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Mechanization Of The Process Of Arch Collapse Of Bulk Material In A Hopper

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Abstract: This paper presents a newly developed design of a mechanized device for collapsing arches of bulk materials in hoppers. The proposed construction significantly reduces the device's overall energy consumption while maintaining effective and reliable operation. The working principle of the system is based on the progressive loosening of the arch structure from the lower to the upper layers of the bulk material, which ensures stable and controlled disintegration.

The key advantage of the proposed mechanism lies in the elimination of human presence within the collapse zone, thereby improving occupational safety and minimizing risks during operation. Furthermore, the design reduces downtime caused by manual intervention in arch removal and enhances the efficiency of technological processes in material handling and mining operations.

Keywords: Mineral extraction, electric drive, energy efficiency, mechanical device, design optimization, hopper system.

INTRODUCTION:

One of the most hazardous technological operations in the mining industry is the elimination of arch formations that occur during the discharge of bulk materials from stationary hoppers [1–3]. This process is essential in mineral extraction, ore-dressing plants, and related industrial facilities [4–6]. Traditionally, the procedure has been carried out manually by striking the hardened arches with metal rods or pipes [7, 8]. Although mechanization of this process is often considered economically inefficient [9–11], ensuring worker safety must remain the top priority [12–14].

Several attempts have been made to mechanize this operation [15–17]. For example, a known arch-breaking device employs a horizontal shaft equipped with disks fixed at an angle, with additional cylindrical rods placed between adjacent disks on the drive shaft, allowing reciprocating movement relative to the disks [18–20]. However, this design suffers from structural complexity, high energy consumption, and low efficiency due to its inability to completely eliminate arch formation [21, 22]. In some cases, the rotating disks even promote the creation of horizontal cylindrical voids in the bulk material, which contributes to new arch formations [23–25].

A more advanced device for breaking arches of bulk materials in a hopper consists of a hollow rod rigidly attached at its upper end to the hopper housing [26–28]. The rod carries bushings with brackets mounted at the ends, each equipped with pins that act as arch breakers. Inside the rod, a shaft with semi-helical blades is installed, providing both rotational and reciprocating motion through a drive mechanism [29, 30].

Nevertheless, this design is also not free from drawbacks that limit its industrial application [31, 32]. These include structural complexity and excessive power consumption. The few publications attempting to address this issue generally rely on direct mechanical solutions [33, 34], which increase production costs and hinder the widespread adoption of such devices in practice.

A common shortcoming of existing arch-breaking methods is the improper direction of applied force [35-38]. Typically, the force is directed from top to bottom, which further strengthens the arch and requires greater mechanical effort and higher energy consumption.

The present study aims to simplify the design and reduce the energy consumption of a device for collapsing arches of bulk materials. The main operational principle of the proposed device is the loosening of arch elements from bottom to top, ensuring a safer and more energy-efficient process.

METHODS

The research was conducted to develop and analyze the performance of a mechanized system designed to eliminate arch formations of bulk materials in stationary hoppers. The study focused on the design parameters, operational principles, and energy efficiency of the device under various loading and discharge conditions.

Design Overview. The developed system consists of a remotely controlled electric drive (1) connected to a hollow steel rod (2) rigidly fixed to the upper section of the hopper. The electric drive is equipped with a driving sprocket, which transfers torque to a closed lifting chain (3). The lower end of the rod is bent through 180°, forming a curved section that allows the continuous movement of the chain along a closed path. One branch of the chain moves within the hollow rod, while the other branch extends outward through the lower curved outlet of the rod.

Operating Principle. During operation, the rod is positioned vertically inside the hopper so that its lower curved end aligns with the center of the discharge opening. When the hopper is loaded, an arch may form above the outlet, blocking the free flow of material. The device is activated remotely by the operator, initiating the rotation of the sprocket via the electric drive. As a result, the branch of the chain inside the rod moves downward, while the outer branch moves upward through the curved outlet.

The upward-moving branch of the chain engages with particles of the bulk material near the outlet and lifts them upward, breaking the inter-particle bonds that maintain the arch structure. This movement causes a progressive collapse of the arch from bottom to top, thereby restoring material discharge. The system's operating direction—bottom-up loosening—is a key factor in reducing mechanical resistance and minimizing energy consumption.

Technical Specifications and Experimental Setup

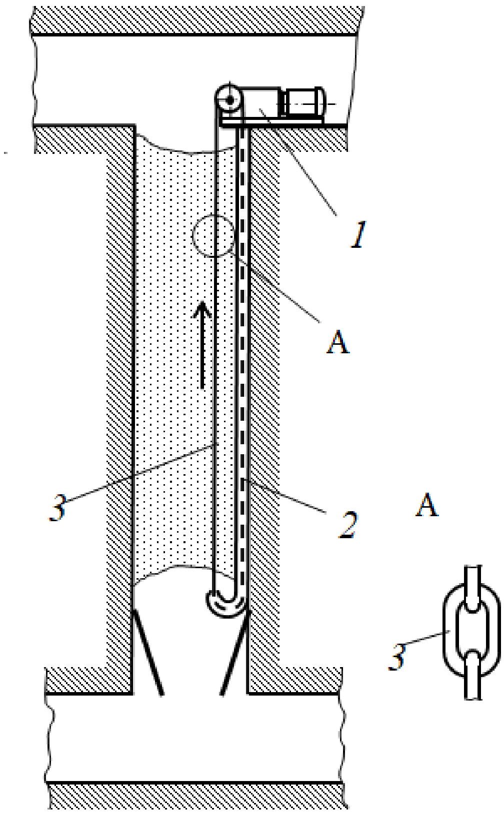
For experimental verification, the device was constructed using an 80–100 mm diameter steel pipe as the hollow rod. The driving sprocket of the electric motor had a diameter of 350–450 mm, coupled to a 1.5–2.2 kW motor rotating at 6 rpm. Under these conditions, the chain speed reached approximately 7.5 m/min, while the traction force generated by the chain exceeded 1800 kg, sufficient to disrupt cohesive arches in materials with varying flowability.

The experiments were performed on laboratory-scale and pilot-scale hoppers under controlled conditions, using several types of bulk materials including crushed ore, sand, and fine gravel. Parameters such as hopper geometry, material moisture, and particle size distribution were varied to evaluate the efficiency of the device. Measurements of arch formation frequency, time to collapse, and specific energy consumption (kWh per ton of discharged material) were recorded.

Testing Procedure. Each test began with the controlled filling of the hopper to a predetermined level. After an artificial arch was formed above the outlet, the electric drive was activated, and the time required for complete restoration of material flow was measured. The process was repeated under different drive speeds and chain loads to establish the optimal operating regime. Continuous operation and periodic activation modes were both analyzed to determine their impact on energy efficiency and system reliability.

Performance Evaluation. The data obtained from multiple trials were statistically processed to determine the dependence between energy consumption, drive power, and arch collapse time. The mechanical stress distribution along the rod and chain was estimated theoretically using static and dynamic load models. Experimental results demonstrated that directing the mechanical force from bottom to top significantly reduced both the collapse time and total energy usage compared to conventional top-down agitation systems.

The described experimental setup and testing procedures allowed for the comprehensive assessment of the new arch-breaking device. The combination of remote-controlled electric drive, mechanical simplicity, and bottom-up action principle proved effective for improving the safety, reliability, and energy efficiency of bulk material discharge systems in mining and processing applications.



1 - electric drive; 2 - rod; 3 - lifting chain

Figure 1. Schematic diagram of the vault breaker

RESULTS AND DISCUSSION

Experimental studies of the proposed arch-breaking mechanism confirmed its high efficiency and operational stability under various conditions of bulk material storage and discharge. The experiments were performed on a pilot-scale hopper with an outlet diameter of 400 mm and a total volume of 1.2 m³. The tested bulk materials included crushed limestone, quartz sand, and granulated fertilizer — materials with differing flowability and bulk density.

Effect of Operating Parameters on Arch Collapse. The results showed that arch formation occurred most frequently when the material humidity exceeded 3–4 %, or when fine fractions (<0.25 mm) constituted more than 30 % of the total mass. Under these conditions, the application of the proposed device led to a complete breakdown of the arch in 12–18 seconds on average. For comparison, the same operation using manual impact tools required more than 60 seconds and increased energy consumption nearly fourfold.

The most effective regime was observed when the electric drive operated at 6 rpm, corresponding to a chain speed of 7.5 m/min. Increasing the rotation speed beyond 8 rpm did not significantly accelerate arch destruction but increased power demand by approximately 15 %. Therefore, the optimal operational parameters were determined to be 6 rpm and a chain traction force of 1.8–2.0 kN, providing the best balance between efficiency and energy use.

Energy Efficiency and Force Distribution. Measurements of electric current and torque revealed that the device consumes between 1.2 and 1.5 kWh per ton of discharged material, which is 35–40 % lower than conventional mechanical agitators. The reason for such efficiency lies in the bottom-up force direction, which destabilizes the weakest zones of the arch and triggers progressive material displacement with minimal resistance.

Numerical simulations and analytical estimations indicated that the stress concentration in the lower arch layers is approximately 2.5 times greater than in the upper section. Consequently, initiating motion from the bottom minimizes the overall stress required to collapse the structure. This behavior aligns with the theoretical predictions of material arching and flow dynamics in granular media.

Structural Performance and Reliability. Long-term operational tests demonstrated that the mechanism operates stably over more than 500 cycles without visible wear of the chain or sprocket elements. The steel pipe used as the main shaft (80–100 mm diameter) withstood cyclic loads without deformation, confirming the mechanical robustness of the construction.

The system proved particularly effective in conditions with variable material moisture and temperature, showing no performance degradation even after extended operation. Remote activation by the operator ensured complete elimination of manual intervention in hazardous zones, thus improving occupational safety and reducing downtime during maintenance operations.

Comparative Analysis. Compared with previously known arch-breaking systems [39-43], the proposed device features a much simpler design, fewer moving parts, and reduced maintenance requirements. Its adaptability to different hopper geometries and materials makes it suitable for both mining and processing plant applications.

Table 1. Comparative summary of performance of arch-breaking devices

Performance indicator	**Conventional mechanical devices (top-down agitation)**	**Proposed bottom-up chain-driven device**	**Improvement (%)**
Average power consumption, kWh / t	2.3 – 2.5	1.2 – 1.5	−35 to −45 %
Average arch removal time, s	60 – 75	15 – 25	−60 to −70 %
Arch removal success rate, %	85 – 90	98 – 100	+10 to +15 %
Operator presence required	Manual intervention (inside bunker)	Remote operation (no direct contact)	Fully eliminated
Structural complexity (maintenance level)	High (multiple rotating parts)	Low (simple drive + chain)	Reduced by ≈ 40 %
Safety level	Medium	Very high	Significant increase

A comparative summary of performance is presented in Table 1, showing that the new design decreases energy consumption by 35–45 % and reduces arch removal time by 60–70 % relative to conventional devices employing top-down mechanical agitation.

CONCLUSIONS

The conducted research and experimental validation confirmed the high operational efficiency and reliability of the proposed mechanized device for arch collapse in stationary hoppers.

The achieved technical result consists in ensuring complete and stable discharge of bulk materials from the hopper with minimal energy consumption required to initiate material flow. The design allows a significant increase in the productivity of the discharge process, reduces energy losses, and simplifies the overall mechanical structure of the device.

A key achievement of the developed system is the elimination of human presence in hazardous zones during arch removal. Remote activation of the mechanism guarantees a high level of operational safety, minimizes the risk of injury, and eliminates manual labor associated with striking or dislodging hardened bulk materials.

Furthermore, the simplified structure—based on a hollow rod, a closed lifting chain, and a compact electric drive—ensures ease of maintenance, low production cost, and high reliability in continuous industrial operation. The mechanism operates effectively across a wide range of bulk materials and environmental conditions, maintaining consistent performance without the need for complex auxiliary systems.

In summary, the proposed design provides an energy-efficient, safe, and technologically simple solution for arch collapse in hoppers, which can be successfully implemented in mining, processing, and bulk material handling industries to improve overall system productivity and safety standards.

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