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Model Studies on the Efficiency of Gravity Blind Backfilling Method and Evaluation of a Pre-Jamming Indication Parameter

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Abstract: This paper discusses experimental research on a fully transparent scaled model of a section of a Bord and Pillar mine working carried out to study in detail the effectiveness of hydraulic blind backfilling as a solution to reduce subsidence problem above old underground water-logged coal mines. The relative influence of sand and water flow rates on the areas of filling from a single inlet point has been studied in detail. Automatic data acquisition system was installed in the model to continuously record the sand and water flow rates along with the inlet pressure of slurry at the entrance of the model. Pressure signature graphs have been plotted directly with the help of computer. Pressure signature analyses for various slurry flow rates and sand concentrations have been carried out. Investigation has also been carried out on evaluation of a pre-jamming indication parameter, which could be used for indication of the final stage of filling.

Keywords: *Gravity blind backfilling, slurry flow rates, sand concentration, data acquisition, pressure signature, pre-jamming indication*

1. Introduction

Subsidence from old abandoned underground water-logged coal mines has become an everyday concern of many people living in coal producing regions in India. 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 records of plans of such workings are generally not available and reliable. 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. Development of suitable methods to stabilize such areas had been neglected in the past. Some attempts had been made earlier for stabilization of old abandoned water-logged underground coal mines situated in Asansol and Raniganj in India using hydro-pneumatic or air-assisted gravity backfilling method. However, these methods have several drawbacks such as frequent jamming of injection hole, short-circuiting of compressed air and filling up of inadequate area from an injection hole, etc.

The effectiveness of simple gravity blind backfilling from a single borehole depends on parameters like slurry flow rate, sand concentration, etc. Experimental studies conducted on a scaled transparent Bord and Pillar mine model to find out the effects of variations in above parameters on the filling process are described here. The model was fabricated to study the process and establish the optimum parameters for achieving maximum sand filling through a single borehole.

1.1 Literature Review: Blind Backfilling

In abandoned mines, due to lack of access, backfill placement work must be done from the surface in a remote controlled fashion and this operation is known as blind backfilling. Placement mechanism-wise, blind backfilling can be classified into:

a) Pneumatic blind backfilling method, and
b) Hydraulic blind backfilling method.

1.1.1 Pneumatic Blind Backfilling

Pneumatic backfilling refers to a form of pneumatic conveying in which the backfill material, i.e. sand, is transported through a blind injection borehole into the mine voids and thrown all around the inlet zone. The water related 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 inlet injection bore hole [1].

1.1.2 Hydraulic Blind Backfilling

Walker [2] has elaborated the state-of-the-art techniques for backfilling abandoned mine voids by hydraulic flushing from single or multiple boreholes. Thill et. al [3] has illustrated the process of backfilling the underground, waterlogged mines using sand or crushed mine refuse. Ghosh et. al [4] and Saxena et. al [5, 6] have described the hydro-pneumatic method, a combination of hydraulic and pneumatic methods, as trial in Ramjivanpur colliery.

There are three variants of hydraulic blind backfilling namely, the simple gravity flushing, the air-assisted gravity flushing and the pumped slurry injection as described below.

1.1.2.1 Simple gravity method

This method is applied when the mine workings are inaccessible. With this approach, a slurry of backfill material is gravity fed through injection wells (either drilled bore holes or a mine shaft) into the mine until say, the particular well does not accept any additional backfill material. The quantity that can be injected down through a single well depends on the conditions of the mine workings underground, such as the inclination, height, and the proximity of pillars in the mine workings [7].

1.1.2.2 Air-assisted gravity method

This method is also known as hydro-pneumatic backfilling technique which had been developed and practiced in India [8]. In this system solid (sand)-water mixture is sent to fill underground voids through comparatively a larger diameter pipe. Compressed air is fed through a smaller diameter pipe placed inside the larger diameter pipe. Detailed research work in this area in the form of model studies had been conducted at I.I.T. Kharagpur, India [9].

1.1.2.3 Pumped Slurry method

Pumped slurry injection as described by Colaizzi et. al [10] is similar to simple gravity blind backfilling except that the slurry is pumped down through a well rather than injected by gravity. In this case, solid particles settle down near the borehole when the slurry is first delivered. Thereafter, the velocity of the injected slurry drops as it enters the mine workings. As more material is injected, the fluid velocity increases in the mine workings and the solid materials are transported further from the borehole. But most of the time filling through the on-going bore holes have to be abandoned due to choking or jamming of the injection pipe and or the roadway.

1.2 Laboratory Scale Mine Model

Two fully transparent 19 mm thick, perspex sheets of 2.4 m × 1.8 m size have been used to construct the scaled mine model to simulate a part of a Bord & Pillar workings of a coal mine as shown in figure 1. 72 wooden pillars of square and rectangular in shape, with roughened surface, have been placed in a grid pattern, in between the top and the bottom of the perspex sheets, representing the roof and floor of the coal mine. The transparent perspex sheet mine models have been fabricated with complete water-tight joints. Flanged end-sheets made of perpex have been used to close the two opposite ends. The flanged arrangements enabled easy removal of the filled sand at the end of each experiment. The pillars have been bolted through in order to join them with the top and the bottom sheets and sufficient tension has been applied to prevent water leakage from the top and bottom of the pillars. The pillars placed in the mine models are of two different sizes and shapes. Half of them are of 180 mm × 180 mm square pillars, simulating 45% extraction and the other half are of 100 mm × 125 mm rectangular pillars, simulating 75% extraction. All pillars have a common height of 125 mm. Several interchangeable inlet holes have been provided to allow injection of slurry from centers, ends and from some other intermediate positions of the model.

Figure 1: *Photograph of the experimental set-up used for gravity blind backfilling*

The entire model is mounted on a strong wooden frame which in turn is mounted on a centrally pivoted steel frame and supported by four telescopic pillars grouted in the floor at four corners. This arrangement can allow easy tilting of the heavy mine model on any convenient angle up to 7.5^0, representing the dip of the coal seam. Apart from the inlet injection pipe and outlet delivery pipes (to remove water from waterlogged mine) a few 2 m high outlets simulating open boreholes (for air purging) are also placed at different locations.

Metered amounts of water and sand are mixed in the mixing tank from which the thoroughly mixed slurry is allowed to enter the model by gravity through a 25 mm bore transparent perspex tube. After deposition of the sand, water is allowed to exit the model by overflowing from two transparent outlet pipes located at the other end of the model, and finally collected in a large storage tank from where the collected water is recirculated using a small pump.

1.3 Direction of Slurry Transportation in Gravity Blind Backfilling

Several experiments were designed and conducted before finalizing the decision on the direction of filling, i.e. whether filling is to be carried out from rise to dip or dip to rise. The experiments indicated that filling from dip to rise produced higher quantity of sand throughput when compared with the same from rise to dip, keeping the other conditions same. Moreover, it was noticed that during filling from rise to dip, the filled-up portion did not touch the roof of the models in all places. Some amount of void remained and persisted between the top of the sand-deposit and the roof of the model. This indicated a lower packing efficiency for filling from rise to dip. Therefore, further experiments on filling were performed from dip to rise in transparent water-logged mine model.

1.4 Filling Process

When the slurry first gravitates down to the open void of the model through the inlet tube, its velocity decreases rapidly and solid particles drop down from the slurry towards the bottom of the model and form a conical-shaped heap on the floor as shown in figure 2. As the height of the heap approaches the roof, the narrowing of the gap between the roof and the fill material causes an increase in the velocity of slurry. The impact of the input slurry forms a crater at the top of the conical heap just under the bottom of inlet hole. The turbulence created by the water helps the sand particles to be in suspension and transports them through the narrowed gap between the top of the truncated conical heap and the underside of the top cover of the model, and finally the particles get deposited along the slope of the conical heap. In this way, the slanted surface of the conical heap advances almost equally in all directions from the inlet pipe.

The channel flow configuration starts after the deposited sand-mound grows further in the form of a top-truncated conical heap with a central crater. It has been observed that at the beginning, four to eight small channels exist, but ultimately after some time, only one, two or at most three channels continued. When this sand-transport along the routed channels continues for some time, the pressure within the channel increases sufficiently to cause a puncture at the top part of the deposited sand-mound, and a new flow-channel is created to deposit sand in a new area of the model. As the new channel starts, the old channel gets plugged with sand. This meandering nature of the channels continues through a sequence of depositions and breakthroughs (i.e. puncturing of a new route). Finally, a diamond-shaped sand deposit is built up extending almost equally along both strike directions and slightly less in the rise direction. This phenomenon of transport of sand is similar to the sediment transport phenomenon in open channels/ rivers. At present, however, sediment transportation depends mainly upon empirical relationships, often not too certain, and on trial and error experience. A wide gap exists between the relatively few known principles and their applications.

1.5 Tests on Repeatability of Experiments

In order to test the repeatability of filling process conducted on the model, several trials were initially carried out by repeating the same experiment with fixed flow rates and concentrations. From the results, it was observed that for the same flow rate and concentrations, the total sand throughput from single inlet was nearly the same with an approximate variation up to 9%. This indicated that the experimentation process conducted in the present study was repeatable within an accuracy of ± 5%.

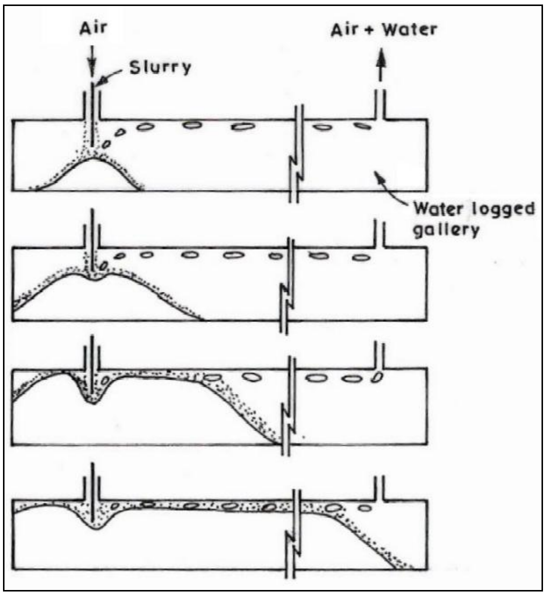

Figure 2: *Sequence of the filling process*

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1.6 Effect of Slurry Flow Rate and Sand Concentration on Maximum Area of Filling from a Single Inlet Pipe

Different experiments with varying slurry flow rate and sand concentration were conducted to determine maximum area of filling from a single inlet pipe with the model kept at 7.5º inclination. The slurry was fed into the model through an inlet pipe of 25 mm diameter located towards the bottom end of the model. It is observed that with decrease in sand concentration in slurry, the area of filling from the single inlet pipe is increased. However, the area of filling from single inlet pipe can also be increased by increasing the total slurry flow rate keeping sand concentration at a fixed value. The entire model could nearly be filled up when experiments with 25 and 30 l/ min of slurry flow rate were conducted with 6% concentration of sand. With 9% sand concentration using above flow rates, the model was nearly filled up to its 90% capacity. Thus, smooth and efficient filling of the experimental model can be carried out by keeping the flow rates in the range of 25 to 30 l/ min and concentration at 9%. Higher concentration can be chosen to expedite the filling process.

1.7 Effect of Model Inclination on the Filling Process

Several experiments on model filling were carried out with flow rate varying from 20 to 30 l/ min and sand concentration varying from 6 to 15% for 7.5º and 3.5º model inclinations. Figure 3 shows a comparison of the results obtained for sand throughput for 7.5º and 3.5º model inclinations.

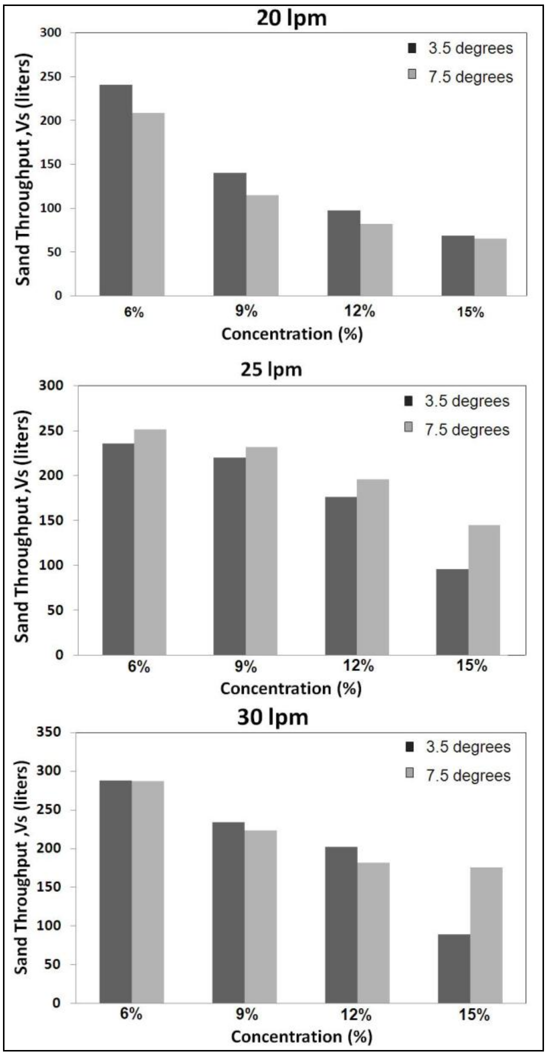


Figure 3: *Comparison of sand throughput at 7.5º and 3.5º model inclinations*

It may be seen from figure 3 that at a flatter inclination, there is marginal change in sand throughput especially at lower concentration. The figure also shows that, at 20 to 30 l/ min flow rate and 6 – 12% concentrations, there is marginal difference in the sand throughput in models of 3.5º and 7.5º inclinations. But there is an exception observed in sand filling at 3.5 º model inclinations. In the said model at 15% concentration, and at 25 and 30 l/ min flow rates, the quantum of sand filling was observed to be sufficiently lower. This suggests that greater sand throughput capacity can be achieved at higher model inclination due to higher buoyant force of the large quantity of entrained air in the slurry mixing cone during filling at higher concentration.

1.8 Pressure Signature Variation Study

Continuous recording of inlet pressures was made using automatic data acquisition system as shown in figure 4. Side by side video recordings were made and high-resolution images at high speeds were also taken of the experiments for explanation of the pressure signature patterns in terms of changes in physical phenomena during the filling process. The pressure signature is found to have two distinct phases:

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

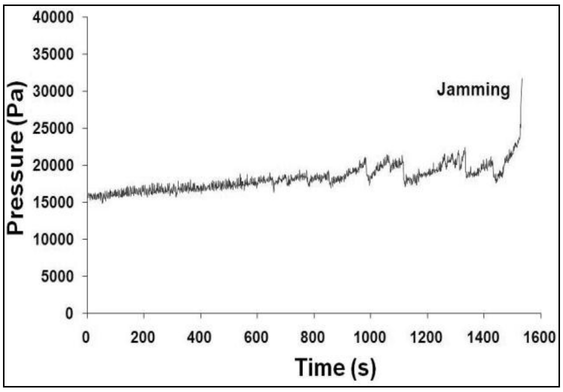


Figure 4: *Pressure-time curve recorded by the data acquisition system during the filling process*

The initial part exhibits a healthy phase, whereas the latter part exhibits an unhealthy phase. Pressure signature graphs were plotted directly with the help of computer in all experiments and analyzed to arrive at a pre-jamming indication parameter which can be used to indicate the final stage of filling.

1.8.1 Analysis of Pressure-Signatures

Computations were made to identify the changeover point from healthy region to the unhealthy region. For this purpose, the pressure signature curve was divided into two parts with the dividing line positioned at t = 10 s. The variance of the pressure values in the left part (σ_1) of the dividing line and that in the right part (σ_2) of the dividing line were calculated. Next, the ratio σ_1/σ_2 was calculated and stored. The dividing line was then shifted by another 10 seconds and the above procedure was followed. Figure 5 shows a plot of σ ratio against the different positions of the dividing line. It was expected that with the sudden change from healthy to unhealthy region, there would be a discontinuity in the curve or sudden steep increase in the variance ratio. But this nature of sudden rise in the value of variance ratio could not be observed on many occasions and, therefore, this particular method was considered to be insufficient.

Another such trial was made where the σ_1 part was replaced by coefficient of variation CV_1 and σ_2 by CV_2. This modification was done with a view to make the graph scale independent. The graph plotted between CV_1 and CV_2 in a similar fashion as above, however, showed its complete inability to distinguish between healthy and unhealthy components of pressure signature.

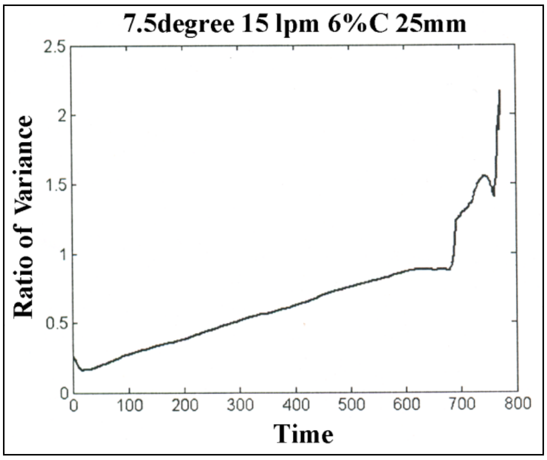


Figure 5: *Variance-ratio curve for detection of the changeover from healthy to unhealthy region*

Next, instead of dividing the entire pressure signature curve into two parts, a fixed window of *n*/10 size was used for sigma ratio analysis following the first procedure, *n* being the total number of data points in pressure signature curve. Figure 6 shows one such a typical variance ratio curve with window size of *n*/10. However, in many cases of such pressure signature analysis, no minima could be identified. To improve the accuracy of detection, the size of window was changed from *n*/10 to *n*/5 and then to some fixed numbers like 50, 100, 200 and 500. None of the above trials could lead to a successful and fool-proof procedure for detection of unhealthy/ final phase of filling. In another attempt, the log-likelihood ratio of the left half and right half of the window was plotted to generate a pre-jamming indication parameter. But this attempt also was not successful.

Next, a fixed window of 200 data points was chosen for future trials without any division in the middle. The variance parameter for the entire window was chosen to be the only indicator for pressure fluctuations. Then, this fixed window was moved on through the whole experimental data set. To remove the trends of the pressure curve, a linear regression line was drawn on each of the pressure time curves; next, a residual data set was computed from this trend line and the original pressure data as shown in figure 7. The variance of this residual data set was subsequently calculated for a fixed window size of 200 points. The window was moved till the end of the data set to obtain the curve of 'time vs variance of the residual'. Figure 8 shows two such graphs for 25 l/ min of slurry flow rate and sand concentrations of 6% and 12%. It may be noted from these curves that the abrupt rise in variance values occur near the end of the data set. Thus, a cut-off level generated based on the multiples of average initial variance (σ) values can be used to indicate the pre-jamming condition. In this research, the indicator is finally chosen to be 4σ for 6%, 9% and 12% concentration and 1.75σ for 15% concentration.

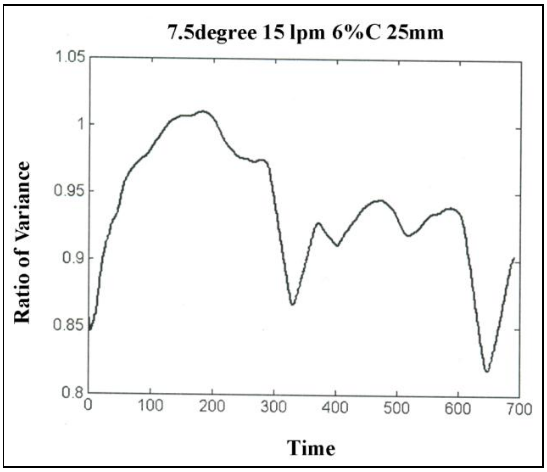


Figure 6: *Variance-ratio curve for detection of unhealthy region of pressure signature at fixed window size*

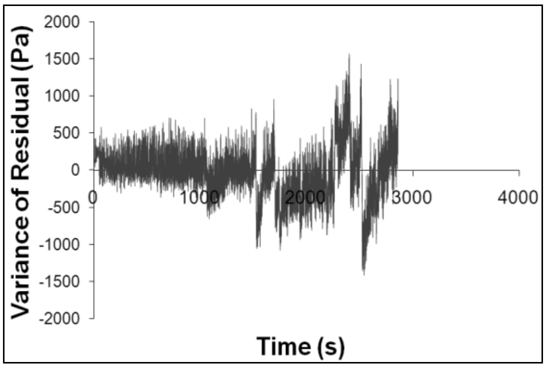


Figure 7: *Curve of time against residual pressure obtained after trend removal*

1.9 Conclusion

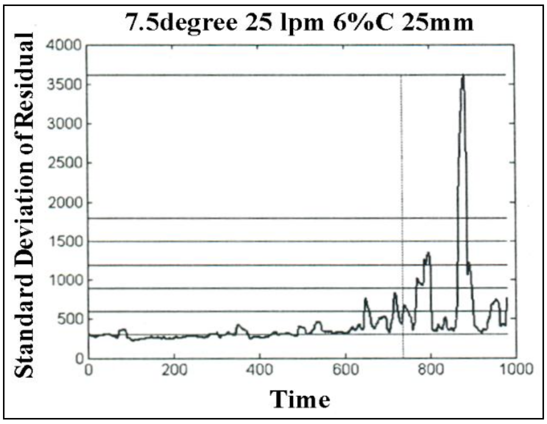
The present experimental study was conducted in a transparent test model for a section of a Bord and Pillar mine with varying slurry flow rates of 15, 20, 25 and 30 l/ min and sand concentration of 6%, 9%, 12% and 15% by volume. On the basis of the experimental results obtained, the following conclusions can be drawn:

- The process of blind backfilling is found to be similar to sediment transportation on river beds. The sand movement occurred along self-formed meandering channels.
- Initial experiments showed that filling from dip to raise produced 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 borehole.

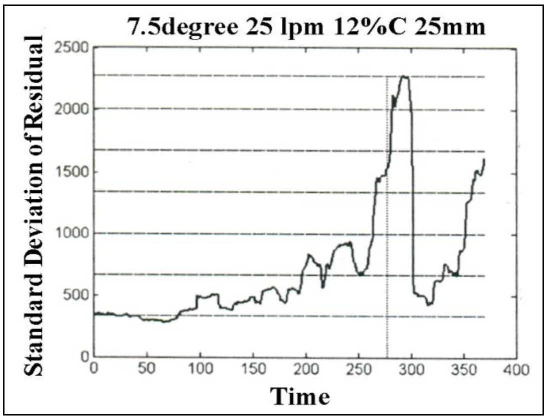
- The gravity blind backfilling method was found to be efficient, i.e. it was able to fill-up a large area of the model from a single inlet point when the sand concentrations were in the range of 6% and 9%, and the slurry flow rates were kept between 20 and 30 l/ min.
- The pressure signature obtained 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.

  The initial part of the pressure signature exhibits a healthy phase, whereas the latter part exhibits an unhealthy phase. Several trials were given to identify this unhealthy, pre-jamming phase by analyzing the variance ratio, log likelihood ratio and the ratio of coefficient of variation between the left and right halves of a moving window along the pressure-time curve. In all of the above trials, partial success could be achieved.



(a)



(b)

Figure 8: *Graphs of variance of residual at 25 l/ min flow rate for (a) 6 and (b) 12% concentrations*

Finally, a residual pressure-time curve was obtained by removing the trend effect from actual pressure-time curve. The analysis of variance of this residual pressure-time curve in a window size of 200 data points showed sharp peaks of high amplitudes during the final phase of filling. The amplitudes of these sharp and high peaks were then compared with the variance value (σ) of the initial 50 to 100 points in the residual pressure-time curve. This operation helped to evaluate a cut-off variance level for the unhealthy phase, which could be used as a pre-jamming indicator.

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