ISSN 0371 - 9538

Vol. 118
April, 2021 - March, 2022

TRANSACTIONS

A Technical Publication of
The Mining, Geological and Metallurgical Institute of India

Established 1906

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Inaugurated 1906 - incorporated 1909 - as the Mining and Geological Institute of India, the word Metallurgical was included in the title in 1937.

Honorary Editor
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Associate Editor
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Price

- Free to Member
  (Rs. 100/- for each additional copy)
- Non- Members
  Rs. 200/- per copy
- Foreign US$ 25.00 per copy

Published by
Ranajit Talapatra, Hony. Secretary
The Mining, Geological and Metallurgical Institute of India
GN - 38/4, Sector - V, Salt Lake City, Kolkata - 700 091

Printed at :
Graphique International
Kolkata

THE MINING GEOLOGICAL & METALLURGICAL INSTITUTE OF INDIA 1906

CONTENTS

PRESIDENTIAL ADDRESS FOR 116TH ANNUAL GENERAL MEETING AT GRAND HOTEL, KOLKATA ON 25TH SEPTEMBER 2022

P M Prasad*

PM Prasad
President

Respected Members of MGMI,

It is my privilege to welcome you all to the 116th AGM of this prestigious organization. It is indeed an honour for me to have been the President of a century old institution and I take this opportunity again to thank each and every member.

India completed 75 years of its independence on August 15 and has now entered 'Amrit Kaal' which will last till 2047. This year we have overtaken our colonial masters to become the fifth largest economy of the world.

The period till 2047 will witness a fast growth of economy. Energy and resource requirement will grow and this will significantly increase demand for coal, oil & gas and new age minerals like lithium, rare earths etc.

Energy use and access are strongly correlated with economic development. But the question is how to meet energy demand of the nation. If we talk about energy option of India, it is very limited. Coal-fired power plants contributes about 70% of India's electricity demand. We are highly dependent on import for oil and natural gas. Domestic oil production has declined 21% since 2010-11 and production of natural gas has declined even more by 35%. This is increasing onus on coal to meet energy and resource security of the nation. Coal is available in abundance and has potential to meet energy and infrastructure demand of the nation and domestic coal production has increased substantially in an effort to cope up with the demand.

The mineral requirement for new power generation capacity has increased by 50% since 2010 as low-carbon technologies, like - renewable and nuclear, take a growing share of investment and its demand for clean energy technologies would rise by at least four times by 2040 to meet climate goals. Manufacturing solar panels, wind turbines, and batteries will shape the supply and demand for critical minerals for the foreseeable future. Mining and mineral industry will continue to be of utmost importance.

The time has come to give emphasis on the need of the Circular Economy and is the only way towards the conservation of resources. India's material recycling rate stands at 30%. The rate of recycling to be increased substantially for Aluminum, Copper and Zinc. We must understand that the future of humanity cannot be built on a 'take-make-dispose' model i.e., Linear Economy. Metal sector needs to be at the forefront of the circular economy model in view of its pervasive applications besides the inherent potential of metals to be amenable and adaptable to business models following 6R principles of Reduce, Recycle, Reuse, Recover, Redesign and Remanufacture.

The country is blessed with young population, with cheap and skilled labour. The country has abundant reserves of coal and minerals. It has FDI inflow. If India is poised to grow into a $5 trillion economy and keep its growth high while generating employment, the Geology, Mining, Metallurgy sector has a big role to play in ensuring energy security and availability of resources while on the other hand, has to reduce carbon footprint. Despite thrust on re-newables, coal won't be easy to

Presidential Address delivered on 25th September 2022 at the 116th Annual General Meeting at Grand Hotel, Kolkata.
**President, MGMI and CMD, Central Coalfields Limited*

shake off and industry needs to adopt new technologies to mine scientifically to remain cost competitive and to ensure environmental sustainability.

All these above needs are where we in MGMI come in, and can strive to be the knowledge and skill partner for many of the arms of the government and other likeminded agencies which are dealing with energy and resource security of the country.

The 9th edition of our flagship event, Asian Mining Conference and International Mining Exhibition (9th AMC & IME) organized by MGMI and held concurrently at Kolkata between 4th and 7th April 2022 was an effort to be back to normalcy by being the first such physical event in the Mining Sector organized in India, after the pandemic induced disruptions that started in March 2020. More than 250 professionals from Mining, Oil & Gas, Earth Sciences, Power companies and Educational & Research Organizations Participated in the conference and about 180 companies (including 6 international Mining and Mining Equipment companies) related to Mining, Earth Sciences and related fields put up stalls exhibiting their wares in the exhibition. Top government functionaries, and Industry leaders spoke during the conference and several eminent persons presented very interesting and enlightening papers.

With the easing up of life, MGMI also held the pandemic delayed 17th Foundation Day Lecture in July this year by Prof S P Banerjee, our past President and a very respected and eminent Mining Academic and was attended by a full house physically and watched by several members through YouTube Live.

Due to the pandemic, some of our Journals could not be published on time, but with the help of our eminent Editorial team, MGMI is trying to make up for the lost time. It is a matter of pride that the quality and contents of the MGMI News Journal are appreciated by the readers and I sincerely hope that they will continue to do so in future. I congratulate the News Journal editorial team led by Shri AK Singh for this and at the same time wishes that efforts are made to further improve and enrich the contents of the News Journal for the benefit of the readers and the members.

Though there was a setback due to the last two years of inaction regarding conferences, MGMI in now again in good financial health. As a not-for-profit society, our goal is to organize events that are affordable for members while maintaining the financial strength and flexibility of the Society. Councils have taken great care in managing the Institute's balance sheet and this year was no different. I would specially like to thank the Honorary Secretary Ranajit Talapatra for his efforts to successfully steer the team of very senior committee members who sincerely toiled over 6 months to make the 9th AMC and IME a grand success despite the odds, even having to rework schedules due to relapse of the Omicron variant in January this year, considering the squeezed timeline. The conveners of the Conference and Exhibition, Sri Rajiw Lochan & Sri Prasanta Roy have given yeoman service in tandem with MGMI staff in getting the maximum participation for this event.

The future programme of this institute involves a Holland memorial lecture held with a Half day Seminar and the President's Golf Tournament, other than short courses held in collaboration with other Mining research and Educational institutes, both Indian and International. We were in talks with CSIR-CIMFR as well as the Polish embassy and GIG, Katowice, Poland for organizing trainings in India and abroad. Hope that my successor will carry that forward and the name of this august institute will transcend boundaries in days to come.

I thank the numerous organizations and individuals who have helped to make my tenure gratifying and successful. We look forward to a healthy, safe and sustainable future of mankind and hope that MGMI keeps contributing to that end. It has been my honour to represent MGMI as President in the last two years. I am thankful to the Council members for the trust they reposed in me. I look forward to this institute's continued success under the new President.

JAIHIND

FROM EDITOR'S DESK

Ajay Kumar Singh[1]

The mining, geological exploration, and metallurgical engineering sectors have been integral to the development of the Indian economy. They have provided essential raw materials, supported industrial growth, created employment opportunities, and enhanced the country's competitiveness in the global market. Continued investment in these sectors, coupled with sustainable practices, will further drive economic progress and social well - being in India.

India possesses abundant mineral resources, with the mining sector assuming a pivotal role in the extraction of crucial minerals like coal, iron ore, bauxite, limestone, and other essential raw materials needed across diverse industries such as steel, cement, and power generation. Concurrently, geological agencies have been instrumental in the exploration of untapped deposits and assessing their viability for exploitation, while the metallurgical engineering has played a vital and indispensable role in the conversion and purification of minerals into valuable metals and alloys, further enhancing the significance of the mining and metallurgical sectors in India's industrial landscape. Through the publication of its proceedings and regular journals such as the Transactions, the Mining, Geological, and Metallurgical Institute of India (MGMI) effectively disseminates knowledge and information pertaining to Mining, Geology, Metallurgy, and related disciplines.

Due to the ongoing pandemic, there have been delays in the publication of the Transactions. The dedicated editorial board is working tirelessly to expedite the process and restore regularity to the publication. At MGMI, we are working hard to ensure that the journal is released in a timely manner while upholding the high standards of the publication and meet the expectations of the readership. This includes streamlining internal processes, coordinating with authors and reviewers, and implementing efficient workflows. The Editorial Board's proactive approach and unwavering determination are key factors in successfully navigating the obstacles and restoring regularity to the publication of the Transactions. We also urge MGMI members to proactively contribute papers to the journal. To encourage such efforts, a committee has been setup by the MGMI Council to select the best technical paper published in the Transactions. These initiatives are particularly targeted at early-career researchers and professionals across academia and industry.

The modernization of the mining and mineral industries requires the adoption of contemporary practices in various sectors, including mining technology, occupational health and safety, environmental management, productivity enhancement, waste utilization, and post - mining site restoration. To achieve this, the industry must embrace cutting - edge approaches such as instrumentation and the application of artificial intelligence. These innovative techniques will play a vital role in improving efficiency, sustainability, and overall performance in the planning and execution of mining operations. By integrating these modern practices, the industry can maximize its potential while minimizing its environmental impact. It is evident that the five 'Panchamrit' goals as envisaged by the Hon'ble Prime Minister of India at COP26 have to be strategically linked to future production plans of companies in this sector.

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The mining industry has always prioritized safety management and adhered to stringent Mining Acts and Regulations worldwide. However, there has been a notable shift in safety enforcement approaches over the past two decades. The advent of advanced technologies, modern information, and communication systems has revolutionized mine management, mirroring the transformation occurring in various sectors of our society. As we embark on the era of digital mining, technology - driven and data - centric management approaches are poised to enhance safety through the principles of "Safety Engineering." This concept aims to establish a self-regulatory safety framework within the mining industry. A notable model for expediting "Safety Maturity" and ensuring "Safety Quality" is the introduction of the "Star Rating" system, developed by IBM, which incorporates a built-in compliance mechanism for environmental and forest safeguards. Such innovative technology and ICT tools will not only recognize exceptional performers in safety but also encourage all mining leaseholders to strive for excellence in engineering safety across all facets of their operations.

To facilitate this transformation, the involvement of a newly emerged stakeholder, in the form of a collaborative institute or organization, adopting a third - party over sight approach in mining, may accelerate progress and the adoption of digital mining practices. Integration of sensor - driven safety engineering, encompassing various sensor technologies like electro - optics, acoustic sensors, active/passive UV to LWIR, ground-penetrating radar, passive mm wavelength, X-ray tomography, neutron activation imaging, multispectral, hyper - spectral, and ultra - spectral imaging, holds the potential to breathe new life into the aging mining industry, ensuring its continued dynamism.

In December 2020, the Department of Mining Engineering at the Indian Institute of Technology Kharagpur hosted a significant event, the International Webinar on Safe Mining and Advanced Resource Technology (SMART-2020). Distinguished academicians, scientists and researchers from around the world presented several papers during the webinar out of which nine papers have been selected for the special issue of this journal on Safety and Occupational Health theme. Prof Khanindra Pathak, Past Honorary Editor of MGMI, and the Convenor of SMART-2020, approached us with a request to publish these papers in the Transactions. These articles have undergone thorough review as they were already presented in the esteemed International Webinar SMART-2020. We are delighted to announce that these papers are being published in the current issue of the Transactions, ensuring that the valuable insights and findings shared during the webinar reach a broader audience and contribute to the advancement of knowledge in the field of mining and resource technology. This meticulously curated collection of articles, handpicked by the organizers from presentations delivered during the webinar, aims to spotlight the devoted individuals who are passionately contributing to the theme. In this collection of articles, we explore a range of topics relevant to industrial applications and safety measures. The articles cover subjects such as digital twins for valves, recovery of valuable commodities from tailings streams, advanced technology mining, controlling human vibration in mines, particle size influence on material properties, InSAR techniques for safety and productivity, UAVs for air pollution profiling, epidemiological approaches to mine injury prevention, and hazards associated with dumpers in mining operations. These articles provide valuable insights and innovative solutions for enhancing productivity, safety, and efficiency in the mining industry.

I would like to express my sincere appreciation for exceptional contributions of Prof B B Mandal and Prof Sunita Mishra as Guest Editors. Their meticulous review and selection of manuscripts have significantly elevated the standards of the current issueensuring its relevance and significance to our readership.

Taking this opportunity, heartfelt thanks are extended to all the members of the Organizing Committee of SMART - 2020 with special appreciation to the then Head of the Department, Prof S K Pal, the Convener, Prof Khanindra Pathak, the Co-Conveners, Prof Shantanu Patel and Prof Rakesh Kumar, as well as the Secretary, Prof Sunita Mishra. Special appreciation is owed to the senior veteran professors, Prof Ashis Bhattacherjee, and Prof Jayanta Bhattacharya, from the Department of Mining Engineering, IIT Kharagpur, whose unwavering inspiration has been instrumental in embarking on this remarkable venture. Contributions of the Authors have encouraged us to move forward with the publication. I sincerely acknowledge the contributions of the Reviewers and the assistances of all members of the Editorial Board and guidance from our Past President, Shri P M Prasad and Present President, Dr B Veera Reddy.

TECHNICAL PAPERS

DIGITAL TWIN OF A VALVE FOR SEVERE SERVICE APPLICATIONS

R Mishra, A Aliyu and M I Irshad

ABSTRACT

Digital twins are gaining prominence in many applications areas because their capability to influence design, operation, and safe disposal of various important assets across a wide range of industry sectors. This paper outlines the work carried out in developing a framework for digital twins for valves for safety critical applications. The use of digital twins is increasing in almost all areas of the process industry and in the present work it has been demonstrated that a multi-fidelity simulation along with a well-designed sensor network supported with an analytical model may provide a well desired multi-level functionality to the digital twins.

Keywords : Digital Twin, Internet of things, Computational fluid dynamics, Simulations, Safety

Introduction

Safety critical valves are used extensively across a number of industrial sectors *(e.g., power generation, oil and gas, chemicals)* to manage and control flow conditions in safety critical applications, which may include extremely hazardous and safety critical environments, such as flow conditions in Oil and Gas pipelines. The design features of these valves have become very complex, with flow paths typically being controlled by internal 'trims' which use intricate and complex geometries to manage pressures and flow rates safely *(Asim et al., 2019; Singh et al., 2020b, 2020a).* The problem becomes much more difficult for valves used in multiphase flow applications as the multiphase flow physics through complex geometries is still a strong and largely unexplored area of research worldwide and hence simplistic design methods do not ensure quality compliance of the developed product. This results in many operational issues during the lifetime of valves especially if process conditions change, for example, change in fluid (single to multiphase flow), flow (cavitation, wear) or geometric conditions (enlargement and choking of flow geometries). These problems cause significant disruption in operations of these industries resulting in huge financial losses. This problem becomes more acute because many of these piping installations are in remote areas and it may not always be easy to manually inspect these.

Industry 4.0 is enabling development of smart processes right from design and analysis stage to manufacture and operation stages of products/processes including end of product life management. Digital twins combine all aspects of current "industrial revolution" and there are several factors that are driving the rapid increase in market share of digital twins. The current work aims at embedding the digital twin technology into the operations of the valve enabling remote control at various levels of operation.

2. Concept of Digital twin and related technologies

A digital twin is the virtual replica of a physical product or asset. It defines the representation as well as the functionality and features of the physical asset. Sensors are installed on physical components to measure data such as temperature, pressure, humidity, etc. The sensors can be connected through the Internet of Things (IoT) to indicate real life processes taking place. The data measured is transferred to a cloud-based system for processing to enable distributed control. This data can then be used to analyse the performance of the physical assets in a virtual environment and perform predictive maintenance operations. Research shows that 24% of the organizations having Internet of Things (IoT) use digital twin technology for their products and there are about 42% of organizations planning to implement this technology by 2022 (Baker and Forrester, 2020).

The reason for this increase in uptake is digital twin's ability to carry out improved monitoring of assets as the digitalization of the actual physical asset can be achieved at different process levels. In the virtual space, the operation of the physical asset is investigated, forecasted, and improved. During the processes of integrating physical assets with the virtual model, the operational data from the physical entity is transferred through sensors and transducers and any variations in the data from their normal range can be used for fault prediction. This data can also be used for simulation, validation, and prediction purposes in the virtual environment (Qi and Tao, 2018).

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Digital twin is a new and emerging technology and extensive research is being carried out both in the academia and the industry to improve the level of twinning. The effectiveness of the digital twin technology gets considerably enhanced when high fidelity simulation is combined with the sensor data. Simulations can be used effectively to evaluate the local effects using digital twin resulting in enhanced prognosis at a local level. Operational data from the physical model can be then integrated with the output of the simulation to forecast the functionality of the asset at the desired level (Gopal, 2017).

The four major tools involved in the implementation of digital twin have been identified and previously reported by (Bevilacqua *et al.,* 2020). They are summarised in the following sections.

2.1 Implementation and control

This tool enables the transmission of data between the physical and virtual environments. Output data (such as pressure, flow rate, temperature, etc.) from the sensors installed on the physical asset are transmitted to the virtual space through the execution of a computer program. Similarly, the input control (such as controlling actuator and ON/OFF switch) from the virtual environment is transmitted to the physical asset through this tool.

2.2 Simulation

This tool assists to produce a virtual model of the physical asset. This tool can perform both online and offline. For an online working environment, it is important to receive real-time data from the sensors whereas, in the case of offline simulation, data can be manually entered into the virtual model to analyse its performance.

2.3 Prediction

Predicting the cause of faults or failures in the product and forecasting the breakdown or Remaining Useful Life (RUL) of the equipment can be achieved by this tool.

2.4 Cloud Platform

This tool provides the storage of live data coming from the sensors and transducers. The cloud platform must be able to acquire and store huge amounts of data from sensors, as well as enable comparison of this data with the data produced by virtual simulations. Important technologies required to enable the application of digital twins are discussed in the next section.

3. Internet of Things (IoT)

Internet of Things (IoT) consists of different computing devices that are interconnected to each other via the internet. The data from all devices are collated and shared through the IoT platform. The devices used should be of suitable type and size. The data collected can be used to analyse the status of the devices or equipment, identify faults, and can be processed to predict a future state. The digital twin uses measured data through IoT devices such as sensors and enables accurate process data exchanges between the virtual world and the real world. To collect a high number of real-time indicators from multiple sources, the IoT is best suited as it enables the connection between real and virtual worlds. It allows collection of data from sensors and enables the processing of data which can then be used in machine learning (Bevilacqua *et al.,* 2020).

To fully utilise the value of digital twin, it is important to consider the use of IoT. As the IoT and IoT platform allows us to collect real data and transfer it in the form of a closed loop, the actual and true value of the digital twin could be ensured. IoT is considered to be the backbone of the digital twin (Immerman, 2020).

3.1. Machine Learning (ML) and Artificial Intelligence (AI)

Machine learning is closely associated with artificial intelligence, which enables systems to automatically learn from data provided to it and improves its ability from experience (Expert.ai Team, 2017). The digital twin has the potential to use high-fidelity data through embedded simulation. A greater number of simulations can be performed at different settings in the virtual space of the digital twin. This simulated data can be used in ML (Alanen, 2019). Systems can be developed to predict the future performance of the products using ML techniques.

In the context of a digital twin, real-time data received from a physical model can be used to perform simulations in a virtual environment. The data collected from simulations can be utilised to train systems to learn about the performance of assets using ML. In this way, ML and DT can be employed for the performance optimization and maintenance forecasting of the product.

3.2. Reduced Order Model (ROM)

Reduced-Order Model (ROM) techniques have been introduced to simplify complicated numerical models and simulations to achieve results in less time. It enables the linkage of simulation models with real-time data, thus helping in prediction modelling. This technology can be used for optimization, test, and develop control software, and build an effective digital twin of products and assets (Kulp, 2019).

Normal CFD analysis takes a huge amount of time (in hours, days, or weeks in some cases) and for online process parameters estimation we need to have alternate, quick and intelligent systems. ROMs can be used for online flow prediction based on simulations with high fidelity models and can be used for analysing real-time data for diagnostic and predictive maintenance purposes (Ansys, 2019). The ANSYS ROM builder enables the evaluation of models in 3-D and provide flow features at various scales enabling quick interrogation of flow field for estimation of local and global performance indicators such as remaining useful life. The ROM is exported as a Functional Mock-Up (FMU) file to the ANSYS Twin Builder.

To evaluate the quality of ROM, the Goodness of Fit allows us to check the quality of the ROM model created. Further more, the quality of ROM can be also analysed using the verification points option. The goodness of fit table and chart could be used to evaluate quality of the ROM by checking the Learning points. Usually, three gold stars give the best quality rating and bad or worst quality is shown by three red crosses (Ansys, 2019).

4. Hardware and Software Specifications for Digital twin of a Valve

To create a digital twin for a valve, it is necessary to select appropriate instruments like sensors, actuators, data acquisition devices, etc. This section of the paper presents the specifications of hardware and software that could be used for the creation of a pressure drop-based digital twin for a valve. The digital twin framework for the valve is presented in Fig. 1. This figure illustrates the arrangement of hardware and software that will enable the digital twin for a valve to be achieved. All the components shown in the Fig.1 will be described in subsequent sections.

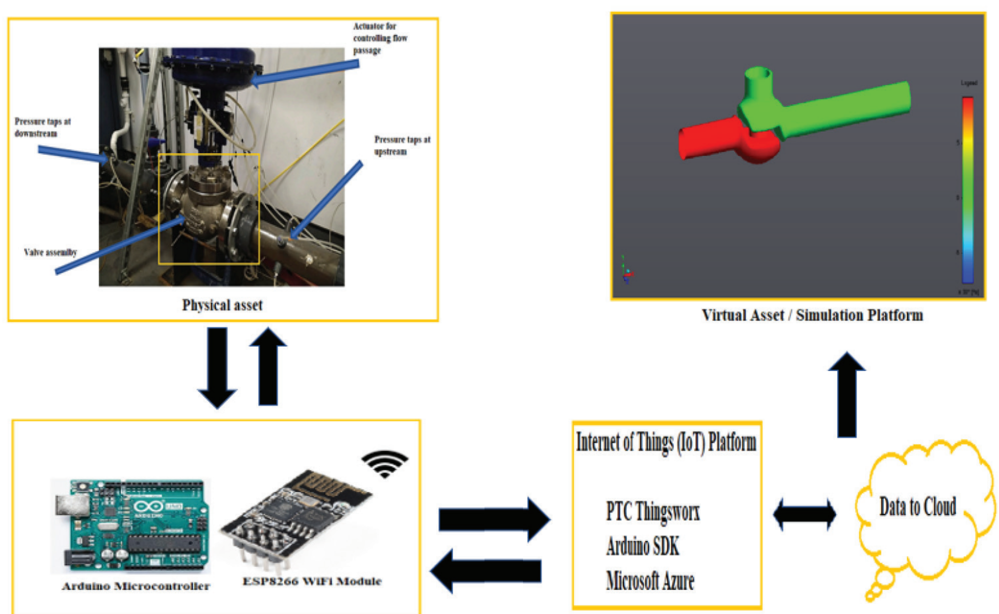


Fig. 1 Digital twin model of a valve

4.1. Hardware Requirements

To create the digital twin of the valve, it is necessary to select appropriate instruments like sensors and actuators. The devices that will be required are those for the measurement of pressure, flow rate, and control the opening of the valve.

4.1.1. Arduino UNO microcontroller

This is a microcontroller consisting of a circuit board and software. The circuit board can be used to acquire data from different sensors and convert them to digital readings such as pressure reading. This is a standard microcontroller used for a different type of projects. The technical specifications of this device are given in Table 1.

4.1.2. ESP 8266 Wi-fi Module

This module can connect Wi-Fi with the Arduino microcontroller. It can be soldered with the Arduino UNO microcontroller. It has an integrated TCP/IP protocol stack, which enables access to the microcontroller to the Wi-Fi.

Table 1 : Technical specifications of Arduino UNO microcontroller (Arduino, 2020)

Parameters	Value
Functioning voltage	5V
Input Voltage	7–12V
Analog Input Pins	6
Digital I/O Pins	14
Current per I/O pin	50mA
Memory	32 KB

4.1.3. MQTT Protocol

MQTT protocol can be used to make sure of a secure connection between the IoT device and the IoT platform. The data from devices like sensors and transducer can be published to the IoT platform which can be then used for digital twin applications.

4.1.4. Transducers (pressure sensors)

Pressure transducers are used to convert the pressure into an electrical signal. A 5V DC pressure sensor can be used to measure pressure at different pressure taps at the valve. The sensor can be used for both air and liquid pressure measurement. Specifications are given in Table 2 below.

Table 2 : Pressure sensor specifications (Seeed Studio, 2021)

Material	Stainless steel
Operating voltage	DC 5V
Output voltage	DC 0.5–4.5V
Operating pressure range	0–1.2MPa
Maximum pressure	2.4MPa

4.1.5. Computer System

To perform simulations of the virtual assets, high power computing systems are required. Usually, simulations using different software like ANSYS, COMSOL Multiphysics, etc., take a long time to complete. Therefore, for analysing the performance of an asset using digital twin needs powerful computing systems.

4.2. Software Requirements

For performing simulations, specific software are required. In this study, ANSYS Workbench and ANSYS Electronics have been used. Ansys workbench can create a Reduced-Order Model (ROM) from 3-D CFD simulations. This ROM allows one to perform quick simulations on the IoT platform and predict real-time data. A stand-alone static ROM Viewer enables the visualisation of 3-D simulations represented by ROM and rapidly predicts the effect of input changes. Input parameters can be easily varied by moving sliders or typing the value.

ANSYS Electronics incorporates the system simulation Twin Builder package. The Twin Builder allows the designs of the digital twin for any product to be created. It can be connected with the physical assets through IoT and Cyber-Physical systems for seamless integration of the physical and virtual models. Twin Builder has been used in several case studies by the ANSYS team (for example, a digital twin for a pump, wind turbine as well as a digital twin for a liquid mixer). In the current investigation this system will be used to test functionality of the digital twin framework.

4.3. IoT Platform

The IoT platform connects the physical and virtual assets. Ansys system can work with PTC Thingworx and Microsoft Azure IoT platform. These two platforms allow users to deploy digital twins and connect them with IoT devices to predict the performance of an asset. In this study, the use of the Microsoft Azure IoT platform has been recommended. Microsoft Azure provides two-way communication to IoT and edge computing devices. Specific language definitions are provided by Azure to facilitate the users for deploying digital twins. Ansys Twin Builder generates a Digital Twin Definition Language (DTDL) which is understandable by the Azure Digital Twin and can easily create an interface with each other (Microsoft Developer, 2020).

The above discussion has clearly indicated the hardware and software requirements for a digital twin. These components can also be developed for specific applications. In general, the digital twins are needed for real life monitoring and depending on the level of twining and usefulness, a Reduced order model can be developed where the information is needed in real-time which may otherwise be not possible from high fidelity model because of long convergence time.

5. Digital Twin Framework

In the present work a framework for digital twin of a severe service application has been developed. The present work explores the possibility of integrating high fidelity simulations with digital twin hardware for the development of an effective digital twin. The high-fidelity simulations are unlikely to be used with digital twin system because of the high computational power needed. To overcome this reduced order model can be developed from the high-fidelity simulations offline. These reduced order simulations can then be used in digital twin system for real life data generation and analysis.

5.1. ROM Builder Setup

After completion of initial CFD simulations, Reduced-Order Model (ROM) has been created that has been used later in the Twin builder for further analysis. For this purpose, initially, one input parameter must be created to enable ROM in Fluent. In this study, inlet velocity has been selected as an input parameter, while domain inlet and outlet pressures have been chosen as two output parameters. After this, a command "define models addon 11" has been used to enable ROM in the fluent. By enabling the ROM, available output parameters can be selected such as static pressure, viscosity, velocity, etc. In the current case, static pressure has been selected for desired locations.

The ROM Builder from the Design Exploration toolbox has been linked with the Fluent as shown in Fig 2. ROM Builder allows the user to enable specific input parameters if multiple parameters have been selected in the Fluent. It must be noted that ROM Builder only accepts input parameters that are defined in the Fluent setup. Any parameters that are defined outside the Fluent setup cannot be used in the ROM builder. Different properties like the type of design of experiments can be specified in the Design of Experiments (RB) toolbox, design type, sample type, and the number of samples. In this case, everything was left as default, only the number of samples has been changed. By default, for a single input parameter, 8 number of samples are created. In this analysis, 16 numbers of samples were selected to better explore the solution space. These settings are shown in Fig 2 below.

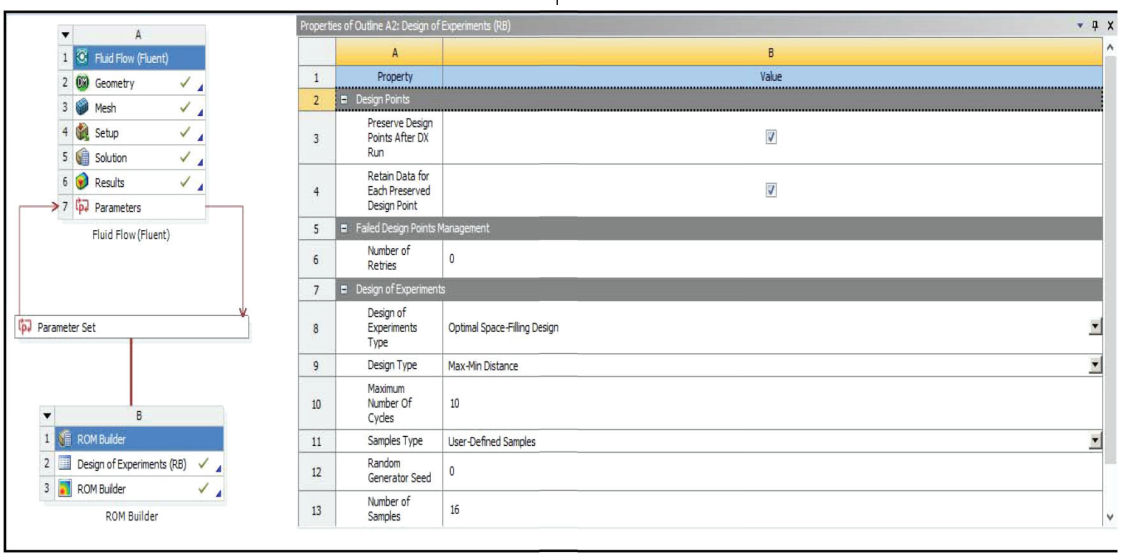


Fig.2 : Coupling of Fluent with ROM Builder and Design of Experiment Properties

After the properties are specified, the range of input parameters has been defined. The input parameter selected in this analysis is inlet velocity, so a range of 1 to 10 m/s has been selected. ROM Builder automatically generates 16 samples of inlet velocity within the specified range. The Design of Experiments was updated to perform simulations. It takes a long time (hours or sometimes a whole day) to complete the simulation which mainly depends on the number of samples specified. Once the simulations were complete, ROM Builder was opened and updated to generate the Reduced-Order Model (ROM). This ROM was saved as an FMU file for further analysis. Moreover, a stand-alone ROM Viewer can be opened in ROM Builder to visualize the 3-D simulation results.

5.2. Parametric Study

5.2.1. Inlet Velocity

In this study, the important output parameter that has been selected for analysis is pressure. In valve analysis, the flow velocity or volumetric flow rate has a significant effect on the pressure drop. Therefore, the inlet velocity has been specified for the parametric study during the creation of ROM. The inlet velocity has been defined as the input parameter. For each VOP, 16 samples of design points have been used having a velocity range of 1 to 10 m/s. ROM builder automatically generated 16 samples of inlet velocity. The value of these samples can be adjusted manually as well but was used as default in this study (Table 3).

Table 3 : Parameters and their values

Parameter	Values
Valve Opening Percentage (VOP)	20%, 40%, 60%, 80%, 100%
Inlet velocity (m/s) Number of Samples	In the range of 1 to 10 16

5.2.2. Valve Opening Percentage

Another important parameter that influences the pressure drop across the control valve is the Valve Opening Percentage (VOP). This parameter has a considerable effect on the flow coefficient of the control valve. In this study, 5 VOPs have been used as 20%, 40%, 60%, and 100%. As discussed before, ROM Builder only accepts parameters defined in the Fluent setup, therefore, to analyse the effect of VOPs in Twin Builder, separate ROMs have been created for each VOP. The percentage of openings for each ROM is shown in Fig. 3.

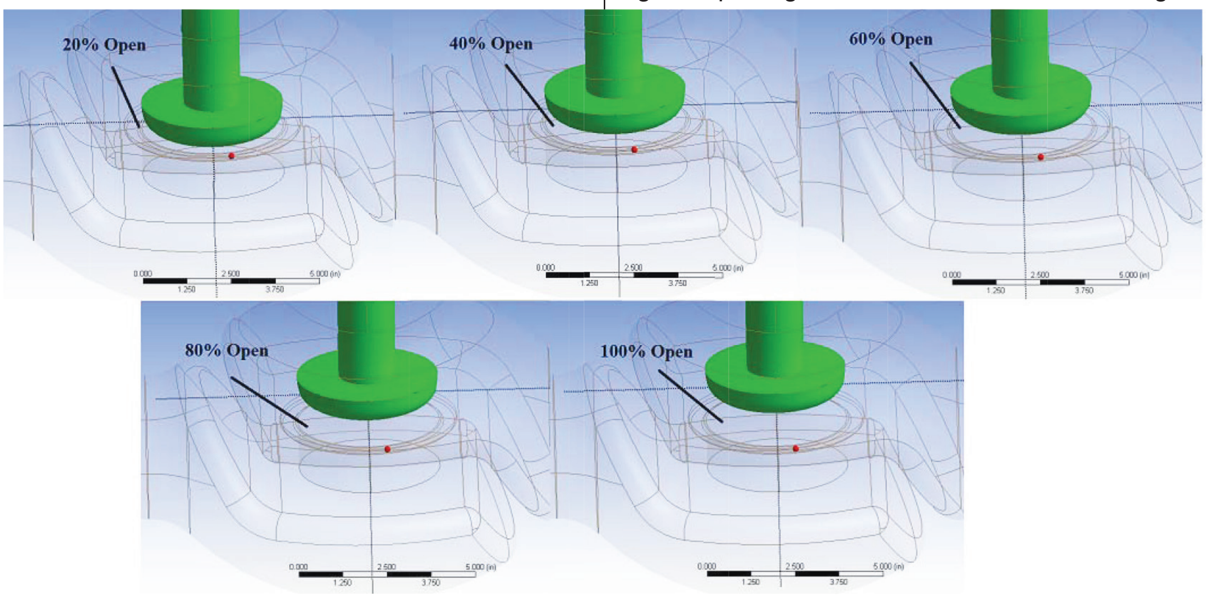


Fig.3 : Valve Opening Percentage (VOP)

5.3. Ansys Twin Builder Setup

The system simulation platform used in this analysis is Ansys Twin Builder. This package has been utilized to investigate the digital twin behaviour of the valve ROM (Fig. 4). Twin Builder is available in the Ansys Electromagnetic Suite. A Functional Mock Unit (FMU) of the ROM has been created. This FMU has been imported into the Twin Builder. Static pressure has been selected as an output parameter. ROM behaves as a virtual model for the valve. In Twin Builder, analytical equations have been modelled using mathematical blocks to compare against the ROM predictions. A sub-circuit for each equation has been created for simplification. The inlet velocity has been selected as the parameter to be varied to analyse the results.

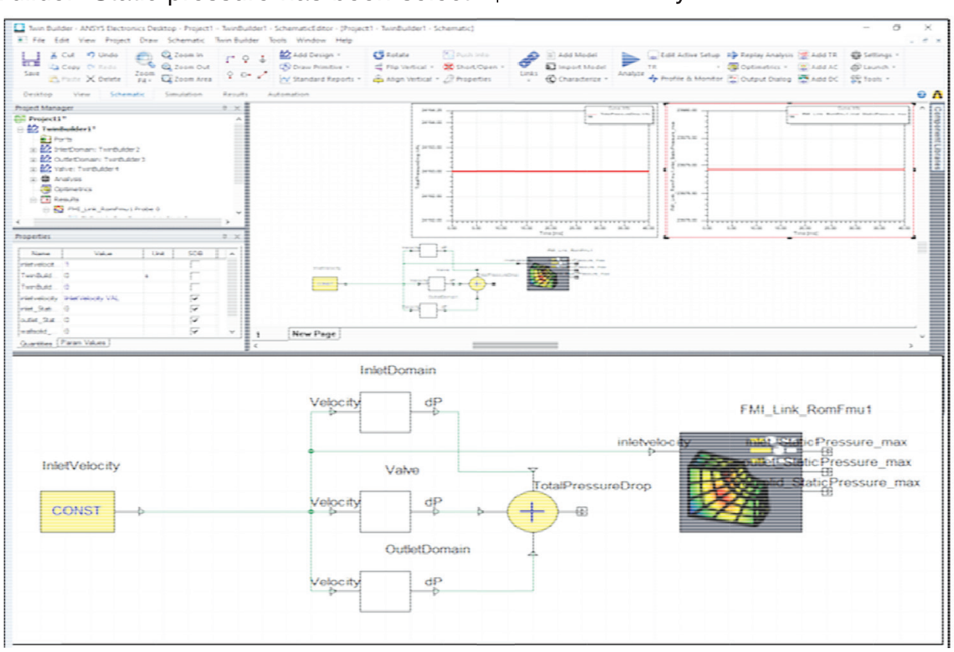


Fig.4 : Digital twin design for the valve in Ansys Twin Builder

Simulations have been performed for each VOP using the same inlet velocity value as used during ROM creation. In Twin Builder, ROM is used for quick simulation and for displaying the output values in various forms. Different types of figures can be used in Twin Builder such as 2-D, digital, and stacked graphs, as well as 3-D rectangular plots. The results plotted on these graphs have been illustrated in Fig.5 and 6.

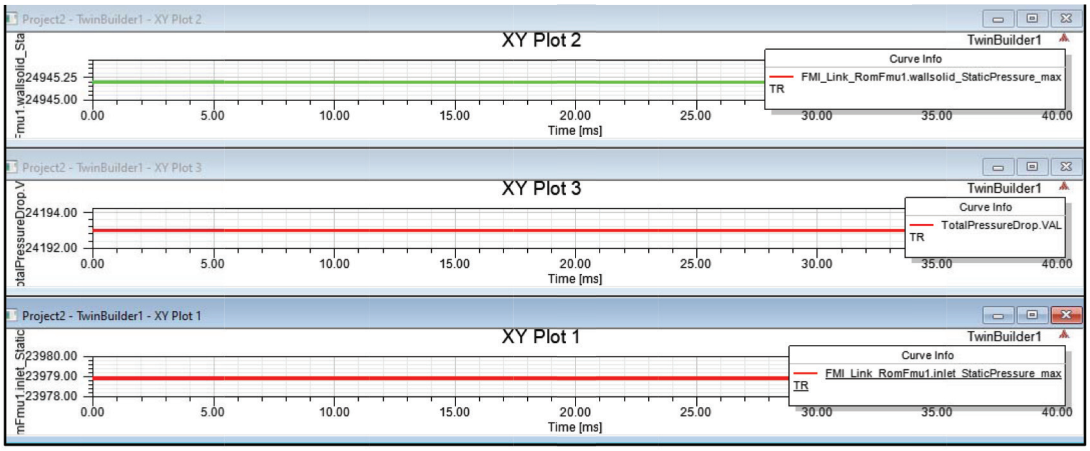


Fig.5 : Data visualisation in Twin Builder

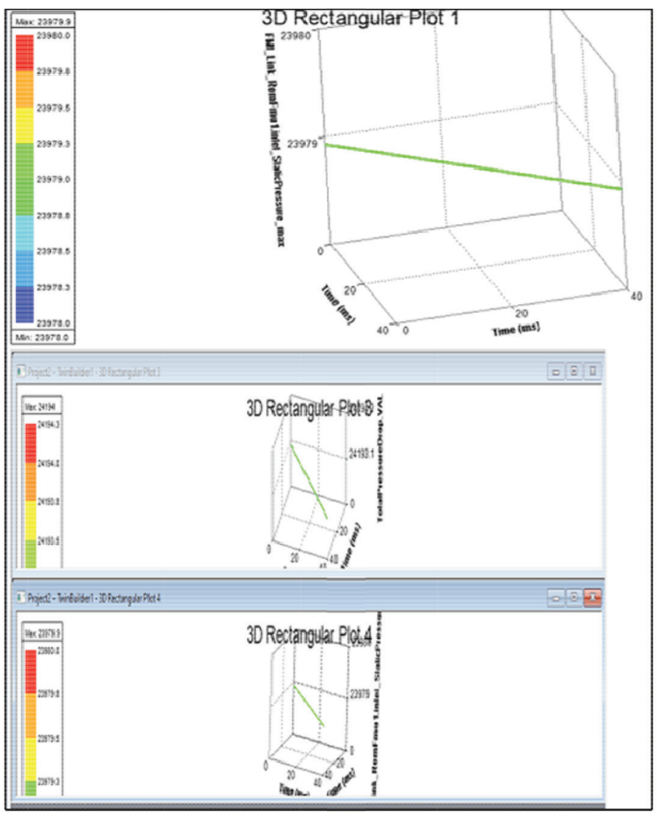


Fig.6 : 3-D Rectangular representation of Twin builder results

6. Evaluation of ROM Model for flow reconstruction

The ROM created for digital twin design comprises of 5 ROMs based on changes in VOPs. Each ROM has been created with velocity values in the range of 1 to 10 m/s. ROM builder has been used to generate random 16 samples within the specified range. At each design point, a snapshot has been generated and pressure drop across the whole domain has been computed. The results computed from the ROM builder have been shown in Fig.7. This figure shows the ROM viewer window that will change as per the change in input parameters.

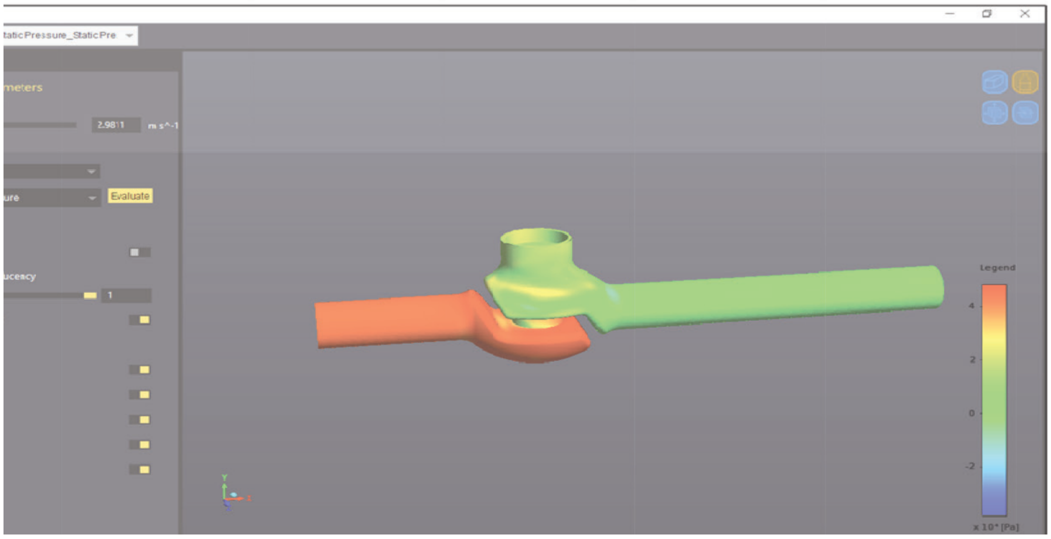


Fig. 7 : ROM Viewer for 3-D visualisation

The static pressure corresponding to different valve opening positions has been shown below (Fig. 8). This figure registers subtle changes in pressure field through the valve very accurately and it can be seen that the flow structures have been reconstructed fairly well using the ROM builder. It is expected that in real life situation this ROM builder will be able to provide both qualitative and quantitative data Almost on real time based on the sensor data embedded with this ROM.

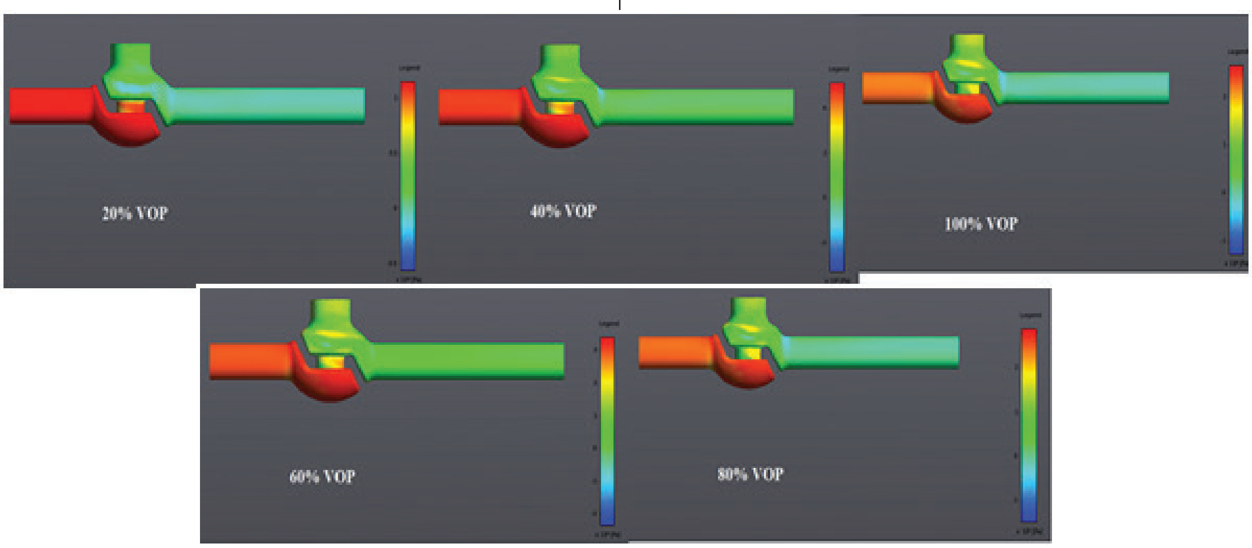


Fig.8 : Static pressure distribution visualised in ROM Viewer at Different VOPs

The quality of each snapshot generated has been checked in ROM Builder using Goodness of Fit indicator. The quality is described in the form of a learning point. The goodness of fit helps to analyse the capability of ROM in predicting the results. Usually, a three-star in the goodness of fit table shows the greater quality of ROM. Figure 9 shows the goodness of fit table for valve ROM. This indicated that the ROM generated in this study has good quality and is useful in further analysis of the digital twin (Fig. 9).

Table of Schematic B3: ROM Builder

	A	B	C
1		Static Pressure	Velocity
2	⊟ Global Relative Norm2 Error (Best Value = 0%)		
3	Learning Points	★★★ 0.015589	★★★ 0.15813
4	⊟ Average Relative Norm2 Error (Best Value = 0%)		
5	Learning Points	★★★ 0.015322	★★★ 0.15185
6	⊟ Maximum Relative Norm2 Error (Best Value = 0%)		
7	Learning Points	★★★ 0.025018	★★ 0.2587
8	⊟ Average NormInf Error (Best Value = 0)		
9	Learning Points	133.8	0.2114
10	⊟ Maximum NormInf Error (Best Value = 0)		
11	Learning Points	215.07	0.44455

Fig.9 : Goodness of Fit showing the quality of ROM prediction for results

To check suitability of ROM in displaying local features the distribution of wall shear has been shown in Fig.10. It can be seen that within the valve body the shear stress values are higher. In valve application this is the area where we can expect wear to be higher especially in multiphase applications and hence any failure is expected to get initiated from these locations.

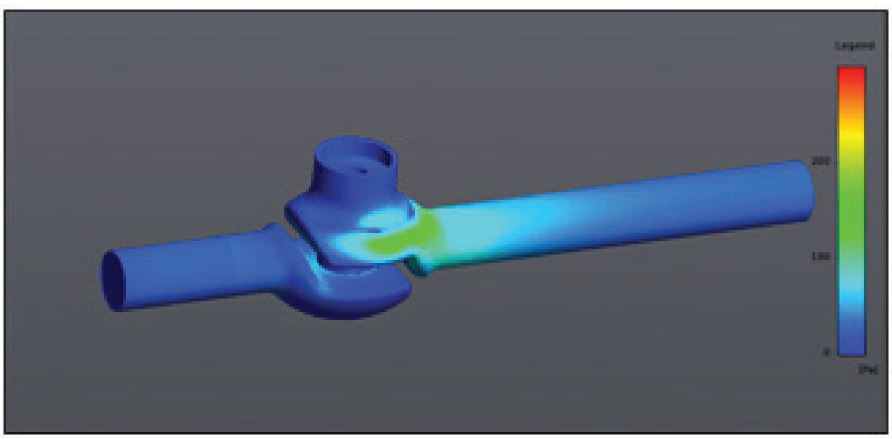
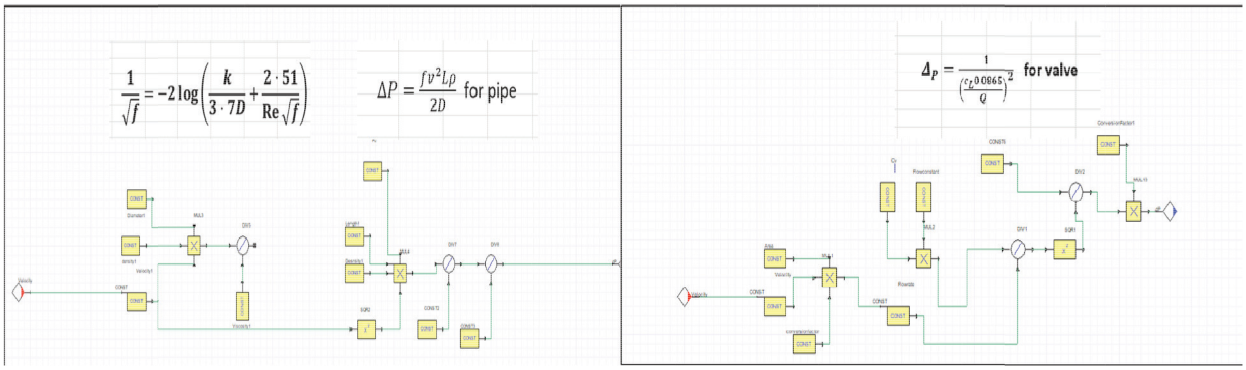


Fig.10 : Wall shear stress distribution on the valve

7. Evaluation of twin builder

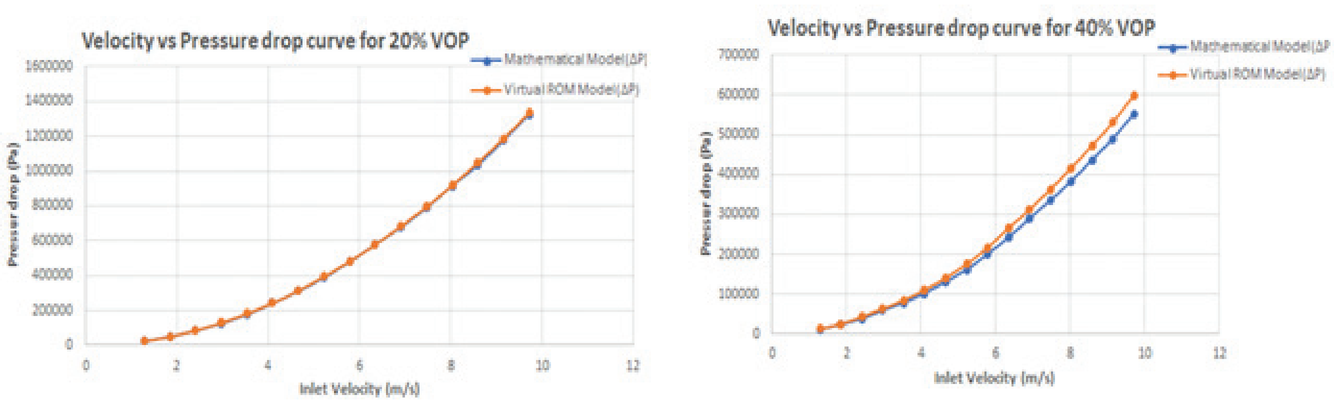
Once the ROM for the valve is ready, Ansys twin builder can be used to carry out system level check on digital twin. For this purpose, the ROM was imported as an FMU file in Twin Builder. To check functionality the ROM outputs were compared against an analytical model. This functionality was tested to enable the ROM data to be compared against a standard set of data to develop analytics for faults and remaining useful life prediction. In the present case a mathematical model for calculating pressure drops across the valve and inlet-outlet pipe has been developed.



(a) (b)

Fig. 11 : Block schematic for pressure drop calculation a) pipeline b) valve

The pressure drop from this model was assumed to be the result of the physical valve. Input parameter (inlet velocity) were kept the same for both mathematical and virtual valve. Simulations were performed by varying the inlet velocity. Change in inlet velocity showed changes in pressure drop across both models. Simulations were performed for different VOPs. The block arrangements created for these models are illustrated in Fig. 11 (a) and (b). A comparison between the pressure drop values computed by the mathematical and virtual models has been investigated.



(a) (b)

Fig.12 : Twin builder results for 20% and 40% VOP

A comparison of the data obtained from the physical model and the analytical model show a good match over a range of valve opening positions as shown in Fig. 12 (a) and (b). In addition, the capability of the twin builder to identify the differences from one set of process data against a reference data can then be used to obtain information necessary for fault prediction. This shows that all the components of the digital twin are working effectively, and this framework of digital twin is capable of functioning at a very high-level of twinning necessary for industrial application.

8. Conclusions

This study has been conducted to design a digital twin for a valve and perform CFD analysis to investigate the digital twin behaviour. The digital twin has been created using the ANSYS software suite (specifically, the Twin Builder Module). Digital twin for a valve requires hardware and cyber-physical systems as well as software for simulations. A detailed description and specifications about these requirements have been provided. A model framework has been developed for the valve digital twin. A procedure has been implemented and discussed for the development of the valve's digital twin. Simulation is an integral part of a digital twin. For this purpose, a Reduced-Order Model (ROM) has been created with five different VOPs. For each VOP, velocity has been selected as an input parameter. The quality of ROMs has been analysed which ensured it to be suitable for digital twin analysis.

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RECOVERY OF VALUABLE COMMODITIES FROM TAILINGS STREAMS - NO MOLECULE LEFT BEHIND

B J Arnold

ABSTRACT

No coal or mineral processing plant is 100% efficient. Valuable components often remain in plant tailings and are discarded in tailings impoundments or are dewatered and disposed in land fills. These tailings often represent a significant resource - if not currently, then often in the future. For example, remining gold tailings in South Africa recovered significant quantities of gold and allowed land to be reclaimed. New optimization technologies using Big Data can assist with improving recovery of these valuable components. In addition, tailings often have minerals like quartz and clay present. Quartz recovery should be evaluated for beneficial use in the construction industry in response to the shortage of construction sand. This paper will discuss these topics with a theme of "no molecule left behind."

Keywords : Tailings, mineral processing optimization, beneficial use of wastes

1. Introduction

Tailings from coal and mineral processing plants are often discarded in tailings dams, also known as, impoundments. Some rather spectacular failures of tailings dams occurred in recent years, including the 25 January 2019 failure of a tailings dam at Vale's Córrego do Feijão iron ore mine in Brazil and the 2015 failure of the Fundao iron ore tailings dam at the Samarco joint venture property (Vale and BHP Billiton) also in Brazil. These failures resulted in fatalities, the displacement of thousands of people, and the contamination of land and water. Methods for building better dams as well as for monitoring existing dams were certainly viewed as necessary by governments, corporations, and professional societies alike, and many international organizations collaborated to develop a tailings dam standard. *The Global Industry Standard on Tailings Management,* launched on 5 August 2020, is available in seven languages at the GlobalTailingsReview.org website (globaltailingsreview.org 2020).

The Standard provides guidance for affected communities; an integrated knowledge base; design, construction, operating, and monitoring tailings dams; management and governance; emergency response and long-term recovery; and public disclosure and access to information. This Standard, of course, describes requirements for ongoing tailings dam facilities and the design of new facilities.

From a mineral processing standpoint, however, it should be possible to either minimize the tailings being impounded or eliminate tailings impoundments altogether. With new dewatering and processing technologies and the ever-increasing need to recover additional valuable commodities from mined ores or to find a beneficial use, mineral processing engineers should be leading the charge for "no molecule left behind," a phrase coined by the US Department of Energy's Oak Ridge National Laboratory as it seeks to develop coal as a pre-cursor to high-value added products (Oak Ridge National Laboratory, 2018).

This focus should lead to mineral processing engineers optimizing processing plants, reprocessing re-mined tailings, and evaluating tailings by-products.

2. Optimizing processing plants

Optimizing mineral processing plants can come in many forms but always begins with an understanding of process mineralogy - knowledge of the relationship between the valuable and gangue minerals - the liberation characteristics and other details of the mineralogy. A knowledge of this resource in conjunction with current and future markets is key.

It is important to take this knowledge and develop testing programs and plant optimization strategies to increase the recovery of all valuable commodities. Ask: can liberation be achieved at a coarser size? What is the trade-off between flotation grade and leaching cost? Certainly, these parameters were evaluated during the initial plant design, but a re-evaluation should be done as the ore body changes. Could there be an opportunity to develop a digital twin with information on differences in the ore from different areas in the mine? And, can you include optimization of crushing, grinding, and flotation conditions?

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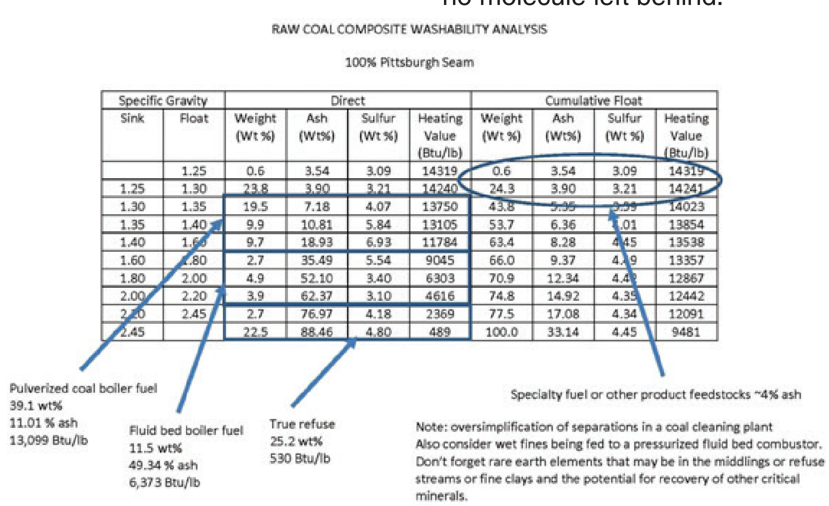
Freeport-McMoran, Inc. did one such study that created a digital twin of their Bagdad, Arizona, copper concentrator. Combined with a machine learning algorithm, they optimized froth flotation reagent consumption, increasing recovery and delaying the construction of an additional concentrator (Gleeson 2020). Big Data and the Internet of Things (IoT) has come to mineral processing! In a study in India, Tripathy and Reddy (2017) investigated ore sorting technologies that use multi-spectral and joint color-texture features to separate gangue from limestone and coal. Their work featured a neural network for fast processing of the images.

When optimizing mineral processing plants, we must also consider a reduction of gangue minerals prior to crushing and grinding to minimize or eliminate tailings dams. With new advances, ore sorting technology may be applied to remove rock prior to energy intensive crushing and grinding operations. Ore sorting technology has advanced significantly and encompasses sensor-based ore sorting systems, such as that tested by Tripathy and Reddy (2017) and those that include X-Ray Luminescence (XRL)-based sorting, X-Ray Transmission (XRT)-based sorting, and Laser-based detections (for example, Robben and Wotruba 2019). Wolfram Bergbau und Hütten AG in Austria, for example, mines up to 500,000 tons of raw tungsten ore. They use a TOMRA X-ray sorting technology to remove 100,000 tons of coarse non-tungsten bearing rocks annually prior to the processing plant to alleviate issues with decreasing ore grade. These rocks are sold as aggregates and do not end up as tailings (TOMRA, 2014). They found a beneficial use for these rocks—now aggregates—that would have been ground previously and disposed of as tailings.

Truly understanding the mineralogy of a deposit, including the presence of any trace elements or metals, can open new markets for new products. Just recently, Rio Tinto announced a tellurium recovery plant for their Kennecott facility in Utah that will produce 20 tons of tellurium annually (Rio Tinto 2021). While that does not seem like a large supply, the total global annual production of tellurium in 2019 was only 470 tons (US Geological Survey 2020). Tellurium is on the US Department of the Interior Critical Mineral list as it is valued for its high technology applications in steelmaking and solar cells and is highly import reliant (Schulz et al. 2018). This Critical Mineral list is serving as a guide to many researchers and developers in the US looking to recover additional valuable commodities from ore tailings and from the coal measures, coal refuse, and combustion byproducts.

It is important to understand the many components found in coal, as it is expected that new markets for coal may require lower ash assays than those that have typically prevailed in the past. Added to these are market opportunities derived from rare earth and other critical elements that may be satisfied by coal reserves. Considering low ash coal specified at 4% ash (dry basis and the current specification for silicon metal smelting), there are many coals in the US that contain such a low ash fraction in good quantity. Fig. 1 shows data for a typical Pittsburgh seam coal washability presented to illustrate the quantity of low ash material and the potential utilization of the remaining fractions. Around one quarter of this coal can be used in this low ash, specialty coal market. Another 39% is still usable as typical PC (pulverized coal) boiler fuel. Around 11.5% can be used as a fluidized bed combustor feedstock, leaving another 25% of this coal as a true refuse. With such a high ash level (and low carbon content), it may qualify as road-bed or construction material depending on the mineral makeup. In this way progress is made toward "no molecule left behind."


RAW COAL COMPOSITE WASHABILITY ANALYSIS

100% Pittsburgh Seam

Specific Gravity		Direct				Cumulative Float			
Sink	Float	Weight (Wt %)	Ash (Wt%)	Sulfur (Wt %)	Heating Value (Btu/lb)	Weight (Wt %)	Ash (Wt%)	Sulfur (Wt %)	Heating Value (Btu/lb)
	1.25	0.6	3.54	3.09	14319	0.6	3.54	3.09	14319
1.25	1.30	23.8	3.90	3.21	14240	24.3	3.90	3.21	14241
1.30	1.35	19.5	7.18	4.07	13750	43.8	5.35	3.59	14023
1.35	1.40	9.9	10.81	5.84	13105	53.7	6.36	4.01	13854
1.40	1.60	9.7	18.93	6.93	11784	63.4	8.28	4.45	13538
1.60	1.80	2.7	35.49	5.54	9045	66.0	9.37	4.49	13357
1.80	2.00	4.9	52.10	3.40	6303	70.9	12.34	4.42	12867
2.00	2.20	3.9	62.37	3.10	4616	74.8	14.92	4.35	12442
2.20	2.45	2.7	76.97	4.18	2369	77.5	17.08	4.34	12091
2.45		22.5	88.46	4.80	489	100.0	33.14	4.45	9481

Fig. 1. Illustration of the potential recovery of low ash coal from Pittsburgh Seam Coal while utilizing middlings and refuse products.

Indeed, Dhawan and Sharma (2019) studied the refining of five Indian coals to obtain super clean coal. Others have also taken up the charge of understanding the many components in Indian coals, including Mishra *et al*. (2019), who evaluated the geochemistry of rare earth elements in India's Lower Gondwana coals in the Talchir Coal Basin. In addition, Bhowmick *et al.* (2017) studied the chemical and mineralogical composition of Kathara Coal from the East Bokaro Coalfield; Saikia and Ninomiya (2011) investigated the mineral matter in Assam (India) coal; Saikia *et al.* (2016) conducted an elemental geochemical and mineralogical analysis of coal and associated coal overburden in the Makum coalfield; Kumari *et al.* (2018) focused their coal cleaning study on the reduction of quartz from an Indian coal; and Banerjee *et al.* (2016) evaluated the distribution of mineral species in various Talcher coalfield coal seams. The results of these studies can be used to improve and optimize coal processing plants; and in conjunction with new processing technologies and new ore sorting techniques, the many minerals and elements found in coal will be recovered and put to beneficial use.

This process mineralogy approach in India also extends to other minerals. For example, Bhushan (2015) evaluated the geology of the Kanthai rare earth deposit, Jena *et al.* (2019) conducted a mineralogical characterization of lean copper ore in the Malanjkhand Deposit, and Kotta *et al.* (2018) thoroughly characterized the chemical, physical, thermal, textural, and mineralogical properties of natural iron ores from the Odisha and Chhattigarh regions (Kotta *et al.* 2018). Indeed, Gedam *et al.* (2013) conducted a comprehensive characterization of Indian mineral wastes that leads directly to the topic of reprocessing tailings.

3. Reprocessing re-mined tailings

Investigators are characterizing old tailings dumps and impoundments to now use more advanced technologies to recover additional valuable commodities. Examples can easily be found in the literature, including those for diamonds, gold, lead-zinc, tungsten-zinc, and copper. Gedam *et al.* (2013) conducted a comprehensive study of mineral wastes in India using physico-chemical, mineralogical, and morphological analyses. This included characterizations of power plant wastes, construction and demolition wastes, slags from steel plants. With a thorough review of properties related to environmental concerns, including pH, acid insoluble residues, loss on ignition, chloride content, sulphate content, reactive silica content, and heavy metal analysis, these materials were evaluated for their use in the cement and concrete industry. Further research on these materials will no doubt lead to the recovery of valuable commodities and beneficial use of these current wastes.

Nummi (2015) documents many success stories related to recovering additional valuable commodities from tailings. With advances in technology, DeBeers Consolidated Mines recovered 815,036 carats of very small diamonds from 6,133,799 tons of tailings in 2013. They expect to continue operations beyond 2030. DRD Gold abandoned traditional gold mining in South Africa in favor of exploiting tailings. New technology allows DRD to recover up to 40% of the gold left in particle form in the tailings, extracting 33,600 ounces of gold in fourth quarter 2013. Mintails expects to recover 58 kg of gold per month from slimes with sufficient material to last until 2025, and Goldfields processes 12,000 tons of current tailings and 88,000 tons of old tailings a month (Nummi 2015).

Beyond diamond and gold tailings and beyond South Africa, Khalil et al. (2019) investigated the use of a centrifugal dense media separation to reprocess Pb-Zn tailings, Portuguese researchers (Figueiredo *et al*. 2019) have studied re-mining tailings from a tungsten and tin mine with the use of hydrometallurgical processes, and Alcalde *et al.* (2018) assessed metal recovery from porphyry copper tailings in Chile.

The author's research will soon focus on tailings from over 100 metal mines that had been operated over the past ~150 years in the Commonwealth of Pennsylvania, USA. The last of these metal mines closed in 1984 (Socolow 1984). It is expected that many of these sites can be re-mined with the tailings being reprocessed to recover valuables commodities, including those on the US critical mineral list as these mines recovered such commodities as iron, rare earth elements, zinc, and cobalt. Clay mining was also prevalent in central Pennsylvania and considerable research is being conducted to evaluate these old mining areas to recover, for example, lithium (Feineman *et al*. 2020).

4. Evaluating tailings by-products

Gold, diamonds, base metals, and some critical metals and rare earth elements are being recovered from tailings or are being investigated for their recovery from tailings. Researchers should also consider some commodities that may not be as valuable but might help to reduce the volume of tailings being disposed. A review of the minerals in coal and fine refuse in the US (O'Gorman and Walker, 1972; Bradley *et al.* 1980a, 1980b) indicates that clay minerals and quartz are found in good quantities (see Table 1). As reported by Heaney and Banfield (1993), silica as quartz is a common accessory phase in many common commodities (see Table 2). As Kotta *et al*. (2018) report, kaolinite and quartz are found in iron ores from Odisha and Chhattisgarh, India, and Bhowmick *et al.* (2017) report on the quartz in Indian coals.

With the prevalence of these minerals as essentially gangue minerals, investigators should consider them as potential commodities for building materials or other applications. This is especially timely as many areas of the world are experiencing “sand wars (Beiser 2019).”

As reported by Torres *et al.* (2017), the world is running out of sand, especially as a construction material. Sand and gravel are the most extracted materials and are now global commodities. In some areas of the world, an illegal trade in sand has developed.

Table 1 Minerals in coal and fine coal refuse in the US

Mineral	Mineral Content of Major US Coal Seams (O'Gorman and Walker 1971)		Mineral Content of Coal Preparation Plant Tailings (Bradley et al. 1980)	
	Mean, %	Range, %	Mean, %	Range, %
Kaolinite	34.8	0-85	11	6-22
Illite	7.8	0-35	53	47-65
Mixed Layer Illite-Montmorillonite	3.2	0-20		
Montmorillonite	0.7	0-10		
Chlorite	1.5	1-10	4	0-7
Quartz	10.1	0-40	15	8-22
Gypsum	11.9	0-60	*	
Rutile	2.3	0-10		
Calcite	*		12	0-22
Pyrite	*		4	1-11
Feldspar	*		*	
Dolomite	*	NA	*	NA

Table 2 Quartz as an accessory phase in common commodities (after Heaney and Banfield 1993)

Commodities		
Antimony	Gold	Talc
Bauxite	Gypsum	Tellurium
Beryllium	Iron ore	Thallium
Cadmium	Lithium	Titanium
Clay	Magnesite	Tungsten
Copper	Mica	Vanadium
Diatomite	Perlite	Zinc
Feldspar	Phosphate rock	Zircon
Fluorite	Pyrophyllite	
Garnet	Selenium	
Germanium	Silver	

Ore and coal tailings may offer a ready source of sand if it is of the right size distribution and meets other quality parameters, such as limits on organic impurities. The shape of the sand grains is also important for construction purposes—weathered, rounded desert sand is not amenable for such purposes. The literature has been filled since the 1950s and even more recently (for example, Fuerstenau and Pradip 2005) with descriptions of the froth flotation of quartz. Is it time to recover this gangue mineral as a valuable commodity?

Manufactured sand plants have also been developed by several equipment manufacturers, including McLanahan (see mclanahan.com) and Metso (metso.com). These plants crush and size aggregates to the appropriate size for addition to concrete and cement. Sreenivasa (2012) of Ultratech Cement Limited Bangalore described manufactured sand as an alternative to river sand. If there is a market for sand that has been prepared in this manner, investigators should surely assess the recovery of quartz from tailings to meet this need. This will go a long way toward reducing the volume of solids reporting to the tailings stream and leaving no molecule behind.

5. Summary

Can the mineral industry meet a goal of "leaving no molecule behind?" Mineral processing engineers must optimize processing plants by fully understanding potential resources and markets and applying Big Data and IoT technologies. Remining and reprocessing of tailings must be expanded to recover additional valuable commodities in their newly optimized processing plants. This will go beyond diamonds and gold and expand to rare earth and other critical minerals. And, knowing all the components in these resources, we must develop new markets for "former" gangue minerals. For example, can we recover quartz, an accessory mineral in many ores, and supplement often scarce sand resources? Are we ready to address the tailings challenge?

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ADVANCED TECHNOLOGY MINING FOR IMPROVED PRODUCTION, PRODUCTIVITY AND SAFETY – A WAY FORWARD

V M S R Murthy and Aarya Raj Singh

ABSTRACT

Global mining technology is making rapid strides both in surface and underground mining may it be coal or metal. However, the adaptation of the same by Indian industry is still to mature. To adopt the right technology for right geo-mining setting needs proper appreciation of both scientific and technological developments as well as make them available at right form and time. This certainly requires an integrated effort from the vast experience gained by the industry and academic/research community on a sustained basis. Considering a steep production requirement of a billion tonne of coal production envisaged by coal industry by 2025 and growing environmental and safety concerns, a great challenge lies ahead in choosing the right combination of technology along with its effective management. Here comes a great opportunity of having a relook at some of the existing technology in mines and methods to scale up. New innovations in mining technology, backed by advanced instrumentation and their seamless integration in mine design and operations, is the only way to meet the current production challenges. This paper aims to highlight some of the key issues in surface and underground mining, the advanced technology and R&D inputs needed for making mining productive and safe. Synergy between Industry-Academia is stressed for quick adaptation with suitable engagement models.

1. Introduction

1.1. The mineral production scenario (coal and metal)

India's economic growth is intimately connected with mineral production. There has been a constant demand for fuel minerals which is evident from the production and value metrics as depicted in Fig.1.

COAL PRODUCTION AND OFFTAKE APRIL - OCTOBER- 2020-2021 (IN MT)

Production					Offtakes/ Dispatch*			
Company	Target	Ach. (Prov)	Actual During Cores Period of Previous Year	Growth (%)	Target	Ach. (Prov)	Actual During Cores Period of Previous Year	Growth (%)
CIL	710.00	282.86	280.38	09%	710.00	305.67	316.34	-3.4%
SCCL	67.50	22.02	35.59	-38.1%	67.50	21.87	35.42	-38.3%
Captive*	91.00	29.00	29.13	-0.4%	91.00	31.07	29.74	4.5%
Others*	10.00	3.61	3.99	-9.5%	10.00	3.60	4.00	-9.9%
Total	**878.50**	**337.52**	**349.07**	**-3.3%**	**878.50**	**362.04**	**385.43**	**-6.1%**

Source : CCO, CIL & SCCL, & Target has finalised

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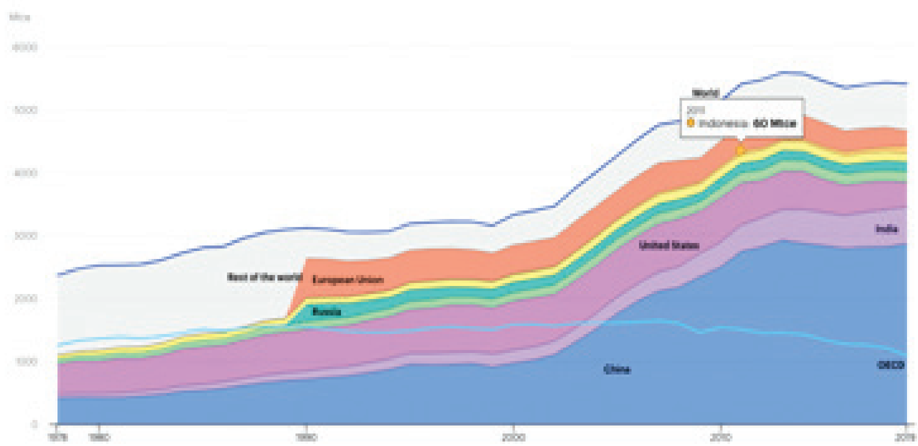

Fig.1 - Production and consumption of coal (Source : MoC, IEA)

It may be observed that there is a rising gap between consumption and production which requires to be addressed on priority. Mining apart from contributing to GDP (close to 3%) has a huge contribution to employment, regional development, education, health and societal growth and more so in economically and socially deprived regions. Modern mining technology has a pivotal role in ushering a new growth pattern in mining and allied industries. Manufacturing and processing industries are heavily dependent on the mining produce and therefore it is necessary to have a robust roadmap for making mining in India self-reliant. With a growing concern on GHG emissions in coal fired power plants, it has become all the more necessary for innovating the coal mining methods and technologies to aim for clean coal production and clean coal technologies. Deep, mega, smart and sustainable mines are the future. To realise this, some of the technological domains in mining, advances and role of academics and industry engagement are detailed in the following sections.

2. Surface Mining

Surface mining contributes majority of coal produce and the challenges of planning, design, operation and management of large scale opencast projects involves adaptation of new mining technology, software and management. Some of the key surface mining issues that require immediate attention along with possible direction are discussed.

2.1. Computerised Mine Planning

Computerised mine planning includes reserve estimation, layout evaluation and equipment selection and scheduling. The software which can be used is Minex, Surpac, Whittle, Vulcan, Data Mine, etc. In contemporary practice the application of mining computer program is significantly expanded and it can be concluded that the computer aided design has become an indispensable part of developing mining projects and optimising the processes.

2.2. Mass Production using Surface Miner

Use of surface miner gained popularity principally due to its mass production capability (1,000 to 1,500 tons per hour), blast-free nature of excavation, higher recovery of resources due to its selective digging capacity (even layers of 10 cm), a sort of all in one technology (drilling, blasting, loading and crushing). Rocks up to 40 MP a uniaxial compressive strength have been successfully mined. This a flexible mining system with ROI in a short span of 3 to 4 years. This technology is pervasive today in coal, limestone, bauxite and even in construction sector. In India L&T manufactures this with some critical import of spares. ADST funded R&D project is in progress at IIT(ISM) in collaboration with L&T for cutting drum design in varied geology along with development of a mining method for selective coal mining and waste disposal.

2.3. Dragline Mining and Integrated Dump Planning

Dump planning has assumed critical proportion due to lesser space available for dumping particularly in case of deep and large opencast projects. The height and width of the dump shall be properly selected to ensure safety in equipment operations and also keeping in view the production. Use of modern mine planning tools and software with adequate training is the need of the hour. Some of the Computer aided mine planning design software relevant in this context are Minex, Haulsim, Dragsim, etc. Height and width of dump depends on following factors :

- Cohesion of dump material
- internal friction angle
- Cohesion of foundation material

- Internal friction angle of foundation material
- Ground acceleration on dump generated due to blasting
- Distance of toe of external dump from nearest surface edge of quarry

Proper dump planning keeping above factors in mind can save space ensuring safety. Use of Virtual Reality Mine Simulation can help in planning the dragline mining operations in a productive way by choosing optimised machine setting as well as optimal dumping sequences within the available pit space.

2.4. Rock Fragmentation aids Mining Machine Productivity

Blast fragmentation management has a direct role on machine productivity and this is critical for surface mine profitability. Improper fragmentation has a cascading effect on downstream operations namely, loading, transport and crushing. Key factors affecting fragmentation need to be identified and optimised. Ground vibration is also one of the main issues during large scale blasting in surface mines. This can be controlled using electronic detonators and blast design simulations. Use of software like Fragalyst and Wipe frog / Wipe joint for the analysis of fragmentation and other blast design software such as J K Simplest, Shot plus, I Blast, for blast design can help achieve optimised blast designs. In one of the studies conducted by IIT(ISM) in NCL mines there has been a clear improvement of 15% in dragline monthly productivity.

2.5. Asset Management

The equipment fleet covering blasthole drills, loading machines and haul trucks are the major chunk of the equipment in use today. A few younger and trained workers are expected to fill the gap thus making mining operations more reliant on their machinery and technology management tools. Key challenge here is how the huge data generated is handled. Use of Big Data and AI applications is the need of the hour and software firms like IBM, Caterpillar and Sandvik have already mobilised the required software and skill sets with use cases. The key objective is to limit the non-operational time due to breakdown of equipment and also use the knowledge compiled for mine system improvement.

2.6. Human Skilling - Going Digital

Human forms the major and critical element behind successful operation of mine and its assets. Right from recruitment, selection, training, placement in right positions, upskilling and keeping workforce motivated are the key functions of human management. Right compensation, rewards, job elevation and training form a major part for retaining skilled work force. Going digital also is placing more reliance on fewer people and their effective management.

3. Underground Mining

Underground mining is going to play a major role in meeting the future production requirements considering the growing limitations of surface mining technology, namely, environment management and land availability apart from other factors. Some of the key issues needing immediate attention are discussed below:

3.1. Rock Cuttability Assessment and Machine Selection

Rock cut ability and machine selection mainly depend on the rock/rock mass, machine and geomining parameters and the type of application. Cuttability assessment will lead to a proper selection of bits for shearers, continuous miners, surface miners and other mining machines. This assessment can also help in the increment of life of a machine and economy of operation.

3.2. Strata Control

Strata control deals maintaining the work place intact preventing possible excessive movement of strata due to under-support or improper excavation system. Deployment of trained set of personnel in designated roles at mine itself is the requirement today. The people involved in front line mining operations must be associated with this activity. Area wise strata control cells shall be established for the testing and monitoring of strata in UG mines. Stability assessment requires information about physico-mechanical properties of rock and rock mass, geo mining conditions, stress fields and mine design features. In bord and pillar mining orientation of mine galleries oblique to major joints or weakness planes can reduce the impact of strata control issues if not avoided completely. Longwall entries also have been successfully oriented in SCCL where the stress fields are clearly defined.

3.3. Development in Roof Bolting

One of the key missing and vital technology link in mechanized mine development with the deployment of continuous miner/roadheader is roof bolting to match the fast advancing face. The use of bolter-miner will lead to faster advance rate of face. The unsupported area will be minimum while using mechanised bolting. The mines, namely, Jhanjhra and Moonidih have already deployed bolter-miners, but their proportion needs to increase. Less unsupported area will give more stability to the surrounding rock mass and thus helps in achieving better strata control. Use of mechanised roof bolter will help in automatic grouting, bolting, uniform application of torque, reduced manpower, fast rate of bolting and enhanced safety.

3.4. Underground Coal Mining Technology - The Scaling Up

The latest technological developments in underground mining are :

- Double ended ranging drum (DERD) shearer – Lowall Mining
- Continuous miner/ Road header for mine development
- Mechanised roof bolter
- Hydraulic face drilling rig
- Environmental tele-monitoring system

The above upgradation will lead to high production, high rate of advance and higher productivity.

3.5. Controlled Blasting and Induced Blasting of Strong Roof

Blasting-off-solid for longer pulls and in weaker roofs requires suitable charge and blast designs for improved productivity and safety. Management of hard roof has been another daunting task in majority of bord and pillar and longwall mining methods. Use of controlled induced blasting has been largely successful in managing such cases. Blasting gallery in Gassy I mines can be revisited where spontaneous heating and roof management are not critical.

3.6. Goaf Edge Supports

At present, the support at the goaf edge during liquidating the standing pillars or in regular depillaring operations in coal mines consists of cogs and props made of timber and steel. Much of the timber cannot be recycled and need to be replaced before the next round of support is erected. This leads to high timber consumption and cost of per ton of coal extracted from the mine. Another disadvantage of the existing practice is that the labour-intensive nature of erecting and dismantling timber and steel cogs and props. The above disadvantages are effectively eliminated by employing SAGES and ABLS in UG mines. SAGES an indigenous development has been successfully deployed in BCCL and SCCL. Currently, IIT(ISM) and APHMEL are jointly developing a 500 tonne capacity SAGES after successful trials of 200 tonne capacity SAGES 200 in association with M/s Jai Bharat Equipment Ltd.

4. Mining Instrumentation

Key areas that need state-of-the-art instrumentation and analysis are described below :

4.1. Planning, Modelling, Rock / Rock mass Charac terisation

Key elements in this are rock mass characterization, rock testing, field measurements, geophysical testing (shallow seismic refraction), anchorage testing and strata monitoring. Slim borehole scanner, refraction seismic tomography, cavity scanning, ground probing radar have been successfully used for mapping the competence of subsurface strata and designing efficient excavations in rock mass.

4.2. VOD Measurement

Velocity of Detonation (VOD) enables evaluation of the performance of explosive in-situ. Measuring velocity of detonation gives a good indication of the strength and quality of the explosive. VOD measurement is done using resistance wire method in continuous column of explosive. This coupled with seismic velocity of rock can help match the explosive and rock impedance for efficient energy transfer.

4.3. Near and Far - field Ground Vibration Analysis

Ground vibration control for reducing its impact on surrounding structures as well as rock has been one of the key areas of research since long. With the advent of advanced instrumentation such as near-field sensors (accelerometers, high - frequency sensors - seismic and acoustic) it has become possible to undertake large scale blasts in large opencast mines by controlling the same within permissible limits of structures. Backbreak control in blasting faces also has been possible for effective bench stability and reduced loss of explosive energy.

4.4. Acoustic Emission to detect the Rock Fracture Propagation

Acoustic emission (AE) indicates the irreversible changes that occur in the rock structure when it undergoes loading. The crack features, propensity, brittleness and competence can be mapped using this study. Its application has grown extensively in assessing the rock failures in deep settings.

4.5. In-situ Stress Measurement

All in-situ measurement techniques consists of the response associated with a disturbance in a rock structure. The main methods used for the measurement of in-situ stress are hydrofracturing method, borehole relief methods and surface relief methods. Designing coal pillars considering in-situ stresses particularly in deeper mines is the need of the hour. Needful instrumentation and use is increasing. Monitoring of sub - surface strata movement is another area which is necessary for strata data dilation under varied stress environment (virgin and mining induced). This could be used in method design and extraction sequencing.

4.6. Specific Energy Studies and Cutting Drum Design

This is another area of research. IIT(ISM) in collaboration with L & T is undertaking a research project funded by DST under clean mining technology initiative (CCORD 2017). This is based on already conducted investigations for estimating cutting performance, diesel and pick consumption while cutting in varied rock settings. This project involves development of an indigenous cutting drum based on the studies on laboratory based proto type rotary cutting rig, numerical simulation, full scale drum development and field studies.

5. Advanced Mine Simulation Facilities

5.1. Virtual Reality Mine Simulators

Use of virtual reality and augmented reality has a great potential to give a true immersion in the mining environment thus enabling the technology seeker and provider an excellent tool to effectively communicate the challenges and also prepare the incumbent with needful skill sets in different scenarios. Though equipment simulators are being used in different mines and establishments still there is no mine simulator where in the entire mine setting can be captured along with equipment, and people involved in different operational environment. One such setup with a 3600 Theatre is in the process of development at IIT(ISM) Dhanbad with the funding from CIL R & D.

5.2. Gas and Dust Explosion Simulators for Coal Mines

Considering the growing coal production needs and the expected rise of share from underground mining it is necessary to develop adequate research capabilities in assessing the gas and dust explosion proneness in coals which are highly gassy and friable. Spontaneous heating of coals, gas evolution characteristics, propensity of gas and dust to explosion coupled with development of re-entry protocols is the need of the hour. IIT(ISM) is establishing a state-of-the-art lab under a joint R&D project with CSIR - CIMFR. This is also funded by CIL R&D. Both these national facilities have been initiated under the Indo-Australian joint initiative under the direction of the Ministry of Coal, Government of India and the broad specifications have been worked out. The Virtual Reality Mine Simulator Project is now being developed by IIT(ISM) in collaboration with NCL, ECL and CMPDIL jointly with indigenous suppliers and developers. Expected to be ready latest by the end of June 2024. Gas and dust explosion simulation facility is yet to take off due to some unforeseen delays. A few global technologies are presented in Table 1.

Table 1 - Some global surface and underground mining technologies in practise

Surface Mining Technology
• Autonomous equipment:hauling trucks, LHDs, and drillers • Integrated remote operation centers: Reduce OPEX and CAPEX of mining operations, improves safety • Smart sensors/ Real Time data capture :Integrated planning and control • Global positioning systems
Underground Mining Technology
Advanced blasting technologies: • micro-explosives for selective fragmentation of boulders • greater control of fragment size, reduces energy requirement for crushing and grinding
Increasing Production, rate of advance and productivity Robotic Assistance : • Wheeled robot equipped with a robotic arm • Attached scanning devices in order to analyze ore samples Robotic drills : • battery operated drill machines capable of drilling different patterns of blasting • lower maintenance costs and do not produce harmful exhaust fumes
Spanning inaccessible areas • Underground carriers fitted with radar and laser scanners. They permit navigation in dark areas that pose reathing hazards

6. Synergizing the Industry Academia Partner ship – The Need of the Hour

Achieving synergy between Industry and Academia is the key for technology advancement and is still a challenge in Indian context. The key challenges and issues are presented here.

6.1. Background and Challenges ahead

- World has changed global challenges demand global collaborations
- Population; Cities; Traffic; Global warming; Natural disasters; Natural Resources; Security of Water, Food and Energy; Health care; Education; Youth unemployment
- Universities have changed: Powerhouses of R & D and Training
- Industry has changed : Globalised, highly competi tive environment
- Strategic Partnerships: Collaboration for mutual and societal benefits

6.2. Foundation for Strategic Partnership

- Whole of the Institution as one party
- Responsive to emerging ideas (both ways)
- Long-term
- Reciprocal
- Partnership Team

6.3. Strategic Areas and Engagement Model

Research

- Energy Scenario and dependence (Coal, Oil-Gas)
    - o Clean mining and coal technologies
    - o Fly ash utilisation
    - o Spontaneous heating and mining methods
    - o Coal to chemicals
    - o Environmental efficiency through operational efficiency
    - o VR Simulators for hazardous workplace simulation
- Solar and wind power research initiatives
- Hydro-power development & research
- Mechanization and automation
- Underground space planning and development

Academics

- Courses relevant to industry
    - o Advanced technologies for safe and productive engineering
    - o Sustainable Initiatives
    - o Clean technologies
    - o Advanced Planning and Design
    - o Data Analytics and AI Applications
- Masters in collaboration with Industry (Training Part in Industry with dual mentorship)

Infrastructure

- Data Analytics Centre
- Knowledge Centres with Integrated Central Research Facilities
- Advanced Research Laboratories (Start ups, Incubation hubs)
- Sports Academy

Faculty Engagement

- Faculty Mobility to state-of-the-art plants and research facilities
- Faculty/Staff/Student mobility (MoUs)

Student Engagement

- Student Interns and Projects with an organised administration
- Innovative Projects
- Industry Talks

Societal Development

- Skill development (jointly) for Employment
- Community Services (Health, Safety, Environment)

Policy Initiatives

- Policy formulation
- Legislative enablement
- Responsive Industry-Academia Linkage

7. Concluding Remarks

The number and dimension of the mining challenges are going to spiral up further. Solution lies in interdisciplinary research engagement with academia. Many issues require to be resolved at the mine level by embracing new technology *(i.e., mining equipment, IT and OT integration)* addressing the entire mining value chain. For routine problems, suitable tech-cells should be developed at mine/area level. Joint capacity building can be done for bridging the skill gaps. While the academia must scale up the curriculum to include latest innovations, the industry also must provide required ambience, training facilities, support, proactive discussion forums and workshops for arriving at suitable solutions. Paid summer training under joint mentorship of academic-Industry should be thought of seriously to encourage budding engineers and scientists. Different challenges can be converted into suitable UG, PG and PhD projects and can be offloaded to academic institutions under active mentorship. This is seriously absent in our current system. Adequate software and instrumentation capacity must be built at subsidiary level with dedicated manpower as this is the only way to address the rising problems. In summary, Indian mining industry has miles to go before we realise at least a few state-of-the-art mines, ambience, technology and management to make mining profession attractive and a choice. Time to synergise efforts in making India AatmaNirbhar and globally competitive.

SEAT FACTORS AS A TOOL FOR CONTROLLING HUMAN VIBRATION IN MINES

Bibhuti Bhusan Mandal

ABSTRACT

Whole Body Vibration (WBV) is a well - known health hazard in mining occupation. Dumper operators are subjected to such vibrations generated from road - tyre interaction and transmitted through the base of the seat. Dynamic parameters of vehicle seat are a vital contributing factor in determining the quality of a seat in use. Therefore the objective of this research case study was to evaluate the transmissibility factor of pneumatic dumper seats used in Indian mines. Total fifteen dumpers of two different makes with pneumatic seats were selected for the study purpose. The tri - axial seat - pad accelerometers (SVANTEK make SV 38A) collected data in all three orthogonal axes of translational or rectilinear vibration. The mono-axial or single axis accelerometer (SVANTEK make SV 80 with mounting magnet SA 32) was simultaneously positioned rigidly on the floor to record signals in vertical direction. The data so obtained were then calculated using a vibration risk calculator in MS-EXCEL to quickly predict the health impacts using the measured vibration magnitude along with period of exposure per day. The results obtained clearly indicated that the drivers of all the fifteen dumpers are indicatively at risk of whole body vibration. It was clear for the SEAT factor calculated using rms and VDV values that the present seats installed in all the fifteen dumpers are not efficient and failed to attenuate the vibration from the floor to seat and ultimately to the body of the dumper operator. It was observed that the further in-depth evaluation of engineering and designing part of the seats used in these types of dumpers is desirable. The further in - depth evaluations necessarily take into consideration the actual working condition to be able to realistically attenuate the vibrations, provide comfort and relief to the dump operators.

Keywords

Occupational health hazards, Whole-body vibration, Mining hazards, Seat transmissibility

Introduction

Mining industry is associated with many occupational health hazards which are well documented. Whole Body Vibration (WBV) is one such hazard known for many years and widely discussed in various literatures due to its potential of negative health impacts of human concerned [1][2][3][4][5][6][7][8][9][10][11][12][13]. In surface mining of minerals, variety of Heavy Earth Moving Machineries (HEMM) are deployed and put in use for all major operations. All these machineries are more often sophisticated and technologically advanced. Transportation of minerals from blasted face of the bench to the crusher plant is one of the essential steps in the mining operations. Dumpers are being extensively used for transportation of minerals and overburden. The capacity of dumpers in Indian mines presently varies from about 10 to 240 tonnes.

This is often that transportation of mineral is outsourced to third party contractor by mine owners. Technical advancements in Indian mines are not uniform in nature; companies use ordinary flat trucks through the contractor. In top mining conglomerates this is coupled with their own dumpers of good quality like Volvo or Komatsu make dumpers for transportation. In either situation the task of driving vehicles and transporting minerals from mining lease area to crusher plant is economically driven and hence very often done even if adverse and strenuous conditions prevail. Vehicle type, suspension or quality of seats all vary in nature from mines to mines. Additionally condition of the haul road is site specific factor and is not always favourable for smooth driving at all. Dumper operators are thus exposed to WBV during transportation of mineral in a moving dumper.

Vibrations reach to the operator's seat through one or more stages of suspension. In one study conducted by B Mandal (2014) in Indian mines, fifty nine (90%) dumper operators out of total 66 were found to be exposed to vibration for at least six hours per day [14]. The magnitude of health impacts of WBV are such that it has become a priority concern in mining sector to look into. Chronic exposure to WBV (0.5 to 80 Hz) manifests in many adverse health impacts on operators. Low back pain (LBP) is considered to be a well - known occupa-

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tional health issue among vehicle operators exposed to WBV [6][2][15][16]. Such health disorders are certainly not desirable and lead to considerable financial compensation in many countries. Moreover, such diseased condition results into a general degradation in the quality of life of mine workers.

Mansfield (2005) points out that there are two primary options available for prevention of these operators from WBV exposure: either to reduce the duration or to lessen the magnitude of exposure [17]. Now, in an eight hours shift, it is not practicable to reduce the exposure to less than six hours. It would be unrealistic because of economic aspects of the mineral transportation by mining industry. In an economic scenario where the industry is more and more moving towards privatisation and where the labourers are increasingly resourced through contractual agencies, the actual exposure to vibration at work may even exceed eight hours due to extended period of work. As a consequence, the only option that would be left for mitigation of risk from vibration is to reduce the intensity of vibration entering in to the human body. For doing so and designing of engineering controlled measure or preventive strategy, efficacy of the seats installed in the dumpers in regard to the transmissibility of vibration from the source to the human body needs to be evaluated. The basic objective of this preliminary investigation is to evaluate transmissibility factor of pneumatic dumper seats used in the mining lease area under study. Seat Effective Amplitude Transmissibility or SEAT factor of pneumatic seats of total fifteen (n=15) dumpers has been calculated in dynamic field condition.

2. Material and Methods

2.1. Selection of dumpers and seats for real-time experiment

Two types of dumpers were selected for the study. The seat type of all the fifteen (15) dumpers was pneumatic. The details of the dumpers used for the preliminary assessment are listed in Table 1. According to the author B B Mandal (2010 & 2014) most dumpers on mining haul roads having the vertical or z axis as their dominant axis of vibration other than in some exceptional cases [15]. In regard to spinal health of people exposed to vibration at work, a specific international standard ISO 2631-5 : 2004 has been issued which deals only with z-axis vibration [18]. Hence it was decided to measure z-axis vibrations on the base (floor) as well as on the seat surface of the dumpers in the mine.

Table 1 : Details of Dumpers studied

Equipment	Make	Model	Capacity	Seat Type (Rigid//Spring/Pneumatic)
Dumper – 10	Komatsu	HD 465-7	55 MT	Pneumatic
Dumper – 11	Komatsu	HD 465-8	55 MT	Pneumatic
Dumper – 12	Komatsu	HD 465-9	55 MT	Pneumatic
Dumper – 13	Komatsu	HD 465-10	55 MT	Pneumatic
Dumper – 14	Komatsu	HD 465-11	55 MT	Pneumatic
Dumper – 15	Komatsu	HD 465-12	55 MT	Pneumatic
Dumper – 16	Komatsu	HD 465-13	55 MT	Pneumatic
Dumper – 17	Komatsu	HD 465-14	55 MT	Pneumatic
Dumper - 20	Komatsu	HD 465-17	55 MT	Pneumatic
Dumper - 23	Komatsu	HD465-7E0	55 MT	Pneumatic
Dumper - 25	Caterpillar	770G	40 MT	Pneumatic
Dumper - 28	Caterpillar	773E	60 MT	Pneumatic
Dumper - 31	Caterpillar	773E	60 MT	Pneumatic
Dumper - 32	Caterpillar	773E	60 MT	Pneumatic
Dumper - 33	Caterpillar	773E	60 MT	Pneumatic

Table 2 : Calibration data of accelerometers

Seat pad Accelerometer SV38A (mV/g)			Uni-axial Accelerometer SV80 (mV/g)
x axis	y axis	z axis	z' axis
101.6	100.5	101.3	102.6

2.2. Instrumentation and measurement

The international standards ISO 8041 : 1990 & ISO 2631-1 : 1997 were followed for measurement of vibration and interpretation of data. A tri-axial seat-pad accelerometer (Figure 1) was placed on the seat between the operator's is chealtuberocities (two parts of the buttock) for recording vibration on the seat surface in three directions (x, y & z).

Figure : 1 A tri-axial seat-pad accelerometer placed on the seat of the operator

The x - axis was aligned in the back to front direction, the y axis in the right to left lateral direction, and the z - axis in the vertical direction. Since the study was targeted for understanding transmissibility of vibration signals in z axis, another mono - axial accelerometer (represented as z') was vertically placed on the floor with a strong magnetic mounting to firmly attach with the metallic base (floor). A part of the floor carpet was occasionally removed from the cabin floor to get access to the metallic floor for magnetic attachment (Figure 2).

Fig 2 : SV80 mono-axial accelerometer magnetically secured to the floor of the driver's cabin

The tri - axial seat - pad accelerometers (SVANTEK make SV 38A) collected data in all three orthogonal axes of translational or rectilinear vibration. The mono-axial or single axis accelerometer (SVANTEK make SV 80 with mounting magnet SA 32) was simultaneously positioned rigidly on the floor to record signals in vertical direction. All four accelerometers were calibrated prior to the commencement of testing in accordance with the calibration data supplied by the test laboratory (Table 2). Operators were instructed to continue with their routine work during the measurement session.

2.3. Prediction of health risk

To understand the severity of exposure that we are dealing with, we first collected the frequency-weighted root mean acceleration (RMS) values of seat vibration. Scale factors for seated exposures (W_d = 1.4 for x and y axes, W_k = 1.0 for z axis) were applied to the RMS accelerations along all three axes. We developed and used a vibration risk calculator in MS - EXCEL to quickly predict the health impacts using the measured vibration magnitude along with period of exposure per day. For this purpose, we calculated the A (8) values for comparison with exposure limits stipulated in EU Directive as well as ISO 2631-1 : 1997 Standard [19] (Table 3). Exposure Action Values and Exposure Limiting Values are commonly expressed in terms of A(8) values. A (8) values are normalized by determining an eight hour exposure equivalent which is derived by the formula :

$$A(8) = ka_w\sqrt{\frac{T}{T_0}}$$

where :

a_w is the measured vibration magnitude (RMS frequency - weighted acceleration magnitude) in one of the three orthogonal directions, x, y and z, at the supporting surface;

T is the duration of exposure to the vibration magnitude a_w ;

T_0 is the reference duration of 8 hours, and

k is a multiplying factor (k = 1.4 for x and y axes and 1.0 for z axis).

The highest A (8) value among x, y and z axis should be used to compare with limiting values [20].

2.4. Measurement of transmissibility

The transmissibility of the WBV from the floor to the seat was evaluated using the seat effective amplitude transmissibility (SEAT) values. SEAT values are the ratio of the intensity at the seat to that of the WBV at the floor. A typical rigid seat would show a SEAT value of unity. SEAT values are usually evaluated using both RMS and VDV values. Mansfield (2005) precisely defined transmissibility as the ratio of the vibration on the seat surface to the vibration at the seat base (usually the floor of the vehicle) as a function of frequency :

$$T(f) = \frac{a_{\text{seat}}(f)}{a_{\text{floor}}(f)}$$

where, T(*f*) is the transmissibility, $a_{seat}(f)$ is the acceleration on the seat, and afloor(f) is the acceleration at the base of the seat at frequency *f*. If there is the same magnitude of acceleration at the floor and on the seat surface, then the transmissibility is unity i.e. there was no practical attenuation. Overall transmissibility can be expressed with a single SEAT value which is a ratio of overall RMS values of acceleration (or VDV) on the seat and floor.

$$SEAT_{r.m.s}\ \% = 100 \times \frac{r.m.s._{seat}}{r.m.s._{floor}}$$

$$SEAT_{vdv}\ \% = 100 \times \frac{VDV_{seat}}{VDV_{floor}}$$

SEAT% value shows the overall performance of a vehicle seat in terms of an indicator in regard to transmissibility of vibration. The further scope for understanding the problem with adequate details for effective engineering control has been kept out of the present research case study.

3. Result and Discussion

It was primarily observed that all the fifteen (15) dumpers had z or vertical axis as their dominant axis of seat vibration. Considering the magnitude of vibration along the dominant axis and respective duration of exposure per day, all their operators had indicated health risk when compared with Health Guidance Caution Zone (HGCZ) of ISO 2631-1:1997 (Table 3).

Table 3 : Health risk assessment for vibration exposure using r.m.s acceleration

Equipment	Frequency weighted rms acceleration (ms-2) awx	awy	awz	rms acceleration factor multiplied by scale (ms-2) awx	awy	awz	Duration of exposure	Health risk assessment as per HGCZ (ISO 2631-1:1997) along dominant axis
Dumper – 10	0.26	0.27	0.67	0.36	0.38	0.67	6.25	Indicated
Dumper – 11	0.30	0.32	0.66	0.42	0.45	0.66	6.25	Indicated
Dumper – 12	0.31	0.30	0.72	0.43	0.42	0.72	6.25	Indicated
Dumper – 13	0.48	0.49	0.78	0.67	0.69	0.78	4.40	Indicated
Dumper – 14	0.36	0.31	0.89	0.50	0.43	0.89	6.25	Indicated
Dumper – 15	0.47	0.48	0.73	0.66	0.67	0.73	4.77	Indicated
Dumper – 16	0.38	0.34	0.87	0.53	0.48	0.87	5.50	Indicated
Dumper – 17	0.33	0.39	0.82	0.46	0.55	0.82	6.25	Indicated
Dumper – 20	0.31	0.30	0.76	0.43	0.42	0.76	6.60	Indicated
Dumper – 23	0.24	0.27	0.62	0.34	0.38	0.62	6.23	Indicated
Dumper – 25	0.43	0.37	0.86	0.60	0.52	0.86	5.50	Indicated
Dumper – 28	0.31	0.39	0.85	0.43	0.55	0.85	5.50	Indicated
Dumper – 31	0.39	0.35	0.66	0.55	0.49	0.66	6.60	Indicated
Dumper – 32	0.33	0.37	0.71	0.46	0.52	0.71	6.23	Indicated
Dumper – 33	0.25	0.32	0.73	0.35	0.45	0.73	6.60	Indicated

Even though exposure duration is below five hours for Dumper -13 and 15, health risk has not come down. It is felt that even a minor increase in exposure duration in all the fifteen dumpers will pose high health risks. Summarily, the r.m.s acceleration values are visibly high enough to cause concern. These health risks mostly refer to the likelihood of developing low back pain (LBP) and other spinal disorders. Surprisingly the peak accelerations of the pneumatic-suspension seats were at least nine times compared to their r.m.s. accelerations. It seems that the advanced suspensions produced more bouncing effects compared to their rigid counterpart. Hence Crest Factors (CF) being greater than nine, vibration dose values for the pneumatic seats was further taken into account for additional evaluation as stipulated in ISO 2631-1:1997.The health risk was further affirmed by additional analysis using VDV values (Table 4). In the prevailing circumstances, none of the fifteen (15) operators were free from adverse health risk due to exposure to vibration during their daily work.

Table 4 : Health risk assessment using VDV_T for equipment where CF> 9

Equipment	**VDVx**	**VDVy**	**VDVz**	**Duration of exposure**	**VDV_T along dominant axis**	**Health risk assessment as per HGCZ (ISO 2631-1:1997)**
Dumper – 10	1.84	2.08	4.08	6.25	-	Indicated
Dumper – 11	2.35	2.65	5.20	6.25	11.63	Indicated
Dumper – 12	2.39	2.30	4.73	6.25	-	Indicated
Dumper – 13	3.12	3.48	5.41	4.40	-	Indicated
Dumper – 14	2.95	2.37	5.73	6.25	-	Indicated
Dumper – 15	2.96	3.07	4.62	4.77	-	Indicated
Dumper – 16	2.93	2.54	5.85	5.50	-	Indicated
Dumper – 17	2.57	3.51	6.06	6.25	13.55	Indicated
Dumper - 20	2.34	2.26	5.83	6.60	12.63	Indicated
Dumper - 23	1.79	2.23	5.80	6.23	12.56	Indicated
Dumper - 25	3.33	3.05	7.08	5.50	15.31	Indicated
Dumper - 28	2.34	2.40	5.60	5.50	-	Indicated
Dumper - 31	3.20	2.81	5.21	6.60	11.26	Indicated
Dumper - 32	2.43	2.62	4.33	6.23	-	Indicated
Dumper - 33	1.91	2.56	5.78	6.60	12.52	Indicated

Hence it becomes more imperative assessment in the interest of the case study and participants to know whether there is effective attenuation during transmission from seat base to seat surface. Hence the ratio of z/z□ was calculated for all these seats (Table 5). Overall, the vibration environment of these fifteen (15) seats was such that only two (2) of the seats were effective at reducing the vibration exposure slightly. Seats of dumper number 31 and dumper number 33 had SEAT values of 79% and 78% respectively using ratio of r.m.s. acceleration values (Table 5).

Table 5 : Frequency weighted r.m.s. acceleration values in seat and floor channels

Seat Channels (ms^{-2})		Floor Channel (ms^{-2})			SEAT Factor (z/z’)
Equipment	**x-axis**	**y-axis**	**z-axis**	**z’- axis**	
Dumper – 10	0.26	0.27	0.67	0.73	0.92
Dumper – 11	0.30	0.32	0.66	0.71	0.93
Dumper – 12	0.31	0.30	0.72	0.64	1.13
Dumper – 13	0.48	0.49	0.78	0.66	1.18
Dumper – 14	0.36	0.31	0.89	0.81	1.10
Dumper – 15	0.47	0.48	0.73	0.65	1.12
Dumper – 16	0.38	0.34	0.87	0.72	1.21
Dumper – 17	0.33	0.39	0.82	0.83	0.99
Dumper – 20	0.31	0.30	0.76	0.65	1.17
Dumper – 23	0.24	0.27	0.62	0.56	1.11
Dumper - 25	0.43	0.37	0.86	0.69	1.25
Dumper - 28	0.31	0.39	0.85	0.77	1.10
Dumper - 31	0.39	0.35	0.66	0.84	0.79
Dumper - 32	0.33	0.37	0.71	0.75	0.95
Dumper - 33	0.25	0.32	0.73	0.93	0.78

The SEAT values based on VDV for these two (2) seats were 79% and 84% respectively which were also lowest in the group. The other thirteen (13) seats had SEAT r.m.s values ranging from 92 to 125% which were far from satisfactory.

Table 6 : Vibration Dose Values (VDV) in seat and floor channels

	Seat Channels ($ms^{-1.75}$)			Floor Channel ($ms^{-1.75}$)	SEAT Factor (z/z’)
Equipment	**x-axis**	**y-axis**	**z-axis**	**z’- axis**	
Dumper – 10	1.84	2.08	4.08	4.73	0.86
Dumper – 11	2.35	2.65	5.20	5.55	0.94
Dumper – 12	2.39	2.30	4.73	4.44	1.07
Dumper – 13	3.12	3.48	5.41	4.56	1.19
Dumper – 14	2.95	2.37	5.73	5.35	1.07
Dumper – 15	2.96	3.07	4.62	4.17	1.11
Dumper – 16	2.93	2.54	5.85	4.89	1.20
Dumper – 17	2.57	3.51	6.06	6.45	0.94
Dumper - 20	2.34	2.26	5.83	4.70	1.24
Dumper - 23	1.79	2.23	5.80	4.19	1.38
Dumper - 25	3.33	3.05	7.08	5.06	1.40
Dumper - 28	2.34	2.40	5.60	5.17	1.08
Dumper - 31	3.20	2.81	5.21	6.62	0.79
Dumper - 32	2.43	2.62	4.33	4.91	0.88
Dumper - 33	1.91	2.56	5.78	6.85	0.84

The results of the case study showed that there is indicative health risk for dumper operators due to vibration exposure. The geometric mean of SEAT factors of all the fifteen dumpers were observed to be 1.03% and 1.05% based on the frequency weighted r.m.s. acceleration values and Vibration Dose Values (VDV) respectively. Results clearly depict that the seats installed in the dumpers are not efficient in reducing the vibration or may have not been installed properly. They are definitely not being used as per procedures usually stipulated by reputed manufacturers. As echoed by Paddan and Griffin (2002) it is equally important to choose an appropriate vehicle seat for reducing the intensity of whole-body vibration. Additionally, incorrect adjustment of a seat suspension system can amplify vibration exposure [21]. As mentioned by Gunaselvam and Niekerk (2005) due to the frequency dependent properties of the suspension system, industrial seats should be selected properly for the specific vehicles or work places [22]. Therefore, further in-depth evaluation of engineering and design part of the seats used in these types of dumpers is desirable. The engineering control methods for whole body vibration are to reduce the transmission of vibration from source to receiver which includes, inter alia, improved vehicle suspension, cab suspension and suspended seats. Role of seat suspension are vital in attenuation of vibrations. It was clearly observed that the seat factor values are largely dependent on the seat-vehicle combination [23]. In our study, results illustrated that all the pneumatic seats are actually amplifying the vibrations received from the body of the vehicle. Further, frequency analysis needs to be conducted for understanding the problem with adequate details for effective engineering control and utilizing the seats more optimally to yield better comfort for the dumper operators.

4. Conclusion

It is vital to first realize the purpose of pneumatic seats instead of rigid seats previously used in the old dump trucks. It can be understood that the purpose of pneumatic seats was to provide comfort and ergonomically correct posture to the dump operators. The authors have presented the first study in India on SEAT factors of mining vehicles. From the case study it can be proclaimed that merely installing pneumatic seats perhaps is not sufficient to solve the purpose. Installation alone should not be considered as an end of responsibility of mine owners. As this study unravels, the efficiency of the seats installed needs to be checked technically and ergonomically in the field condition. The seats need to be adjusted frequently considering the weight of the operator but the overall effect needs to be re-checked since vibration intensity has multifactor origin. Hence information in respect of the surface on which the vehicle is to be used more frequently, condition of the road, speed of the vehicle, driving style of the operator, weight and height of the operator, loading and unloading condition of the dump truck are required to resolve the issues holistically.

Conflict of Interest

Author states that there is no conflict of interest.

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LABORATORY INVESTIGATION OF INFLUENCE OF PARTICLE SIZE ON COHESION AND ANGLE OF INTERNAL FRICTION ON SHALE AND SANDSTONE MIX MATERIAL

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ABSTRACT

Overburden dump materials comprises of a complex mixture of rock fragment, soils and rock fines in different proportions which made it to behave differently unlike soils. Shear strength behaviour of loose and unconsolidated material depends on moisture content, presence of amount of fines, maximum particle size and particle size distribution. This study revealed that the particle size influences the cohesion and internal friction angle of the material mix greatly for coal mine overburden dump. For the particle size less than 300 μm, the cohesion of the material increases from 47.08 kPa (for particle size 106 μm) to 107.91 kPa (for particle size of 300 μm). The material had shown decreasing trend for angle of internal friction between the size ranges from 106 μm (friction angle, 16.69 degree) to 300 μm (friction angle, 10.64 degree). For the particle above 1 mm (cohesion, 84.36 kPa), the cohesion decreases as the particle size increases upto 4 mm (cohesion of 41.16 kPa) and then increases upto 13.9 mm (cohesion of 108.9 kPa). In context of internal friction angle, it had shown increasing trend as the particle size increases from 1 mm (internal friction angle, 19.38 degree) to 8 mm (internal friction angle, 35.81 degree) and then started decreasing upto 13.9 mm (friction angle, 20.8 degree) size.

Keywords

Material Cohesion, Internal Friction Angle, Direct Shear Test, Material Mix

Introduction

The presence of rock fragments of varying size in overburden dump materials greatly influences the shear strength behaviour of the dump materials *(Fakhimi et. al., 2008)*. Many study had been done in the past to understand the effect of particle size, particle shape and particle size distribution on the shear strength behaviour of the dump and embankment materials. Holtz and Gibbs had conducted a number of triaxial test to study the effect of material density, amount of gravel, maximum particle size and particle shape on river sand, gravel and quarry material (Holtz and Gibbs, 1956). Hennes in his study, studied the effect of particle size, particle shape and gradation on internal friction angle of dry crushed rock and gravels of rounded shape. He found that as the maximum particle size increases, there is a decrease in angle of internal friction *(Hennes et. al., 1952)*. Rathee studied on granular soils by conducting direct shear test in 30 cm x 30 cm shear box and found that the internal friction angle of sand-gravel mix increases as the maximum particle size increases, while for uniform gravel size, angle of internal friction was nearly constant for increasing maximum particle size *(Rathee et. al., 1981)*.

The effect of scale of the test for finer material (like fine soil) is negligible on the measured values of dilation angle (which is ratio between maximum vertical stress and shear displacement) and internal friction angle obtained from direct shear test (Palmira and Milligan, 1989). For material mixes, which are obtained from overburden dump, the scale of the test has a significant effect on the measured values of internal friction angle, cohesion and dilation angle as well. While shearing the material in the direct shear box, the rate of shear loading is very important. Palmer (1999) mentioned the importance of shearing rate in his study, and observed that when the shearing rate is too fast, even silt and sand can also exhibit dilation consequence to generation of significant suctions which ultimately resulted to increased effective stress and hence, shear resistance. Many researchers have suggested different rate of shearing as per the purpose of shearing. For studying the shear strength parameters i.e., cohesion and angle of internal friction of overburden dump material for slope study or embankment stability analysis, rate of shear loading should be 1mm/ min (Bauer and Zhao, 1993). Frederick (1961) studied the particle size effect on the macroscopic response of the sand and found that, particle size is responsible for change in shear strength and also observed that angle of internal friction increases with increasing particle size.

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Literature Review

Cohesion of loose material like soil, rock dust and fines can be defined as the binding force that connects its constituent fine particles. Cohesion in any material can be due to chemical bonding, electrostatic attraction, cementation or other similar processes between the constituent particles

A short review of the same is presented in Table 1. Theoretically, cohesion is the property of the material and should not be changed as the particle size changes, but due to the presence of fines in varying proportions and moisture, it changes. However, cohesion value obtained from direct shear test comprises not only cohesion due to cementation, but also due to chemical bonding and grain characteristics as well. Friction angle is the resistance to motion offered by shearing layers. It depends on factors such as fineness, grain surface characteristics, angularities and sphericity. The factor of safety designed for the slope utilises the values obtained from the direct shear tests only. Thus, the effect of particle size on composite values obtained as these two properties in direct shear test is important. Many researchers have studied the particle size effect and presence of maximum particle size, sphericity and moisture content on cohesion and internal friction angle.

Table 1. Review on particle size effect on cohesion and internal friction angle

Year	Author	Findings
1961	J Kolbuszewski and M R Frederick	The internal friction angle of the material (here, sand) increases as the particle size increases
1965	W M Kirkpatric	The shear strength of the loose material (for sand having uniform size) decreases with increasing particle size
1972	N D Marschi, C K Chan & H B Seed	Internal friction angle of uniform (almost) sand decreases as the particle size of the material increases
1974	C M Nieble, Silveria and N F Midea	They observed that for uniformly crushed basalt, as the maximum particle size increases, the angle of internal friction decreases. He also suggested that to avoid size effect in measuring angle of internal friction, maximum particle size should be less than 5% of the width of shear box.
1993	G E Bauer and Y Zhao	Rate of loading should not be greater than 1mm/ min or else increase in suction pressure increases effective shear strength
2000	G T Sitharam and S M Nimbkar	He noticed that particle size and particle size distribution in the material influences the stress- strain behaviour greatly
2008	A Fakhimi and H Hosseinpour	He observed that due to presence of oversize material in the sample, friction angle and dilation angle, both increases
2009	A K Gupta	For Ranjit Sagar Rock fill material angle of internal friction increases with increasing particle size and the behaviour is opposite for Purulia Rock fill materials, i.e., the angle of internal friction decreases with increasing particle size
2016	Terezie Vondrakova	Cohesion get reduced with increasing plasticity of soils. Effective cohesion get decreased as the grain size increases.

Methodology

The materials were collected from overburden dump of a coal mine of Barakar measures. The material was basically collected from top as well as the bottom of the dump. The reason for this type of collection strategy is that the finer material settles at or near crest of the dump slope while the larger fragments roll down towards toe of the dump. The size of the material at the bottom of the dump ranges from 0.7 mm to 1.2 m as observed (also image analysis using Fraglyst software has been done). But as there is a limitation of maximum particle size for testing in our available Direct Shear Testing machine, we have conducted the test for the particle size ranging from 106 μm to 16 mm. The collected material was then sieved as per the Hard son sieve series. The material after sieving is shown in Figure 1. For the finer material, sieve size of 106 μm, 112 μm and 300 μm was used. The sieved material were then dried separately in oven for 48 hours before each were conducted. The dried material is then fed into the 30 cm X 30 cm shear box for testing.

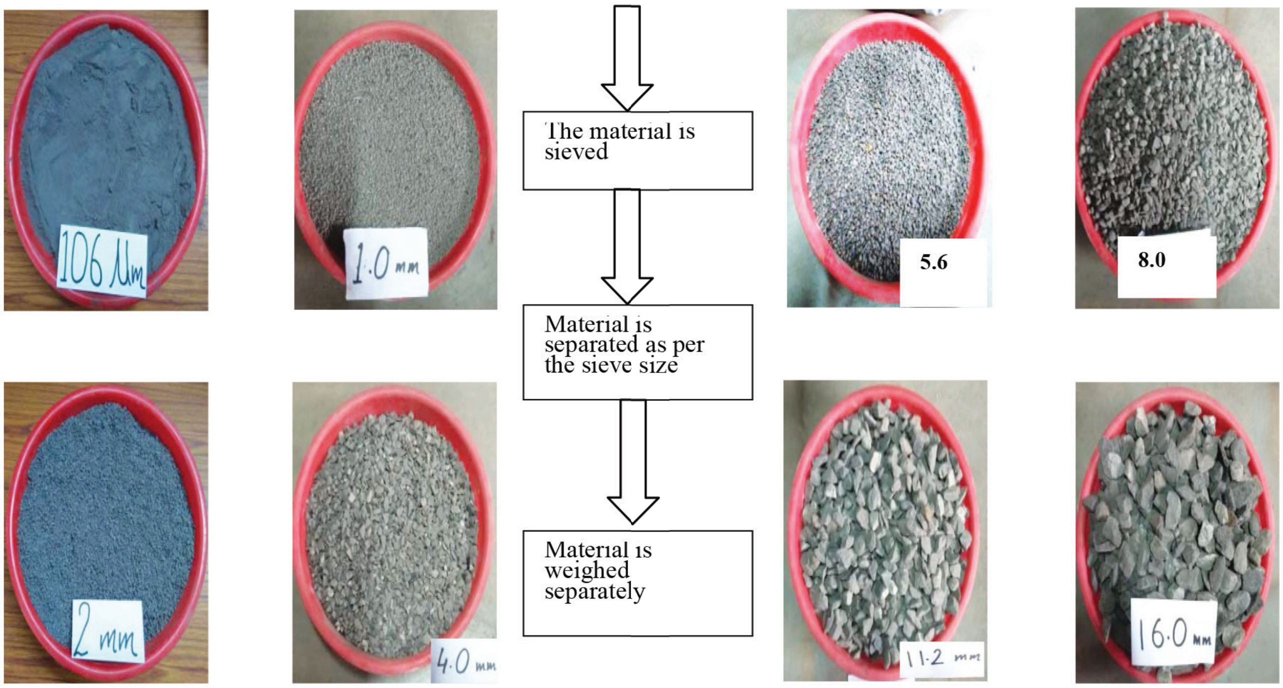


Figure 1. Different sizes of the material mix used for after sieving obtained from overburden dump

The weight of the material was taken each time before putting it in the shear box. This will tell us about the the degree of compaction which is measured by the amount of settlement after the application of normal load. Three number of tests were conducted for each of the material size. In each test, three different normal load were given. The normal load applied were 1 kg, 2 kg and 4 kg which yields a corresponding normal load of 100 kPa, 200 kPa and 400 kPa.

The setup for conducting direct shear test is shown in Figure 2. The shear testing set up used in this study is totally software controlled, so the probability of encountering error in loading (normal or shear), taking reading is minimized to a great extent. The rate of normal loading for the entire experiment was fixed to 1mm/min. The rate of shear loading was also kept to 1 mm/min. For all the eight set of materials, shear testing test to obtain cohesion and friction angle were performed.

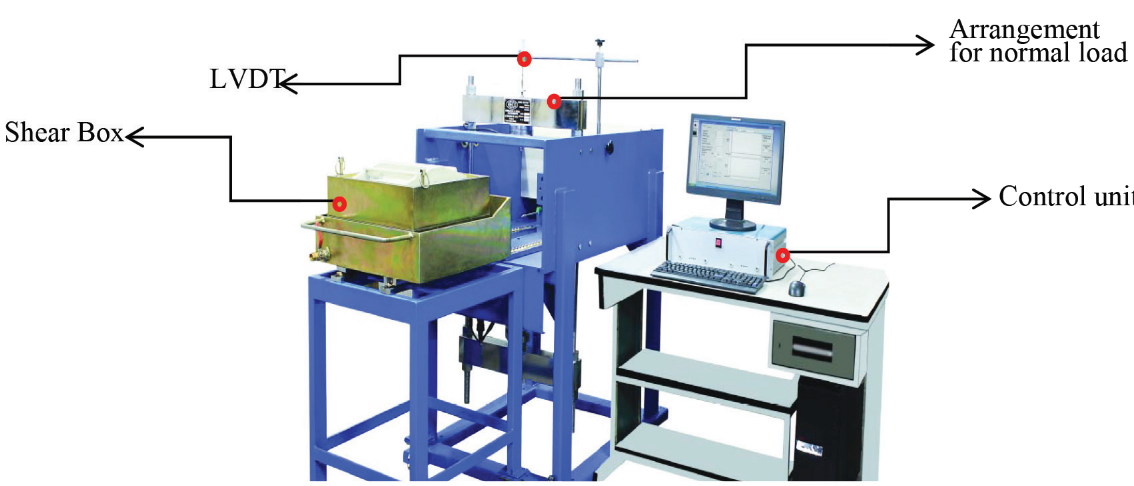


Figure 2. Direct shear testing setup of 30 cm X 30 cm shear box size

The make and model of the shear testing machine is Heico-M Servo Controlled (30x30). The shear box used was of size 30 cm by 30 cm to maintain the uniformity of setup during the entire test procedure.

Results and Discussion

The sieving of the material is performed as per the Hard son sieve series. For the finer particles, sieve size of 106 μm, 112 μm and 300 μm were used generally. The size range varying between 106 μm to 13.2 mm were used in the study. The result of the sieve analysis is shown in Figure 3. A plot of shear stress against shear displacement is shown in Figure 4. It depicts that the maximum shear stress were developed against the material (particle size of 1mm) at normal load of 100 kPa is 100.06 kPa, for normal load of 200 kPa is 161.86 kPa and for 400 kPa normal load, shear stress is 210.91 kPa. For 1 mm particle size, as shown in the figure 4. the friction angle obtained is 19.38 degree and cohesion obtained is 75.5 kPa.

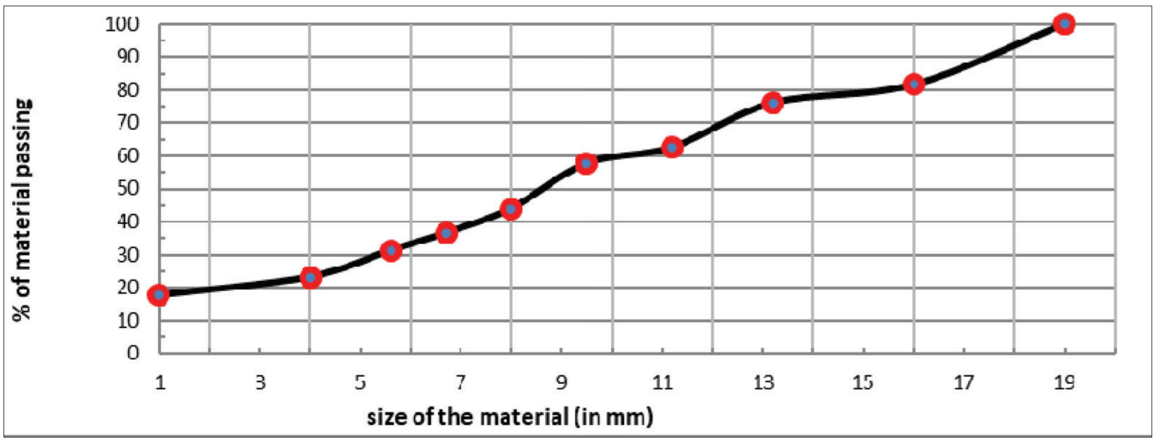
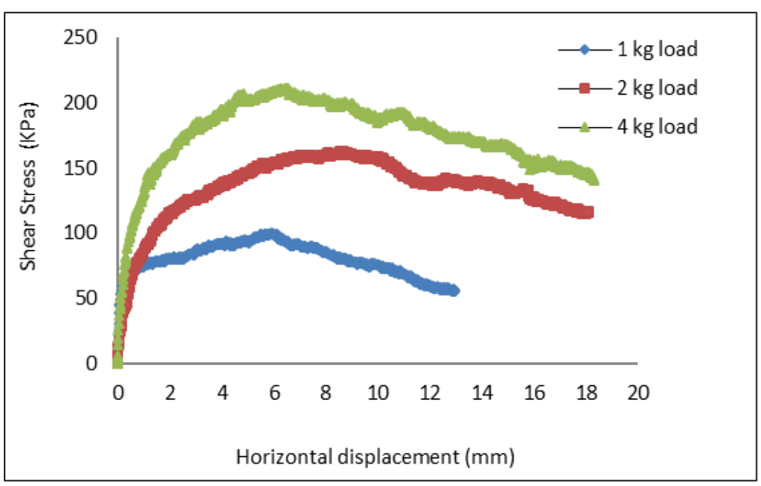


Figure 3. Percentage of material passing versus sieve size of the material

To obtain the cohesion and angle of internal friction of the material, we have used the shear displacement value vs shear load value obtained from the direct test result. Then we have plotted the graph for maximum shear stress vs maximum normal load. The equation of the fit yielded the internal friction angle and cohesion of the material. The same is performed for all the material size. One such plot is shown below in Figure 4.



Particle size: 1 mm
Cohesion : 75.5 kPa Friction angle : 19.38 Deg.

Max. Shear Stress (in KPa)	Normal Applied Stress (in KPa)
100.062	100
161.865	200
210.915	400

Figure 4. Example plot of shear stress (in kPa) vs horizontal displacement (in mm)

The above plot is for the 1 mm particle size. Here the cohesion obtained is 75.5 kPa and friction angle obtained is 19.38 degree.

The internal friction angle is plotted against the particle size of the material. It was found that, for finer particle size range, i.e., from 106 μm to 300 μm, there is a decrease in angle of internal friction. Furthermore, for the particle size greater than 1 mm (internal friction angle, 19.38 deg.), it increases till 8 mm (internal friction angle, 35.81 deg.) particle size and then again start decreasing upto 13.2 mm (internal friction angle, 20.8

deg.) particle size. The main reason for increase in internal friction angle for size greater than 1 mm is the complex particle shape, irregularities in its structure, and their particle to particle interlocking.

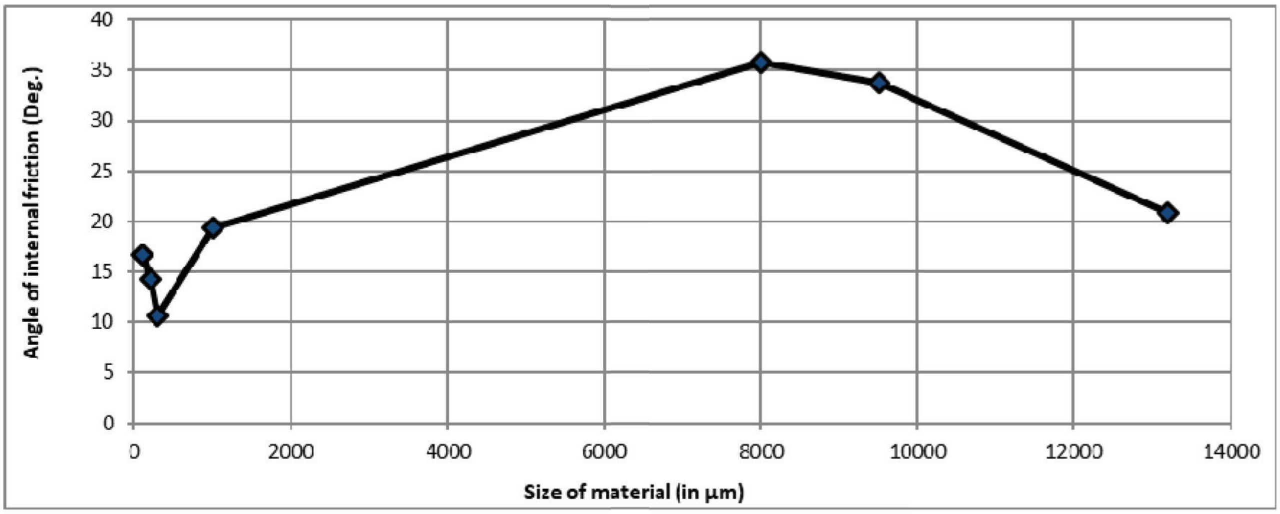


Figure 5. Variation of angle of internal friction (in deg.) with particle size of the material (in mm)

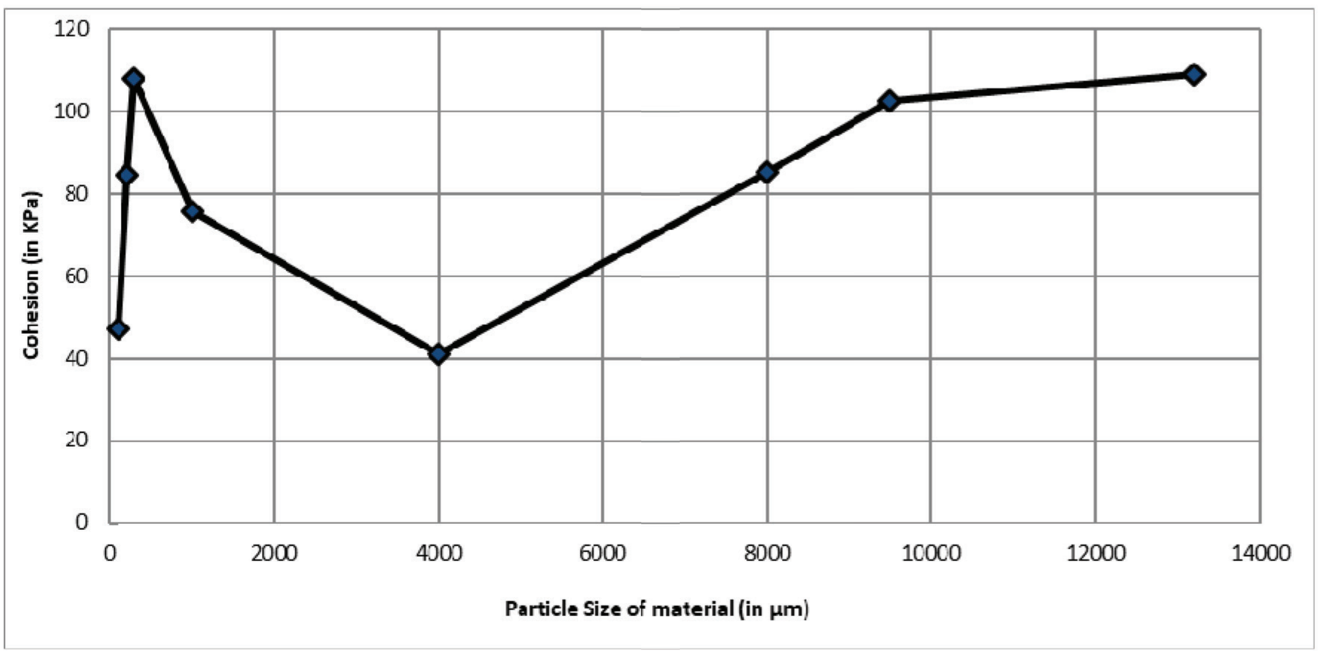


Figure 6. Variation of cohesion (in kPa) with particle size of the material (in mm)

In uniform and homogenous material, the presence of substantial amount of fines, moisture, maximum particle size, there is a considerable change in cohesion as these parameters changes. In the present study, the particle size is varying between 106 µm to 13.2 mm, so the cohesion obtained from direct shear test also changes. For finer particle size of 106 µm, the cohesion was 47.08 kPa. The cohesion of the material increases from 47.08 kPa for 106 µm size to 107.91 kPa for 300 µm size. As there is increase in particle size from 300 µm to 4 mm, the cohesion decreases and then again increases as the particle size increases from 4 mm to 13.2 mm.

Conclusion

Particle size of the material mix is very important parameter which needs to be considered in understanding the behaviour of material mix of sandstone, shale as well as other loose materials of the dump. The increasing particle size decreases the internal friction angle of the material due to decreasing contact area of the material holds good here in the experiment, but for the very fine material. For the coarser size particle, the internal friction angle is not showing the uniformly increasing or uniformly decreasing trend due to the complex, structure of exposed surface, its shape and their general arrangement at the shearing plane after the normal load is applied. At shearing plane, the particles orientation of the material mix changes gradually with gradually increasing shear load (rate of shearing is fixed at 1mm/min). Cohesion of the material is also affected by the amount of fines present in the shear box and its proportion with coarser material. For the finer material, cohesion increases as the particle size increases. When there is further increase in particle size, the cohesion first decreases upto 4mm size and then showns increasing trend.

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EXPLOITATION OF INSAR TECHNIQUES AS A SUPPORT OF IN-SITU SENSORS TO IMPROVE SAFETY AND PRODUCTIVITY IN MINING OPERATIONS

J Duro, R Iglesias, D Monells, R Calvo

ABSTRACT

Mining operations are typically monitored by employing sparse networks of in-situ sensors. This information does not cover the totality of the possible areas affected by deformation. In this context, spaceborne synthetic aperture radar (SAR) interferometry (InSAR) technology represents an attractive alternative to complement the monitoring of mining operations due to its capabilities. Satellite InSAR could provide measurements of terrain deformation with millimetric precision over wide areas.

The satellite InSAR technology allows the exploitation of key indicators revealing precursors in the trend of deformation time-series. This paper takes Cadia and Brumadinho as test sites and shows the potential of cross-sections and inverse velocity analysis to complement in-situ sensors for the rapid identification of critical deformations on tailing dams and slopes in open pits.

An example of an online platform is presented as a way of improving the user experience to exploit InSAR monitoring services jointly with in-situ information over a map of reference..

Keywords

Mining, Ground Deformation, Monitoring, Stability, Satellite, open pit, InSAR, Radar

1. Introduction

The exploitation of satellite imagery represents an extremely useful tool to analyse data from local to regional scale at a lower cost compared with conventional in-situ techniques. In this framework, radar measurements linked to spaceborne platforms are increasingly being used for the monitoring of a wide range of ground displacement phenomena.

This is the case of synthetic aperture radar (SAR), which allows obtaining all-weather, all-day reflectivity images with a fine spatial resolution. If SAR images are taken at different times, SAR interferometry (InSAR) techniques allow exploiting phase differences between multi-temporal pairs of SAR images in order to obtain displacement information of areas affected by deformation phenomena (Massonet & Feigl 1998; Bürgmann et al. 2000) with millimetric precision (Gabriel et al. 1989).

SAR sensors allow measuring surface displacement phenomena due to different causes (slopes, tailings, dewatering, injection heave, etc.) and at different scales (faults, slope areas, entire mines, etc.). These measurements provide a high level of spatial detail and can be integrated with information coming from in-situ sensors, to get a unified view of ground deformation effects and to better understand their causes. This is crucial to guarantee safety and efficiency in operations in different sectors such as mining, where geotechnical managers are increasingly using data collected by SAR sensors to detect precursors, prevent accidents and improve productivity in the following areas :

- **Open pits :** InSAR techniques can prevent slope failures in open pits, monitor local displacements to timely alert managers about potential problems, and to initiate slope management programs for failure mitigation.
- **Tailings dams :** Security of tailings facilities is now a recognised priority at a corporate level and the concept of sustainable mining is an accepted part of the modern industry, often required by regulators. The increasing focus on tailings dam safety brings with it an increasing awareness of the importance of a reliable monitoring program to confirm that the tailings dam is in a safe condition. InSAR measurements can provide alert warning systems to be timely informed about any potential dam failure.

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- **Waste dumps :** Landslides, erosion and subsidence of waste dumps are a challenge for the mining industry because they could lead to environmental problems, which can have a negative impact on their surroundings.
- **Leach pads :** When heaping ore for leaching, the stacking heights can sometimes reach up to 100 m, so an analysis of slope stability is of high importance. Leach pad failures can be caused by extreme heights, base pressures, or long-term chemical and biological degradation of ore.

2. Methodology

2.1. From classical InSAR to multi-temporal InSAR

InSAR consists of the combination of the phase information of two SAR images of the same illuminated scenario, acquired at different times. The result is known as interferogram, whose phase $\Delta\varphi_{int}$ is sensitive to the scene topography and deformation phenomena :

$$\Delta\varphi_{\text{int}} = \frac{4\pi}{\lambda r_0}\frac{B_n \Delta r}{\tan\alpha} + \frac{4\pi}{\lambda r_0}\frac{B_n \Delta h}{\sin\alpha} + \frac{4\pi}{\lambda}\Delta\rho + \Delta\varphi_{APS} + \Delta\varphi_N \tag{1}$$

where :

$\Delta\rho$ = increments in deformation between two certain spatial points of the interferogram.

Δr = increments in range distance between two certain spatial points of the interferogram.

Δh = increments in height between two certain spatial points of the interferogram.

λ = the nominal wavelength of the radar.

B_n = indicates the perpendicular baseline.

r_0 = the sensor-to-target distance, the incidence angle.

$\Delta\varphi_{APS}$ = accounts for the atmospheric artefacts (typi cally known as the atmospheric phase screen in the InSAR literature).

$\Delta\varphi_N$ = refers to the noise component of the interferometric phase.

If we ignore for a moment the atmospheric and noise phase contribution to the interferometric phase, there are three main terms in Equation (1) that provide information about the SAR acquisitions. The first term is known as the flat-earth component. It is deterministic and depends on the acquisition geometry so it can be computed in advance and compensated from the interferometric phase. The second term is the topographic component that contains information about the elevation profiles of the area. Finally, the third term is the deformation component that provides information about subsidences and uplifts on the area.

If a ground deformation occurs during the acquisition period, the phase of the interferogram contains both the topographic and the deformation components. By using external information about the topography of the area such as an existing digital elevation model (DEM), the topographic phase component can be estimated and compensated for. The result of subtracting the topography from the interferogram is known as a differential interferogram, and the resulting phase can be directly related to ground deformation. One full cycle in the interferometric fringes represents a displacement equivalent to half the wavelength of the electromagnetic wave employed by the SAR sensor. Figure 1 illustrates the displacement retrieval process (assuming no significant atmospheric phase screen (APS) contribution) over a subterranean mine area in Central Catalonia, using two SAR images acquired with the C-band satellite Sentinel-1, with a temporal baseline of two months.

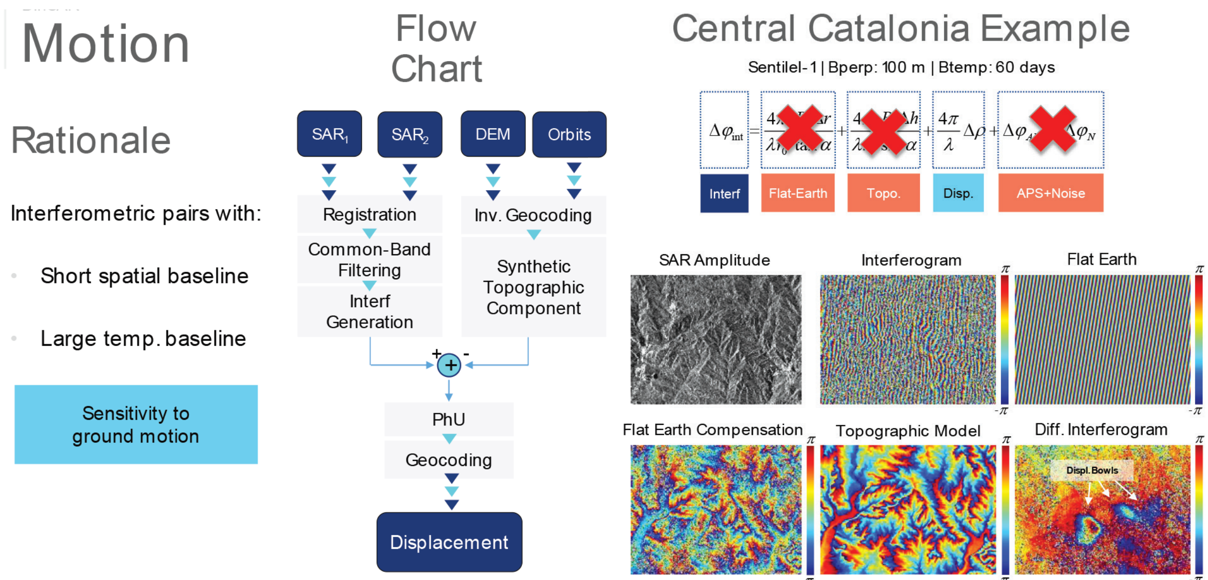


Figure 1 Displacement retrieval process over a subterranean mine area in Central Catalonia

Unfortunately, not all the points within the differential interferograms have enough phase quality to provide reliable information. Furthermore, the interferometric phase of differential interferograms is compromised by inaccuracies in the DEM employed during the compensation of the topographic component and, in general, by the impact of APS.

In order to compensate the topographic height errors and separate APS from displacement in differential interferograms, multi-temporal stacks of radar data are exploited using the so-called Persistent Scatterers Interferometry (PSI) technique. During the last 20 years, several PSI techniques have demonstrated their potential for measuring a wide range of deformation phenomena (Ferretti *et al.* 2001; Mora *et al.* 2002; Bernardino et al. 2002; Arnaud et al. 2003; Hooper et al. 2004; Lanari *et al.* 2004).

Figure 2 illustrates the objective of PSI, which is based on the identification of reliable measurement points in the illuminated scenario and in the compensation of phase-delay coming from atmospheric artefacts through the exploitation of multiple satellites passes.

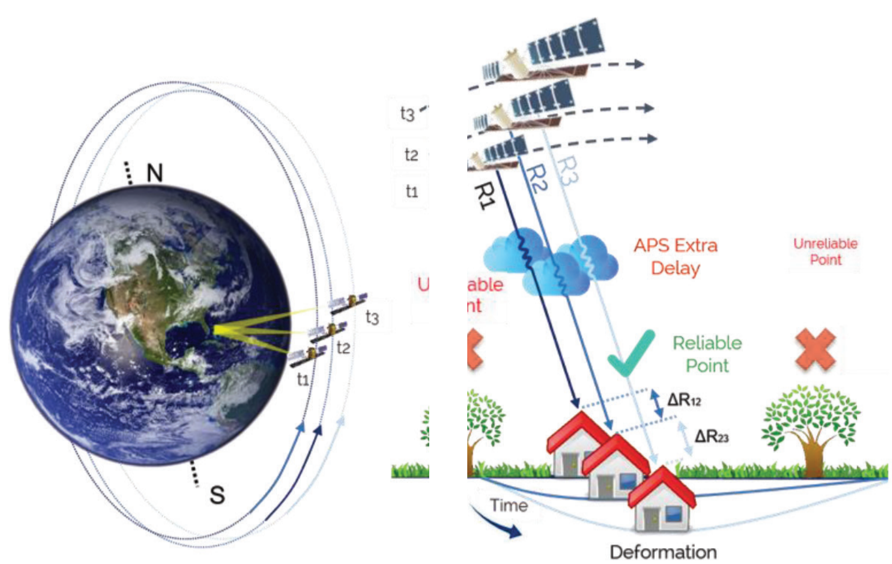


Figure 2 Persistent Scatterers Interferometry rationale

2.2. The Coherent Pixels Technique

Among the different PSI techniques available in the literature, DARES TECHNOLOGY employs the Coherent Pixels Technique (CPT) to obtain reliable ground displacement measurements. This PSI technique was developed in 2002 by the Remote Sensing Laboratory (RSLab) of the Universitat Politècnica de Catalunya *(Mora et al. 2002).* CPT allows the estimation of the linear and non-linear components of displacement, the topographic error, and the atmospheric artefacts.

In general terms, the CPT is divided into three main blocks :

2.2.1. Selection of differential interferograms and pesistent scatterers

The first block is focused on gettng a set of differential interferograms that are used to identify reliable scatterers (persistent scatterers). The persistent scatterers are points with high phase quality along the set of interferograms. These are the points that will be used in the PSI process to minimise the impact of decorrelation phenomena and ensure millimetric precision in the final ground displacement results.

2.2.2. Linear estimation block

Once a set of persistent scatterers is available, the estimation of the linear contribution of the differential phase is carried out. This is related to the linear component of ground displacement and the residual topographic error component remaining in the differential interferograms.

The first step of this block consists of doing a triangulation of the pixel candidates selected previously. This process works with phase increments between neighbouring pixels, instead of absolute phases. The objective of this approach is two-fold. On the one hand, atmospheric artefacts are minimised since they change smoothly in space in relation to the length of the links between neighbouring pixels. On the other hand, it cancels out the inherited phase offsets of each interferogram. The interferometric phase increment of each arc of the triangulation may be estimated with the following linear model :

$$\Delta\varphi_{\mathrm{mod}} = \frac{4\pi}{\lambda} T\Delta v + \frac{4\pi}{\lambda}\frac{B}{r_0 sin\alpha}\Delta\varepsilon + \Delta\varphi_{res} \tag{2}$$

where :

- Δv = the linear deformation rate in the line-of-sight (LOS).
- $\Delta\varepsilon$ = the vertical topographic error increment.
- Λ = the wavelength.
- T = the temporal spatial baseline.
- B = the perpendicular spatial baselines.
- r_0 = the sensor-to-target distance.
- α = the incidence angle.
- $\Delta\phi_{res}$ = accounts for the atmospheric, non-linear and noise components of the phase.

In order to estimate the linear deformation rate and the residual topographic error components of the interferometric phase, the model defined above is adjusted to the data through the minimisation of a cost function known as model adjustment function (MAF). With a suitable distribution of temporal and spatial baselines, the model can be correctly adjusted even in cases where some of the phase increments are wrapped since the solution is found in the complex plane. Once the linear deformation rate and the topographic error increments are obtained, the MAF is evaluated as a measurement of the quality of each arc. The low-quality arcs are truncated and at the same time, pixels that are isolated are removed. This process removes the pixels that do not fit the linear model, despite the fact that they have fulfilled the pixel selection thresholds. The objective of this step is cleaning those links largely affected by atmospheric artefacts. Finally, the absolute values of linear deformation and topographic error for each pixel are calculated through an integration process, using one or multiple seeds with known behaviour as tie points, leading to the a priori deformation results.

2.2.3. Non-linear estimation block

The non-linear estimation block compensates the atmospheric artefacts present in the interferograms and provides precise time-series of the displacements produced in the area of interest. First, the computed linear model is removed from the interferometric phase, so residual phases are generated. These remaining phases are supposed to be affected only by non-linear displacement and atmospheric artefacts. The separation of these components is based on a filtering process, taking advantage of their different temporal and spatial behaviour in a large set of images. Atmospheric artefacts are characterised by having a low spatial frequency behaviour for each interferogram, due to its roughly 1 km correlation window (Hanssen 2001). Regarding its temporal behaviour, for a given pixel (belonging to an image, not to an interferogram), it can be considered as a white process, since atmospheric conditions change randomly for typical acquisition intervals of current spaceborn SAR systems (6–20 days). Contrarily, non-linear displacement terms are considered to present a narrower spatial correlation window compared with APS and to behave low-pass along the temporal axis. The separation of the atmospheric artefacts and the non-linear component of displacement can hence be achieved, carrying out a filtering process in both the spatial and the temporal domains. In order to apply the temporal filtering, phase residues must be unwrapped, i.e. convert phase cycles into absolute phase values. Since a large number of fringes has been removed during the linear block, the phase unwrapping is supposed to be easier at this stage. Finally, since the process is based on the spatio-temporal behaviour of the deformation and the APS, the larger the number of images, the better the estimation of both components.

2.3. Heading

Figure 3 shows an example of ground displacement results and time-series over a mine in the Atacama Desert, Chile, using six months of data gathered by the European Space Agency Sentinel-1 (S1) satellite in descending mode. Red points refer to displacements moving away from the radar while blue ones indicate points approaching it.

As shown in the figure, thanks to the global view of radar satellites, whole mines can be monitored with millimetric precision. In this case, slope stability over pit areas, settlement of waste dumps and subsidence in infrastructures areas and tailings dam can be clearly appreciated.

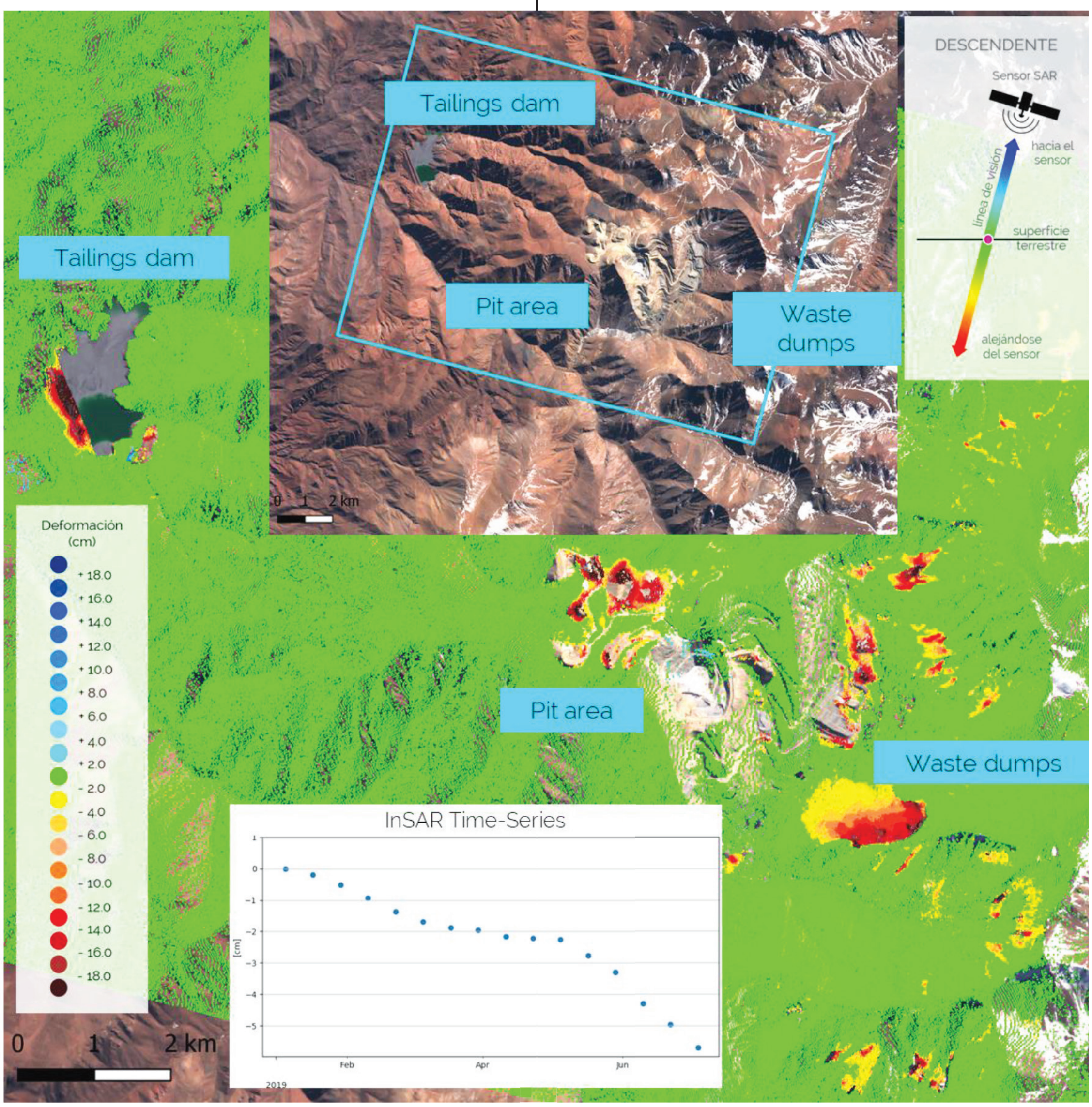


Figure 3 Persistent Scatterers Inferometry results at a mine in the Andes, South America, using data collected by the European Space Agency SENTINEL-1 (S1) satellite. Red points refer to displacements moving away from the radar while blue ones indicate points approaching it. InSAR time-series show the evolution of ground deformation trough the time, allowing identification of acceleration periods

Despite the wide coverage and the large number of measurements shown, PSI products can be highly improved. On the one hand, mid-term reports are not enough to prevent failure events such as the one that occurred in Cadia gold mine on 9 March 2018 or in Brumadinho on 25 January 2019, since a frequent update of information is required. On the other hand, PSI standard products can be difficult to manage and to understand, especially over locations with topographic changes such as mining areas.

2.4. From conventional Persistent Scatterers Interferometry results to advanced products for mine industry

First of all, the retrieval of the complete magnitude of displacement is proposed. SAR sensors are only sensitive to displacements produced along the LOS direction and therefore, the measured displacements are a projection of the total magnitude. For the current polar-orbiting SAR sensors, the look direction is either east or west, for the ascending or descending pass respectively. Hence, SAR sensors are only sensitive to vertical displacements and/or horizontal ones along the east or west direction. If the displacement obtained by both acquisition modes ($V_{LOS,ASC}$ and $V_{LOS,DSC}$) are combined, the up - down (UD) and east–west (EW) displacement components, V_{UD} and V_{EW}, can be computed. With the incidence angle α and the track heading δ of both geometries, UD and EW components can be obtained solving the following system of linear equations (Hanssen 2001) :

$$\begin{pmatrix} -\cos(\alpha_{\mathrm{ASC}}) & \sin(\alpha_{\mathrm{ASC}})\times\cos(\delta_{\mathrm{ASC}}) \\ -\cos(\alpha_{\mathrm{DSC}}) & \sin(\alpha_{\mathrm{DSC}})\times\cos(\delta_{\mathrm{DSC}}) \end{pmatrix} \begin{pmatrix} V_{UD} \\ V_{EW} \end{pmatrix} = \begin{pmatrix} V_{LOS,ASC} \\ V_{LOS,\mathrm{DSC}} \end{pmatrix}$$

Once the UD and EW components of displacement are obtained, a good magnitude of the displacement is generally computed from the modulus of both components.

The following advanced products can be now defined :

- Rapid reports **:** the generation of rapid reports through the computation of classical InSAR is firstly proposed. Instead of using PSI-derived displacement time-series, a single differential interferogram is generated with each satellite pass in order to identify any increase in deformation magnitude and / or in the shape of deformation areas with respect to the previous image. The precision of this product is around one twentieth of the wavelength (which corresponds to 0.5 cm for sensors at C-band such as S1). Although it is not the highest precision that InSAR can achieve, it is extremely useful to identify new areas of deformation.
- Acceleration indicators and cross-sections : once hot spots of deformation are identified with rapid reports, PSI time-series can be analysed in detail. The problem at this point is that checking the large number of points provided by InSAR techniques can be a difficult task, sometimes impossible to fulfil. The computation of the acceleration over the last images of the time-series is proposed in this paper in order to highlight the potentially vulnerable areas in terms of increasing ground instabilities. Furthermore, the computation of cross-sections in these areas allows for spatio-temporal analysis of ground deformation along specific spatial profiles. An increase in the separation between consecutive graphs indicates an acceleration in the deformation process.
- Moreover, further analysis can be done in order to predict potential failures. The so-called inverse velocity approach (Carla *et al*. 2018) allows forecasting of the date of failure under a purely kinematic point of view (without accounting for the geology or the geotechnical features of the site). First, the velocity is computed as a derivative of the displacement $v = \frac{d\rho}{dt}$, and then a linear regression over the inverse velocity $\frac{1}{v}$ is calculated in order to find the intersection point with zero in the temporal axis. The potential failure date can be hence obtained through the coefficients of the linear regression.
- Visualisation and integration services: finally, the reporting of InSAR-derived products with in-situ information is proposed. In this framework, web GIS services represent an excellent alternative to allow end-users to easily zoom over detailed optical images as background, and precisely identify ground deformation areas and compare them with in-situ information. Finally, the computation of prediction indicators or the generation of transects can be easily incorporated on top of these services.

3. Results and discussion

3.1. Rapid reports and cross-sections

Mid-term reports represent a useful tool to identify areas with significant accumulated deformation. This is generally used by the survey team to identify potential field areas for detailed in-situ inspections.

In order to overcome this limitation, rapid reports allow the detection of areas susceptible to structural problems by analysing the last satellite acquisitions. This advanced product allows a weekly or bi-weekly update to detect relevant time-series of risky areas and to timely inform managers about any potential change in the deformation magnitude and / or extension.

To provide the identification of hot spots with deformation, DARES TECHNOLOGY deliveries are based in a set of isolines in the areas affected by displacement. This way of presenting results eases the assessment of the areas affected by ground motion. No data areas (mainly due to geometric distortions) are indicated with a grey mask. The rest of the areas (without isolines) present stability.

Figure 5 corresponds to a rapid report example of the open pit area of a mine in Chile in late 2019 using the S1 satellite with a revisiting time of 12 days. The figure shows the total accumulated ground deformations over the last 12 days by the rapid reports, checking ground deformation increase over any area. The left-top and middle-top images present the motion in the ascending and descending LOS components, respectively. Through the decomposition approach described in Section 2.4, the corresponding UD and EW components can be obtained, represented in the left-bottom and middle-bottom images. The analysis of the decomposition reveals a dominant west motion detected in the northeast wall of the pit area. The main image on the right shows the total deformation, which is the magnitude of the EW and UD motion vector, directly related to the total magnitude of the motion present in the area. Displacement time-series taking into account one year of data in the area is presented showing an accumulated displacement of more than 2 cm during the last 12 days.

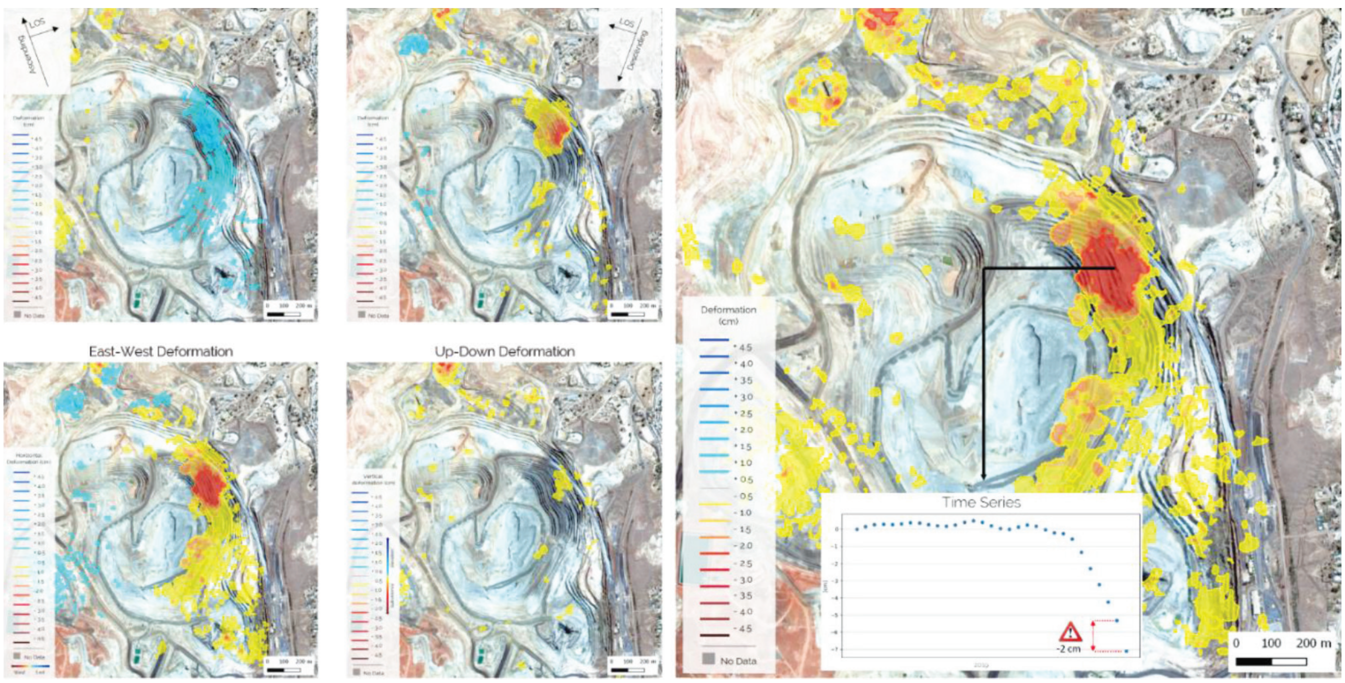


Figure 5. Rapid report example of the open pit area of a mine in Chile in late 2019, using S1 satellite. The left-top and middle-top images present the motion in the ascending and descending line-of-sight components, respectively. The left-bottom and middle-bottom images present the up-down (UD) and east-west (EW) displacement components, respectively. The main image on the right shows the total deformation, which is the magnitude of the EW-UD motion vector

The comparison of rapid reports in time can help in detecting the geotechnical precursors in mining areas. It can, therefore, help decision-makers to make better decisions about mine operations. However, further information can be retrieved from data to help in understanding the deformation dynamics exploiting multi-temporal data.

In order to include the temporal axis in the analysis of the areas of interest, the generation of cross-sections is proposed in this paper. An increase in the separation between consecutive transects is related to an acceleration in the deformation process.

Figure 6. shows a cross-section over a tailings dam located in the USA. The deformation dynamics cover a time period of one year (from April 2018 to April 2019) and including a period of heavy rains. The figure shows a clear acceleration followed by a deceleration with the arrival of autumn.

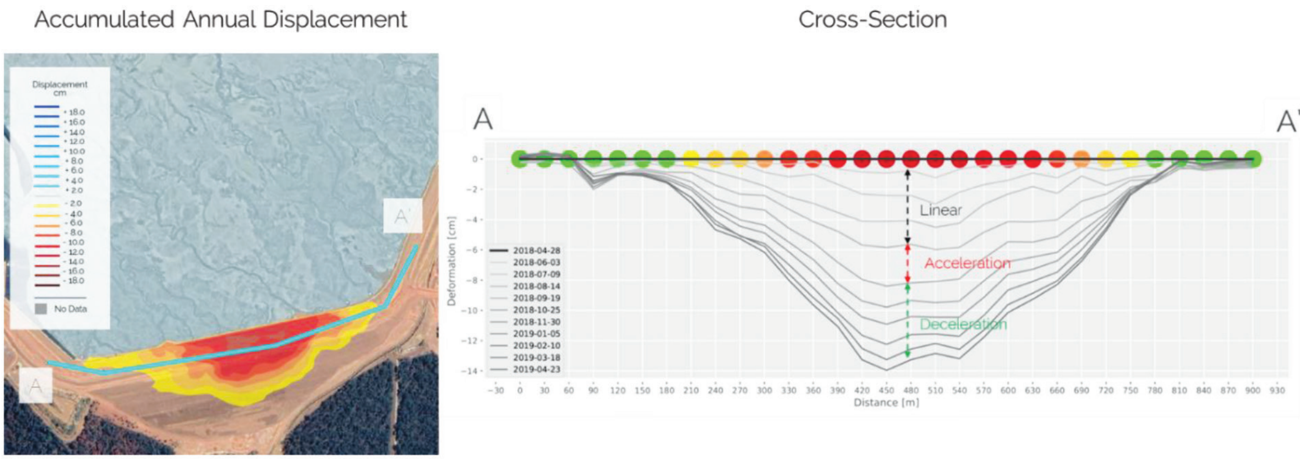
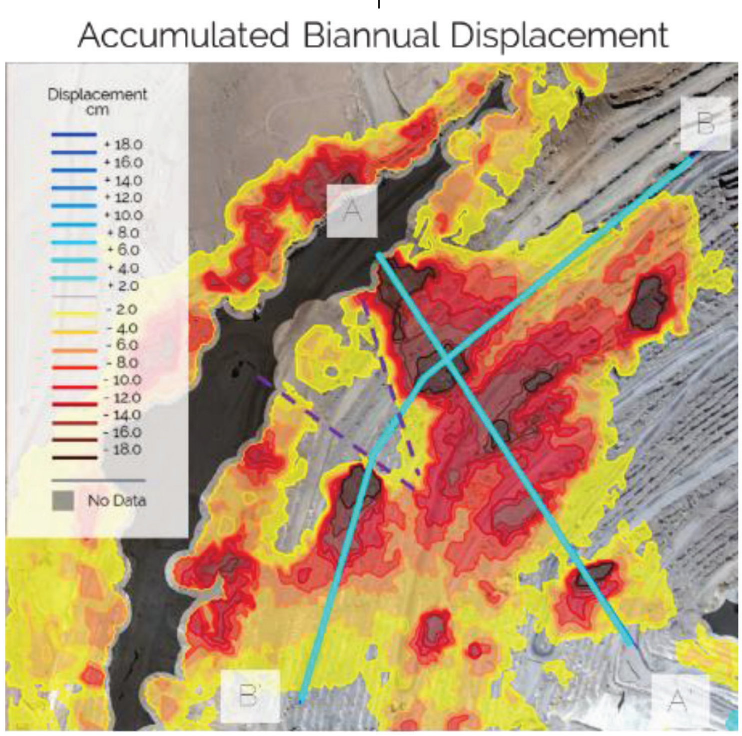


Figure 6. Cross-section over a tailings dam located in the USA. The increase in the separation between consecutive graphs (which are equally spaced in time) of the cross-section indicates an acceleration during August 2018 (shown as acceleration in the graph), coinciding with a period of heavy rains

The right part of Figure 6 shows deformation values for each satellite acquisition date. It shows accumulated deformations, showing the first reported deformation at the top and the last deformation line at the bottom of the cross-section. Please note cross-section from A to A' (as can be seen in the left side of the figure). Red dots correspond to the most severe deformation of the cross-section and green dots are stable points with no deformation in the period.

Another interesting advantage of using cross-sections is the ability to spot different behaviours in a complex scenario. An example is shown in Figure 7 corresponding to a cross-section of an open pit in a Chile mining area. It is a bi-annual report and it shows accumulated deformations that occurred in a two-year period. Profile AA' begins at the top of the northwest wall and ends at the bottom of the pit, crossing different areas of deformation. The corresponding cross-section reveals different acceleration behaviours depending on the area. Profile BB' is drawn following one of the terraces of the open pit, with two main areas of deformation separated by a stable area due to the presence of a fault.



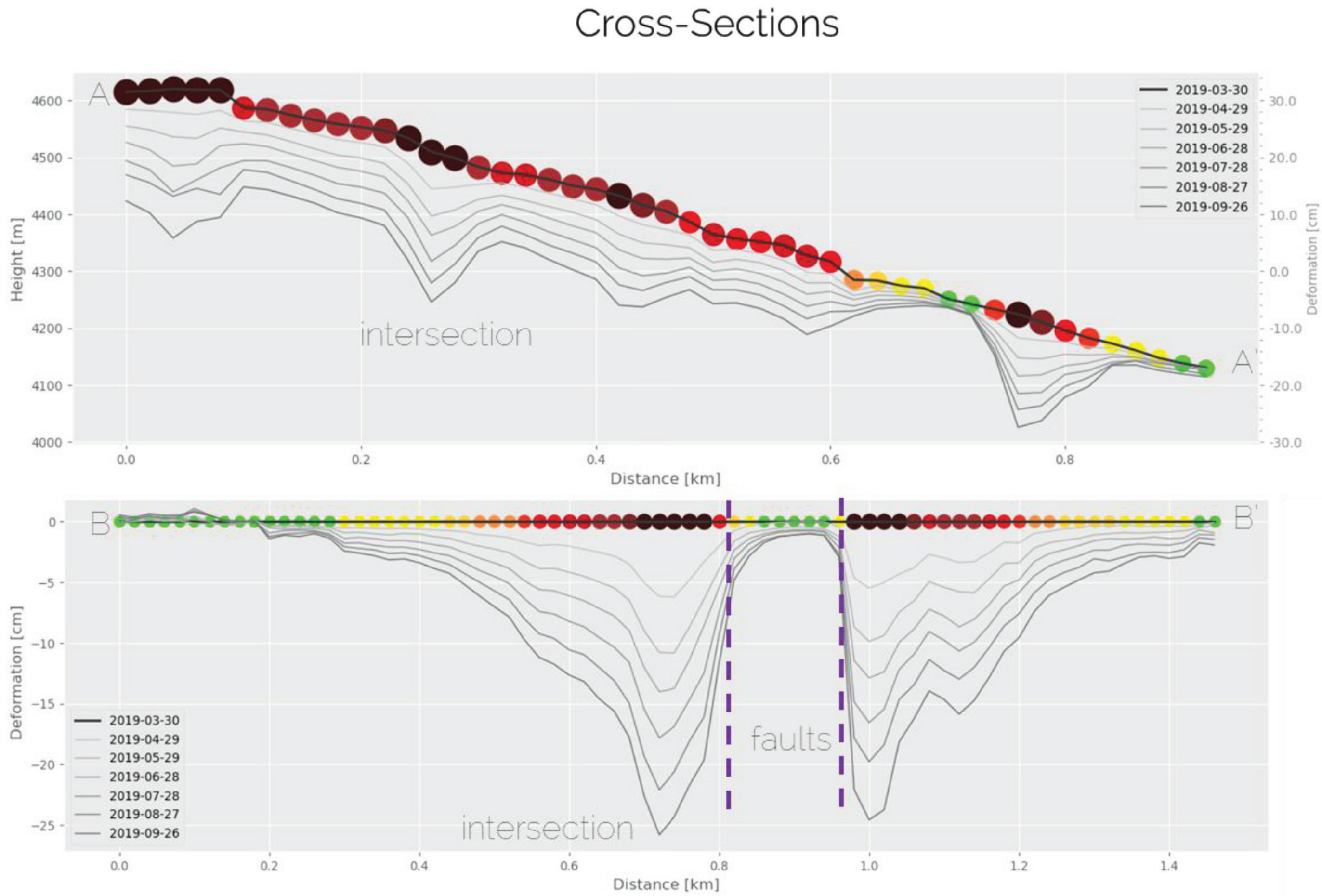


Figure 7. Cross-sections over an open pit located in an open pit mine in South America. The identification of an area of deformation separated by a stable area is related to the presence of a fault in the area

3.2. Prediction indicators

At this stage, the analysis of mine areas allows for the detection of deformation increase between consecutive acquisitions and its spatio-temporal behaviour is presented. The problem at this point is that checking the large number of points provided by InSAR products is a difficult task. For this reason, the next step is to look for time-series presenting an acceleration in the last period in order to detect behaviours that may lead to potential failures. In this framework, the computation of an acceleration indicator is proposed.

In order to illustrate the utility of this indicator, the back-analysis of Cadia gold mine in Australia, which suffered a tailings dam collapse on 9 March 2018, is presented. In Figure 8., the accumulated displacement measured before the event (from December 2017 to February of 2018) is superimposed over an optical image. Through the computation of an acceleration index over the time-series, the area that finally collapsed is clearly highlighted, showing a high concentration of points experiencing an acceleration in the last period. Acceleration means that the deformation evolution over time (time-series) shows a non-linear evolution, increasing the velocity of deformation over time.

Figure 8. Rapid report and an acceleration index over Cadia mine tailings dam made in back-analysis thanks to archive satellite data a vailable

As explained in the previous section, an inverse velocity analysis can be carried out in order to forecast the potential date of failure. This analysis can be performed over the areas highlighted by the acceleration index, thus providing an extremely useful early warning system to help managers in the decision-making process. In the back-analysis of Cadia presented, a prediction with four days of error is reached (see Figure 9.)

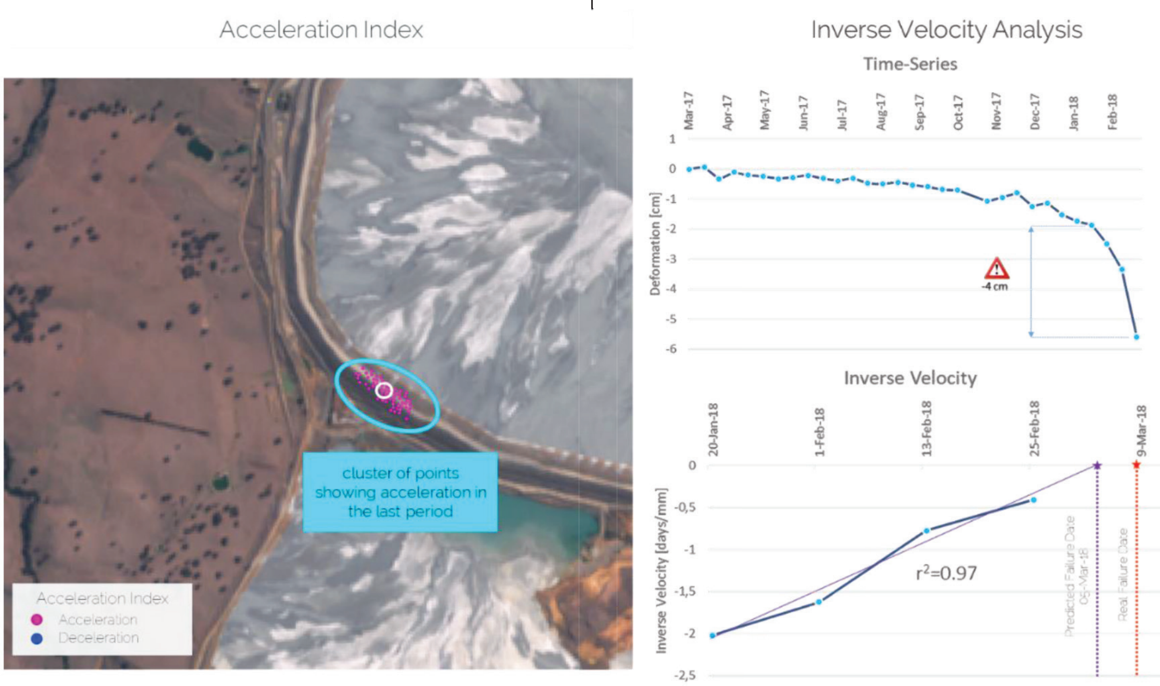


Figure 9. Acceleration index and inverse velocity back - analysis of the Cadia mine tailings dam failure using the measurement point highlighted with a white circlew

Another interesting example is the back-analysis of the Brumadinho dam disaster that occurred on 25 January 2019, when a tailings dam at the Córrego do Feijão iron mine, 9 km (5.6 mi) east of Brumadinho, Brazil, suffered a catastrophic failure. The dam released a mudflow that advanced through the mine's offices, including a cafeteria during lunchtime, houses, farms, inns, and roads downstream. At least 237 people died as a result of the collapse. As seen in Figure 10, results show a displacement rate reaching up to 3 cm/year in the top of the dam. It is more interesting that another area of the dam is reaching higher velocities (of up to - 4 cm/year) in an area located at its base. Time-series analysis shows how this area experiences a clear acceleration at the end of 2018. Notice that the period of acceleration started about one and a half months before the collapse. An inverse velocity analysis has been used to determine whether the time of failure could have been predicted (28 January 2019). In this case, a prediction with three days of error is reached.

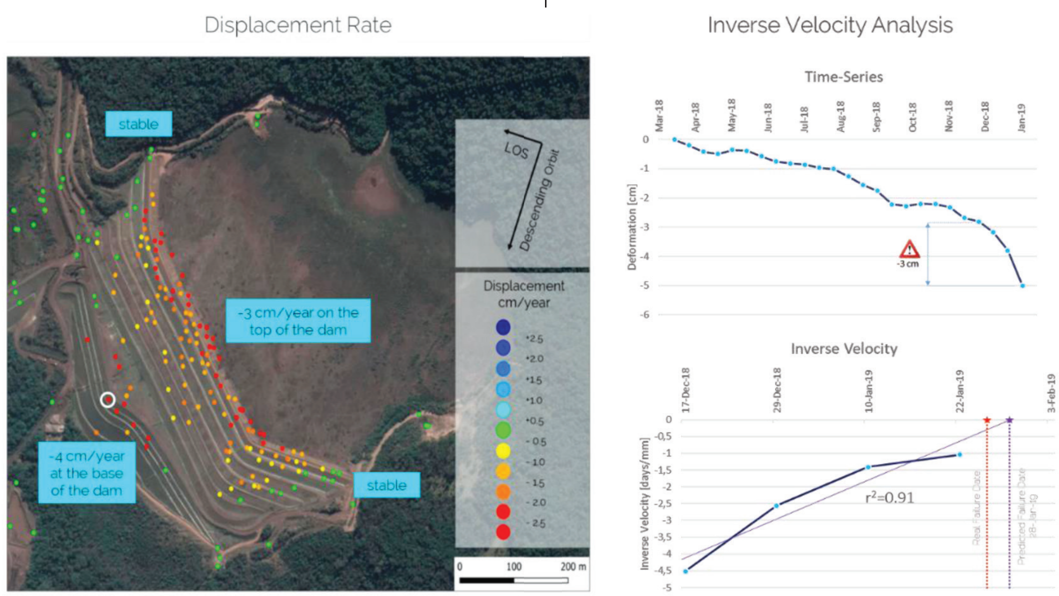


Figure 10. Displacement rate and inverse velocity back-analysis over the Brumadinho mine tailings dam failure using the measurement point highlighted with a white circle

Finally, the same analysis has been applied over an open pit failure in a gold mine in the USA (see Figure 11). The objective of this analysis is to demonstrate the capabilities of InSAR techniques to detect precursors in open pit areas. For confidentiality reasons, neither the location of the mine nor the failure date can be revealed, with errors of five days in the estimated potential failure date.

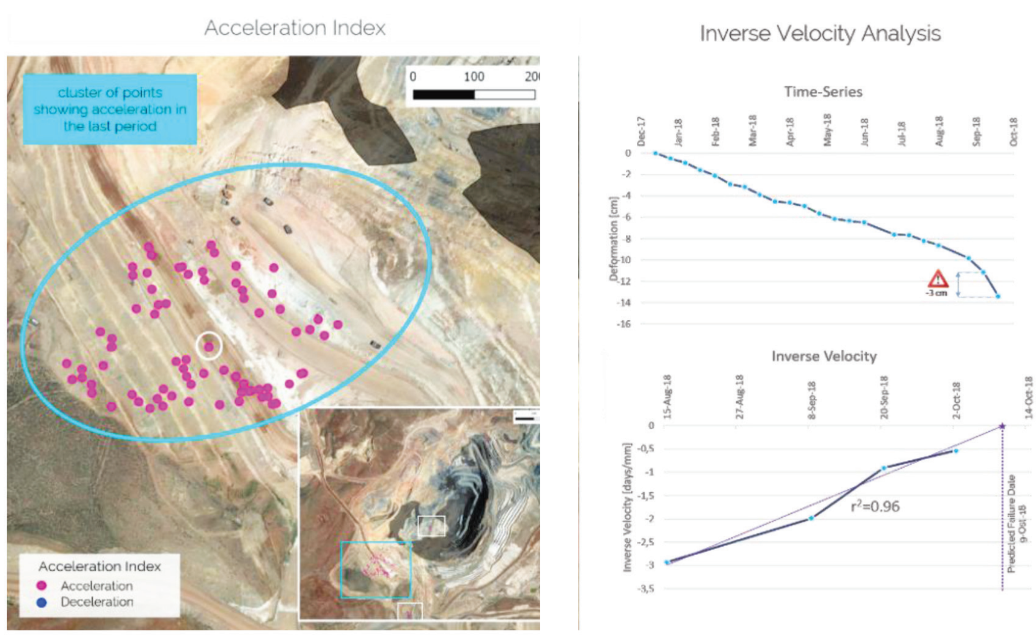


Figure 11. Acceleration index and inverse velocity back-analysis over an open pit mine in the USA. The graphs on the right side of the image correspond to the points inside the white circle on the left side of the image

3.3. Web-based visualisation tools and correlation with in-situ sensors

Nowadays, there is a lot of geotechnical data gathered through in-situ instrumentation, models or remotely (ground radar, laser scanner, satellite InSAR, etc.). Indeed, in-situ instrumentation provides valuable information to be exploited in an integrated scenario with other data providing multiple benefits towards a transversal approach. The management and automatic update of large databases of geotechnical data for the cross-correlation and the integrated analysis of multiple sources is one of the major challenges.

The combination of all InSAR products shown in the previous sections with in-situ information clearly helps in the decision-making process by helping to identify potential risk areas and the cause-effect of unstable slopes in open pits and tailings dam.

For instance, piezometric measurements prove to be an important asset in the previously described scenario where the dynamics of water or fluids induce surface motion in the operations area. The simultaneous and near-real-time access to surface dynamics and piezometric level variations can detect the correlation between both the surface motion and the cover dynamics with the water level variations. Derived from this, correlation susceptibility maps or heatmaps can be derived to emphasise the relevant areas that can be affected by future events. Data from other sources of information, such as ground-based radar, GPS, total stations, meteorological data, PRISMs, piezometers, extensometers, etc., can be integrated with InSAR products.

Finally, the reporting of InSAR services with in-situ information can benefit from webGIS services. In this framework, a solution for integrating all the geotechnical information is presented (see Figure 12). Online interactive webGIS InSAR services with in-situ data integration improves conventional reporting (reports, emails, etc.), allowing end-users to easily zoom in and out over a detailed optical image as background in order to precisely identify where ground deformation is happening and to make further analysis comparing this information with in-situ sensors, computing prediction indicators or generating transects over affected areas.

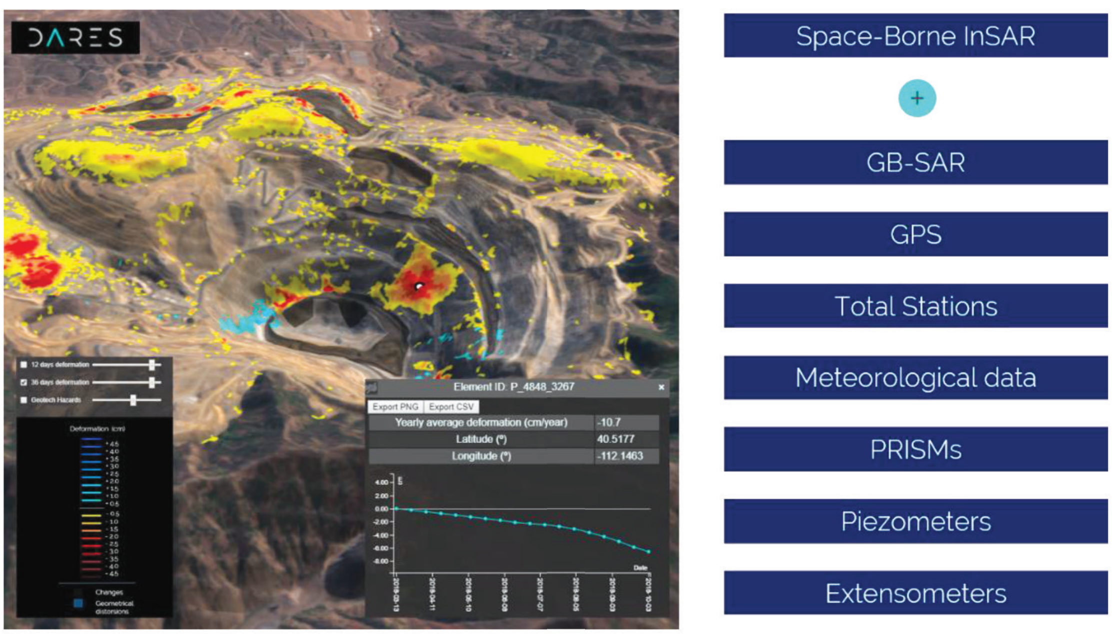


Figure 12. Basic configuration of the webGIS service DARES MAPPER, showing InSAR results and time-series over a mining area

Figure 13. shows a configuration of DARES MAPPER providing the accumulated vertical deformation from 19 August 2018 to 15 March 2019 in an area corresponding to a tailings dam, and the time-series evolution of the measurement point selected in the platform (highlighted with white circle). As illustrated, the cumulated deformation is represented jointly with the piezometric information for the same temporal span. The simultaneous analysis of the temporal evolution of the piezometric level and the deformation (two closest InSAR time-series) reveals a clear correlation pattern with a correlation coefficient of 0.92. Despite the lack of continuous piezometric measurements (light blue line), it is clearly visible that both deformation trends (orange and dark blue lines) behave in a similar way with a detectable delay.

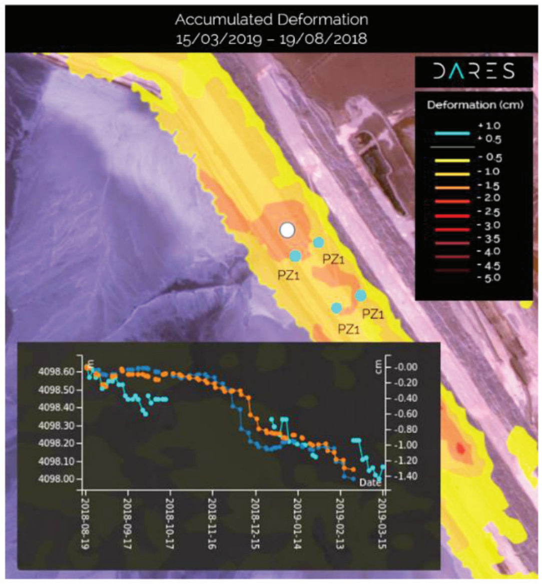


Figure 13. DARES MAPPER configuration showing the correlation between two closest InSAR time-series and piezometers, with a correlation index above 0.9

Finally, Figure 14. shows InSAR results compared to rainfall data giving by an in-situ meteoritical station. The webGIS allows automatic integration (trough wifi data-loggers) and shows rainfall data superimposed to ground deformation time-series. As explained in the previous subsection, the automatic detection of acceleration periods and the correlation with in-situ data (rainfall data in this case) allows possible interpretation and better understanding (or triggering) of slope instabilities.

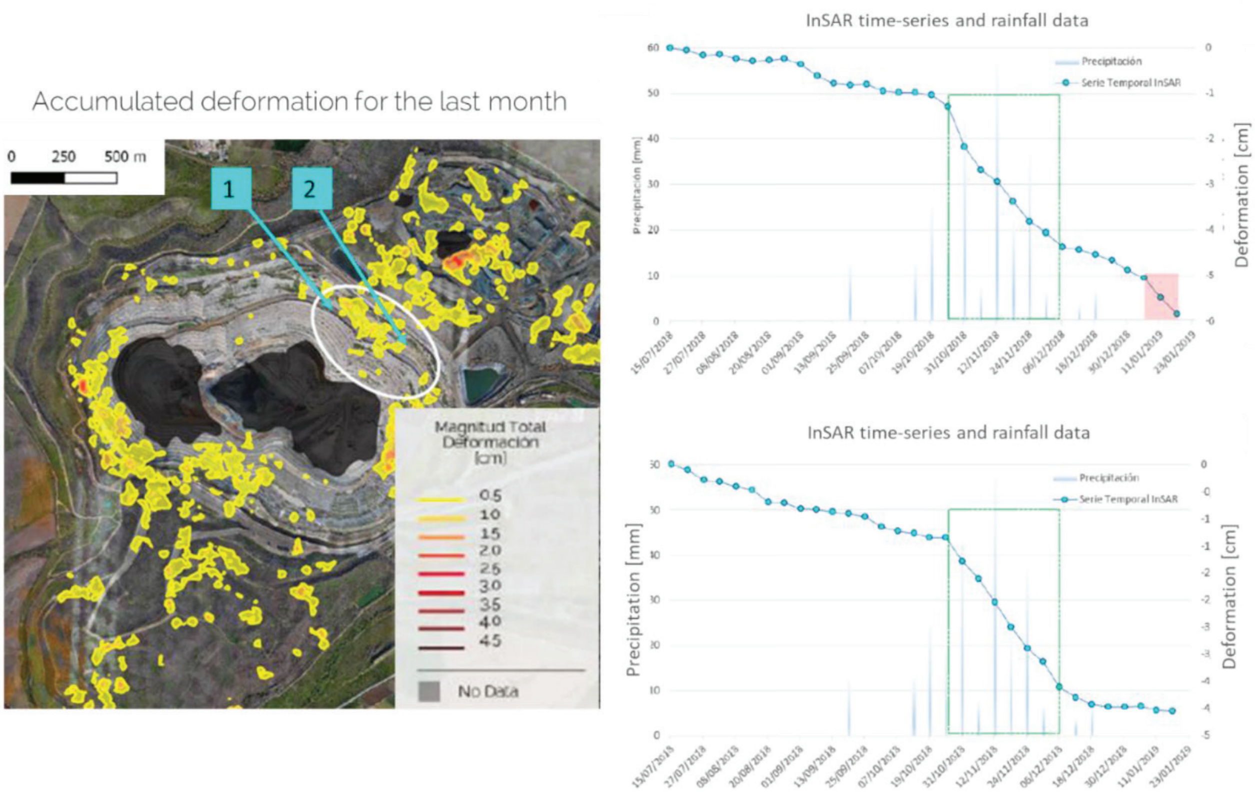


Figure 14. DARES MAPPER configuration showing the correlation between InSAR time-series and rainfall data

4. Conclusion

The increasing focus on mining safety brings with it an increasing awareness on the importance of reliable monitoring programs which include different surveying technologies. InSAR technology based on satellite radar data allows monitoring of ground displacements in mine areas with high precision and efficiency (remotely and for the whole area). InSAR can provide continuous monitoring of ground instabilities by providing information about accelerations on a weekly to monthly basis.

Loading the InSAR data in online webGIS servers, together with other geotechnical survey data gathered from in-situ sensors, allows a better understanding of ground instabilities. Interactive analysis through cross-sections allows spatio-temporal analysis of ground deformation, along with specific transects that ease the understanding of the displacement dynamics. Additionally, automatic detection of ground displacement accelerations allows the systematic application of the inverse velocity technique, which in turn, provides a prediction of the date of a potential failure, based purely on a kinetic approach.

Several examples shown in this paper demonstrate the potential of InSAR data to detect geotechnical failures. The back-analysis over three events shows accelerations in ground deformations some weeks prior to the failure. The application of the inverse velocity technique provides an estimated time for the potential failure with errors of 3 - 5 days.

This paper also discusses that all these analyses and information can be obtained interactively by using online webGIS services, improving the user experience and allowing the comparison of different InSAR-derived products with in-situ information. This paper shows examples of how data interpretation and trigger information of slope instabilities can be derived by combining InSAR data with ground piezometry and rainfall information. This type of combined analysis allows a better understanding of the phenomena and provides more complete information about the precursors of geotechnical instabilities, contributing to the decision-making process in the daily risk evaluation. The complete integration and automatic update of in-situ instrumentation data in webGIS platforms, combined with InSAR information, is a complex task. Nevertheless, unification and centralisation of geotechnical databases, including InSAR, is one of the main future trends in geotechnical monitoring for mine operations.

Acknowledgement

We would like to acknowledge the European Space Agency and the Copernicus Satellite program for the availability of Sentinel-1 satellite data

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APPLICATION OF UAV FOR VERTICAL PROFILING OF AIR POLLUTION

A K Patra & R Dubey

ABSTRACT

Air pollution is a major threat to the health of the huge population in India. The majority of the air pollution related studies in past were carried out at the ground level. On the other hand, the study of vertical distribution of air pollutant can help in better understanding of the complex phenomenon of air pollution dispersion. The understanding of dispersion of air pollutants helps in decision making for air pollution prevention and control strategies. There have been several methods in the past to carry out the vertical profile of distribution of the pollutants, but each one has its own merits and demerits. With the recent development and advancements in the field of unmanned aerial vehicle (UAV), it has become easier to handle and modify UAVs. A module of sensors consisting of PM and/or gaseous pollutant sensors along with meteorological sensors can be mounted on a UAV to get a three dimensional profile of the air pollutants and meteorology. The paper briefly discusses various options available for monitoring air pollutants at different heights from the ground level.

Keywords : UAV, Vertical profile, Meteorological towers, IoT application, LIDAR

1. Introduction

Most of the air pollution related studies in the past have been focused on ground level distribution of air pollutants concentration with respect to time and season. Ground level distribution study of air pollutants conventionally involves sampling at different locations in an area and then the collected samples are analysed in the lab to get the concentration levels of the pollutants (with the availability of latest instruments, the concentration levels can be retrieved directly without any laboratory analysis). It also involves collection of meteorological data along with source inventory and source emission data to carry out source apportionment studies and modelling. On performing several statistical analyses on the collected data set, statistically most significant factor is determined (Kaur and Nieuwenhuijsen, 2009) and also predictive mathematical models are generated for the horizontal space distribution of the air pollutants.

However, recently the focus is also shifting towards understanding of the dispersion of pollution vertically. The knowledge of vertical profile of pollutants can potentially help in understanding the varied exposure level of the residents staying in high-rise building in cities, locating the air intake duct of the centralised air-conditioning system of high rise apartments, in addition to monitoring the dispersion of air pollutants emitted from major ground based sources. A brief review of technologies used for monitoring vertical profile of the pollutants is presented in this paper.

2. Vertical profile studies

2.1. Meteorological towers

A typical meteorological tower involves a large capital investment, therefore the height of meteorological tower is decided according to the purpose as well as financial constraints. It is usually equipped with anemometers, vanes, and data loggers that record wind speed and direction and other required meteorological parameters, this data is then downloaded at regular intervals either manually or online database system is provided that allows data to be downloaded as and when required (Alnes 2015). Along with meteorological parameter sensors, different sensor for air pollutants can also be placed at different heights to get the vertical profile variation of air pollutants. Usually towers are not higher than 80 meters and it also disturbs the natural flow of wind around its periphery and thus the values obtained may not be true representative of the actual condition.

Past studies show that towers with height ranging from few meters to as high as above 300 meters have been used. High towers (height up to 9m) have been used in India to study atmospheric boundary layer characteristics (Satyanarayana et al. 2003). Meteorological sensors for wind direction, wind speed, temperature and humidity were mounted at 1, 2, 4 and 8 m heights on the towers. In urban areas most of the vertical profile related study is carried out on a building which is in the close vicinity of an expressway or any other urban corridor. The main reason behind this is that in the

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urban areas most of the fine and ultrafine particles are emitted by the vehicular exhaust (Perez *et al.* 2010) and new particle formation by photochemical reaction (Pey *et al.*, 2009). This method of using tower has its own limitations such as height of monitoring and data collected is not continuous and does not cover many points so the profile data collected is not uniform and does not serve the purpose of vertical profiling. Vertical distribution of concentration levels of PM2.5, PM10 and SO_2 has been done by at Beijing using a 325 meters high tower, the vertical distribution of data was used to validate the data simulated by the model generated to predict the air pollution in Beijing (Li *et al.* 2009).

2.2. LIDAR

LIDAR stands for LIght Detection And Ranging. LIDARS harness the fundamental properties of laser light to perform precise detection. LIDARS are similar to RADAR but they use light rather than radio waves. LIDAR technology falls under the category of active remote sensing that involves using a laser beam that which is pointed towards the area of interest. The incident ray falls on the objects and gets scattered and a fraction of it is reflected back termed as backscattering. Based on the optical properties of reflected wave, depolarization ratio and the time difference between the incident ray and reflected rays the analysis is carried out. Time difference is used for ranging purpose i.e. calculating the distances. The device is capable of collecting information only about the objects in size equal to or greater than the wavelength of waves. Since the laser pulses have wavelengths 105 times smaller than those of radio waves, LIDARS can detect much "smaller" particles.

Wong et al. (2017) set up a continuous PM monitoring system using LIDAR at Wuxi, China. An autonomous LIDAR D200, developed by Wuxi Photonics was used to get the concentrations as well as type of particulate matter through extinction coefficient and depolarization ratio respectively. The data was obtained and one case each of heavy pollution and light pollution are discussed. The observed aerosol extinction coefficient and depolarization ratio are plotted against time and altitude. The higher extinction coefficient is an indicator of presence of aerosol. Depolarization is caused by the particles that are non-spherical (usually dust particles), therefore higher depolarization is an indicator of dust aerosols and lower depolarization ratio is an indicator of presence of water droplets which are spherical. Tao et al. (2016) used the relationship between aerosol extinction coefficient and PM2.5 concentrations with a system designed consisting of a charge-coupled device (CCD) side-scatter LIDAR with a PM2.5 sampling detector.

The common backscattering LIDAR system has a limitation at lower altitudes because of the geometric form factor (GFF) caused by the configuration of the transmitter divergence and receiver's field of view (FOV) at the near range (Mao et al. 2012). This can be overcome by using side scatter LIDAR which is more effective in the lower altitudes than the common backscattering LIDAR.

3. Need of UAV

The above-mentioned methods have their own limitations. The meteorological towers require huge capital investments. Also the vertical profile data collected is not throughout the vertical height as the sensors are placed at some interval of height. All the tower related vertical profile studies from the literature show that the samples are collected at different interval of height of the tower or a high rise building. In order to achieve continuous monitoring of air pollutants and meteorological parameters in vertical direction aircrafts and air balloons have been used in past. But the cost of aircraft and air balloons is very high and thus make it practically not feasible. Also the size is much larger and maintenance costs make them impractical to be used for vertical profile monitoring (Villa et al. 2016).

3.1. UAV

UAV can provide high temporal and spatial resolutions that cannot be retrieved from any other method due to some or the other constraint. It involves mounting the light-weight electronic sensors that can be carried off by a UAV. These sensors monitor the required air pollutants and meteorological parameters continuously. A GPS system is placed along with sensors to control the flight and also record the vertical height along with the different parameters. Along with GPS a barometric sensor can also be used to get the actual vertical height. An IMU (Inertia Measurement Unit) is also placed to account for the pitch, roll and yaw of the UAV and thus incorporate the necessary corrections.

Spiess et al. (2007) developed a sensor package for vertical profiling of meteorological parameters for an already available carrier aircraft UAV carolo T200. The package is named as mini-UAV (M2AV). It is capable of measuring the wind vector within the atmospheric boundary layer. Fast temperature and humidity sensor detects changes in temperature and humidity respectively. The validation tests show that the meteorological parameters measured by the M2AV are accurate and thus it can be used in actual field.

Weber et al. (2017) carried out the measurement of concentrations of PM10, PM2.5 and PM1 near a bridge to determine the vehicular traffic induced air pollution using UAV. The instruments mounted on the UAV for this study are GRIMM 1.109, DISC mini and AE52 to measure particulate matter of different sizes and black carbon concentrations respectively. The major conclusion drawn out by the results obtained is that in the upwind direction the vehicular exhaust emission had no effects whereas, on the downwind side the vehicular traffic emissions had a major impact on the PM and black carbon concentrations as seen from Fig. 1.

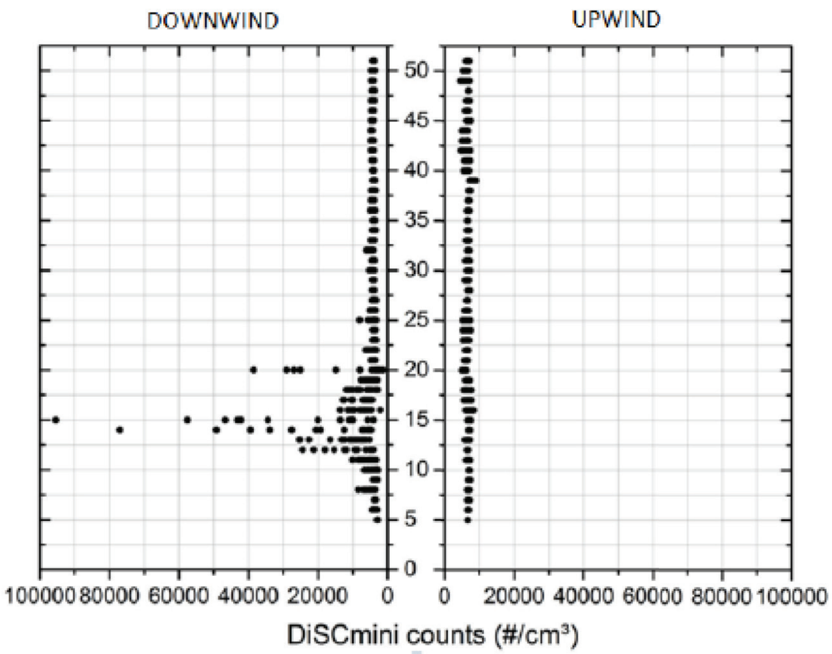

Fig. 1PM count at the upwind and downwind side of the Bridge. (Weber et al., 2017)

UAV has also been used in obtaining black carbon concentration and identify strong smog black carbon concentrations due to temperature inversion, which was invisible to the Ceilometer due to its technical limitations close to the ground. The UAV data was successful in obtaining very a high gradient of decreasing Black carbon concentrations that was beyond the technical capabilities of Ceilometer *(Chilsinki et al. 2018)*.

4. Discussion

Conventional methods of sampling/monitoring in the field of environmental engineering have been used for years and will be used for years to come. The use of more portable instrument and sensors along with IoT application of real time decision making will continue to grow due to its flexibility as discussed. UAVs can be used in the areas beyond the reach of conventional techniques. UAVs can also be used in areas that are too risky for conventional technique involving a personnel. Horizontal flight paths across roadway using UAV will assist in validation and improvement of the dispersion modelling and forecast of traffic pollution. Researchers have developed and tested algorithms for autonomous navigation systems for UAV to automatically analyze pollution values within a target area. Such algorithms allows a UAV to autonomously monitor a specific area by prioritizing the most polluted zones, thereby obtaining a complete and detailed pollution map of the target region.

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GLOBAL TREND FOR PREVENTION OF MINE INJURIES THROUGH EPIDEMIOLOGICAL APPROACHES

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ABSTRACT

Epidemiology is the basic science of public health and was applied very successfully to infectious diseases around the countries in the world. Changes in epidemiologic research began to further develop into injury research. The epidemiological approach is designed to associate various patterns of possible injury causes with the occurrence of an accident. In assessing injury causation, a scientist or engineer will typically apply investigative and analytical efforts on unsafe acts and unsafe conditions. This is done in response to statistical evidence which demonstrates that approximately 90 percent of workplace accidents are caused by unsafe acts and unsafe conditions.

The concept of injury epidemiology is presented in this paper to assess the relationships of some personal and impersonal factors to occupational injuries which were experienced in three underground coal mines. A case-control study design is presented through a case study in underground coal mines through the application of analytical epidemiology. The study demonstrated that physical working condition and some individual factors may play significant roles in occupational injuries in underground coal mines.

1. Introduction

Occupational injuries represent a major problem of public health with serious social and economic consequences. It is well known that the mining sector is an inherently hazardous industry. However, the global response of the mining industry to health and safety challenge can be seen in the decline in fatality rates over the years, even though it is still reasonably high. These results have become possible by considerable improvement in the safety procedures and the risk management techniques used to identify, measure, and address safety hazards.

The Indian mining Industry is still paying heavily towards injuries in terms of human suffering, health care expenses and compensation. The total number of operating coal and metalliferous mines in India are about 590 and 2,398 respectively and the mining industry in India employs over half a million workers on a daily average basis (DGMS, 2019). The death rate per thousand persons employed in the mines is hovering around 0.30 for the last thirty years. In Indian coal mines, the number of fatalities and serious injuries for the year 2018 were 62 and 232 respectively, and their rates per 1,000 persons employed were 0.18 and 0.68 respectively. In the Indian coal mines, fatal/serious accidents in the underground mines were frequent. Several reasons may be responsible including physical hazards and individual related factors. Different studies indicated that behavioral factors along with other personal factors have a major role to play in underground coal mine injuries *(Bhattacherjee et al., 2013; Kunar et al., 2010; Paul and Maiti, 2007)*. Peake and Ritchie (1994) suggested in their study that while human behavior plays a major role in many injuries, mechanical and environmental failures also play a significant causative role and consequently must be addressed if any meaningful and long-term reduction in mine injuries is to be achieved.

Applications of risk management approaches are necessary to identify and quantify potential hazards and to suggest effective solutions. Moreover, research on behavioral factors represents a promising approach to the improvement of workers' safety. This paper explores the injury epidemiology as a risk assessment tool to identify and quantify hazards. This will provide a basis to the mine safety management to control and minimize hazards.

2. Epidemiologic Approach

There are several causal factors responsible for the occurrences of injuries in mines. In several studies, some of the individual and occupational factors are claimed as potential risk factors of occupational injuries in mines. The present study mainly focuses on assessing the role of some of risk factors to the occurrences of injuries in underground coal mines using an epidemiologic approach. Injuries are usually caused by the com-

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bination of the personal and impersonal factors, each of which may vary from situation to situation and may often be closely interrelated. The personal factors may include all individual factors namely demographic factors, socio-economic factors, behavioural factors, and health related factors and the impersonal factors include occupational factors, and management and supervision. The occupational factors may include various job hazards and environmental hazards. In this study, the following individual factors are considered: body weight, education, experience, regular alcohol consumption, presence of disease, poor safety perception and poor work organization.

There are three principle study designs used in epidemiological work. These are as follows: cross-sectional study design, cohort study design, and case-control study design (Gregg, 2002). In a cross-sectional study, a group of individuals is randomly identified from a population under study without considering the variable of interest (injury). The individuals are studied and the exposures are assessed simultaneously at the same period of time. A prospective cohort study is a study in which a cohort of subjects with exposure and without exposure is observed for a specified duration. The number of subjects that develop injury of interest (outcome) is noted. In a retrospective cohort study, the data are gathered retrospectively. A case-control study is a study in which two groups of individuals are identified:
(i) a group that has faced injury (the cases) and
(ii) a group that has not faced injury (the controls).

The design, which was used in the case study, was an individually matched case-control study. Cases were individually matched to a set of controls (1: n ratio); n can vary from 1 to the desired number of controls for each case. For selection of samples three underground coal mines were selected from the Central Part of India. The mines were selected from the same geographical location to facilitate the study. A total of 405 subjects from the three mines were recruited in this study that adequately represented the target population. The 2 - year injury period was taken in the analysis. For each case, the respective controls were randomly selected from the non - injured population of the same mine based on the matching criteria age and job.

3. Case Study

The survey was conducted for a period of two years in underground continuous miner worksite. The cases and controls were aged between 18 and 60 years who were working in these three mines during the period of the study. The 135 cases were randomly selected from the workers working at continuous miner worksite and suffered injury at least once during the 2 - year study period (2016 - 2017). For each case, two controls matched on age and job were randomly selected among the workers who did not face any injury during the past five year period. So, in total, 270 controls were included in the study.

A standardized questionnaire, which was completed by the personnel interviews, included birth-date, height, weight, education, experience, regular alcohol consumption, various diseases, job occupation, and occupational injuries. All of the variables were divided in two categories according to their descriptions. The behavioral factors considered in this study are the following: poor safety performance, and poor work organization. The scores were computed for each behavioral factor by summing the score of individual items. 90th percentiles of the scores of the controls of each trait were used as threshold values. The variables alcohol consumption, and presence of diseases were categorized into two categories with values of 1= Yes and 0= No.

To assess the relationships of behavioral factors, job experience, life style factors and presence of disease with occupational injuries in underground coal mines, crude odds ratios (ORs) and their 95% confidence intervals were computed considering all the subjects using the Mantel-Haenszel test for paired data. The strength of bivariate relationships amongst the factors was measured by the Phi Coefficient. The comparisons of the various factors between the two groups were made using the paired chi square test. The significant bivariate relationships amongst the factors were represented in a path diagram. Stata and IBM - SPSS packages were used for statistical analysis.

4. Results

The Mantel - Haenszel test were performed based on the survey data of 405 mine workers to determine whether there was any significant association between hypothesized risk factors and an injury which was experienced from the continuous miner section. The test revealed that significant risk factors were educational, alcohol consumption, presence of disease, poor safety perception, and poor work organization. Results of the Mantel-Haenszel test are presented in Table 1.

Table 2 represents the correlation between the risk factors through phi - coefficient and Figure 1 shows the interrelationship of the factors. To assess the effect of various factors on occupational injuries, the crude odds ratios and their 95% confidence intervals (CI) were also computed for the paired data. The odds ratio calculated through Mantel - Haenszel test provides a measure of the risk of experiencing an injury among the workers with the risk factor to the risk of experiencing an injury among the workers without the risk factor. The odds ratios along with their 95% confidence interval for the various risk factors are given in Table 3. The odds ratio and 95% CI of statistically significant factors were : no - formal education (OR : 2.84; 95% CI 1.61 – 5.03), regular alcohol consumption (OR : 3.06; 95% CI 1.70 – 5.52), presence of disease (OR : 2.58; 95% CI 1.46 – 4.57), poor safety perception (OR : 2.78; 95% CI 1.69 – 4.55), and poor work organization (OR : 5.68; 95% CI 2.73 – 11.82).

5. Conclusions

Examination of the progress made so far in mitigating the risks to an acceptable level in the Indian mining industry reveals that the Indian mining industry requires a systematic risk management based approach which will focus on identification, quantification, and control of hazards at workplaces. It has to be kept in mind that compliance to regulations will not be sufficient to control or eliminate hazards at workplaces. For prevention of accidents and injuries from workplaces, systematic and comprehensive approaches should be used to manage risk. Literature review reveals that extensive studies have been carried out throughout the world for development of new models and methods for risk assessment, reduction, and monitoring. In this study, epidemiologic approach is presented as an effective risk analysis tool for identification and quantification of the potentials risk factors for occupational injuries in mines.

In the case study it was noticed that the personal factors do play an important role in injury occurrences for the workers. It has been observed in the case study mine that the perception of safety is significantly higher for the non - accident group (Control group) of workers in comparison to that of accident group (Case group) of workers. The demographic factor experience was not significant between Case group of workers and Control group of workers. It can be noticed that the poor work organization resulted in increased job stress among workers.

While major improvements have been achieved by focusing mainly on the engineering approach to safety, there is much to be gained by devoting proper professional attention to the emerging areas such as human component of the system, particularly as the success of a modern technology depends on the behavior of work personnel operating the system.

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Table 1 : Characteristics of cases and controls (%)

Risk factors	% of cases	% of controls	Comparison of the two groups
Overweight (BMI>23)	43.0	39.6	NS
No-formal education	58.5	34.1	p<0.001
Less overall job experience (≤ 10 yrs during the career)	35.6	37.0	NS
Regular alcohol consumption	73.3	47.8	p<0.001
Presence of disease	37.0	18.1	p<0.001
Poor Safety perception	85.2	63.3	p<0.001
Poor work organization	85.9	59.6	p<0.001

Table 2 : Correlation (Phi coefficient) between risk factors

Risk factors	1	2	3	4	5	6	7	8
Overweight (1)	1.00							
No-formal education (2)	0.06	1.00						
Less overall job experience (3)	0.01	0.12*	1.00					
Regular alcohol consumption (4)	-0.01	0.16*	0.11*	1.00				
Presence of disease (5) 0.52**	0.07	0.12*	0.06	1.00				
Poor safety perception (6)	-0.06	0.06	-0.07	-0.03	0.01	1.00		
Poor work organization (7)	0.04	0.16*	0.02	0.13**	0.04	0.04	1.00	
Injury (8)	0.03	0.23**	-0.02	0.24**	0.21**	0.23**	0.27**	1.00

*p<0.05, **p<0.01, ***p<0.001

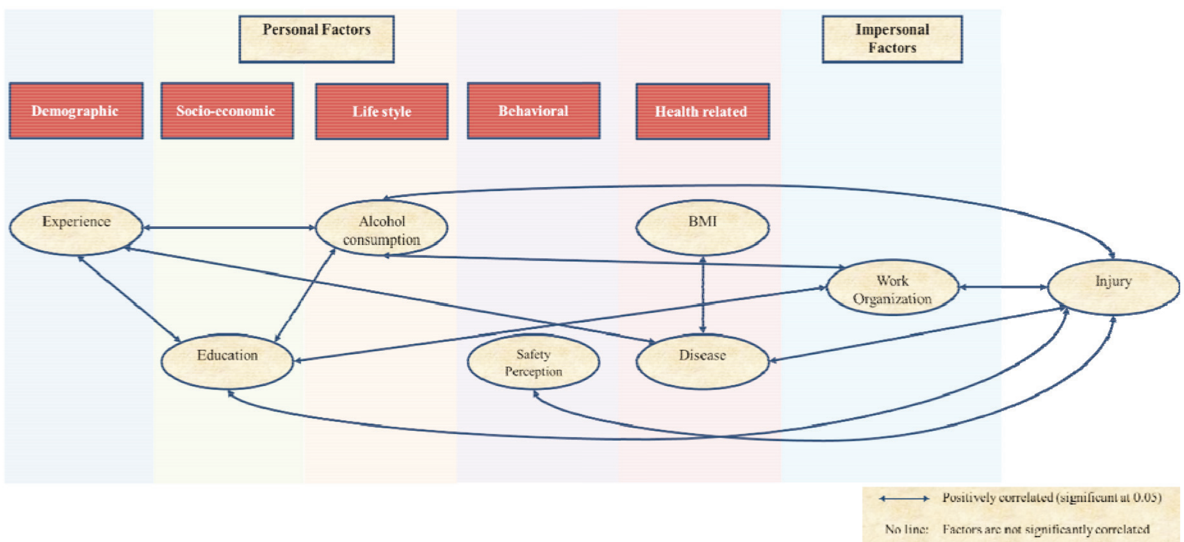

Figure 1 : Diagram showing nature of correlation among various factors

Table 3 : Relationship between various factors and occupational injury

	Odds ratio	95% CI	
		Lower limit	Upper limit
Overweight (BMI>23)	1.45	0.87	2.43
No-formal education	2.84***	1.61	5.03
Less overall job experience			
(≤ 10 yrs during the career)	0.81	0.45	1.46
Regular alcohol consumption	3.06***	1.70	5.52
Presence of disease	2.58***	1.46	4.57
Poor safety perception	2.78***	1.69	4.55
Poor work organization	5.68***	2.73	11.82

*p<0.05, **p<0.01, ***p<0.001

HAZARDS DUE TO DUMPER AND PREVENTIVE MEASURES

Samir Kumar Das

ABSTRACT

The following are the hazards associated with surface haulage and to recommend measures that can be used to minimize these hazards :

1. Walking to and from Equipment

1.1. Potential hazards

- Muddy walkways.
- Moving vehicles.
- Congested area.

1.2. Preventive measures

- Walk around vehicle as part of preoperational inspection to check for people around the machine.
- Sound the horn or other warning device before starting to move.
- Be sure backup alarm and brakes are operating properly.
- Always look in the direction of travel.
- Be alert for pedestrians.

1.3. Checking around Equipment and Mounting and Dismounting

Make sure vehicle is not loaded and is secured against motion before inspection.

1.4. Potential Hazards

- Missing wheel lugs.
- Low tire pressure.
- Tire damage.
- Lowest ladder rung too high.
- Missing or broken steps, ladder rungs, hand rails, etc.
- Slick (muddy, greasy) boots and/or ladder.
- Both hands not free for climbing.
- Miners in dangerous position around equipment.
- Poor access to areas that must be checked.
- Undetected suspension or steering damage.

2. Preventive Measures

- Make a thorough preoperational inspection a habit. Include tires and wheels, ladders and platforms, suspension and steering, and walking around the vehicle to check for persons or obstructions. Report any safety defects.
- Clean mud, grease off boots and ladders. Wear gloves to ensure a good grip.
- Use belt hooks, pockets, etc., to carry materials up ladders and keep both hands free for climbing. Use ropes to hoist bulkier items. Face ladder and use three points of contact when climbing (two hands and one foot or two feet and one hand in contact with ladder at all times).
- Sound horn or other warning device before starting engine or starting to move.
- Be sure backup alarm is operating properly.
- Always look in the direction of travel.

3. Entering Cab and Starting Vehicle

3.1. Potential hazards

- Loose items in cab.
- Seat belt not buckled.
- Parking brake off when starting engine.
- Congested parking area.
- Dirty windshield resulting in poor visibility.
- Possibility of fire.
- Defective brakes, gauges, steering system, or retarder.

3.2. Preventive measures

- Keep cab free of extraneous material; secure necessary items carried.
- Check equipment for warning tags.
- Make sure parking brake is set and controls are in neutral prior to starting.

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- Adjust seat and buckle up.
- Keep cab windows clean.
- Check around equipment before getting on and, to the extent possible, use mirrors before moving.
- Check gauges and warning lights before and after starting engine. Check for smooth idle and unusual smoke or noise. Check wipers and lights.
- Make sure all controls are working properly before moving.
- Check for fuel leaks. Know the location and operation of fire extinguishers.
- Do not use equipment with safety defects.
- Sound horn or other warning device before starting engine or moving equipment.
- Check all brake systems, steering systems, and retarders in accordance with company policy or manufacturer's recommendations.

3.3. Truck Operation

- Avoid running over rocks or into potholes.
- Drive with thumbs on the outside of the steering wheel to avoid injury if the wheel spins.
- At the end of the shift write a NEAT AND LEGIBLE REPORT in the mine office on the form provided.
- Be sure the truck bed is all the way down before driving under overhead cable bridges, power lines, or other overhead obstructions.
- Drive defensively at all times.
- Be aware of the locations of runaway ramps, berms, and other means to stop the truck in case of electrical or mechanical failure.
- Check gauges and warning lights frequently. Whenever a gauge does not indicate specific pressure, shut down immediately.
- Observe all signs and signals.

3.4. Dumping hazards

- Backing over a person, equipment, or obstruction.
- Backing over edge of a dump.
- Pulling down high-lines and other obstructions.

3.5. Dumping precautions

- Check air gauge and brakes before backing up to dump.
- Whenever possible, view dump crest before turning on dump and backing up. Leave a minimum of one truck width between truck and dump crest when making turns at the dump.
- Do not back up if visibility is impaired.
- Set service brake (electric drive) or parking brake (mechanical drive) before and during dumping.
- Back up to the dump berm squarely and make sure truck is in neutral before dumping.
- Make every effort to back up against the dump berm.
- However, NEVER RELY ON THE BERM TO STOP THE TRUCK. BERMS SHOULD BE USED AS A GUIDE ONLY
- Plug out any low spots in the dump berm by dumping short.
- Lower truck body completely before pulling away from a dump location.
- Do not pull truck body through material after dumping.
- Do not let truck body come in contact with berm material so that the wheels are lifted off the ground while dumping.
- Use signal lights for dumping at the primary crushers.
- Red light : Do not spot on crusher dump pocket and pullout if already spotted.
- Amber light : OK to spot on dump pocket, but do not dump. If given an amber light while dumping, stop dumping.
- Green light : Proceed to dump.
- If necessary to lower a loaded body, gently bleed off hoist cylinder pressure using the dump lever. Do not push lever all the way into the lower position or the body will fall materials.

4. Safe Practices

4.1.Materials

- If material to be dumped over edge of stockpile or high wall, examine area carefully, especially at the beginning of a shift, for signs of unstable ground and lack of berms.
- If the ground at a dump site could fail, arrange to dump material a safe distance back from the edge.
- Stay in truck when waiting at dump area.
- When dumping at a stockpile, do not dump over the edge where the toe of the stockpile has been removed.

4.2. Remedial procedures

- Cross windrows at an angle, one wheel leading, to reduce jarring the load, the truck, and yourself.
- Be sure the dump area has been checked for cracks along the top edge or sunken or soft areas, which indicate an unstable edge. Also check for steep slopes. The weight of a truck near an unstable edge can be enough to break it loose, taking the operator with it.
- Never dump over the edge of an unstable dump slope.
- When possible, approach the dump site from left to right and make sure the dumping berm is in place (contact the supervisor if it is not). This also provides better visibility to look over the area for obstacles or unstable conditions along the dump edge and slope. Keep at least one truck width away from the edge berm. Most mines use mid-axle height as a minimum for berm construction.
- Report loss of night time area lights that provide the capability of seeing around the dump point at night. Do not dump in areas where lighting is inadequate.
- Check that the dumping area is level or sloping slightly up toward the edge. A slight-up slope to the edge will help keep the truck under control when backing uphill. It will also drain water away from the edge so the dump edge remains dry and stable.
- If more than one truck is dumping at a time, keep at least two truck-widths apart to spread the weight and to avoid hitting another truck if a tip-over occurs.
- Be aware that rain and other weather effects can weaken the dump and lead to unstable slopes.
- Make the turn to back up at least one truck-width away from the dump berm to avoid overloading the dump edge.
- Back up almost perpendicular to the dumping berm so the left rear tire approaches the berm first. This improves dumping position and can help keep the truck from penetrating or going through the berm.
- Back up slowly and come to a gradual stop at the dump point to avoid loading the rear axle and causing the edge of the dump to break away.
- Do not use or expect the berms or bumper blocks to stop the truck. Stop just before the berm. This avoids accidentally breaking through the berm and going over the edge.
- If people or equipment operators are nearby, wait to dump a load. Raising the truck body can cause materials to fall off and can injure or kill those around the truck.
- Shift the truck into neutral and set the appropriate brake when dumping. This avoids accidental movement forward or backward while the driver is focusing on dumping. Do not use the retarder as a brake.
- Be alert for the presence of material stuck in the bed when hauling wet or damp materials. Materials stuck in the bed can cause truck stability problems.
- Before leaving the dump area, lower the truck bed completely. Lowering the truck bed provides better truck stability, reduces damage to equipment, and reduces the likelihood of electrocution
- When pulling out, turn left whenever possible, which gives a better view of the area the truck is turning toward.

4.3. Dumping in Designated Area

Drivers must dump only at a location designated by the supervisor. If a driver is unsure where to dump, then he shouldn't dump. Drivers should contact their supervisors and determine the correct dumping location rather than to take a chance and dump at a potentially unsafe area. A supervisor may designate dump locations not only on the basis of production requirements, but also on safety considerations of which drivers may be unaware. When drivers are assigned to a dump location, they should stay alert for potential hazards and notify the supervisor immediately if a problem is spotted. If dumping is done in an area where dozers are being used to push material over the edge of the pile, drivers should use them appropriately. Loads should be dumped back from the slope edge as directed. Accidents have occurred when a truck dumped a load over an edge even though a dozer had been assigned to push material over. In many of these cases, the crest of the pile was not strong enough to support the weight of the truck or the berms were inadequate.

4.4. Backing Orientation

As a truck is backed at an angle to the slope edge, one set of rear dual tires will reach the edge before the other. If the rear tires on the side of the truck opposite the operator's compartment reach the slope edge first, the chance for an accident increases. This happens when the operator is watching side of the truck and unexpectedly contacts the berm with the other side so that the far - side tires bump the berm too hard and the truck either goes through or over the berm. If the berms are inadequate or other impediments are not in place, then the operator may simply back the far-side dual tires over the edge. Therefore, it is important for drivers to back their trucks square to the edge of the slope or at a slight angle that places the operator's side closer to the slope edge. Drivers should primarily use the mirrors on their side of the truck when backing. It is much easier to judge backing distance when using the near-side mirrors. They are closer and provide a larger image than the mirrors on the far side of the truck.

In summary, Drivers should back square to the edge using the closest mirror. They should glance occasionally at the far mirrors to check for correct orientation and possible obstacles.

4.5. Backing Speed

Drivers should approach the slope edge at a moderate-to-slow speed when backing to dump and should apply the brakes gradually while stopping. Breaking hard at the last moment imposes a large horizontal force on the truck in addition to the overhead power lines. Normal vertical force imposed by the weight of the truck. This additional horizontal force substantially increases the chance of a slope failure. Even when backing to the slope edge slowly, it is important to brake gradually. Braking hard at the last minute at a slow speed will also increase the potential for a slope failure.

In addition to slope failures, there are other hazards associated with backing too fast. It decreases the driver's reaction time if hazards occur at the dump point or problems develop with the truck. It also increases the risk that the driver will contact the berm too fast, going over or through it.

4.6. Unlevel Ground

A vehicle's centre of gravity rises as the bed is raised into the dump position. If the truck is parked on a slight downhill grade toward the berm or if it is leaning sideways, it may be in danger of tipping. The potential for tipping increases when the load is hanging up in the truck bed or the material is not flowing out freely.

The dump point should never be constructed so a truck is parked on a downward slope toward the berm. If the decline is too steep and material hangs up in the truck bed, then the truck is in danger of tipping over backward. Creating a slope toward a dump point also provides poor drainage, allowing water to accumulate at the berm, which can result in decreased slope strength and soft footing that allows the rear tires to sink. Stopping on a decline also requires additional braking force, which places additional reliance on the braking system and imposes greater forces on the slope, increasing the potential for a slope failure.

The dump point should be constructed level or at a slight upward incline. Maintaining the dump point at a slight upward angle (1° to 3°) allows for drainage and decreases the amount of force required to stop the truck. It also decreases the chance of tipping over backward should material hang up in the truck bed. The dump point should be constructed so a haulage truck sits flat and does not lean to the side. If the sideways angle is too steep or material hangs up in the truck bed, the truck is in danger of tipping on its side. This is also a problem when the dump point is soft. The rear tires may sink as the truck bed is raised into the dumping position. If the tires do not sink evenly, the truck will lean to one side, again increasing the chance of tipping over. Soft material will also force the operator to apply more power to the drive wheels when approaching the berm, complicating control of the truck in this potentially hazardous area.

4.7. Truck Bed Position

As the operator approaches the dump site, he should look for any overhead obstructions, such as power lines. After backing to the dump point, the truck should be brought to a complete stop and the parking brake or a holding brake applied. The procedures provided in the operator's manual should be followed for a particular truck being operated.

After the load is dumped, the driver should pullout slowly. The transmission should be engaged before the parking brake is released to prevent the truck from rolling backward. The truck bed should be low as soon as possible. If material is hanging up in the bed, moving the truck can increase the chance for tipping over. The truck bed should be fully lowered before leaving the dump site and entering the haulage road.

4.8. Haulage Trucks Backing over an Edge

An operator must stay alert when operating a haulage truck near the crest of a stockpile. They must know where the rear tires are in relation to the slope edge. A surprisingly high number of stockpile accidents occur when a haulage truck is simply backed over the edge of a pile. When operators are end dumping over the crest of a stockpile, they must make sure that it is in a designated area with adequate berms or other impediments. Mirrors must be clean and properly adjusted. When dumping at night, lighting should be adequate to see the edge. Brakes must be tested to ensure they are working properly. Operators should back slowly to ensure there is adequate time to react and stop before contacting the berm. Berms cannot be relied on to stop a truck. When a spotter is used, the spotter should stand where his/her signal can be clearly recognized. Spotters should use signal lights at night and when visibility is limited.

4.9. Berms

Backing through or over a berm is a common cause of stock pile accidents. A normal rule of thumb states that berm height should be equal to mid-axle height of the largest truck using the dump site. Coal mine safety and health policy also requires that berms be equal to the axle height of the largest truck at the work site. The berms should be constructed strong enough to survive a moderate impact. However, they should not be relied on to stop a truck. Berms should be used as a visual indicator of where the truck should be stopped or to provide a “feeling” of the berm as the rear tires contact it. A berm should be used for spotting only. If a berm is present, it should not be assumed that the area is a safe place to dump. The haulage truck driver should verify that material has not been removed from the toe of the pile. Routine supervisory inspections should also be performed to ensure that the slope is stable. Berms, bumper blocks, safety hooks, or similar impeding devices shall be provided at dumping locations where there is a hazard of over travel or overturning. Truck drivers must make sure that they dump only where a berm or impeding device is provided.

4.10. Seat Belts

The chance of surviving an accident is greater when a seatbelt is worn. In fact, the safest place to be during an accident is in the cab with a seat belt fastened. Nearly half of all mobile mining equipment fatalities involved operators who were not wearing a seat belt or who took it off in a futile attempt to jump clear of the equipment. Staying with the machine is almost always better than attempting to jump out. A significant number of fatalities can be prevented by the simple act of wearing a seat-belt and by remaining in the cab. With a few exceptions, Federal regulations mandate that seatbelts be provided on dozers, scrapers, front-end loaders, haulage, etc.

5. Stockpiles

A stockpile is a temporary pile of ore or other material that will be used later. Stockpiles are especially hazardous if activities are being carried out at the top edge and the toe. Loading out material at the toe causes sloughing that can cover a loader. It can also over steepened the slope, making the top edge of the pile unstable for trucks that may be dumping at the top. Always dump in an area where nothing is happening immediately below and never dump over and over steepened slope. If possible, dumping should be done at least one truck-length away from the edge and materials, then pushed by dozer to final position. Always look around.

5.1. Spoil Piles

Spoil piles are usually permanently placed materials or spoils. Because the layout and characteristics of dumped materials change, there can be soft spots, weak and loose materials, and steep slopes, all of which can cause unstable piles. Of special concern are dumps that are constructed by trucks end-dumping over the dump edge to form angle-of-repose slopes. Careful in section of the dump edge for sloughs and cracks along the edge should be done before approaching the dump. Look for the minimum suggested heights (to mid-axle) of dumping berms. Remember also that too much moisture can weaken the pile. Be careful.

5.2. Bins and Hoppers

Bins and hoppers are engineered structures for storing or channelling materials. These structures have a specific dump point with features such as overhead obstructions, chutes, trucks, etc., and that they be maintained in working condition.

5.3. Drug and Alcohol Abuse

The safe operation of mobile equipment is extremely dependent upon the capabilities of the operator, especially when the size and power of modern equipment are considered. Drugs and alcohol dull senses. They reduce response time, attentions pan, and a person’s ability to identify an impending problem. More importantly, they inhibit a person’s ability to react when in a hazardous situation. Miners who use drugs or alcohol affect not only themselves, but the people working with them. A person under the influence of drugs or alcohol is more likely to be involved in an accident and suffer an injury. More importantly, a person under the influence of drugs or alcohol is more likely to cause a serious injury or death to a co worker, not to mention damage to company property. For everyone’s sake, don’t mix drugs, alcohol, and mining.

5.4. Stockpiles

Look over an area before pulling in to dump to check for any damage to any of the features like stopping blocks, guide rails, etc. Dumping at these areas is very repetitive, and special efforts are needed to maintain driver awareness. Stay alert.

5.5. Stockpiling Techniques

Stockpiling techniques vary depending upon the size of the mine, the type of material handled, and type of equipment available. Some techniques are safer than others and should be used when applicable.

A "Good" Method of Stockpiling

A "good" method of stockpiling involves dumping a load back from the crest of the pile, after which the material is dumped over the edge by a dozer or a front-end loader using other material. This method allows the easy construction and maintenance of berms and keeps mobile equipment away from the edge of the pile where the chance of being involved in an accident is highest. When combined with well-trained operators and routine inspections for signs of slope instability, this method drastically reduces the likelihood of an accident.

A "Fair" Method of Stockpiling

A "fair" method of stockpiling involves dumping a load directly over the crest of the pile. For this method to be performed safely adequate berms must be maintained and equipment operators must be well trained to recognize stockpile hazards. Other factors, including the type of material, condition of the material, weather and type and size of haulage truck, also need to be considered. It is also important to inspect the dump area routinely for signs of slope instability. When using this method, it is important to ensure that material is not removed from the toe of the pile where dumping is taking place.

A "Dangerous" Method of Stockpiling

A "dangerous" method of stockpiling involves dumping a load directly over the crest of a pile where material has been removed from the toe. Removing material from the base of a pile generally results in a steepened slope. A steepened slope is less stable and cannot support as much weight, creating a hazard for equipment operating near the crest of the pile if the slope fails. The mine supervisor, loader operator, and haulage truck driver must ensure that dumping does not occur where the slope has been steepened by reclaiming activities. The practice of dumping over the edge of a stockpile in an area where the slope has been loaded out at the toe should be prohibited.

5.6. Good Alternative Method

A very good alternative method involves the construction of stockpiles in layers. In this method, loads are dumped as piles on a single level. After a level is complete, it is then smoothed over by a dozer and dumping continues on the next layer. Operating mobile equipment compacts the previous layer and creates a pile of greater strength. The method also permits the slope angle to be maintained lower than the angle of repose, resulting in greater slope stability. Haulage trucks are also kept away from the edge of the pile. From a quality control standpoint, this method also avoids undesirable size separation of material.

6. Primary Injury Classification

A. Truck activity : What was the truck doing?

1. Moving forward
2. Backing up
3. Stationary dumping
4. Other
5. Unknown (not enough information)

Note : These activities are based on truck movement. If the truck was dumping while moving, the activity was coded as either moving forward or backing up. If the truck was dumping, but movement was not indicated, the term "stationary dumping" was used.

B. Incident result : What happened to the truck?

1. Fell over edge, i.e., travelled over an edge and came to rest at a lower level.
2. Hung up on edge, i.e., travelled onto an edge and got stuck without falling over.
3. Rolled over, i.e., quarter rolls and other rolls on the same level.
4. Collision, i.e., collided with mobile equipment or other large stationary objects.
5. Struck by object, i.e., struck by moving object that was not a piece of mobile equipment. This category includes an object coming into the cab.
6. Bounced or jarred, i.e., a sudden release of energy that caused the truck to bounce or lurch forward or backward.
7. Fire
8. Contacted power line.
9. Other.
10. Unknown (not enough information).

C. Operator impact : What happened to the truck driver?

1. Struck against object, i.e., operator thrown against something within truck cab.
2. Jarred/tossed, i.e., sudden release of energy caused operator to be shaken up or tossed within the truck cab without striking against something. (Examples : truck bed shifted or
3. Dropped; the truck was backed over a rock or large chunks, went through a hole, or collided with something at low speed.)

4. Musculoskeletal injury (MSI), i.e., operator hurt while twisting or turning, reaching too far, pulling or pushing on something, or lifting something.
5. Landed outside of cab, i.e., operator either jumped or was thrown from truck cab and struck the ground.
6. Struck by object, i.e., operator hit by moving object that came either from within or outside the cab.
7. Drowned.
8. Burned.
9. Electrocuted.
10. Other.
11. Unknown (not enough information).

D. Contributing factors : Events that contributed to the injury incident.

1. Edge failure, i.e., ground at the edge of the dump site gave way.
2. Mechanical/hydraulic failure, i.e., a mechanical or hydraulic truck part failed.
3. Undercut pile, i.e., material removed from the base of a pile compromised the stability of the pile.
4. Travelled through berm/barrier, i.e., the truck went through an edge berm or barrier.
5. No berm/barrier, i.e., no berm or barrier had been constructed at the dump site edge.
6. Uneven ground, i.e., the truck travelled over elevated ground, through holes, or over obstacles.
7. Load unbalanced or shifted, i.e., truck bed material either shifted or dropped.
8. Weather, i.e., weather conditions were severe.
9. Truck stalled, i.e., truck lost power and moved without operator control.
10. Inadequate power line clearances, i.e., power lines in a truck dumping area were close enough to the ground that they could be contacted by a raised bed.
11. Limited visibility, i.e., the truck operator had difficulty seeing because of darkness or severe weather conditions.

Note : More than one factor might have contributed to each incident.

7. Secondary Injury Classification

A. Exit cause. The way the operator left the truck cab in incidents in which the operator landed outside the cab.

1. Jumped.
2. Thrown out.
3. Either jumped or thrown out.

B. Seat belt usage. Indication as to whether the truck operator was wearing a seat belt.

1. Seat belt worn.
2. Seat belt NOT worn.

8. USA Experience

In USA More than 90% of the serious injuries occurred while stationary dumping or while backing up. Falling over an edge, rolling over and being bounced and/or jarred resulted in 83% of the serious injuries. Falling over an edge resulted in 37% of the serious injuries and 85% of the fatalities. The combination of backing up and falling over an edge accounted for 26% of the serious injuries and 73% of the fatalities. In fact, one in five of the backing - up and-falling-over-an-edge incidents resulted in death.

Eleven of the twenty - six fatalities (42%) occurred when the operator landed outside the cab. This was a key reason for separating these incidents from other “struck against objects” incidents. In particular, 70 of the 95 injuries that involved backing up and falling over an edge were classified as “struck against object” and 17 were classified as “landed outside cab.” Nineteen operators were killed while backing up and falling over an edge. Nearly half occurred when the operator landed outside the cab. These findings indicate that backing up, falling over an edge, and landing outside the cab describe incidents most likely to have resulted in a fatality. Two secondary classifications were used with injuries in which the operator landed outside the cab. These classifications were “exit cause” and “seat belt usage.” In 35 of the 52 cases, the operator jumped from the cab, 13 times the operator was thrown from the cab, and four times it was not known whether the operator jumped or was thrown out. In 40 of 52 cases, it was not determined if the operator wore a seat belt, 11 times a seat belt was not worn, and only one incident was reported in which a seat belt was worn. Thus, in at least 10 of11 fatal cases, a seat belt was not being worn.

Injuries that resulted in falling over an edge had the most contributing factors identified. “Edge failure” and “travelled through a barrier” were identified most often.

The most common contributing factors to rollover incidents were "uneven ground" and an "unbalanced or shifted load." The most common contributing factors to bounced or jarred incidents were "mechanical/hydraulic failures" or "unbalanced/shifted loads."

Devices have been developed to improve a mobile equipment driver's ability to detect obstacles and hazardous situations. Mirrors, video cameras, and backup alarms are continually being upgraded and added to existing equipment as technology improves. The use of these technologies may help to explain the drop in haulage truck injuries while backing up at dump sites. Lux examined limitations to using mirrors on large mobile equipment. He concluded that, in order for a mirror to be effective, an operator must understand how to use it and must take into account its limitations. Researchers at the Spokane Research Laboratory (SRL) of NIOSH tested a number of commercially available and experimental sensors that monitor obstacles in a vehicle's blind spots. None of the sensors had been used in commercial applications on rigid-frame surface mining trucks. It was determined that radio-frequency identification (RFID) and radar technology show the most promise for detecting obstacles in the blind spots of mining equipment. However, more development work is needed to meet the unique requirements of mining equipment and the mine environment. The USBM developed INSLOPE3, a computer software package to analyze the effect of haulage truck operation on dump site stability. INSLOPE3 provides estimates of safe operating distances from slope edges to aid in the development of safe dumping procedures. The two main methods for dumping waste at spoil piles are edge-dumping and short-dumping. While edge-dumping is the most common method, short-dumping is used when there are safety concerns about edge-dumping.

- Haulage truck drivers are taught to back up with the rear of the truck square to the edge or berm by using the near side mirror, so that the left rear tire approaches the berm first. This improves the dumping position and helps keep the truck from penetrating or going through the berm. At the same time, far side mirrors should be used to check for correct orientation and potential obstacles.
- Drivers should travel backward at a moderate-to-slow speed. Backing too fast decreases reaction time if problems develop at the dump site or with the truck and increases the risk that the truck will reach the berm too quickly, so that the truck could go over or through it. Backing through or over a berm is a common cause of injuries at dump sites. Drivers must not expect a berm or bumper block to stop the truck.
- Similarly, it is important for drivers, when preparing to dump, to brake to a gradual stop just before reaching the edge or berm. The danger that the slope will fail is increased by braking hard at the last moment.
- Haulage truck operators dumping at the edge of a stock pile or high wall need instruction in how to examine the dump site. Careful inspection of the area prior to and at the start of the shift to check for signs of unstable ground and lack of a berm is a necessity. To ensure safety, the dump site should be checked for cracks along the top edge and over steep slopes, and for sunken or soft areas, all of which indicate an unstable edge.
- Drivers must not dump over the edge if the toe of the stockpile has been removed. Furthermore, they should never dump over the edge of an unstable slope. If there is any question about the stability of an edge, another dump location should be chosen, or material should be dumped short of the edge away from any cracks and then pushed over.
- To operate a safe and effective dump site, sound dumping procedures must be combined with a good maintenance program and meaningful worker training. One way to enhance training for a mobile equipment operator is to use driving simulators.

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Name of the Publications	Year	US$	Rs
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New Finds of Coal In India – Resource potential and Mining Possibilities	1993	30	300
Computer Applications in Mineral Industry	1993	40	400
Indian Mining Directory (4th Edition)*	1993	40	400
Asian Mining 1993	1993	85	850
Mine Productivity & Technology	1994	75	500
Maintenance Management for Mining Machinery*	1995	60	600
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Mineral Industry Development in India – Issues, Perspective & Policy	1996	20	200
Disaster Prevention Management for Coal Mines, Vol I	1996	50	500
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Regular publications
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Published by : **Honorary Secretary, The Mining, Geological and Metallurgical Institute of India**
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Website : www.mgmiindia.in

Price : Free to Members : ₹ 200.00 or US$ 10.00 per copy to others

Printed at : Graphique International, Kolkata - 700 015, Phone : (033) 2251 1407