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Field Application of Gravity Blind Backfilling Method to Abandoned Underground Waterlogged Coal Mine

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Abstract: *Blind hydraulic backfilling is a commonly used technique for subsidence control of the strata over unapproachable water-logged underground excavations. In an investigation performed earlier, studies were carried out on simple gravity hydraulic blind backfilling in laboratory scale within a fully transparent model of a section of underground coal mine worked on bord and pillar method. Subsequently, field investigation at an abandoned underground waterlogged coal mine of Eastern coalfields Limited, a subsidiary of Coal India Limited, has been taken up to verify the findings obtained in the laboratory scale model study. The paper describes the field arrangements made for the backfilling process, and the use of remotely operated vehicle mounted camera and its sonar imaging facility for mapping of the abandoned underground waterlogged mine and for monitoring the progress of the sand filling during consecutive stages of the backfilling process.*

Keywords: *Underground coal mine subsidence, bord and pillar mining, gravity blind backfilling, remotely operated vehicle mounted (ROV) camera, sonar imaging.*

1. Introduction

In earlier days, most coal mines in India have been worked under shallow cover and were practically extracted using Bord and Pillar system of working. Correct and reliable records of plans of such workings are generally not available. Over the years, the strength of pillars left as support of the roof has severely deteriorated and frequent collapse of these pillars endanger some important structures and properties constructed above these pillars on the surface due to subsidence.

Depillaring with regular stowing provides adequate support of the voids and reduces the risk of accidents arising out of pillar spalling and premature collapse of large areas. But depillaring with stowing cannot be always followed due to various constraints. Therefore, the coal mines which have been worked by caving method became either fully or partially water-logged and are unapproachable. Development of suitable methods to stabilize such areas had been neglected in the past. However, some attempts had been made earlier for stabilization of a few old abandoned water-logged underground coal mines situated in Asansol and Raniganj using hydro-pneumatic or air-assisted gravity backfilling method. But these method faced several short comings viz., frequent jamming of injection hole, short circuiting of compressed air and filling up of inadequate area from an injection hole etc.

The effectiveness of the proposed simple gravity blind backfilling depends on parameters like slurry flow rate, sand concentration, etc. Experimental studies were conducted in a previous project on a scaled transparent bord and pillar mine model to find out the effects of variations of slurry flow rate, sand concentration, model inclination and injection velocity on the filling process. The models were fabricated to study the process and establish the optimum parameters for achieving maximum sand filling through a single borehole. Subsequent to the laboratory investigations, field implementation of the laboratory findings has been taken up and executed to prove the effectiveness of the gravity blind backfilling method in the field conditions.

1.1 Literature Review

There exists number of differences between backfilling methods in active mines and those used in blind backfilling of abandoned mines. The main difference is the lack of access to the abandoned mine voids. The backfilling operation in active mines can be directly observed. The backfilling operation in such cases can be controlled locationally for the amount of fill material deposited.

In abandoned mines due to lack of access, all the work must be done from the surface in remotely controlled fashion. According to placement mechanism, the blind backfilling can be classified into:

(i) Pneumatic method, and
(ii) Hydraulic method.

1.1.1 Pneumatic blind backfilling method

This pneumatic backfilling refers to a special form of pneumatic conveying in which the backfill material is transported through a blind borehole into the mine and thrown all around the inlet zone. The water related

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problems are eliminated in this technique. This method can only be used in dry mines. With suitable design good packing of fill may be achieved in the area of fill from one small inlet [1].

1.1.2 Hydraulic blind backfilling methods

Walker [2] had described the state-of-the-art techniques for backfilling the abandoned mine voids by hydraulic flushing from single or multiple boreholes. Thill *et al.* [3] described the process of backfilling the flooded mines using sand or crushed mine refuse. Saxena *et al.* [4, 5] presented a field trial carried out at 'Jogta Fire Project' stabilizing unapproachable workings. Ghosh *et al*. [6] described the hydropneumatic method as trial in Ramjivanpur colliery.

There are three important methods to achieve hydraulic blind backfilling. These are:

(a). Simple gravity flushing,
(b). Air-assisted gravity flushing, and
(c). Pumped slurry injection.

1.1.2.1 Simple gravity flushing

This method is used when the mine workings are inaccessible to workers. With this approach, a slurry of backfill material is gravity fed through a well (either a drilled well or a mine shaft) into the mine until the well will not accept any additional backfill material. The quantity that can be injected down a single well depends on the conditions at underground, such as the slope, height, and the proximity of pillars in the mine workings. [7, 8].

1.1.2.2 Air-assisted gravity flushing

This method is also known as hydro-pneumatic backfilling technique which is developed and practiced in India. In this system, solid-water mixture is sent to fill underground voids through a larger diameter pipe and compressed air is fed through a smaller diameter pipe placed inside the larger diameter pipe. The solids used for filling may be sand, fly ash, small size gravel, crushed stone or washery-rejects. Detailed research work in this area in the form of model studies had been conducted at CMRI and at I.I.T. Kharagpur, India [4, 9].

1.1.2.3 Pumped slurry injection

Pumped slurry injection is similar to blind flushing except that the slurry is pumped down a well rather than injected by gravity. With this approach, increased distribution of the fill material within the mine can be achieved due to the increased velocity at which the slurry is injected. Solid particles settle out near the borehole when the slurry is first delivered and the velocity of the injected slurry drops as it enters in the mine workings. As more material is injected, the fluid velocity increases in the mine workings and the solid materials are transported further away from the borehole [10].

Various types of material (i.e. crushed stones, mine refuse, and or fly ash) can be used for pumping them into the mine with water. The fill material is transported into the mine as slurry and deposited in the void until the void is completely filled. But most of the time filling has to be abandoned due to choking or jamming of the injection pipe / roadway. The energy provided from the pump and the static head of the borehole gives the backfill material the required velocity to keep the fill material in suspension and determines the size of the area that can be flushed from a single borehole.

2. Field Arrangements and Facilities

After selection of the project site, the drilling work of various types of boreholes was taken up with studying the details of existing underground workings in the site to be filled-up. On completion of the drilling of boreholes the following other provisions have been made at the project site prior to the actual filling work:

(i). Pumps and pumping arrangements,
(ii). Electrical arrangements,
(iii). Sand storage and re-handling arrangements, and
(iv). Movable backfilling laboratory.

The following sections describe the project site and other preparatory facilities created on the surface in the project site.

2.1 The Project Site

The Krishnanagar Colliery under Kenda Area of E.C.L. was abandoned in the year 1989 due to severe roof related problems which prohibited further underground depillaring work. This mine was allotted to the project team of I.I.T. Kharagpur by Eastern Coalfields Limited for carrying out the field trail of simple gravity blind backfilling technique. The selected project area in an underground mine map is shown in Figure 1, where the extent to be filled-up is marked by the blue dotted line. The mine was worked by bord & pillar method with the gallery dimensions of about 3 m × 2.5 m. The void area computed from the map is about 30,000 m^3. The filling work was scheduled to start from the dip-most side and progress towards the rise direction, in accordance with the findings of the model study where it was established that filling from dip to rise is better than filling from rise to dip.

2.2 Drilling of Boreholes

A total of 45 holes were drilled with more than 80 percent success in connecting the boreholes to underground workings. Twenty four air holes were drilled mainly at the rise most locations covering the entire top part of the filling zone. The purpose of these holes is to release the trapped air which often enters the mine along with the vertical feed of the sand-water slurry. About ten large diameter boreholes have been drilled with steel casing for insertion of underwater ROV camera for exploring the underground mine before filling as well as for locating the spread of sand-bed along different directions. Two medium-sized boreholes were drilled for installation of submersible pumps which are used to supply water from the water-logged mine into the mixing vat for preparation of sand-water slurry. Water in slurry when fed through mother borehole creates a close circuit flow of mine water. Adjacent to the first mother borehole a small size piezo-hole was drilled for insertion of a piezo-meter which would indicate the fluctuations in the inlet slurry level. Figure 2 shows the positions of different types of drillholes drilled for the backfilling work in the field.

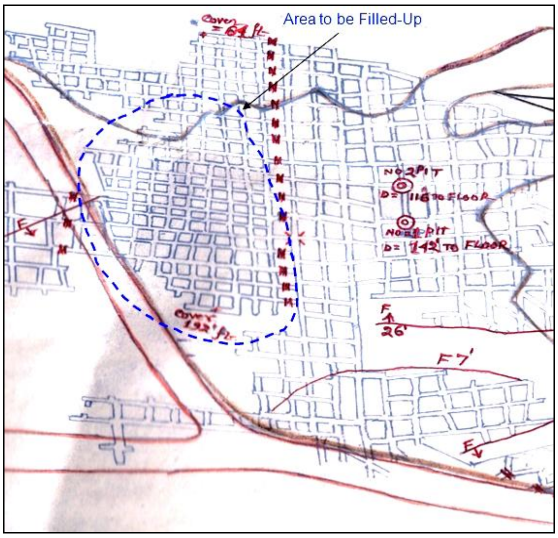

Fig. 1: *A part of the underground map of Krishnanagar Colliery depicting the proposed area to be filled-up*

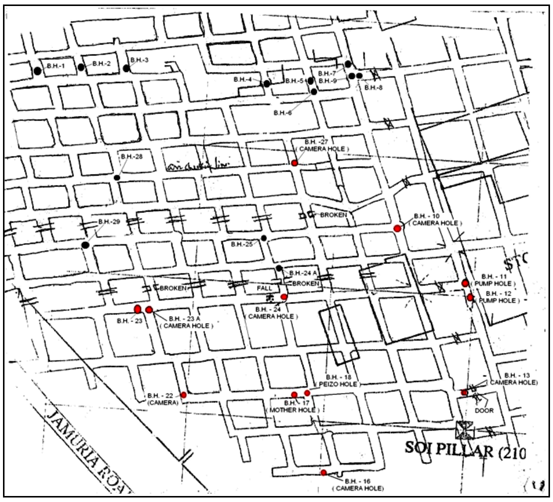

Fig. 2: *The underground map of Krishnanagar Colliery showing the positions of different types of boreholes*

2.3 Pumps and Pumping Arrangements

Two 30 HP, 600 GPM submersible pumps were installed at a depth of 40 m below the surface inside two pump boreholes. The pump room of 12’ x 12’ size was constructed to accommodate the main switches and starters of the pumps. Figure 3 shows the pump room and its inside fittings. The pumps can be operated either from the pump house or from the movable filling laboratory via wireless antennas.

2.4 Electrical Arrangements

As the existing transformer in the abandoned mine was used to supply power to the local residents as well as to run a pumping station of a water supply unit, the required power for the project activities could not be obtained from the same transformer. The total power requirement in running the project activities was estimated to the tune of 60 to 70 kVA and, therefore, a new 100 kVA transformer station was installed near pit top of the abandoned colliery using the available 11 kV power supply line. It has also been observed that frequent power cuts were a regular feature in and around the project site. Therefore, a diesel generator set of 125 kVA was commissioned near the transformer so as to facilitate filling operation to be continued even during frequent power cuts. Figure 4 displays the photographs of the transformer station and the DG set installation.

2.5 Sand Storage and Feeding Arrangements

The total amount of sand that has been filled up in this project is slightly more than 20,000 m^3. As there was shortage of storage space, the sand was collected in phases of about 3,000 to 5,000 m^3 and filling progressed in phases. The deposited sand on the surface was re-handled by a payloader of Terex Vectra make. This payloader has a highly efficient turbo charged engine of 90 HP power and one cubic metre loader bucket capacity and 0.25 cubic metre back hoe bucket capacity. The payloader is used to load sand on to a small bunker near the movable laboratory, from where a measured amount of sand is taken into the mixing vat through a bucket elevator as shown in Figure 5. The calibration curve for sand feed rate by the bucket conveyor to the mixing vat is shown in Figure 6.

Fig. 3: *Pump room with pump outlets, main switches and starters*

Fig. 4: *100 kVA transformer station and 125 kVA diesel generator*

Fig. 5: *Photograph of sand bunker feeding sand to bucket elevator*

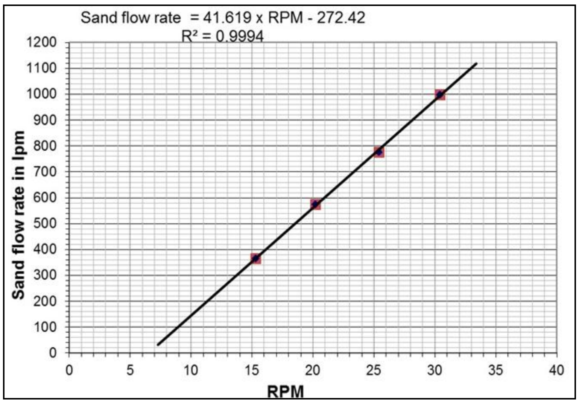

Fig. 6: *Calibration curve for Sand flow rate*

2.6 Movable Backfilling Laboratory

A movable backfilling laboratory was designed and fabricated in the form of a caravan, which is positioned exactly above the mouth of mother borehole. Water from pumps and sand from bucket elevator is mixed together in a mixing vat constructed inside the caravan and the slurry is then allowed to flow down into the mine by gravity through the mother borehole. As a safety measure, an overhead water tank of 5000 litres capacity is placed over the top of the caravan so as to release the water from the tank through a motorized valve to the mixing vat in case of sudden power failure. This additional water would keep the flow channels open and prevent accidental jamming. Figure 7 shows the caravan and the overhead tank. Figure 8 shows the mixing chamber inside of the caravan.

Fig. 7: *Photograph of the caravan, inlet water pipelines and the overhead tank*

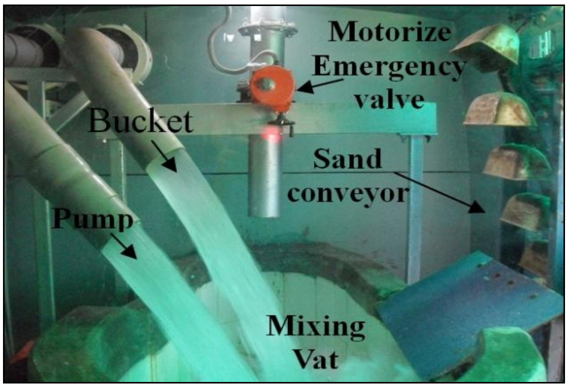

Fig. 8: *Photograph of inside of the caravan showing the mixing chamber*

2.7 The Control Panel

The backfilling laboratory is fitted with a control panel where different displays or indicators for water flow rates from the two pumps, the total flow rate, conveyor RPM, laser water level and piezometer based slurry head are mounted. An electrical vibrator motor is fitted at the lower side of the sand bunker for permitting continuous flow of wet sand from the bunker, which otherwise gets stuck at the mouth of sand bunker causing jamming of sand flow from the bunker to the bucket elevator. The electrical push-on type switch for vibrator motor is located at the control panel for ease of operation by the operator sitting in front of the panel. A high capacity UPS is also placed at the control panel for uninterrupted monitoring of various parameters in the case of sudden power failures. Figure 9 shows the control panel with different displays or indicators.

2.8 Continuous Data Recording System for Flow Parameters

An eight-channel continuous data recording system was installed in the caravan for recording of the water flow rates, sand conveyor RPM, fluctuations in laser water level as well as piezometer water level during filling operations. Figure 10 shows the front view of the continuous data recording system, in which fluctuations in the piezometer water level is shown in the form of a graph with respect to time. Instantaneous rise and fall of water levels indicated by both laser distance meter and piezometer are also shown symbolically by the rise and fall of levels in two vertical bar-type indicators in the right-hand side of data acquisition window. The time interval of recording the data sets was kept at 1 second during filling through the first two boreholes, and subsequently reduced to 0.3 second.

Fig. 9: *Control Panel with different displays*

3. Field Experimentation

Initial laboratory experiments showed that filling from dip to rise produces higher quantum of filling in more compacted form. The tests on repeatability of experiments indicated a maximum variation of 9% in the sand throughput from a single bore hole. The gravity blind backfilling method as experienced in all experiments is an efficient method and it was possible to fill-up a large area of the model from a single inlet point by suitably adjusting water and sand flow rates as filling progresses. Relationships between maximum sand throughput from a single bore hole with slurry flow rate and sand concentration was derived in the model study. The field experimentation has been designed to replicate the results obtained from the laboratory model.

3.1 Gravity Filling Work

Since filling from dip-most side has been found to be more effective in the laboratory experiment, the Borehole No.17, which is located towards the dip-most zone of the proposed filling area, was chosen to be the first mother borehole. To measure the fluctuation in the slurry level a piezometer and a laser distance meter was set-up in the 6" diameter companion Borehole No. 18 located close to the mother borehole. The diameter of the mother borehole was kept at 200 mm so that the inlet velocity of the slurry becomes nearly 3.0 m/s. In the beginning of the filling work through the first mother borehole the sand concentration in the slurry was kept at 15 percent and it was gradually reduced to 9 percent as the filling progressed. During downward movement of slurry through the borehole air bubbles get trapped and enters the mine, which are then released from other boreholes located on the rise side.

The first mother borehole was jammed after injecting 6689 m^3 of sand. Next, the caravan or movable backfilling laboratory was shifted to borehole no. 23 and filling was continued. Due to presence of series of stoppings on the rise side, filling through the second mother borehole could not be progressed beyond 1427 m^3.

In the same way, filling was continued in borehole nos. 28, 29 and 27. The borehole No. 29, being located in between the two series of stoppings, could not intake sufficient amount of sand and was jammed with a total sand throughput of 1544 m^3. Lastly the filling was continuing in borehole No. 3 and the project was terminated in December 15, 2011 with 1357 m^3 of sand being sent into the mine through the last motherhole. In this way, a total of 21,476 m^3 of sand was sent into the mine. Table 1 displays the quantities of sand deposited against each borehole.

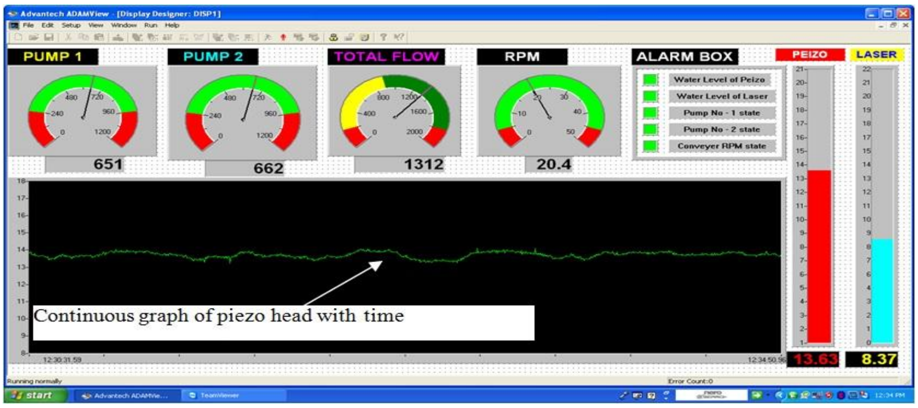

Fig. 10: *Close-up view of data logger during data recording*

Table 1: Details of sand filling through different boreholes

Sl. No.	Borehole No.	Sand deposited (m^3)	Cumulative amount of sand deposited (m^3)	Remarks
1.	17	6689	6689	Unhindered filling
2.	23	1427	8116	Hindered filling due to stoppings
3	28	6236	14352	Unhindered filling
4	29	1544	15896	Hindered filling due to stoppings
5	27	4223	20119	Unhindered filling
6	3	1357	21476	Incomplete filling (no jamming)

3.2 Monitoring of the Filled-up Area

For the first time in the world, the position of the sand-bed in a blind backfilling process could be traced using special underwater ROV camera shown in Figure 11. Before the actual filling process started the sonar-head mounted on the ROV camera was used to produce a map of the required part of the abandoned mine. Hereafter filling work was initiated and at short intervals monitoring of the deposited sand-bed was taken up by guiding the ROV to the deposited sand-bed from different directions.

Fig. 11: *Remotely operated vehicle (ROV) mounted camera*

3.3 Mapping of Abandoned Mine before Filling

Before actual filling operation of the mine takes place, the concerned section of the abandoned mine is explored using the underwater ROV camera. The sonar head is fitted inside the top dome of the camera. The ROV camera is inserted into the mine through the 14" diameter camera borehole using remote operating device for the camera system. On entering the mine gallery the camera is slowly moved towards different directions getting guided by the indicated azimuth from the built-in compass as well as from the sonar image.

The screenshots of the sonar image were used to build a map of the path travelled by the camera. The orientations of camera during the screenshots were also noted and this information was used while superimposing the screenshots with one another. At least three well identified common points in the two successive screenshots were also utilized for superimposition of photos during construction of the mine map. The complete reconstructed map of the explored area covering more than 50 pillars is shown in Figure 12.

3.4 Mapping of the Filled-up Area during Filling

Filling was done through six boreholes, out of which the first five boreholes were filled up to the final limit till jamming took place. Filling from the sixth borehole was continuing when the project term ended. Monitoring during filling in each borehole was performed from surrounding camera boreholes using ROV mounted camera.

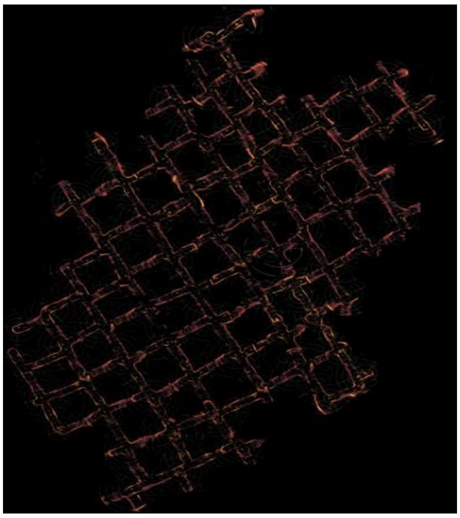

Fig. 12: *Complete reconstructed map of the explored area of the mine*

Normally water in underground mine galleries become very turbid during filling and visibility becomes very poor. Therefore filling is done in stages of about 400 to 500 m^3. After input of 400 to 500 m^3 of sand, filling is stopped for 2 days for allowing sand and dust particles to settle so that water in underground roadways become clear. Then the ROV camera is inserted from surrounding holes in a sequence and brought close to the deposited sand bed from different directions. Then, photographs of sand bed were taken and simultaneously sonar imaging of the underground gallery was done to obtain the exact position of the deposited sand bed with respect of the mine void. Sand spread during filling through 1st, 2nd, 3rd, 4th and 5th boreholes are shown in Figures 13 – 15.

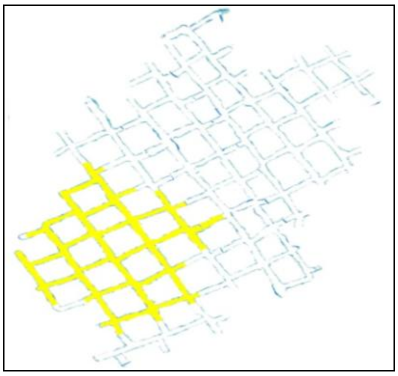

Fig. 13: *Positions of filled-up sand bed at the end of filling through 1st borehole*

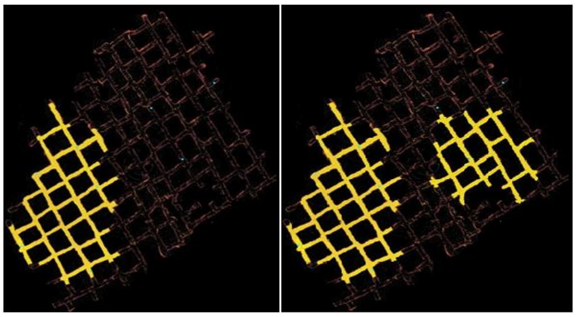

Fig. 14: *Positions of filled-up sand bed at the end of filling through 2nd and 3rd boreholes*

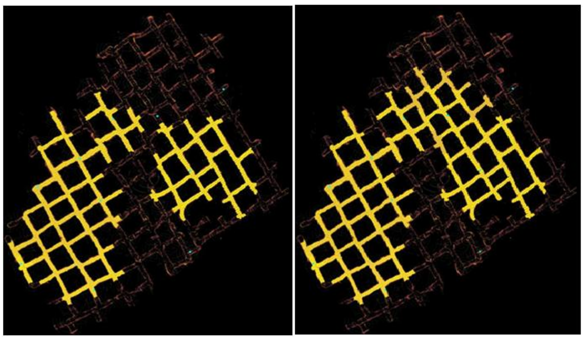

Fig. 15: *Positions of filled-up sand bed at the end of filling through 4th and 5th boreholes*

4. Pressure-Signature Analysis

Continuous recording of inlet pressures has been made using DAS alongside the record of all other parameters of filling during the field experimentation in order to explain the pressure signature patterns in terms of changes in physical phenomena during the filling process. The general nature of pressure-time curve as recorded by the DAS during the model study laboratory experiments is shown in Figure 16. As observed in the Figure, there has been a gradual rise of the pressure-time (p-t) curve with moderate fluctuation till about 6700 seconds beyond which a restless nature in pressure signature pattern could be noted which indicates the arrival of final phase of filling and a pre-jamming condition. This restless nature in the pre-jamming condition had created a special saw-tooth type of pattern which differed slightly depending on the changes in flow-rate and sand concentration.

The above nature of pre-jamming pattern was investigated in the field experimentation also. Table 2 shows the ratios of standard deviations at initial phase to pre-jamming phase as a measure of pre-jamming indication parameter. It can be seen that this standard deviation ratio is above 20 for all the five boreholes, but the same was found to be above 4 for laboratory experiments in the model study under similar range of sand concentration. In all the above cases, except for the 3rd borehole, the pre-jamming indicator manifested itself after more than 78.8% of maximum filling had occurred. Therefore, after the appearance of the pre-jamming indication, an average of 21.2% additional filling will be conceivable before the final jamming of the mother borehole takes place.

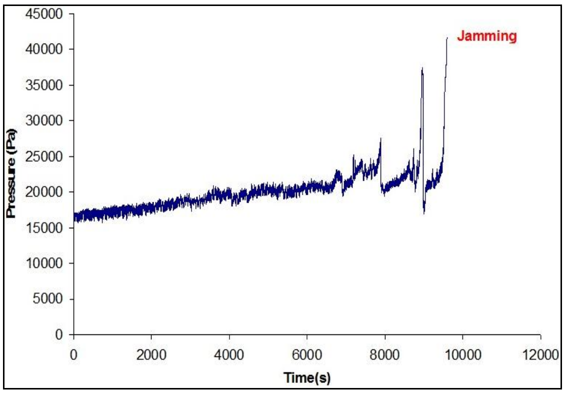

Figure 16: *General pattern of pressure signature during laboratory experiments*

Table 2: *Standard deviation values in initial phase and in pre-jamming phase*

Sl. No.	Borehole No.	Standard deviation		Standard Deviation Ratio	Percentage of Filling at Pre-Jamming Indication
		In Initial Phase	In Pre-Jamming Phase		
1.	1st	0.1	2.9	29.0	80
2.	2nd	0.125	2.6	20.8	80
3.	3rd	0.08	2.0	25.0	68
4.	4th	0.06	1.5	25.0	86
5.	5th	0.07	2.0	28.6	80

5. Conclusions

paper has described the field implementation of blind backfilling process to an abandoned underground waterlogged coal mine, and the use of ROV camera and its sonar imaging facility for mapping of the abandoned underground waterlogged mine and for monitoring the progress of the backfilling process. The filling was started with high sand concentration of 15%, and then it was gradually reduced to 9% or less. This was done to ensure maximum filling from single borehole at a quicker rate. In this way, it was possible to fill a little more than 6000 m^3 of sand into the mine from a single mother borehole under favorable geo-mining conditions. For precise determination of arrival of pre-jamming or unhealthy phase of filling, the plots of standard deviation of inlet pressure against time during filling through 1^{st} to 6^{th} borehole were computed. The ratios of standard deviations at pre-jamming phase to initial phase as a measure of pre-jamming indication parameter were found to be above 20 for all the six boreholes.

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