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Overview of energy-efficient bulldozer blade designs

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Abstract. The comprehensive research of modern energy-efficient and adaptive designs of bulldozer blades used in transport construction, mining and special engineering works, are carried out in the paper. The geometric parameters of the blades, the regularities of the drag prism formation, the force interaction of the blade with the soil, as well as the influence of various profiles (S-blade, SU-blade, U-blade, Σ-blade, VPAT and DSAB) on cutting resistance, performance and specific energy consumption are considered.

The research is based on the principles of soil mechanics, modeling of cutting forces, estimating the soil drag prism volume, determining the resistance to movement and calculating the technical performance of bulldozers with different types of blades. Particular attention is paid to innovative designs of Σ-blade and dual-stabilized angle blade, which provide a reduction in soil resistance by up to 15–28% and an increase in performance by up to 45% compared to blade traditional solutions.

The results obtained confirm the effectiveness of profiled and adaptive blades by optimizing the geometry of the working surface and adjusting the cutting angle. Engineering recommendations are proposed for the implementation of adaptive systems in modern bulldozers in order to reduce fuel consumption, reduce the load on the transmission and increase the energy efficiency of the machines.

Keywords: bulldozer blade, Σ-blade, DSAB, drag prism, cutting force, cutting angle, energy efficiency, performance, adaptive geometry.

INTRODUCTION

Bulldozers remain the basic machines for earth-works in the construction of highways, airfields, hydraulic structures, in open-pit mining and during planning and preparatory operations. Up to 60–70% of the total machine time is spent on the processes of cutting, moving, and leveling the soil. Therefore, it is the blade as a working element that determines the level of performance, energy consumption, and durability of the bulldozer [1–3].

Traditional blade designs (S-blade, SU-blade, U-blade) were created under conditions of limited requirements for profiling accuracy, fuel efficiency and adaptation to changing soil conditions. Modern requirements for machines have changed dramatically and include [4–8]:

– increase in profiling accuracy;

– increase in the resource of working elements;

– reduction of specific fuel consumption;

– adaptation to variable physical and mechanical properties of soils;

– automation of cutting process control;

– reduction of negative impact on the environment.

The insufficient adaptability of traditional blades to changes in cutting angle, cutting depth, soil density and speed leads to increased resistance, transmission overload and excessive fuel consumption of the machine. In this regard, profiled and adaptive Σ-blades, VPAT, DSAB are intensively developed in modern mechanical engineering.

The problem under consideration is a scientifically based assessment of the impact of geometry and cutting angle adjustment on the energy efficiency and performance of bulldozer blades.

The classical foundations of determining cutting forces and soil displacement are laid down in [1, 9–11]. The soil is considered as a semi-plastic medium, and the interaction with the working element is described through the forces of adhesion, friction and shear.

Recent research focuses on:

– curvature optimization of the blade working surface;

– reduction of the internal friction for the soil drag prism;

– control of the soil mass movement trajectory;

– application of variable blade geometry.

At the same time, most papers lack a systematic combination of analytical models, calculation dependencies and operational indicators, which determines this research relevance.

PURPOSE OF THE PAPER

The purpose of the paper is to substantiate the energy efficiency of adaptive designs of bulldozer blades by analyzing the geometric parameters of the blade, cutting forces, the formation of the drag prism, performance and energy consumption.

RESEARCH RESULTS

Several key development directions of bulldozer blade designs can be traced in modern mechanical engineering [2, 5, 11–16]. Foremost, this is an increase in versatility – the transition from highly specialized blades (straight, hemispherical, spherical) to multifunctional designs with the possibility of changing the geometry (PAT, VPAT). Such technical solutions allow for both rough movement of significant soil volumes and high-precision surface planning without the need to change the working equipment, which directly affects the efficiency of using the machine in variable operating conditions.

An important trend is the focus on energy efficiency, which is achieved by optimizing the profile of the front blade surface, reducing soil resistance forces, using high-quality wear-resistant steels and new composite materials. This allows you to reduce the specific fuel consumption of the machine by 10–15% while maintaining or even increasing technical performance. These trends are directly reflected in the change in the calculated parameters of cutting forces, the volume of the drag prism and resistance to soil movement.

The third key development direction is digitalization and automation. Leading models of bulldozers use integrated GPS navigation systems and automatic control of the cutting angle and blade inclination. This allows minimizing soil loss, ensuring high profiling accuracy (up to ±2 cm) and significantly reducing the impact of the human factor on the earthworks process.

Separately, it is worth noting the trend towards environmental friendliness and sustainability: manufacturers strive to reduce the environmental footprint of machine operation by implementing adaptive traction control systems, reducing vibration loads and using highly efficient hydraulic drives. As a result, modern blades become not only a performance working element, but also an element of the overall system of energy-efficient construction process management.

The analysis of information from open sources shows that leading manufacturing companies (Caterpillar, Komatsu, John Deere, Liebherr) are actively introducing new types of blades with increased functionality (Fig. 1). Among the most common design solutions are:

– Pitch Angle Tilt (PAT) and Variable Pitch Angle Tilt (VPAT) blades – universal multi-position designs with the ability to change the angle of inclination and rotation directly during operation;

– Universal (U-blade) – large-sized blades for moving significant volumes of soil over long distances;

– Semi-U (SU-blade) – compromise designs for road construction;

– Sigma (Σ-blade) – an innovative blade with the special profile that reduces soil resistance by 10–15%;

• Angle Blade / Dual-Stabilized Angle Blade (DSAB) – the new generation adaptive blade that provides «oblique cutting» of the soil and increases performance by 30–50% compared to the straight blade.

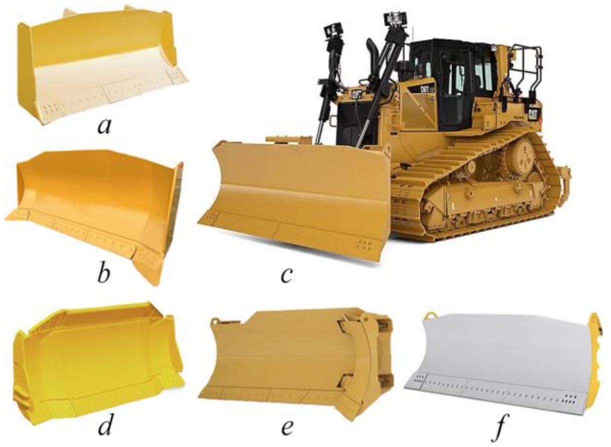

Fig. 1. Bulldozer blade designs:
a – U-blade; *b* – SU-blade; *c* – S-blade; *d* – Σ-blade; *e* – VPAT; *f* – Angle Blade / DSAB

The use of modern blades in combination with electronic control systems allows to significantly increase the efficiency of machines in various operating conditions. In particular, the introduction of VPAT blades in road construction provides a reduction in the duration of earthworks by 12–18%, and the use of Σ-blades in quarry conditions allows reducing fuel consumption by 8% [2, 17].

Thus, modern bulldozer blade designs are an example of the successful integration of mechanical improvements, innovations in materials science and digital technologies. These together form the new paradigm of energy efficiency in transport construction and directly affect the design parameters of the blade's interaction with the soil environment.

The decisive stage is the initial cutting of the soil in the process of bulldozer operation, at which the main load on the working equipment and power plant is formed [4]. The cutting force of the soil will be determined by the expression

$$F = k_c \cdot b + k_\varphi \cdot h^2 + c \cdot b \cdot tg\varphi, \qquad (1)$$

where k_c – soil cohesion factor; b – knife width; k_φ – factor that takes into account internal friction; h – cutting depth; c – soil adhesion; φ – angle of soil internal friction.

From the above expression (1), it follows that with increasing cutting depth, the resistance force increases. This is important for heavy and dense soils. In modern adaptive blades due to optimized geometry and adjustment of the cutting angle, it is possible to significantly reduce this force value.

The drag prism is formed after cutting the soil in blade front, the geometry of which determines the mass of the soil being moved and the resistance level

$$V = \frac{b \cdot h^2}{2 \cdot tg\left(\varphi + \alpha\right)}, \qquad (2)$$

where α – cutting angle.

We note that the drag prism has the smaller height and volume with increasing cutting angle and internal soil friction, which reduces resistance to movement and helps reduce energy consumption.

Resistance to movement of the soil prism

$$W_{dp} = \gamma \cdot V \cdot \frac{\sin\left(\alpha + \varphi\right)}{\cos\varphi}, \qquad (3)$$

where γ – volume soil density.

Dependence (3) shows that an increase in the cutting angle without optimizing the blade geometry leads to the significant increase in resistance, which confirms the feasibility of using adaptive working surface profiles.

We determine the bulldozer performance by the equation

$$Q = \frac{V_p \cdot k_f}{t_c}, \qquad (4)$$

where V_p – volume of soil movement per cycle; k_f – blade filling factor; t_c – work cycle duration.

Increasing the blade filling factor by stabilizing the soil prism in the Σ-blade and DSAB directly increases machine performance [14]. Forming the soil drag prism in DSAB

$$h_{ef} = h - \Delta h_d. \qquad (5)$$

Reducing the effective height of the soil prism due to sections leads to the reduction in displacement resistance of up to 28%, which experimentally confirmed the DSAB energy efficiency [2].

The comparative assessment of the efficiency for different blade types in terms of performance, soil resistance and specific energy consumption was performed (Fig. 2–6), based on the above analytical dependencies, as well as the generalization of operational data of modern bulldozers.

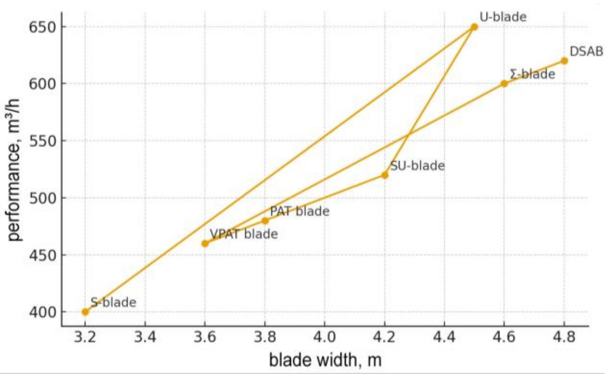

Fig. 2. Dependence of bulldozer performance on the blade

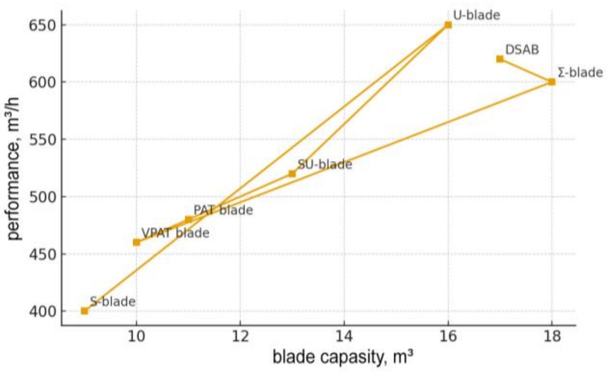

Fig. 3. Dependence of bulldozer performance on the blade capacity

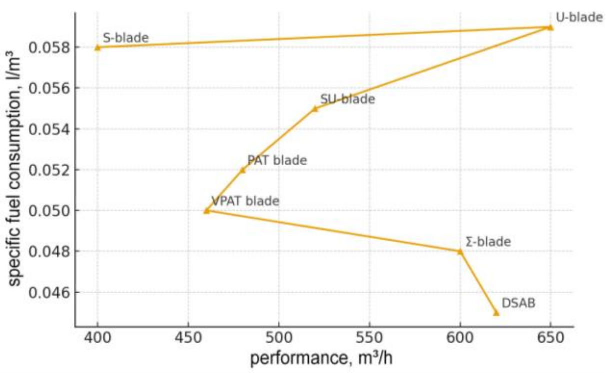

Fig. 4. Dependence of bulldozer specific energy consumption on the blade type

Performance increases almost proportionally with increasing blade capacity. However, for traditional blades, after a certain value, there is the decrease in efficiency due to lateral soil scattering. This effect is almost not observed due to the stabilization of the drag prism for Σ-blade and DSAB.

Comparative analysis (see Fig. 4) shows that specific energy consumption is within:

0.055–0.060 l/m^3 for S-blade;

0.042–0.050 l/m^3 for Σ-blade;

0.040–0.048 l/m^3 for DSAB.

Thus, the use of adaptive bulldozer blades allows reducing the specific fuel consumption of the machine by up to 15–20% compared to traditional designs.

Analysis of the performance dependences on the cutting angle shows that with increasing cutting angle, there is an initial increase in performance, which is due to an increase in the volume of the soil drag prism. At the same time, after reaching a certain optimal value of the cutting angle, performance begins to decrease due to the sharp increase in the resistance force to soil movement.

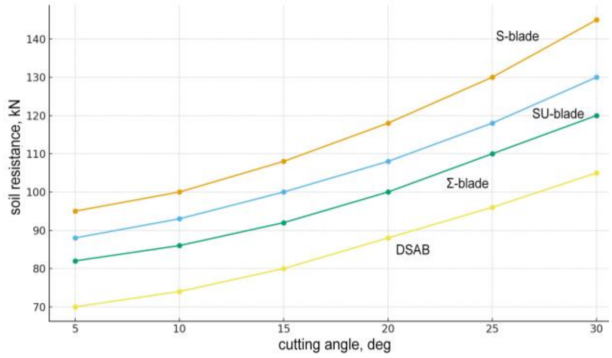

Fig. 5. Dependence of soil resistance on cutting angle for bulldozer blade types

Different optimal cutting angle values have been established for different types of blades:

48–52° for S-blade;

about 42° for Σ-blade;

32–36° for DSAB;

35–45° for SU-blade;

40–45° for U-blade;

30–55° for PAT/VPAT blades.

The obtained graphs on Fig. 5 demonstrate:

– resistance increases almost linearly with increasing cutting angle for S-blade;

– smoother curve of resistance decrease in the zone of average angle values is characteristic for Σ-blade;

– minimum resistance force is observed in the range of 30–35° for DSAB, which is explained by the effect of partial soil rolling.

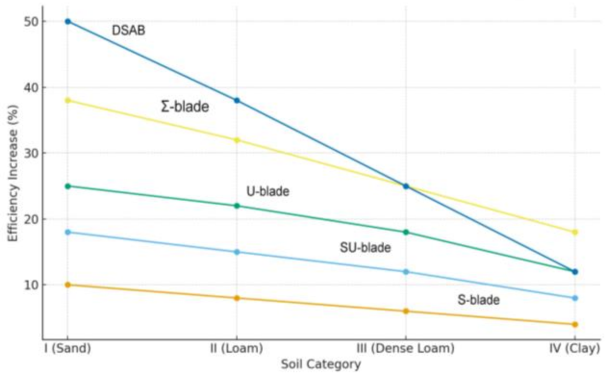

Fig. 6. Efficiency comparison of bulldozer blade types on soils of different categories

Thus, adaptive and profiled blades allow for effective operating modes at smaller cutting angles, which directly reduces the load on the power plant.

Reducing resistance to movement directly affects the reduction of energy consumption and the stability of the bulldozer operation.

The results (see Fig. 6) show that dual-stabilized angle blade (DSAB) is the most effective blade on:

– category I soils (sands) performance increase up to 50%;
– category II soils 35–40%;
– category III soils 20–25%;
– heavy clays 7–12%.

This confirms the versatility of DSAB while at the same time its greatest feasibility for weak and medium soils (Table 1).

Analysis of tabular data confirms that adaptive bulldozer blades provide higher planning accuracy, lower energy consumption and stable power plant load modes.

CONCLUSIONS

1. It has been established that adaptive and profiled designs of bulldozer blades provide the reduction in soil resistance by up to 28% compared to traditional straight blades.
2. The most effective in terms of energy efficiency and performance are Σ-blade and DSAB, which allow increasing the technical performance of bulldozers by up to 45%.
3. Optimal operating modes of bulldozer with adaptive blades are achieved at smaller cutting angles, which reduces the load on the transmission and extends the service life.

Table 1. Technical characteristics of bulldozer blade different types

Blade type	Main purpose	Planning accuracy, cm	Performance, m^3/h	Specific fuel consumption, l/m^3	Design features
S	Planning, development of dense soils	±3.0	300–450	0.055–0.060	Simple profile, high reliability
U	Moving large volumes of soil over the distance	±4.5	500–700	0.060–0.065	Large side wings, high capacity
SU	Embankments, slope formation, universal works	±3.5	400–600	0.050–0.058	Compromise between S and U blade types
PAT	Precise profiling, universal application	±2.0	350–550	0.048–0.055	Tilt and swivel angle are hydraulically adjustable
VPAT	Planning complex surfaces, work in limited conditions	±1.5	320–520	0.045–0.052	Variable blade geometry, GPS integration
Σ	Quarry work, reducing energy consumption	±2.5	480–650	0.042–0.050	Special sigma profile, reducing soil resistance
DSAB	Adaptive cutting, increased energy efficiency	±2.0	450–650	0.040–0.048	«Rolling prism» effect, reducing soil resistance
Special	Snow, coal, forest areas	±5.0	250–400	0.050–0.060	Increased height or profile for the material

4. DSAB demonstrated the best results on categories I–II soil, which makes it appropriate for road and industrial construction.

5. VPAT blades are recommended for high-precision planning work, where minimal profiling error is required.

Practical recommendations:

– introduce adaptive blades in the bulldozer fleet of construction organizations;

– use adjustable cutting angles depending on the soil type;

– focus on reducing the effective height of the drag prism when designing new blades;

– use wear-resistant and composite materials to reduce the weight of the blade;

– integrate electro-hydraulic systems for automatic blade position control.

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Огляд енергоефективних конструкцій бульдозерних відвалів

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Анотація. У роботі виконано комплексне дослідження сучасних енергоефективних та адаптивних конструкцій бульдозерних відвалів, що застосовуються у транспортному будівництві, гірничій промисловості та спеціальних інженерних роботах. Розглянуто геометричні параметри відвалів, закономірності формування призми волочіння, силову взаємодію відвала з ґрунтом, а також вплив різних профілів (S-blade, SU-blade, U-blade, Σ-blade, VPAT та DSAB) на опір різанню, продуктивність і питомі енергетичні витрати.

Дослідження ґрунтується на положеннях механіки ґрунтів, моделюванні сил різання, оцінюванні об’єму ґрунтової призми волочіння, визначенні опору переміщенню та розрахунку технічної продуктивності бульдозерів з різними типами відвалів. Особливу увагу приділено інноваційним конструкціям Σ-blade та відвалам DSAB, які забезпечують зниження опору ґрунту до 15–28% та підвищення продуктивності до 45% порівняно з традиційними рішеннями.

Отримані результати підтверджують ефективність профільованих та адаптивних відвалів за рахунок оптимізації геометрії робочої поверхні та регулювання кута різання. Запропоновано інженерні рекомендації щодо впровадження адаптивних систем у сучасні бульдозери з метою зниження витрат палива, зменшення навантаження на трансмісію та підвищення енергоефективності машин.

Keywords: бульдозерний відвал, Σ-blade, DSAB, призма волочіння, сила різання, кут різання, енергоефективність, продуктивність, адаптивна геометрія.