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Evaluation of pre-jamming indication parameter during blind backfilling technique

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ABSTRACT

Hydraulic blind backfilling is used to reduce subsidence problems above old underground water-logged coal mines. This paper describes experimental research on a fully transparent model of a straight underground mine gallery. An automatic data acquisition system was installed in the model to continuously record the sand and water flowrates along with the inlet pressure of the slurry near the model's inlet. Pressure signature graphs and pressure loss curves with bed advancement under different flow conditions are examined. Pressure signature analyses for various flowrates and sand slurry concentrations are conducted to evaluate a pre-jamming indication parameter, which could be used to indicate the arrival of the final stage of filling.

1. Introduction

Subsidence from old abandoned underground water-logged coal mines has become an everyday concern for many people living in coal producing regions. In earlier days, most coal mines in India worked under shallow cover and were partially extracted using the bord and pillar system of working. Correct records of the plans for many of these mines are not available and also in many occasions are not reliable. As time passes, the strength of the supporting coal pillars left behind in these abandoned mines gradually reduces and the collapse of several adjacent pillars often leads to sudden subsidence in the overlying region. Deterioration of pillars can also occur due to acid mine drainage in an abandoned mine as reported in a case study of an abandoned coal mine near Carbondale, Illinois, USA (RoyChowdhury, Sarkar, Deng, & Datta, 2016). Walker (1993) shows that when the common 'dilute phase' approach is used, an air/backfill mixture typically consisting of less than 5% backfill material is moved through a pipeline at relatively high velocity when compared to fluid. This approach is used for dry mines or where water is scarce.

Some authors have used a probabilistic approach to evaluate mine subsidence (Galve et al., 2009a; 2009b). To avoid problems of ground subsidence, a backfilling technique is used to fill the void space of abandoned mines (Andreyev & Koons, 2010; Aydan & Ito, 2015; Li & Pengyu, 2015; Li, 2013; Wissmann & Peterson, 2013) without dewatering. Aydan and Ito (2015) have presented the effect of the depth and groundwater on the formation of ground subsidence associated with abandoned room and pillar lignite mines under static and dynamic conditions and discussed the effects on the areas aforementioned abandoned lignite mines. Dang, Liu, He, and Liu (2013) have described research involving a feasibility test using phosphogypsum as a backfill aggregate, focusing on the mixture ratio of filling materials and the filling process.

In the majority of earlier mines lying at shallow depth, depillaring with stowing was not practiced due to several constraints and this has led to a high risk of subsidence in the areas lying above those mines. Therefore, the coal mines which utilized the caving method became either fully or partially water logged and have now become unapproachable. Development of suitable methods to stabilize these unapproachable mine voids has, to date, been neglected.

There are a number of differences between backfilling methods in active, approachable mines and those used in the blind backfilling of abandoned, unapproachable mines. The main difference is the lack of access to the abandoned mine voids. The backfilling operation in active mines can be directly observed and the location of filling can be controlled by suitably guiding and releasing the backfilling material directly at the void space which is to be filled.

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However, in abandoned mines, due to a lack of access, all the work must be done from the surface in a remote-controlled fashion (Pal, 2003; Sand, Boldt, & Ruff, 1990). The area to be filled cannot be directly controlled in such a case.

Hydraulic blind backfilling has three variants, namely, air-assisted gravity blind backfilling (Saxena, Parti, Kumar, & Singh, 1984), pumped-slurry injection (Whaite & Allen, 1975) and simple gravity blind backfilling (Pal, Ray, & Barve, 2001). In the hydraulic gravity blind backfilling method, the slurry of backfill material is fed by gravity through a borehole into the water-logged underground mine until the borehole will not accept any further backfill material. This blind backfilling method has been found to be as equally effective as pumped-slurry injection or air-assisted gravity blind backfilling, especially when flowrates are high (Pal, Mukhopadhyay, Panda, & Tripathi, 2010). The quantity that can be injected down a single borehole depends, mainly, on the flow characteristics of backfill material such as slurry flowrate and sand concentration. By using the gravity blind backfilling technique, the occurrence of sudden, pre-mature jamming is a major hurdle in the filling of large areas from a single borehole. To achieve the successful filling of a large area from a single borehole it is essential to make use of a pre-jamming indication parameter.

The aim of this research is to create a pre-jamming indication parameter through a detailed experimental study of the simple gravity blind backfilling method and in-depth analysis of inlet pressure variation during the process of filling.

2. Materials and methods

A fully transparent model has been created and used in a gravity backfilling set-up to critically examine the filling process and analyze inlet pressure variation during the filling-up of the model.

2.1. Transparent model of a straight underground mine gallery

Fully transparent 14 mm thick perspex sheets were used to construct a model of a straight, horizontal mine gallery of 4.9 m × 0.4 m × 0.3 m in size. The geometric scale of the model is 10:1 and it is used in a gravity backfilling set-up, as shown in Fig. 1. The maximum pressure head of the gravity filling process is kept at 1.5 m. One inlet hole is provided to feed sand-water mixture into the model. After depositing sand from the sand-water mixture, the clean water overflows from the model through two outlet holes provided at the two ends.

2.2. Water feeding and metering arrangement

A small capacity centrifugal pump is used to deliver water through a turbine type flow meter into a mixing funnel. The volumetric flowrate of water is varied by means of a manually operated throttle valve. The water flowrate is measured by the flow meter and displayed on an LED display unit located in the control panel.

2.3. Variable-speed sand feeding conveyor and metering arrangements

River sand is sieved, initially, through a 2 mm sieve to remove oversized particles and then through an ASTM No. 140 sieve to remove finer particles which can hamper the proper visualization of the filling process in the transparent model. It is then stored in a bunker. The sand is then transported from the bunker to the mixing funnel using a variable-speed bucket elevator. Sand flowrate is measured by calibrating the sand quantity transported with the rpm of the bucket elevator. To ensure sand-water slurry of any desired concentration, metered amounts of sand and water are fed into the mixing funnel. As the sand-water mixture gravitates down the inlet feeder pipe, it is mixed thoroughly to form a homogeneous slurry.

2.4. Data acquisition system for continuous recording of inlet pressure of the slurry and sand-water flowrates

An automatic data acquisition system is installed in the computer in the control panel and this receives output signals from the pressure sensor, water flowmeter and sand conveyor rpm meter. The data acquisition software calibrates the received signals in terms of respective units of the measured parameters and records them. Values of the measured parameters are recorded every second. The data acquisition software has the capability to display time-variations of the parameters in graphical form in separate windows as well as record the data in an Excel file.

2.5. Experiments on the maximum area of filling from a single inlet pipe effect with varying slurry flowrate and sand concentration

A detailed experimentation on hydraulic gravity blind backfilling in the transparent test model using the complete experimental set-up, as outlined in the previous sections, was carried out using varying flowrates and sand concentrations. During these

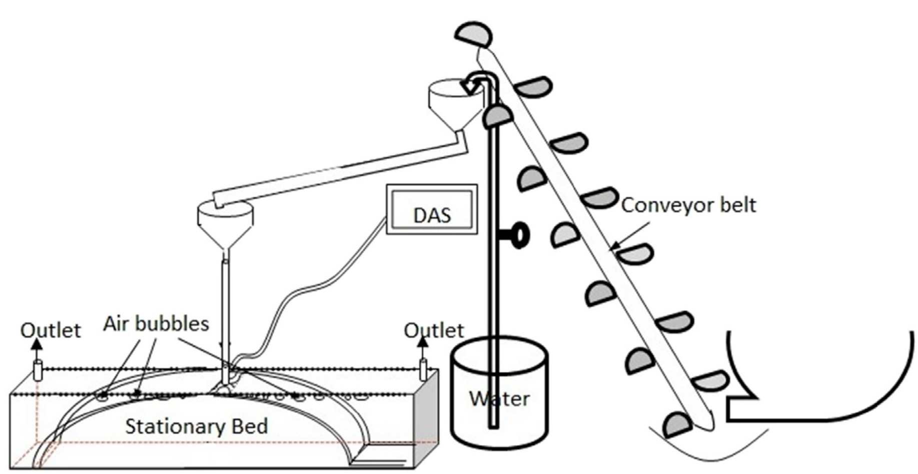

Fig. 1. Schematic diagram of the experimental set-up for gravity blind backfilling.

experiments a critical observation was made to understand the mechanism of the blind backfilling process carried out under the influence of gravity.

2.5.1. Mechanism of the blind backfilling process

Several experiments have been conducted in the transparent model with varying slurry flowrates and sand concentrations in order to critically inspect the filling process. As soon as slurry enters the large space of the model, the solid particles drop down by becoming separated from the water and they are deposited at the bottom. In this way a conical-shaped heap is formed at the bottom of the model directly below the inlet point and it continues to grow in size (Fig. 2a). As the height of the heap approaches the roof, the gap between the roof and the fill material at the top of the heap gradually reduces and the slurry velocity in this gap increases sufficiently enough to keep the solid particles in suspension and finally push them to the sloping edge of the heap of the deposited sand-bed. The slurry entering from the inlet hole impacts the top of the conical heap just under the bottom of the inlet hole. The turbulence created by the water helps the sand particles to stay in suspension and transports them through the small gap between the top of the conical heap and the underside of the top cover of the model and finally the particles continue to be deposited along the slope of the bed. In this way, the slanted surface of the deposited bed advances almost equally towards both the left and right side of the inlet hole of the model (Fig. 2b). It can be observed that between two and four channels exist at the beginning, but ultimately after some time the number of channels gradually reduces to one (Fig. 2c), thereby transporting solids to any one side of the model at one time. When the length of the deposited bed in any one direction increases to a point that the pressure required for transporting the solids along the long path becomes very high, this high pressure becomes sufficient enough to create a new path in another direction by puncturing through the top layer of the deposited sand bed. As a result, the older channel slowly gets blocked and the sand transport continues in a new path. Finally, the sand bed continues to grow in the direction of the new channel. In this way, the sand bed advances almost equally in both directions in an alternate

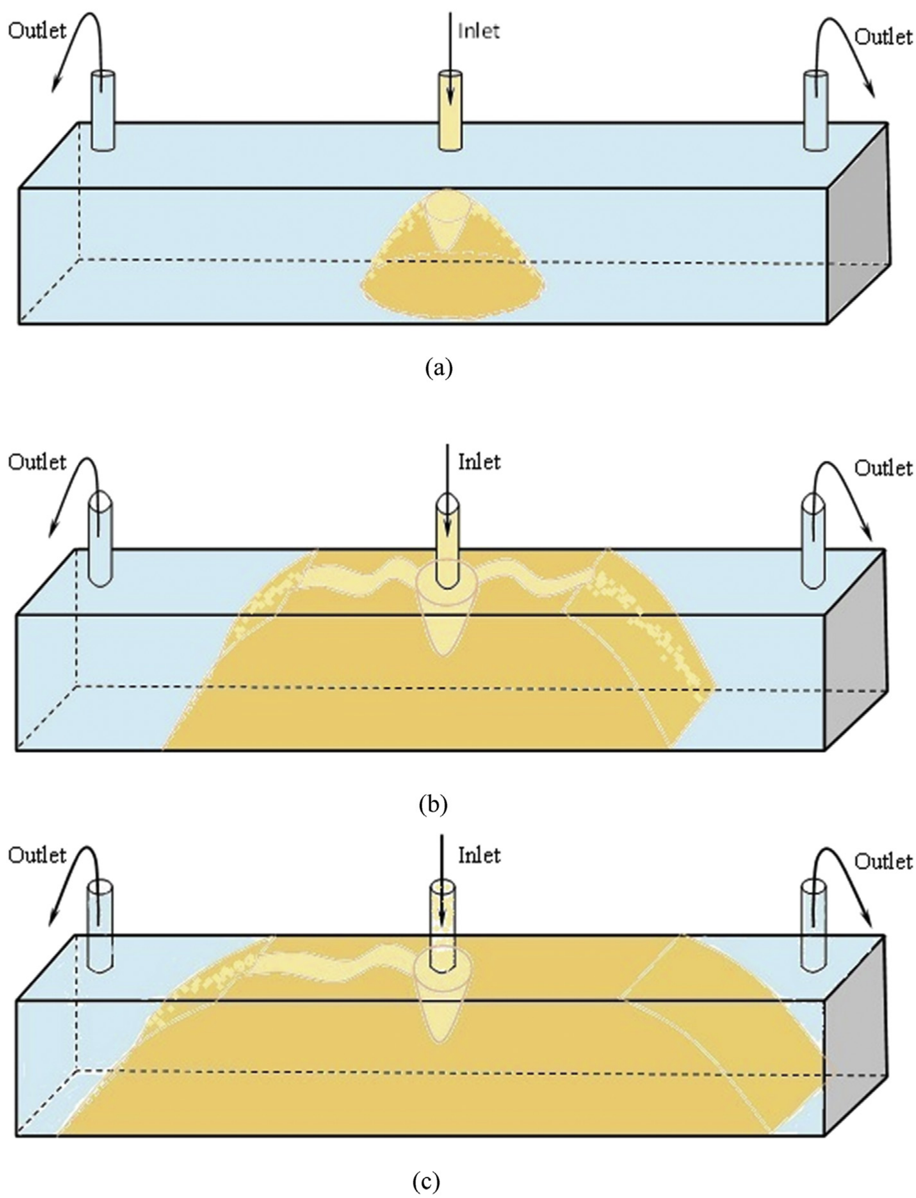

Fig. 2. Sequence of the filling process.

manner. Finally, jamming occurs when the maximum available slurry head in the model is not sufficient to puncture a new alternative flow path.

2.5.2. Maximum volume of sand throughput

In this experimental study slurry flowrates of 20, 25 and 30 L/min have been used and sand concentrations have been kept at 6%, 10% and 14% by volume. Therefore a total combination of nine experiments have been conducted and the volume filled by the deposited sand bed during each experiment is noted.

Table 1 depicts the flow of the deposited area of the sand bed at the end of each experiment. It may be observed that with a decrease in sand concentration, the area of filling increases. Also the area of filling can be increased by increasing the total slurry flowrate whilst keeping sand concentration constant. The filling of a large area from a single inlet hole is highly beneficial and also, in all likelihood, less costly since filling the same large area will require multiple inlet holes when smaller area of filling occurs with higher concentrations and/or lower flowrates. In future cases, the cost of drilling additional holes can make the total filling job slightly more costly than the first case.

3. Results

3.1. Pressure loss and bed advancement

The pressure loss data for different lengths of the channel is obtained from the continuously recorded inlet pressure data. A sample average of 20 pieces of pressure data is considered against the corresponding bed length data. In this way a number of data sets of average pressure loss and corresponding channel length were obtained for a particular flowrate and sand concentration. Fig. 3 shows the plots of this pressure loss data with bed advancement under different flow conditions. It can be observed from the best-fit line of the data that pressure drop increases as the bed advances because of the increase in the flow channel length. In each case of linear fit, it is visible that the slope of the line is always less than 1, which indicates that for every millimeter of progress of the channel, the additional pressure required to continue the flow is less than 1 Pa under the present flow conditions.

From Table 2, it can be seen that a variation of the slope is present for different flow conditions. To find a healthy condition for the filling process, S is plotted against $\frac{C}{Q^{1/4}}$ and the best-fit linear plot is shown in Fig. 4.

The relationship as obtained from the best-fit line is given in Equation (1)

$$S = 0.1304\frac{C}{Q^{1/4}}\ ,\ (\mathrm{Pa/mm}) \tag{1}$$

Q is in litre/min and C is the volumetric concentration of solid in slurry by percentage.

This implies that lower flow pressure loss can occur with an increase in flowrate or decrease in concentration, which can lead to a higher quantum of filling under a constant hydraulic head.

3.2. Pre-jamming indication parameter

Continuous recording of inlet pressures is accomplished by using an automatic data acquisition system. Fig. 5 shows a typical pressure-time curve recorded by the data acquisition system for the slurry flowrate of 25 lpm and 14% sand concentration.

The restless nature in the pre-jamming condition creates a special signature pattern which is visible to the human eye. It has been observed that the pressure fluctuation in the initial phase of filling is low when compared to the final phase of filling. The magnitude of pressure fluctuation and the exact shape of these curves differ when flowrates and sand concentrations are varied. In order to eliminate bias concerning the estimation of pre-jamming condition, a statistical analysis of pressure-signature curve is required to be performed in order to obtain a dependable pre-jamming indication parameter independent of flow conditions. This parameter may also be used to obtain an indication about the arrival of the pre-jamming phase in an automated backfilling system.

A closer inspection of pressure-time data revealed that the entire region of the pressure-time curve can broadly be divided into two sections:

- Healthy region,
- Unhealthy region.

In the healthy region, pressure fluctuations are low, whereas in the unhealthy region, pressure fluctuations are comparatively high. There is a strong possibility of jamming during the backfilling process in this unhealthy region and therefore it is essential to identify the arrival of this unhealthy phase in the pressure time curve for indicating a pre-jamming condition.

Several trials have been carried out to identify the initiation of this unhealthy, pre-jamming phase by determining different statistical parameters of the pressure-time data, such as variance ratio, log likelihood ratio, the ratio of the coefficient of variation (Thill, Hulk, & Stegman, 1983), etc. Out of all of the above trials, a reasonable success has been achieved from the analysis of the coefficient of variation.

The coefficient of variation is a dimensionless parameter and it measures the variability of a series of numbers independently of the unit of measurement used for these numbers. In the present study the Coefficient of Variation (CV) of a variable window size is used as the pre-jamming indication parameter. The analysis started after 210 s when the first 210 pieces of pressure data are recorded and the CV for these initial 210 pieces of pressure data, which is termed as 'CV_{210}', has been computed and recorded against a time value of '210 s'. The next analysis of CV is performed

Table 1
Area of filling for different flow.

Flowrate, Q (litre/min)	Concentration, C (volume %)	Maximum filled area (mm ^{2})
20	6	14,66,667
20	10	6,66,666
20	14	5,60,000
25	6	14,66,667
25	10	12,25,000
25	14	6,41,666
30	6	14,66,667
30	10	9,16,200
30	14	6,58,000

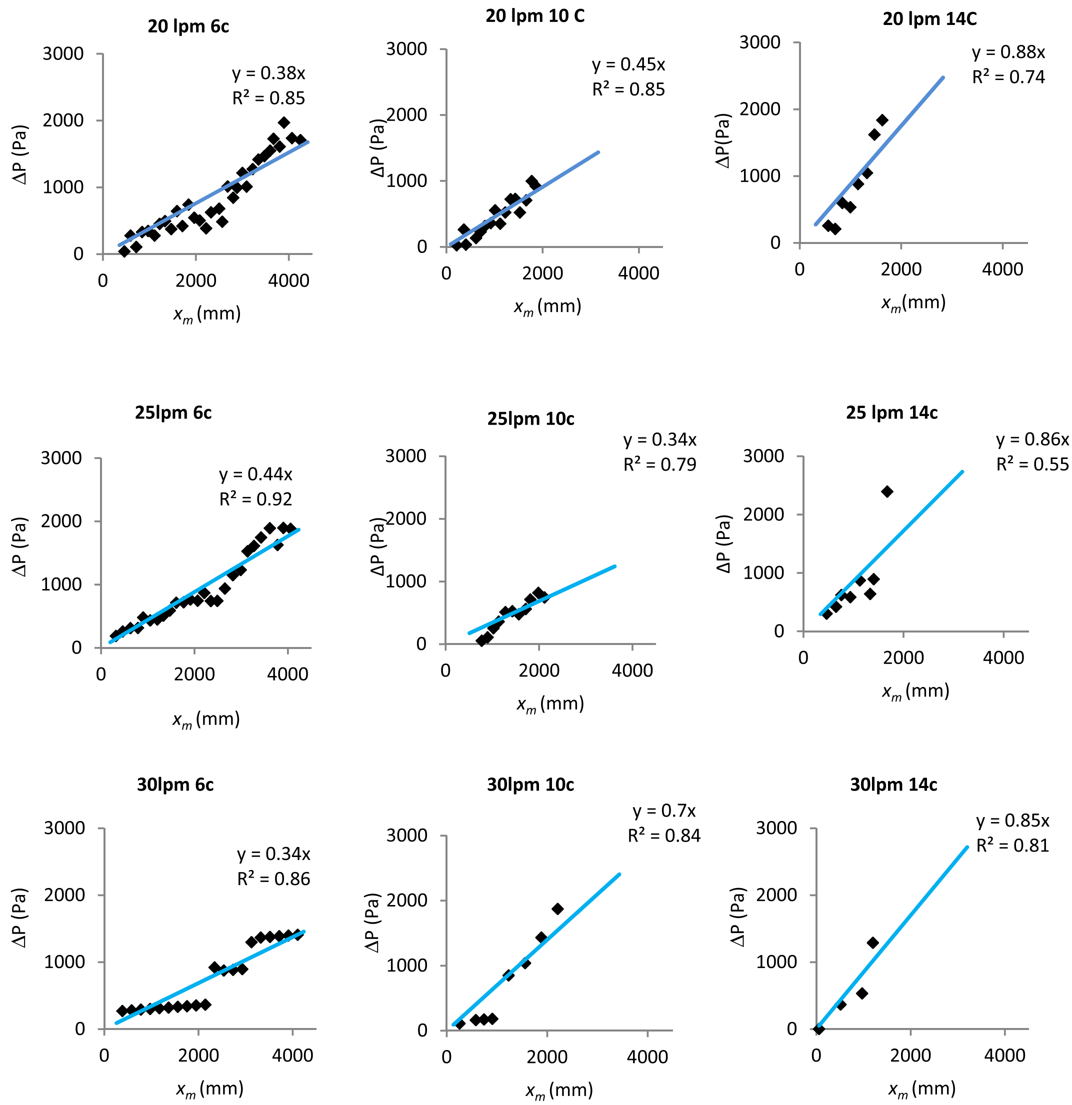

Fig. 3. Pressure loss curve with bed advancement for different flow conditions.

Table 2
Slope of best-fit line between pressure loss and bed advancement.

S. No.	Flowrate	Concentration	Slope (S) of the linear fit equation between pressure loss ΔP and bed advancement x_m	R^2
1	20	6	0.44	0.92
2	20	10	0.45	0.85
3	20	14	0.88	0.74
4	25	6	0.44	0.93
5	25	10	0.34	0.79
6	25	14	0.86	0.55
7	30	6	0.34	0.86
8	30	10	0.70	0.84
9	30	14	0.85	0.81

after 10 s when a total of 220 pieces of pressure data have been recorded and the second value of CV is computed and recorded against a time value of ‘220 s’. In this manner the CV values are computed for all of the recorded pressure data and marked against the corresponding time data at intervals of every 10 s until the occurrence of jamming. Figs. 6–8 represent the variation of CV against time for different slurry concentrations and flowrates. One critical observation of the CV values from these figures is that

Table 3 shows the percentage of filling that has taken place at the time when the CV value reaches 1.3 times the CV_{210}. It may be concluded from Table 3 that a minimum of 74% of the ‘maximum filled-up area’ could be achieved using a cut-off CV value of 1.3 times CV_{210}. Therefore the parameter ‘1.3 × CV_{210}’ can be used as a pre-jamming indication parameter applicable for all flow conditions adopted in the present study.

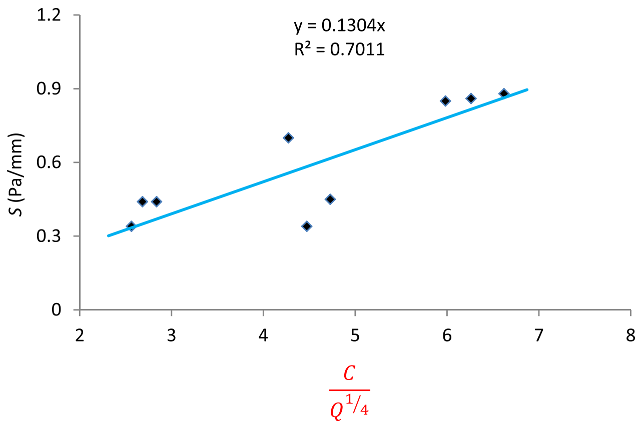

Fig. 4. Plot of slope S vs $\frac{C}{Q^{\frac{1}{4}}}$.

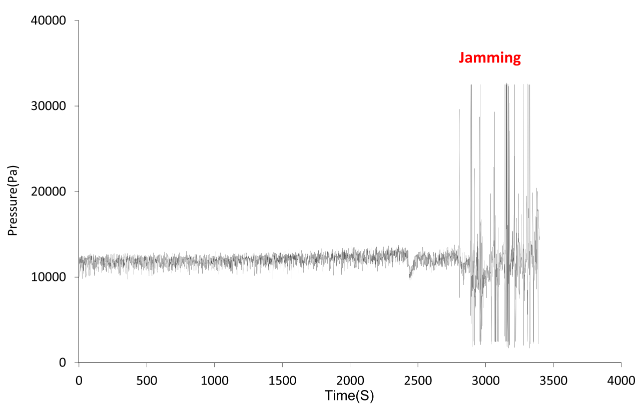

Fig. 5. Pressure-time curve recorded by the data acquisition system during the filling process.

4. Discussion

This experimental study was conducted in a transparent test model for a section of a straight underground mine gallery with varying slurry flowrates of 20, 25 and 30 lpm maintaining different sand concentration of 6%, 10% and 14% by volume. The process of blind backfilling was found to be more similar to sediment transportation on river beds rather than slurry transport through pipelines. The pressure signature obtained during the experiments is observed to have two distinct phases:

(i) Healthy/normal phase where the pressure fluctuations are low, and
(ii) Unhealthy/abnormal phase where the pressure fluctuations are severe in nature.

Pressure losses per unit length continuously increase with bed advancement and a time comes when the inlet pressure available for continuing slurry flow is not enough to overcome the pressure loss along the route or it is not sufficient enough to puncture a new, shorter flow path, then sudden jamming takes place (Pal, 2003). It is also revealed that higher slurry flowrate and low sand concentration can lead to the filling of a larger area from a single inlet borehole. The initial part of the pressure signature exhibits a healthy phase, whereas the latter part exhibits an unhealthy phase and sudden jamming is witnessed during this phase. A pre-jamming indication parameter of '1.3 × CV_{210}' is established for all the flow conditions under the present study. This pre-jamming indication parameter depicts the arrival of the pre-jamming phase of filling and ensures the completion of at least 74% of the maximum area of filling. For further continuation of filling from the same inlet hole, either the slurry flowrate must be increased whilst keeping the same sand concentration, or the sand concentration must be decreased whilst keeping the same slurry flowrate. In this manner the filling process can be prolonged long enough to fill a very large area from a single

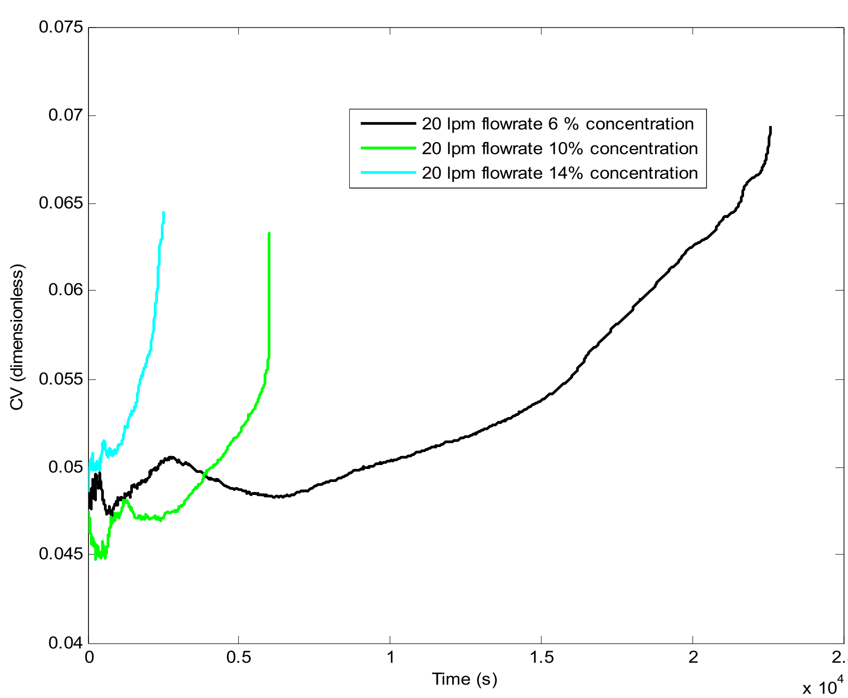

Fig. 6. Plots of the coefficient of variation of inlet pressure for a slurry flowrate of 20 lpm and varying concentration of 6%, 10% and 14%.

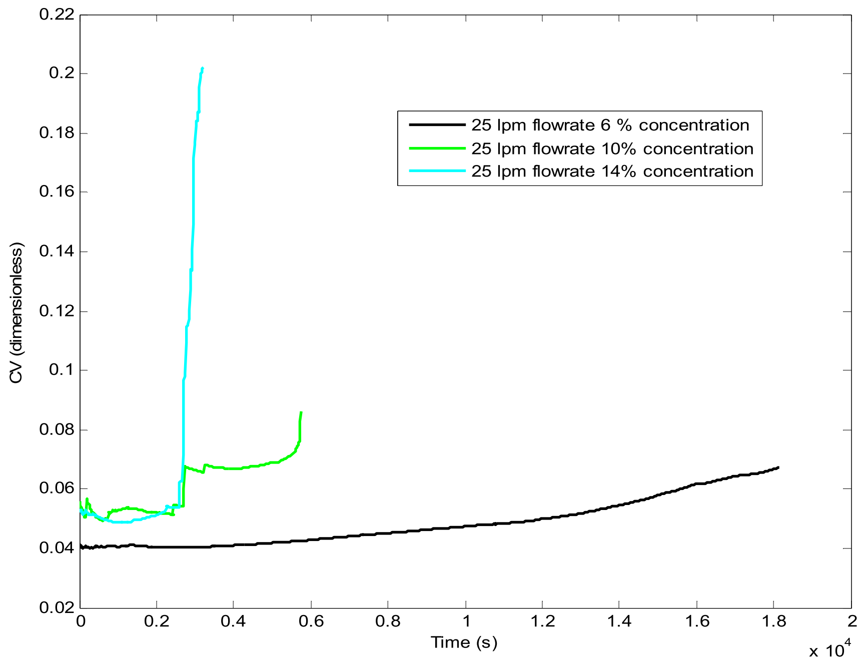

Fig. 7. Plots of the coefficient of variation of inlet pressure for a slurry flowrate of 25 lpm and varying concentration of 6%, 10% and 14%.

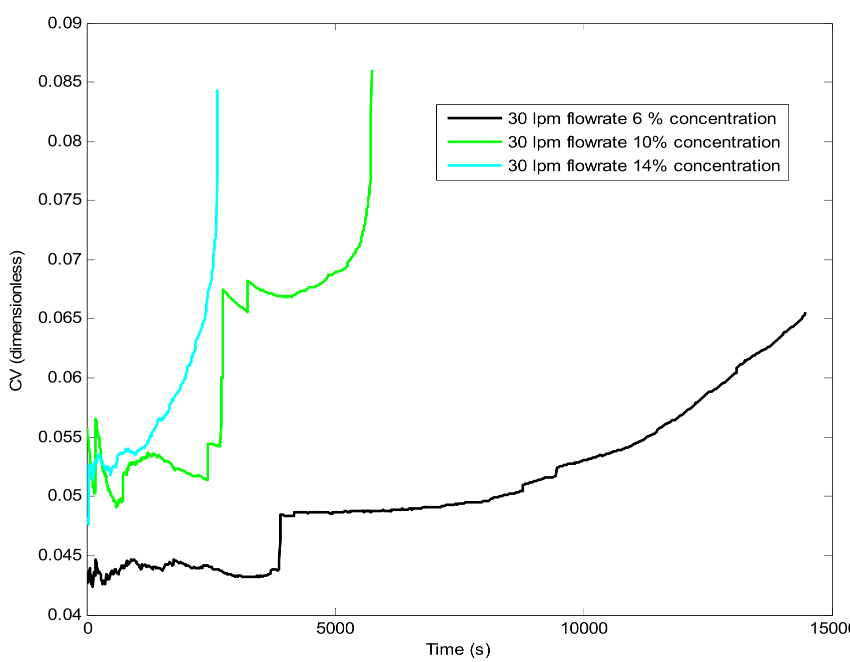

Fig. 8. Plots of the coefficient of variation of inlet pressure for a slurry flowrate of 30 lpm and varying concentration of 6%, 10% and 14%.

Table 3
Percentage filling of different experiments with 1.3 × coefficient of variation cut-off.

S. No.	Flowrate, Q (liters/min)	Concentration, C (%)	Percentage filled when '1.3 × CV_{210}' is used as cut off level
1	20	6	95
2	20	10	99
3	20	14	99
4	25	6	74
5	25	10	97
6	25	14	85
7	30	6	79
8	30	10	97
9	30	14	84

inlet point. Finally, the above exercise can possibly lead to an overall saving in the cost of filling by reduction of the number of boreholes drilled for the filling of a similar large area.

5. Conclusions

Occurrence of sudden pre-mature jamming is a major hurdle in ensuring the success of the gravity blind backfilling technique. Evaluation of a pre-jamming indication parameter is an important step towards the avoidance of sudden jamming during the filling process. Using the developed pre-jamming indication parameter one can avoid sudden jamming and fill additional space by altering the flowrate or sand concentration so as to lower the flow path resistance. The developed pre-jamming indication parameter for this model can be applied in field conditions of some abandoned mines to establish its efficacy in actual flow conditions during field application. Once established, the pre-jamming indication parameter can be applied in order to design an automated filling system which can maximize filling from a single feeding point by understanding the arrival of the pre-jamming phase and thereby taking necessary steps to avoid pre-matured jamming of the gravity backfilling process.

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