\) and the main moment \(\overline{L}_{cw}\). Then, as shown in [8], the main moment of the inertia forces of the load \(\overline{L}_{cw} = -J_{cc} \vec{e}\) is zero. In turn, the main vector of inertia forces \(\overline{R}_w\) is directed in the opposite direction of the movement of the load (Fig. 1), and its modulus is equal to: \(R_w = m_2 \ddot{s}\).

Taking into account the obtained relations, equation (1) is written as:

\[ -\sum_{x=1}^{3} m_x g \cos \Theta \cdot X_x + \sum_{x=1}^{3} m_x g \sin \Theta \cdot Y_x + R_1 \cdot L - R_w (y_2 + Y_0 \cos \varphi + X_0 \sin \varphi) = 0, \]
Here, the coordinates of the centers of mass of the platform 1 and the load 2 in the stationary \((X_k, Y_k)\) and mobile \((x_k, y_k)\) coordinate systems are related to each other by the following relations:

\[
X_k = x_k \cos \varphi - y_k \sin \varphi - X_O; \quad \text{(3)}
\]

\[
Y_k = x_k \sin \varphi + y_k \cos \varphi + Y_O, \quad (k = 1, 2) \quad \text{(4)}
\]

If the angle of inclination of the platform is equal to the critical angle \(\theta^*\), the front wheels of the dump truck break away from the support. In this case, the total reaction \(R_0\) on the front wheels will become zero and equation (2) will take the form:

\[
-g \cos \theta^* \sum_{k=1}^{3} m_k X_k + g \sin \theta^* \sum_{k=1}^{3} m_k Y_k - m_2 \dot{s}(y_2 + Y_0 \cos \varphi + X_0 \sin \varphi) = 0. \quad \text{(5)}
\]

In the case of sticking (freezing) of the load to the platform \((s = 0)\) from equation (5), we find the critical angle of inclination of the platform:

\[
\theta^* = \arctg \left( \frac{\sum_{k=1}^{3} m_k X_k}{\sum_{k=1}^{3} m_k Y_k} \right) \quad \text{(6)}
\]

After substituting the relations (3) and (4) in the formula (6), we get:

\[
\theta^* = \arctg \left( \frac{(m_1 x_1 + m_2 x_2) \cos \varphi - (m_1 y_1 + m_2 y_2) \sin \varphi - (m_1 + m_2) X_0 + m_1 X_3}{(m_1 x_1 + m_2 x_2) \sin \varphi + (m_1 y_1 + m_2 y_2) \cos \varphi + (m_1 + m_2) Y_0 + m_1 Y_3} \right) \quad \text{(7)}
\]

Thus, according to the formula (7), already at the design stage, it is possible to calculate the critical slope angle of the platform and make an assessment of the stability of the dump truck during unloading.

In the case of cargo movement \((s > 0)\), the following algorithm for solving the problem is developed to calculate the critical angle of inclination. We set the initial values of the angles \(\theta = 0^\circ\) and \(\varphi = 0^\circ\), the coordinates \((x_k, y_k), \quad (k = 1, 2)\) of the centers of mass of the platform and the load in the initial position, and other parameters. Then discretely, we increase the angle \(\varphi\) of lifting of the platform. When the total angle \((\varphi + \theta)\) becomes equal to the angle of the natural slope \((\approx 30^\circ)\), we simulate the movement of the load. To do this, at each step of changing the angle \(\varphi\), we calculate all the parameters included in equation (5).

In particular, the acceleration \(a_c = \ddot{s}\) of the center of mass of the load is found from the differential equation of its motion:

\[
m_2 \ddot{s} = m_2 g (\sin (\varphi + \theta) - f \cos(\varphi + \theta)), \quad \text{(8)}
\]

where \(f\) – is the coefficient of friction of sliding the load on the platform.

Integrating equation (8), we find the displacement \(s\) of the load. From the relations (3) and (4), we calculate the new coordinates of the center of mass of the platform and the load. All the found parameters are substituted into equation (5). If the sum of the moments in equation (5) is greater than or equal to zero, the car will overturn. This completes the calculation and fixes the value of the critical angle of inclination of the platform. Otherwise, we increase the angle by one degree and repeat the unloading process. Thus, by consistently changing the angle of inclination of the platform, we determine its critical value in the case of cargo movement.

4. Calculation of the stability of KAMAZ dump trucks.

To assess the longitudinal stability based on the formula (7), two models of KAMAZ dump trucks were selected. Their technical characteristics are presented in Tables 1 and 2.
Table 1. Technical characteristics of KAMAZ dump trucks.

| Complete set of the dump truck | Front axle load, kg | Rear axle load, kg | Weight, kg |
|-------------------------------|-------------------|------------------|-----------|
| Model                        | 1    | 2    | 1    | 2    | 1    | 2    |
| Complete                     | 5300 | 7500 | 9500 | 13000| 14800| 20500|
| Curb weight                  | 3450 | 4525 | 3450 | 4200 | 6900 | 8725 |
| Chassis                      | 3400 | 4025 | 2050 | 2800 | 5450 | 6825 |

Note: Model: 1 - KAMAZ-43255; 2 - KAMAZ-53605.

Table 2. Parameters of KAMAZ dump trucks.

| The parameters of dump truck | KAMAZ-43255 | KAMAZ-53605 |
|-------------------------------|------------|------------|
| Cargo weight, kg             | 7750       | 11700      |
| Wheelbase, mm                | 3500       | 3950       |
| Coordinates of the pivot support, mm | $X_o = 950$ | $X_o = 960$ |
|                               | $Y_o = 1050$ | $Y_o = 1065$ |
| Maximum lifting angle of the platform | 55° | 50° |
| Lifting time, sec.            | 30         | 30         |

Based on the parameters of the cars (Table 1 and 2) the initial data for calculating the critical slope angle of the platform are obtained. The results of calculations of critical angles when changing the lifting angle of a loaded platform are shown in Figure 2.

![Figure 2](image_url)

Figure 2. Plot of changes in the critical slope angle of the platform.

1 - KAMAZ-43255; 2 - KAMAZ-53605

From the graphs shown, it can be seen that these models of KAMAZ dump trucks have high longitudinal stability. So when lifting a loaded platform to the maximum angle ($\theta = 50^\circ$), the KAMAZ-53605 maintains stability on the platform with an angle of inclination $\theta = 17^\circ$, and the KAMAZ-43255 on the platform with an angle $\theta = 13^\circ$.

In the case of a moving load, the critical angle of inclination of the platform will be greater than the obtained values. This is due to the forces of inertia of the load, which tend to keep the dump truck in a stable position.

Note that the design scheme of the dump truck did not take into account the elastic properties of the suspension and tires. However, this can be done within the framework of this model. Indeed, when lifting the platform, the load on the rear axle increases. As a result of the additional deflection of the rear suspension springs and tires, the dump...
truck has its own angle of longitudinal inclination. Calculations have shown that the maximum angle of proper inclination (at the end of the platform lift) is 2-4 degrees. Therefore, the actual critical slope angle of the platform will be less than the calculated value by the specified amount. A similar angle of inclination of KAMAZ dump trucks occurs when the rear wheels sink into the ground by 800 mm and 500 mm, respectively.

5. Conclusions
The proposed method is an effective tool for express analysis of dump truck stability. Using formula (7) to calculate the critical angle of inclination of the site for a dump truck with a stuck load, it is possible to carry out multivariate calculations at an early stage of vehicle design in order to select the optimal design solution. With this approach, the timing of the development of cars and the cost of conducting expensive tests are significantly reduced.

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