

Safety and health engineering solutions to HISLO vibrations in surface mining

Abstract

The use of large shovels to load large trucks in surface mining has resulted in high-impact shovel loading operations (HISLO). HISLO generates high-frequency shockwaves that cause extreme vibrations exposing operators to whole body vibrations (WBV) and injuries. Previous research has formulated numerical simulation models for understanding HISLO vibrations and their impact on operators. The results showed that the vertical root-mean-square (RMS) acceleration of the operator's seat was 3.56m/s^2 . This RMS value exceeds the ISO 2631-1 limits for extremely uncomfortable zones posing safety and health risks to operators over long-term exposures. This research provides solutions to high WBV problems. The primary objective is to reduce or completely eliminate HISLO RMS accelerations. The research focused on re-engineered seat, impulse force reductions and enhanced add-on suspension systems using the 4100XPB shovel to load CAT 793 trucks to achieve this objective. The results showed that these interventions reduced the RMS acceleration by 50.84% from 3.56m/s^2 to 1.75m/s^2 , and with further research, a projected target of 0.30m/s^2 could be achieved with continuous flow dumping. This research is a pioneering effort that significantly improves the workplace safety and operator health in HISLO conditions.

Keywords: HISLO, engineered seat, impulse force, enhanced add on suspension, safety and health, RMS acceleration

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Abbreviations: HISLO, high impact shovel loading operations; WBV, whole body vibrations; RMS, root mean square; MSHA, mine safety and health administration

Introduction

Surface mining comprises complex geometries, dangerous operations and human controlled machines. Due to human errors, unstable layouts, geological deformations, and design problems, safety and health hazards including fatal accidents occur. The 2016 fatal accidents review by the Mine Safety and Health Administration (MSHA) showed that mobile machines accounted for 58.3% (2012), 36.4% (2013), 39.1% (2014), 57.1% (2015) and 59% (2016) fatalities.¹ Previous MSHA data shows that, out of 250 fatalities in surface mining, 40% was attributed to powered haulage. An average of 675 accidents and 21 powered haulage fatalities occur each year in surface mining and 20% of these accidents involve dump trucks.¹ The use of large shovels to load large trucks in surface mining has resulted in HISLO. HISLO generates high-frequency shockwaves that cause extreme vibrations exposing operators to high WBV levels and injuries. Aouad² and Frimpong and Aouad et al.,³ showed that the vertical RMS acceleration of the operator's seat was equal to 3.56m/s^2 during the loading of the CAT 793D in oil sands formation. This RMS value exceeds the ISO 2631-1 limits³ for extremely uncomfortable zones ($>2.5\text{m/s}^2$), and may cause short-term and long term injuries. The most common type of accidents was jarring (37.7%), which results in back injuries. ISO 2631-1 also shows that operators exposed to WBV with RMS values $\geq 1.0\text{m/s}^2$ over 8hour durations have a high probability of experiencing sacrum, lumbar and cervical problems.³ Frimpong S⁴ undertook an ergonomic evaluation of excavations for understanding musculoskeletal epidemiology.

Using pilot experiments, he showed that digging and hauling had higher levels of total weighted acceleration than idling. They also showed that the seats were not designed to protect against high WBV levels. Frimpong S et al.,⁴ extended the study into awkward postures. They showed that operators are afflicted by musculoskeletal injuries of the arms, shoulders, neck and lower back. This research was undertaken to provide engineering solutions to HISLO problems. The primary objective was to reduce significantly (below 0.315m/s^2 RMS acceleration) or completely eliminate the impact of RMS accelerations on operators. The 0.315m/s^2 value is the upper threshold for the "Comfortable" region of the ISO 2631-1 Limits.³ The elements of this objective were to develop:

- i. Enhanced engineered add on suspension systems to absorb significant levels of shockwaves.
- ii. Impulse force technology to reduce the magnitudes of shockwaves.
- iii. Re engineered seat to reduce the impact of RMS accelerations. The research addressed the vibration problems associated with loading large trucks, such as the CAT 793 and 797 and the Komatsu 930 series by large shovels, such as the P&H 2800XPB, 4100XPB, 4100BOSS or BI 495.

Enhanced engineered add on suspension system

- a. Previous numerical simulation results showed the vertical RMS acceleration at the seat was 3.56m/s^2 . This exceeds the "Very Uncomfortable" limit of 2.5m/s^2 .¹ Thus the first step was to reduce these accelerations by isolating the shockwaves using commercially available components in critical places. The simulated HISLO

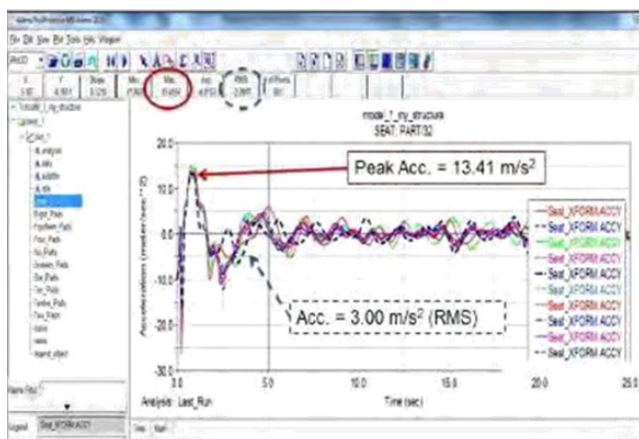
model with 39-DOF (degrees of freedom) showed the weakest suspension-chassis links. These links include: the contact between the truck bed and the chassis.

b. The chassis.

Cabin interface. The bed frame rests on the chassis with steel on steel contact. The bed is allowed to pivot around one end located above the rear axle with the assistance of hydraulic pistons.



Once ready for loading the bed rests on the steel chassis with highest contact forces towards the opposite location from the pivot point. The deformation analysis results of the longitudinal beams at the bottom of the bed where it rests on the chassis, showed that the tip on these two beams require insulation in order to attenuate the HISLO vibrations. Once identified rubber pads were added in pairs and the dumping process was simulated under HISLO conditions using a set of 2, 4, 6, 8 and 16 pads. Simulation results showed that a set of 16 pads gave the optimum results. The addition of the 16 pads in these areas reduced the RMS seat vertical acceleration by 15.7% to 3.00m/s².⁵



Impulse force reduction technology

The HISLO impact is magnified by gravity dumping from high vertical distances. The previous work assumed that the 100 tons of materials is applied at the center of gravity of the truck bed without considering dumping height and the accumulated material acting as a cushion to dampen subsequent loads. First, the input impact force (or load) was modeled as a 5-step function, each equivalent to 20tons with the cumulative static applied load as 100 tons. This cumulative step function mimics the gradual dumping process with a total of 5

seconds of applied force. The virtual simulation of the 39-DOF truck model showed an 11.2% reduction in the RMS vertical acceleration at the seat level, lowering its value to 2.54 m/s². To further reduce HISLO vibrations, research focused on developing mathematical and empirical algorithms to model the continuous flow of material dumping into the truck.



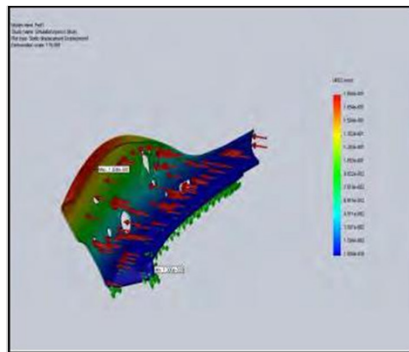
The continuous material flow ensures that the 100+ tons of payloads is distributed over time during the dumping process. The distributed material from the first pass forms a “cushioning” base for subsequent materials, and thus, reduces the impact force. The 3-D virtual simulator of the HISLO process was simulated using the P&H 4100XPC loading the CAT 793D in PFC3D. The results showed that the cushioning effect from continuous flow of materials reduced the maximum impact force from 1,000 KN to 211.7 KN for the same maximum dumping height of 7.33m. For the optimum dumping height of 4.90m, the maximum impact force was reduced to 172.5 KN, an 82.8% reduction. This reduction has the potential to lower the 1.75m/s² to 0.302m/s², below the “Comfortable” region of the ISO 2631-1 Limit. However, further research is required to scientifically verify this value.



Engineered operator seat development

The research examined the operator’s seat design and its response to high frequency HISLO vibrations, and the subsequent seat re-engineering to reduce or completely eliminate the impact of RMS accelerations. The current seat was virtually modified using Solid Works®, and then simulated using MSC.NASTRAN® for strength

analysis and MSC.ADAMS® for dynamic modeling and acceleration tracking [MSC, 2010].

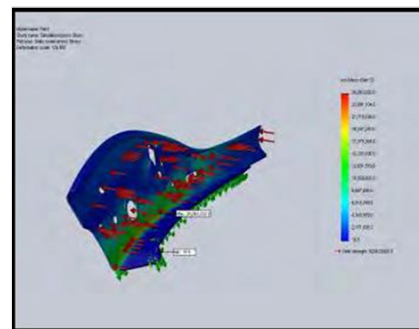


The aim of the proposed virtual seat modifications is to create an ergonomic seat with reduced vertical and lateral accelerations in order to reduce operator’s exposure to extreme HISLO accelerations. The engineered modifications of the operator’s seat were divided into two main categories:

- a. The seat frame modifications (SM),
- b. The seat-cabin interface modifications (SCM).

The seat frame and structure were reinforced to align the spine and support the lower and mid back areas, thus maintaining a combined center of gravity (seat + operator) around the hip-pelvic area. An additional back stabilizer was introduced to replace the mesh wire type back in order to create a stiffer back area that is simply supported by four points at the edges of the added plate. The additional plate resulted in a stable back structure that reduces the vibrations through the seat. Also it added some weight to the seat, which pushed the center of gravity to the hip pelvic area. The second category of modifications for the re-engineered seat focused on the seat cabin interface, where the seat is firmly attached to the cabin base platform. This modification achieved an additional 8.85% reduction in the overall vertical RMS acceleration at the seat level. The addition of a rubber pad insulator between the cabin platform and the seat base allowed the reduction of the high frequency wavelength traveling from the cabin through the seat. This vibration damping, oil-resistant rubber pad made with neoprene pads had a capacity of 500 psi per mounting point and 9/16” thickness. Moreover, the seat lateral side curvatures were increased to contour around the operator’s lower back and “hug” the operator in a way to attach the operator firmly to the seat without allowing any side movements. Furthermore, stress analysis was performed on the modified components to insure that the proposed seat is robust and

avoids structural failure. The stress analysis showed that the lateral side additional curvatures have a maximum deflection of 0.007 inches (0.18mm) with maximum Von Mises stress of 3771 psi (26 MPa). These combined design modifications lowered the overall seat vertical RMS acceleration by 31.1%. The SM contributed 24.4% reduction and the SCM contributed 8.85% reduction. The overall reduced vertical RMS acceleration at the seat level was recorded to be 1.75m/s². Table 1 highlights the reduction steps. Comparing the vertical RMS acceleration of 3.56 m/s² from Aouad et al.,² to the achieved value of



1.75m/s², one can conclude that the vertical RMS acceleration at the seat level was lowered by 50.8%.

Conclusion and novelty

Overall, the engineered systems in Table 1 reduced the RMS acceleration by 50.84% from 3.56m/s² to 1.75m/s², and with further research, a projected target of 0.302m/s² could be achieved with continuous flow dumping. These reductions are significant, and if the projected 0.302m/s² RMS acceleration value can be verified, the “Comfortable” region of the ISO 2631-1 Limits would have been achieved. The 0.302m/s² RMS acceleration is a projection from a research initiative based on rigorous mathematical and empirical algorithms to model the continuous flow of materials from the dipper into the truck. The results show that the cushioning effect from continuous flow of materials reduced the maximum impact force from 1,000KN to 211.7KN for the same maximum dumping height of 7.33m. For the optimum dumping height of 4.90m, the maximum impact force was reduced to 172.5KN, an 82.8% reduction. This reduction could significantly reduce further the 1.75m/s² to 0.302m/s², the comfortable region in the ISO 2631-1 Limits. However, the 0.302m/s² is yet to be verified and cannot be relied upon as a scientifically verified fact. This research is a pioneering effort that significantly improves the workplace safety and operator health in HISLO conditions.

Table 1 Major research progress and achievements

Research ID	Research description	Vertical seat acc. (RMS)	% Reduction
Base	Previous Work	3.56 m/s ²	-
1	Addition of 16 Pads	3.00 m/s ²	15.73%
2	Height Reduction	2.86 m/s ²	4.67%
3	5-Step Input Force	2.54 m/s ²	11.13%
4	New Seat Design & Modifications	1.92 m/s ²	24.41%

Table continued...

Research ID	Research description	Vertical seat acc. (RMS)	% Reduction
Base	Previous Work	3.56 m/s ²	-
5	Additional Damping at Seat Base	1.75 m/s ²	8.85%
6	Continuous Flow Modeling	0.302 m/s ² *	82.8%*

*The continuous flow modeling resulted in 82.8% reduction in the maximum impact force but vertical acceleration reduction is a projection and yet to be verified

Broader impact of HISLO vibrations research

This research initiatives advances knowledge and frontiers in HISLO vibrations resolution for ultra large dump trucks and creates the potential for further advanced vibrations research associated with mining machines in different environments. It further achieves technological advancements in enhanced engineered add-on suspension system, impulse force reductions, and engineered operator seat for ultra large mining trucks for reducing operator exposures to high WBV levels. These technological interventions have reduced the RMS acceleration by 50.84% from 3.56m/s² to 1.75m/s². With further research, a projected target of 0.302m/s² could be achieved with continuous flow dumping process. These reductions significantly improve workplace safety and health especially for ultra large mining truck operators. Ultimately, this research provides potential paths for a new generation of improved mining truck design.

Acknowledgments

None.

Conflict of interest

Author declares that there is no conflict of interest.

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