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Applications of Wireless Sensor Network for Displacement Monitoring in Opencast Coal Mine Slopes

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Abstract

Coal is the primary source of energy for the production of electricity as well as other industrial purposes. Despite being one of the largest coal producers in the world, India still imports coal to meet domestic demand. Coal is mainly extracted from opencast mines with high mechanization and deeper depths to meet the required coal demand. However, there are many problems with deeper opencast projects, like slope stability and its failure, which can be caused by slope geometry and rock properties. These failures result in equipment damage and human fatalities. It is necessary to monitor the stability of the slope to keep the working conditions safe. Traditional instrument techniques are currently deployed in opencast mines for regular slope monitoring. These traditional instruments usually rely on humans to collect and analyze data offline, which involves huge costs for manpower utilization. Moreover, it only works during daylight, and reliability is also not up to the mark. On the other hand, the latest instruments like Light Detection and Ranging (LiDAR) and Radio Detection and Ranging (RADAR) can efficiently monitor slope movements; those are more expensive and require highly skilled manpower. To eliminate this uncertainty and to obtain real-time data for studying the dynamic behavior of workings, Wireless Sensor Networks (WSN) are introduced. This study uses a node with a sensor and a receiver to collect data based on slope displacement measured in millimeters in a selected opencast mine. Data obtained using a WSN-based monitoring system was observed to be close to the existing total station monitoring method. ANSYS finite element-based numerical modeling software was used for simulating the field conditions and validated the results obtained by the WSN-based sensor's real-time monitoring and existing traditional field monitoring system.

Keywords: *ANSYS Software, Internet of Things, Pit Slope Monitoring, Real-Time Slope Monitoring, Wireless Sensor Networks*

1.0 Introduction

India is the 2nd largest coal-producing country and holds 5th place in the largest proven coal reserve. Nearly 75% of the energy demand in India is supplied by coal. Based on demand analysis, 1 Billion Tonnes (Bt) of coal by 2023-24 is projected to reduce the demand-supply gap and non-essential import of coal in the country[1].

Coal imports have increased to 251 Million tonnes (Mt) in 2019-20 and reduced continuously during the next years to 217 Mt in 2020-21 and 209 Mt in 2021-22. Therefore, despite a sheer increase in actual demand for coal from 906 Mt in 2020-21 to 1027 Mt in 2021-22, coal imports could be controlled due to increased domestic coal production to 818 Mt in 2021-22[2]. Figure 1 gives the year-wise assessment between opencast and underground coal production in India for the last decade. It displays that India produced around 778.19 Mt of coal in the year 2021-22 and 716.084 Mt in 2020-21. In the last decade, there has been a 47.98% rise in coal production

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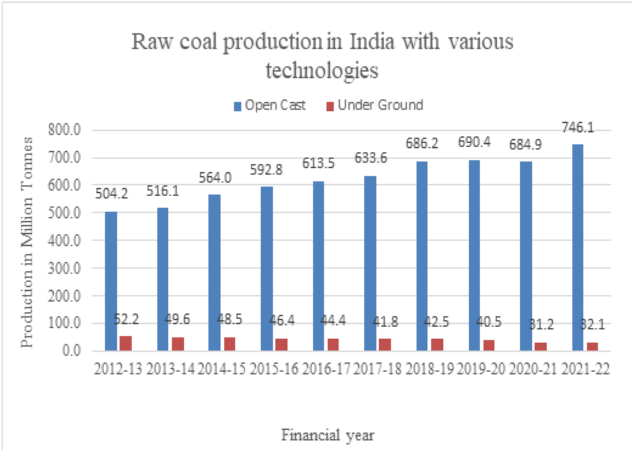

Figure 1. Raw coal production in India with various technologies[2].

from opencast mines and a 38.55% reduction in coal production from underground mines.

Out of the total coal production during 2021-2022, about 95.88% came from opencast mining. Compared to underground mining methods, surface mining results in maximum extraction of the deposits, leaving minimum coal in the in-situ, but in the underground method, coal recovery is less. Hence, in surface mining projects, the production will be high, and only opencast projects can help meet the demand for coal.

1.1 Need for Slope Monitoring

Surface coal mining industries in India are moving towards deeper deposits, nearly 500m deep, to supply the energy demands. It has experienced pit slope failures and fatalities in some cases. Various slope monitoring techniques are currently available methods like visual inspection and crack monitoring to the latest technologies like the total station with prism monitoring given at a time only. Whereas the latest real-time monitoring technologies like Radar and Lidar will give results in a short span of occurrence, these technologies are more expensive and require highly skilled manpower[3]. Due to the limitations of the above existing monitoring systems, some authors started research in the Wireless Sensor Network (WSN) field and showed remarkable results at a low cost. Hence, this field has a scope to study for real-time monitoring of the slopes.

As described by the author[2], monitoring the slope of an opencast mine is essential to avoiding potential problems. In order to reduce monitoring expenses and increase safety, Wireless Sensor Networks (WSNs) provide real-time data collecting and analysis for efficient slope monitoring. The slope conditions are wirelessly relayed via Internet of Things (IoT) and inexpensive microelectromechanical sensors, enabling quick insights. Slope behavior can be predicted by monitoring variables including wetness, vibration, and displacement. It is also possible to create the alert message on the movement of the slope (laboratory experiment done by the author) to the management by using IoT and WSN.

2.0 Slope Monitoring Techniques

The primary objective of slope monitoring is to sense any instability in the bench slope prior to the slope failure. Predicting the slope failure in advance helps prevent men and machinery and also to plan and implement necessary reinforcements to avoid the failure. It can be brought down predictably if the failure is unavoidable.

The early detection of movement zones in a slope allows steps to be taken to minimize the impact of mining on stability by implementing corrective measures and providing for optimum coal extraction. The active monitoring system permits early and confident decision-making by management for safety purposes.

2.1 Classification of Slope Monitoring Systems

Methods of slope monitoring are broadly classified into visual inspection, surface and sub-surface monitoring (Figure 2). The Slope monitoring systems are classified based on the parameters that are monitored by the system[4,5].

Slope monitoring system measures physical and geometrical parameters such as borehole profiles, tilt angles, the distance between points, groundwater pressures, and internal and externals stresses. The measurements of the system can calculate slope displacements or deformations. Visual slope monitoring inspections are to be carried out by routine inspection at the pit, access ways, high walls and crest, which are close to potentially dangerous working areas by an engineer. Crack displacement measurement with tension crack meters. All it involves is a scale mounted across the sides of the crack. The surface measurement

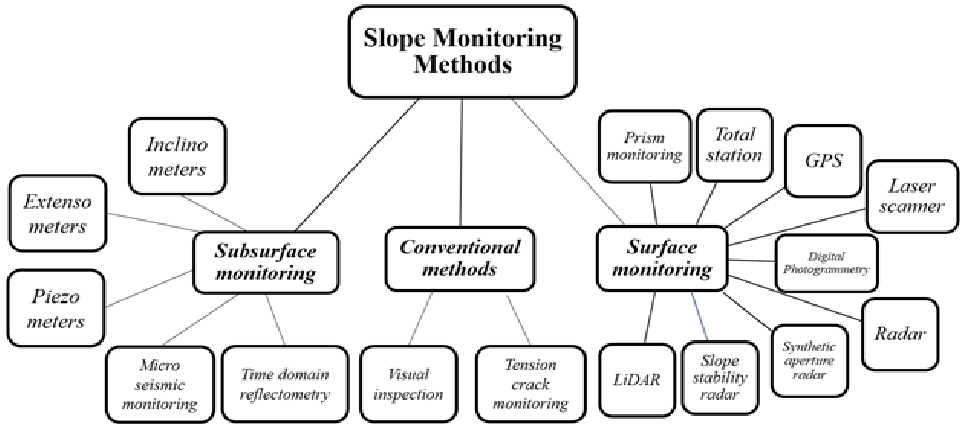

Figure 2. Classification of Slope Monitoring systems[5].

involves many techniques, among which a survey with a network of sensor devices is one. Total station is an electronic transit theodolite integrated with Electronic Distance Measurement (EDM) to measure vertical and horizontal angles, the slope distance from the instrument to a particular point, and an onboard computer to collect data and perform triangulation calculations. Global Positioning System (GPS) is a satellite positioning technique used in geophysical research particularly active crustal deformation measurements. It is a suitable and potential tool for monitoring slopes due to its efficiency, affordability, adaptability, and versatility. The above-mentioned slope monitoring methods have their own advantages, but they all have similar disadvantages which is not capable of sensing more than one parameter that affects the stability of the slope. WSN helps overcome this disadvantage and enables multi-parameter monitoring.

3.0 Wireless Sensor Network (WSN)

The most dynamic development in information and communications technology is the advent of the Wireless Sensor Network (WSN). The WSN system is a new-age technology that enables many advantages over traditional systems, such as the frequency of data measurement and data transmission. High frequency in data detection and transmission enhances data processing. WSN systems have little tolerance for latency, which frequently means that they process many functions related to measurement data in the local device itself without any time delay in data transmission to the central location, such as a data center. Many researchers such as Karthik *et al.*,[6-8] and Yadav *et al.*,[9] have used WSN in their research and concluded stating that WSN is an effective method for slope monitoring.

3.1 Real-Time Monitoring of Slope Stability using Wireless Sensor Network

Real-time slope monitoring is a major requirement in large opencast mines for their safety. Wireless Sensor Network (WSN) is a novel technology that can be effectively implemented for real-time slope monitoring. WSN is composed of sensor nodes at the transmission end, which detect the slope parameters and a reception node at the receiving end where the measured data will be processed (Figure 3).

The sensor node comprises different sensors as the sensing unit, a microcontroller as the controlling unit, a transceiver for transmission and reception, and a battery to power the node (Figure 3). The sensing unit is a collection of sensors that detects environmental changes. Identifying suitable sensors is a vital obligation to monitor and detect slope behavior. The most significant parameters to be monitored for slopes are landslides. Landslides are caused by the strength reduction of the slope due to external load, stress caused by the load, moisture content affecting the slope density, pore pressure as additional stress, and rainfall[10]. For this study, deformation is selected for slope monitoring.

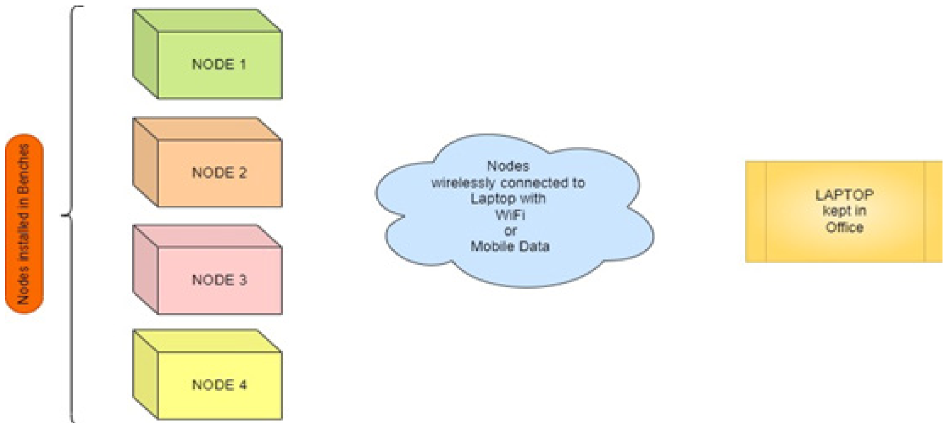

Figure 3. Implementation of Wireless Sensor Network.

The Central Processing Unit (CPU) in the microcontroller controls the node's operation, which has a read and writeable memory where programs for input/output peripherals can be saved. It has incredible features such as small in size, operable in low power requirements and ease of programming with an embedded ADC. It processes the sensor data and executes the communication protocols and signal processing. The transceiver unit transmits the processed data from the microcontroller to the receiver node. Sensor nodes in the network are connected in the network through the transceiver unit. Various technologies, like Wi-Fi, Bluetooth, GSM, LoRa, Zigbee, etc., could be used to transmit data within the network of nodes.

The receiver unit is located at a base station in the field with a display unit attached. It is accountable for receiving and displaying the coordinator's data in analog or digital representation. It comprises a database server and a workstation, which processes the sensor data and gives signals while detecting any abnormality in an emergency[11].

3.2 WSN Devices used for Slope Monitoring

The devices and related gadgets selected for slope monitoring in this study are verified and calibrated in the lab for their performance and functionality with wireless sensor networks and other Wi-Fi modules[12].

3.2.1 Displacement Sensor (Slider Potentiometer)

The slider Potentiometer is an electronic module that detects the movement of the slider attached to the sensor. Combined with any microcontroller, such as Arduino, Raspberry Pi it can be effectively used to detect the slope displacement (Figure 4).

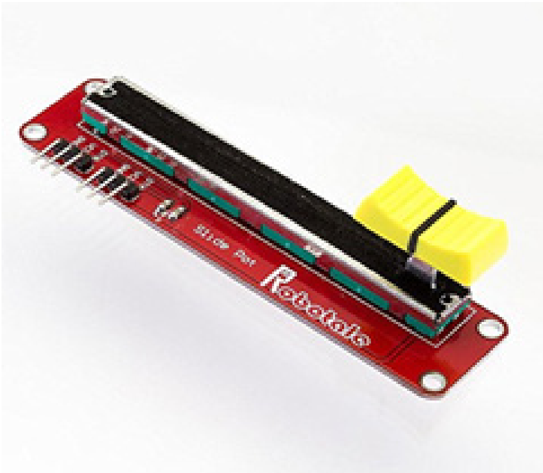

Figure 4. Sliding Adjustable Potentiometer.

3.2.2 ESP8266 Wi-Fi Module

The ESP8266 Wi-Fi (Figure 5) Module is a type of microcontroller that has an inbuilt Wi-Fi module for data transmission. The ESP8266 module can be programmed using Arduino IDE to perform data processing and data transmission. It works on a 3.3 to 5V power range; if a battery of 12 v or mover is used to power the node, an additional voltage regulator is required. It has a single analog pin and multiple digital pins to transmit and receive analog and digital signals to and from the sensor. The Micro USB port provided in the board can be used to update the task program and to power the board. A flash button is provided in case the existing program needs to

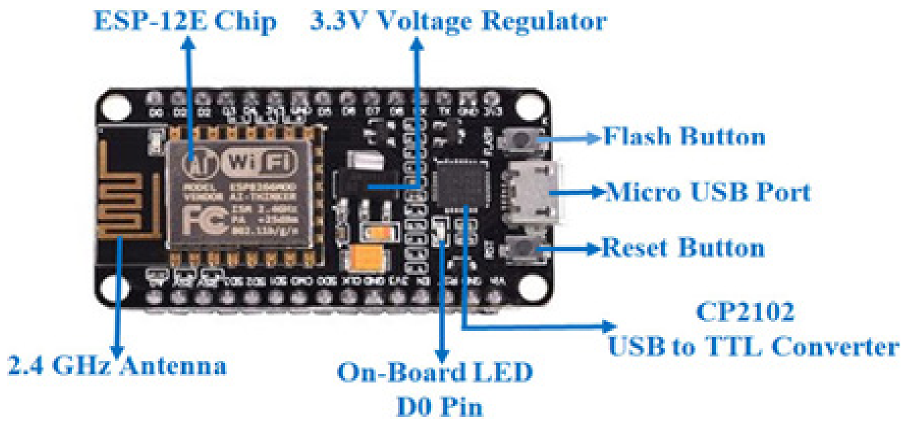

Figure 5. ESP8266 Wi-Fi Module and its pinouts.

be cleared, and a reset button is provided to restart the program from the beginning.

4.0 Ansys Software

ANSYS software is a general-purpose software used in all disciplines of engineering, such as physics, fluid dynamics, civil structural, thermodynamics, heat transfer, and mining works. ANSYS can integrate with other software to import and export files such as CAD drawings, etc. The development of computer designing techniques and the theory of generalized plastic mechanics of soil, the Finite Element Program, make significant progress in nonlinear modeling. Its pre and post-processing have become more convenient for deriving solutions in Deformation, Safety Factors, etc.

In this study, the ANSYS software is used to evaluate the rock slope stability of the study mine. Element displacement vectors, Strain, Stresses, Plastic state of slope, and safety factors can be calculated using ANSYS[13]. The stability problems in the Sanyou Limestone mine were studied using elastic-plastic finite element theory by ANSYS software[14]. Analysis of the stability of slope over and underground workings using ANSYS software to estimate the deformation[15].

5.0 Flow Chart for Real-Time Slope Monitoring and its Validation

The initial step in the implementation of Real-time slope monitoring is to collect the mine data of the study area to

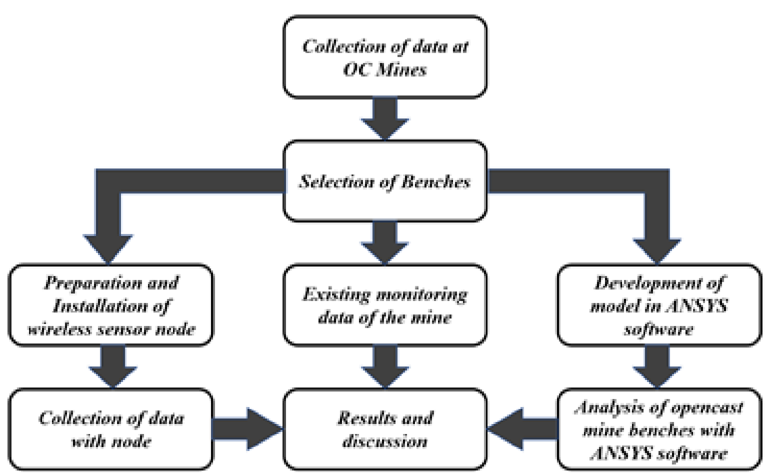

Figure 6. Flow chart used for the real-time slope monitoring and its validation.

identify the benches that tend to deform and slide. From the analysis of mine data, Four slope benches were selected for observation via the proposed WSN slope monitoring system and Total station. Total station observation readings were later used to validate the WSN readings. Following that, Numerical models were developed and analyzed based on the site condition and were verified with the WSN and Total station readings. The brief about the methodology is discussed in the following sections.

As seen in Figure 6, after gathering data from slope benches, the number of benches to monitor was decided upon, and the prepared nodes were installed to track the growth of slope deformation. The identical benches are modeled in the Ansys software to obtain the deformation while comparing the current deformation values obtained from the total station monitoring system. The deformation values obtained by the three monitoring systems were then compared and validated.

Figure 7. A broad view of the KTK opencast- II project.

5.1 Field Investigations

5.1.1 Description of the Mine

Kakatiyakhani Opencast-II (KTK OCP-II) Project is carved out of Kakatiya Khani-2 (KTK-2) Incline underground mine. KTK OC-II Project is located between North Latitudes 18° 26' 41" to 18° 28' 8" and East Longitudes 79° 50' 17" to 79° 52' 36" falls in Survey of India Topo sheet No: 56 N/15. The project is located on the North-West side of Jayashankar Bhupalpalli town. The nearest railhead to the project is Uppal railway station, lying on the Balharshah-Kazipet section of the South Central Railway, which is located at a distance of about 55 Km away.

A total of fifteen coal seams are present in the mine property, and they are IB, IA (Top), IA (Bottom), I, II (Top), II (Bottom), III C, III B, III A, III, IVA, Index seam above IV, IV, Index seam below IV and V in descending order. The eleven workable coal seams considered for extraction in the KTK OC-II project are IA (Top), IA (Bottom), I, II (Top), II (Bottom), IIIC, IIIB, IIIA, III, IVA, and IV seams up to 250m depth of III seams in this OC project. The seams I, II, and III were partly developed and depillared earlier by underground mining methods

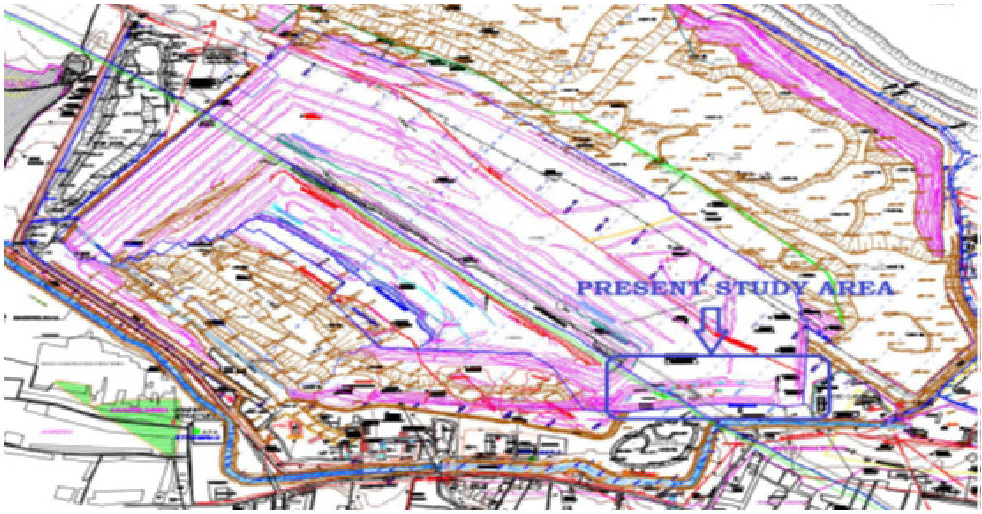

Figure 8. Present study area of the KTK OC-II Project.

and other seams are left virgin. The average gradient of coal seams is 1 in 3. A broad view of the KTK opencast- II project is shown in Figure 7.

Based on the above observation, it is understood that the east side low wall benches tend to slide due to the crop area and are prone to moisture because of nallah existing near the site. Hence, for the observation, the east side benches are selected for the present study (Figure 8).

5.2 Selection of Benches for Slope Monitoring

The Singareni exploration department in the vicinity of the disturbed benches at the eastern rise side benches carries out geological mapping. The bottom benches are carved on surface soil and weathered sandstone strata. The in-crop clays of 1B, 1A Top, and 1A bottom seams traversing across these benches are shown in Figure 8. The top two benches appear stable and compact, but the benches got disturbed locally, and there is a chance of failure as per the mine authorities.

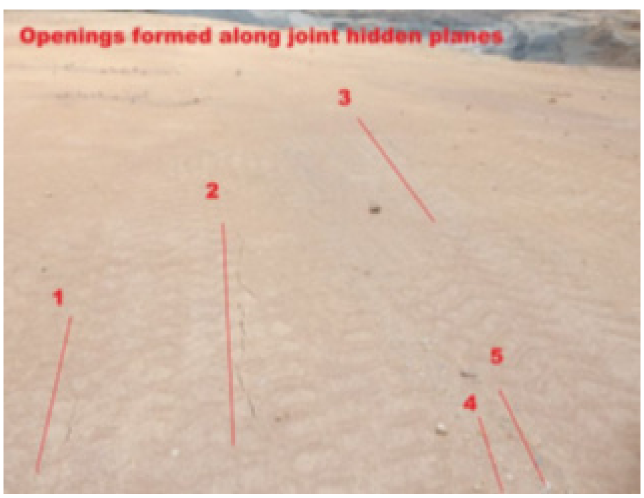

Figure 9. Showing tensional cracks developed on RL870 bench surface.

It is observed that tension cracks developed on the surface of this bench, and they may be an extension of joints in sandstone strata present below this bench, as shown in Figure 9. The formation of tension cracks is an indication of instability. Cracks form when slope material has moved toward the pit. During the rains, water will enter into these discontinuities, i.e., tension cracks, and may build up pore pressures. Thus accelerating the instability of the benches.

During studies, monitoring was done in probable failure benches, i.e., 875RL and 870RL along the slope with both methods. Eight locations were monitored; at each location, data was captured.

5.3 Real-Time Slope Monitoring by Development of Wireless Sensor Network (WSN)

5.3.1 Selection of Wireless Sensor Network Devices

The paper primarily focused on the movements of slopes and their monitoring. Hence, the parameter selected for slope monitoring is deformation, and to represent this, a slide potentiometer as the wireless sensor is chosen. The Wi-Fi module for transmitting data from the sensor to the base station is elected ESP8266.

5.3.2 Preparation of Node

Wireless sensor nodes were prepared with the selected wireless sensor and Wi-Fi module. The node module was

Figure 10. Different displacement sensor nodes were prepared for installation.

built using transparent acrylic sheets. For power, elected 9V batteries and prepared node as shown in Figure 10.

5.3.3 Field Investigations with Wireless Sensor Nodes

Wireless sensor nodes were installed at selected monitoring points, namely N301, N302, N303, N304, N401, N402, N403 and N404 in 875RL and 870RL benches (Figure 11).

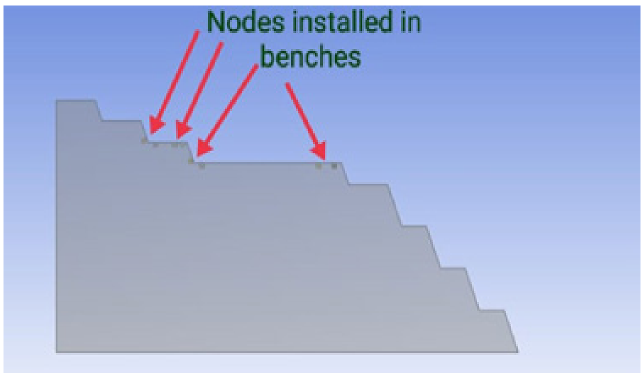

Figure 11. Monitoring points in the opencast benches.

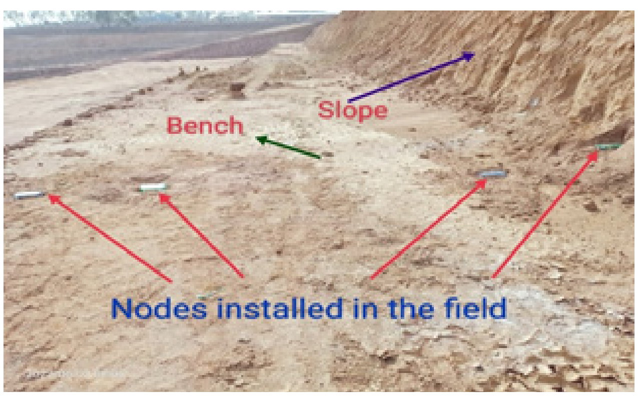

Figure 12. Location of monitoring points by installing the sensor nodes on the 875RL Bench.

Displacement sensor nodes were installed, as shown in Figures 12, 13, and 14, and connected to the Wireless network through the ESP 8266 Wi-Fi module. The sensor nodes capture the data and convert it into the signal (sensed data) using a signal conditioner.

ESP8266 microcontroller continuously captured the data from the Displacement sensor node, converting the sensor data to readable data format using Analog-to-Digital Converter (ADC). Subsequently, the sensor's

Figure 13. Location of monitoring points by installing the sensor nodes on the 870RL Bench.

data were sent to the base station using Wi-Fi for data processing. At the base station, the measured data received from various sensor node transmitters were displayed with the time stamp. A depiction of the same is provided in Figure 15.

Arduino IDE has a user-friendly Graphical User Interface (GUI) in its serial monitor that helps display data and export easily. After the receiver node receives

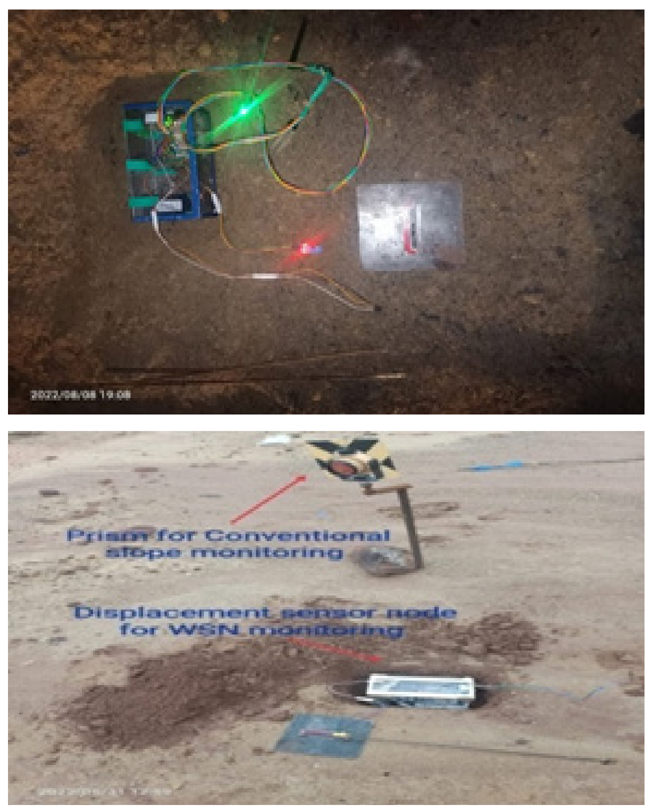

Figure 14. Fixing of deformation node in the 870 and 875 RL Benches.

Figure 15. Monitoring of slope deformation using wireless sensors in the field.

the sensor data through the transceiver in the module, the same will be displayed in the serial monitor, as shown in Figure 16.

5.3.4 Slope Monitoring with Wireless Sensor Node

The 870RL and 875RL benches were selected for fixing sensor nodes and installed at various locations on the benches. A large sum of slope deformation data was generated continuously through Wi-Fi-based data transmission. At each individual location, data were collected at a frequency of one per second. Data were collected for a duration of one week from 1st to the 6th of June 2022. In total, 8 different locations were studied, from which mean values of deformation were obtained, as shown in Table 1.

Table 1. Deformation at different monitoring points using wireless sensors

Bench RL (m)	Monitoring point no.	Average Reading (mm)
870	N301	4.16
870	N302	3.51
870	N303	4.29
870	N304	4.68
875	N401	4.03
875	N402	5.06
875	N403	3.90
875	N404	4.16

5.4 Existing Slope Monitoring in the Field with Total Station

Conventional slope monitoring is carried out at KTK Opencast project II using a Total Station and Prisms installed regularly on the proposed monitored low wall benches. Prism is installed on critical areas throughout the benches horizontally and vertically at regular spacing. The prism positions are measured regularly, and the data is reviewed for any displacement. The Total stations are kept on strategic points by permanent stations for monitoring the prisms on a regular basis. Monitoring is done by installing 21 prisms permanently on low walls.

Figure 16. Slope monitoring with the total station by the mine authorities.

Table 2. Variation in deformation at monitoring points using Total Station

Bench RL (m)	Monitoring point no.	Deformation (m)
870	N301	0.004
870	N302	0.003
870	N303	0.004
870	N304	0.005
875	N401	0.003
875	N402	0.005
875	N403	0.004
875	N404	0.004

Out of them 7 on the 1st bench, 6 on the 2nd bench, 4 on the 3rd bench and 4 on the 4th bench. Readings are tallied with initial reading and previous reading to know the slope movement.

The deformation obtained as of 06.06.2022 by the total station slope monitoring at the KTK OCP II mine is given in Table 2, and the observation of the prism by the total station is shown in Figure 16.

5.5 Numerical Modeling

The numerical modeling study was adopted to assess the bench's stability in surface mining operations. In this, modeling analysis was carried out exclusively based on the site conditions using ANSYS Workbench software. The models were designed consisting. different benches of overburden, as shown in Figure 17. In total, there were eight overburdened benches. Input parameters like rock properties and bench configuration for modeling were obtained during the site visits, and the same is presented in Table 3

5.5.1 *Slope Monitoring with Modeling on Field Conditions*

Field cases were modeled to validate the data generated by monitoring with Wireless sensors and conventional Total station monitoring during field investigations. Rock properties and other design parameters like bench height and width were obtained during field studies. Models

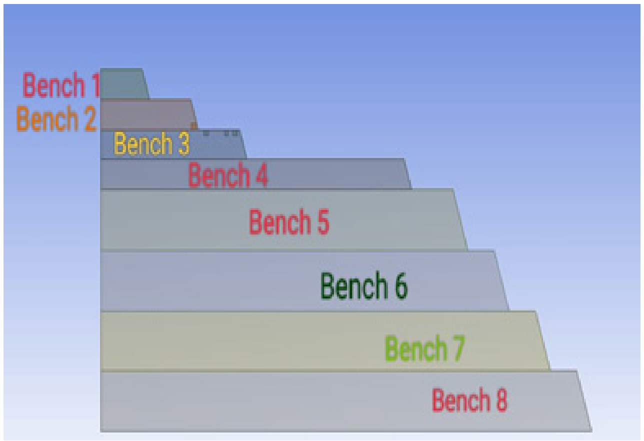

Figure 17. Overview of a simulation model of opencast benches.

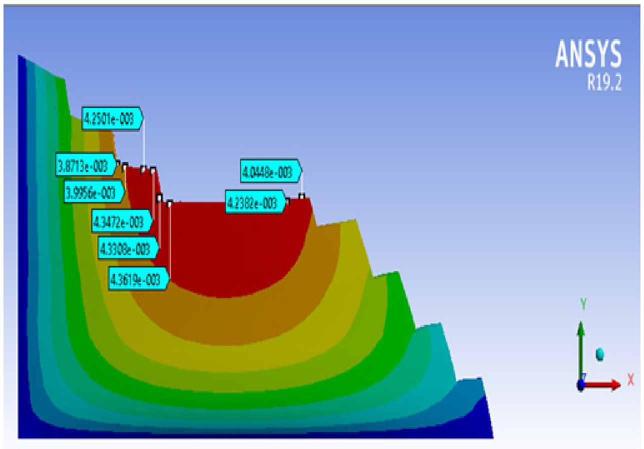

Figure 18. Variation in deformation in ANSYS using numerical modeling.

Table 3. Rock properties used in ANSYS workbench

Bench No	Bench height (m)	Density (gr/cc)	Tensile strength (MPa)	Compressive Strength (MPa)	Young's Modulus (MPa)	Poisson Ratio
1	5	2.19	0.22	3.24	3432.33	0.24
2	5	2.19	0.22	3.24	3236.19	0.24
3	5	2.19	0.66	4.61	3530.39	0.24
4	5	2	0.38	6.57	3334.26	0.25
5	10	2	0.83	15.10	4118.79	0.25
6	10	2.17	2.02	20.40	5687.86	0.25
7	10	2.22	1.75	15.35	4020.73	0.25
8	10	2.03	2.38	11.01	3726.53	0.25

developed for the bench geometry, and the results of the ANSYS model for geometry are shown in Figure 18.

Deformation values at monitoring points, namely N301, N302, N303, N304, N401, N402, N403, and N404 in 875RL and 870RL benches, are obtained from the model are shown in Figure 19 and tabulated in Table 4.

Table 4. Difference in deformation at various monitoring points using numerical modeling

Bench RL (m)	Monitoring point no.	Deformation (10-3m)
870	N301	3.8713
870	N302	3.9956
870	N303	4.2501
870	N304	4.3472
875	N401	4.3308
875	N402	4.3619
875	N403	4.2382
875	N404	4.0448

6.0 Results and Discussion

6.1 Slope Monitoring Data Obtained in Field Investigations

Field observations were carried out using total station and wireless sensors, and the deformation obtained at different monitoring points N301 to N304 and N401 to N404 on 875 and 870 RL benches is shown in Table 5. To validate the data generated by wireless sensors, the conventional total station monitoring with prisms is installed on the same bench to observe the deformation under similar field conditions to the wireless sensors.

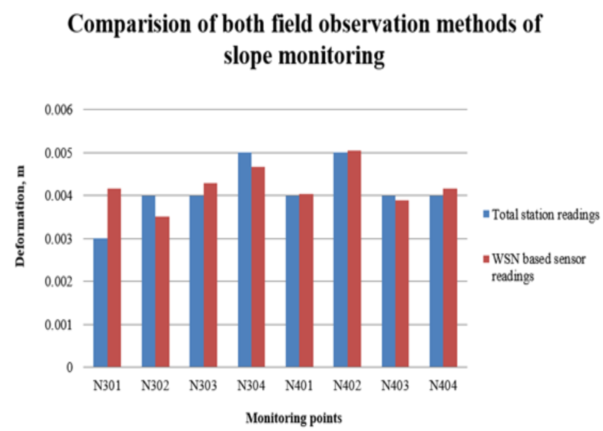

Figure 19. Comparison of both Field observation methods of slope monitoring.

Observing the field slope monitoring methods results shows both are similar and can be reliable with the advanced wireless sensor monitoring for real-time monitoring of slopes in opencast mine (Figure 19). The variation between Total station and wireless sensors monitoring is only around -4% to 12.25%.

6.2 Comparison of Field Studies with the Numerical Modeling Study

Maximum deformation values using Total station, WSN monitoring, and Numerical modeling from Table 6 are 5.0mm, 5.06mm, and 4.36mm for 870RL and 875RL benches, respectively. Similarly, minimum deformation

Table 5. Deformation of both Field observation methods of slope monitoring

Bench RL (m)	Monitoring point no.	Total station readings (m)	WSN readings (m)	Percentage of variation in (%)
870	N301	0.003	0.00416	38
870	N302	0.004	0.00351	-12.25
870	N303	0.004	0.00429	7.25
870	N304	0.005	0.00468	-6.4
875	N401	0.004	0.00403	0.75
875	N402	0.005	0.00506	1.2
875	N403	0.004	0.00390	-2.5
875	N404	0.004	0.00416	4

Table 6. Variation of deformation observed in slope by different monitoring methods

Bench RL(m)	Monitoring point no.	Total station readings (m)	WSN readings (m)	Numerical modeling readings (m)
870	N301	0.003	0.004	0.00387
870	N302	0.004	0.003	0.00399
870	N303	0.004	0.004	0.00425
870	N304	0.005	0.004	0.00434
875	N401	0.004	0.004	0.00433
875	N402	0.005	0.005	0.00436
875	N403	0.004	0.003	0.00423
875	N404	0.004	0.004	0.00404

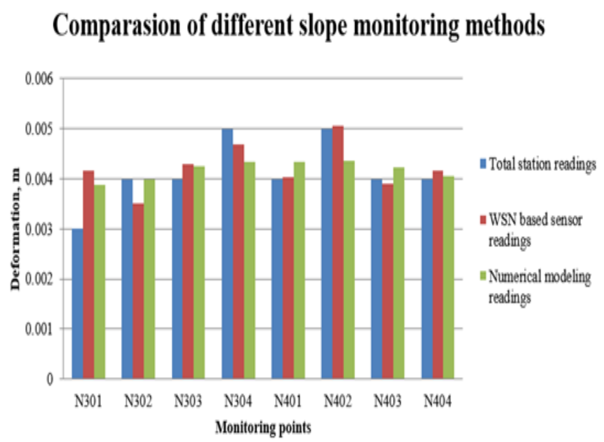

Figure 20. Comparison of different slope monitoring methods.

values using Total station, WSN monitoring, and Numerical modeling are 3.0mm, 3.51mm, and 3.87mm for 870RL and 875RL benches, respectively. Total station and WSN monitoring variation is only around -4% to 12.25%. The variation between Total station and Numerical modeling is around -6.25% to 13.06%, and WSN monitoring to Numerical modeling is -7.66% to 12.15%. Figure 20 depicts the same in a graph where the x-axis denotes the specific monitoring station and deformation is denoted in the y-axis. It can clearly be seen that the difference in obtained deformation between each method varies only about 10% and less. However, the data obtained using WSN monitoring is close to the existing conventional total station monitoring and almost similar variation to Numerical modeling, thus indicating that the WSN monitoring method is reliable.

7.0 Conclusions

The conclusions drawn from the research work carried out:

1. Wireless sensor nodes were developed, deployed, and installed in the field.
2. Based on the developed wireless sensor network setup, the deformation in the slopes of opencast benches was monitored from the base station.
3. Based on various monitoring methods adopted in this study, the results were validated and compared and found in the permissible percentages to suggest real-time monitoring in the field, such as the following.
   a. The maximum deformation observed by the wireless sensor was 5.06mm, whereas 5mm was observed by Total station monitoring under the same field conditions. The maximum deformation obtained from numerical modeling studies was 4.36mm.
   b. Numerical modeling analysis results indicated that deformation was maximum at 870RL and 875RL benches, similar to the field observations.
   c. The variation between wireless sensor monitoring and Total station monitoring is around -4% to 12.25%. The variation between wireless sensor monitoring and numerical modeling is around -7.66% to 12.15%, and numerical modeling to Total station monitoring is -6.25% to 13.06%. However, the data obtained using wireless sensor monitoring is close to the existing total station monitoring

method. As rock is non-homogeneous, such variation can be considered within acceptable limits.

8.0 References

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