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Experimental studies on stabilization techniques for ground over abandoned subsurface excavations

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Abstract: Blind hydraulic backfilling is a commonly used technique for subsidence control of the strata over unapproachable waterlogged underground excavations. In this investigation model studies on all the three variants of this technique, namely, hydro-pneumatic or air-assisted gravity backfilling, pumped-slurry backfilling and simple gravity backfilling, have been carried out in fully transparent models of the underground excavations.

On examination of the filling process, it was revealed that in all the three cases, the basic process of filling occurs by sand transport along one or more meandering channels. The relative influence of sand, water and air flow rates on the area of filling from a single inlet point and the hydraulic pressure loss per unit length were studied in details. In hydro-pneumatic backfilling process, the air bubbles while moving upward through the meandering channels provide an additional buoyant force over and above the available hydraulic head. In this way the area of filling from a single borehole may be quite large even at small flow rates of water. During actual field implementation the injected air, if not released completely from the rise side holes, may cause troubles by way of creating potholes on the surface. The pumped-slurry technique has shown its capability of filling a relatively larger area at faster rate, especially when high-volume, low-pressure method was selected. But simple gravity filling was also found to be equally effective method as slurry pumping, especially when flow rates were high. In the second and third method discussed above, examination of variations of injection pressure was also done and its relation with physical phenomenon was also attempted. Some empirical relationships were also developed using multivariate regression with a view to help the practicing engineers.

1. Introduction

Surface subsidence is often the consequence of underground operation. Removal of mineral from beneath the earth's surface produces voids and the weight of the overburden gets re-distributed. For extraction of minerals from shallow depth, the voids must be filled by stowing. But in earlier days most coal seams of India lying at a very shallow depth were partially extracted using bord and pillar system. Correct records of plans of such workings are generally not available. Over the years, the strength pillars left as support was severally deteriorated and frequent collapses of these pillars endanger some important surface structures and properties. It is estimated that there is still danger of subsidence in more than 60 localities in Jharia and Ranigunj coalfields alone (Saxena N.C. et al, 1989). Most of these underground working are waterlogged and unapproachable and the most suitable alternative for ground stabilization is the blind backfilling technique.

2. Blind backfilling methods

Blind backfilling operations are conducted from the surface by connecting the underground workings through several boreholes. The method does not require personnel or equipment underground. The blind backfilling techniques are grouped into two categories, namely, point support method and areal backfilling method.

Point support method

In this method small volume of inexpensive fill material is mixed with little water and binding agent and the mixture is sent underground at high solid concentration through boreholes by gravity. It requires a large number of boreholes at close spacing for filling a relatively smaller area. Monitoring often may be accomplished by borehole cameras. This method is useful only to protect important individual structures on the surface. Depending upon conditions underground, such as, dip of the workings, their height, the proximity of pillars etc., the maximum amount of material that can be injected varies from 15 to 1500 m^3.

Areal backfilling

Areal backfilling is commonly done by sending solids like sand, fly ash, or mine refuse underground through a large diameter borehole by pneumatic and hydraulic means, the latter being most popular. The hydraulic backfilling has two variants as discussed below.

Hydro-pneumatic backfilling technique

This method is developed and practised 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, gravel, crushed stone or washery rejects.

Pumped slurry backfilling technique

This method was first demonstrated in 1970 at Rock Springs, USA (Colaizzi, R. H. et al, 1981), and has been used extensively in the past 10 years (Thill R. E. et al, 1993). Backfilling solids are mixed with water and sent underground through boreholes at high pressures using large capacity slurry pumps. The usual concentrations of solids are low and are in the range of 11 to 21% by weight. Water for the slurry is provided by submersible pumps drawing water from boreholes located far away from the injection or feeder borehole. Usual pipe sizes are of 150 to 355 mm diameter and releases slurry at a velocity varying from 3 to 14 m/s. The collar of the feeder borehole is usually encased and cemented up to several metres above the mine roof, so that a positive pressure can be exerted on the slurry at the inlet zone.

3. Experimental Studies

To study the various aspects of filling, two transparent models of sections of bord and pillar mines were fabricated and influence of different parameters on the filling efficiency was investigated using both hydro-pneumatic and pumped slurry backfilling technique. In addition, the efficacy of the third method called gravity backfilling was also investigated. The last method requires least equipment and surface arrangements and hence may prove to be quite simple and cost effective.

The filling process

In all the three methods the basic sequence of filling process is similar. Fig. 1 shows the sequence of filling process in hydro-pneumatic method. When fill material is introduced into the water-logged models through a feeder pipe, the sand particles drop down on the floor of the model owing to enormous decrease in velocity of flow inside

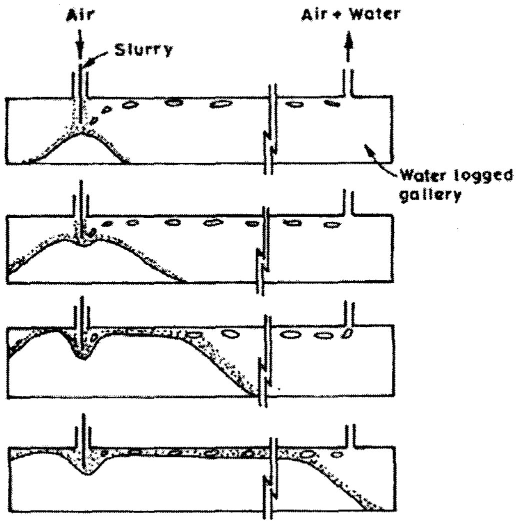

Fig. 1. The sequence of filling process for hydro-pneumatic method.

the large void portion of the model. Settled sand piles up into a conical heap, which grows in size and tries to touch the top plate of the model, thereby attempting to choke the flow. At the centre of this heap an inverted conical crater is formed due to erosive impact of the entering jet. In hydro-pneumatic method air bubbles released in this portion creates additional turbulence which further assists the suspension of solids in water.

With further increase in size of the deposited sand bed the area of flow for the slurry decreases and its velocity at the entrance region increases. Due to the high velocity, the sand particles are now not allowed to settle and are pushed to the edge of the deposit. In hydro-pneumatic method, the released air in the form of rapidly fired bubbles moves with a high velocity between the roof of the model and sand heap. This also helps the slurry flow by creating an additional thrust for movement of sand to the edge of the deposit.

At a larger stage, flow of sand-water takes place through one or more channels created through the top layer of the deposited sand bed. The sand-water slurry now moves along these channels and finally sand gets deposited at the end of the channels. When the length of one channel becomes long enough a breakthrough occurs and an alternate channel of shorter length is created along the top layer of sand bed in a different direction. In this way the channel keeps on changing its path frequently and deposits sand all around. Thus the deposited sand bed advances all around maintaining a slope angle of nearly 33^0 at the edge. It was possible to completely fill both the small and big models from one feeder pipe with a slurry flow rate of about 20 litres per minute. But the volumetric sand concentration in the slurry had to be kept at a low value of about 10%. This nature of ever changing direction of these channels has earned them the name 'meandering channels'. In other two methods the filling process remains same excepting the presence of air-bubbles. Fig. 2 shows the different filling routes or flow paths during of the intermediate filling stage of the smaller model by hydro-pneumatic method.

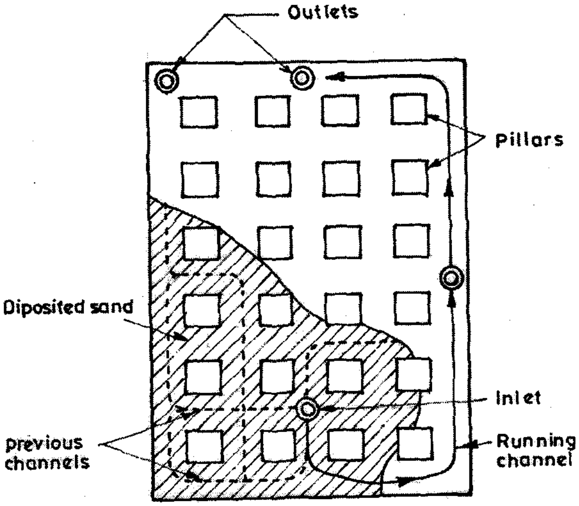

Fig. 2. Different flow paths during filling of the smaller model.

4. Some Critical Observations on the Sand Transport Process

The entertainment, transport and deposition of sand particles depend partially on the properties like mean grain size of sand particles, fall velocity of sand particles in water, sand concentration of slurry, volume flow rate of slurry and its dynamic viscosity. The following principles of sand filling process were noted:

a. The total sand movement is the sum of two categories -
   i) Bed load movement
   It is the rate of movement of the sand particles along the bottom of the channel by the process of rolling, sliding, and/or hopping. In the hopping process the flow turbulence picks up the sand

particles from the bed and then drops back to the bed. The hopping process is usually associated with higher sand concentrations and high flow rates of slurry.

ii) Suspended load movement

It is the rate of movement of sand particles that are supported by the turbulent motion in the stream flow. There is continuous exchange of particles between these two layers and the same sand particles can be transported sometimes as bed load. For simplicity, the suspended load movement of sand is taken as the rate of movement of sand particles between the top of the bed load-layer and water surface.

b. When the inlet water jet is impinged onto the deposited sand bed, the depth of scour is solely dependent upon the mass flow rate of jet and the fall velocity of sand particles..

c. When the inlet jet contains sand water slurry the scour hole will be filled up until equilibrium is established. Under equilibrium state the rate of sand inlet equals the rate of bed load transport.

d. If the momentary transport capacity of the flow in any locality is greater than it is actual load capacity, additional scouring will occur and thus more material is entrained. On the other hand if the momentary capacity is less than its actual load capacity, a portion of the bed load will be deposited.

e. Sand particles are moved by the flow whenever the magnitudes of the instantaneous fluid force acting on sediment particles exceeds the resistance force against the motion. The particles may be moved by the flow for a short period and then rest on the steam bed for a relatively long time.

f. For a given sand concentration, number of simultaneously flowing channels increases with the increase in slurry flow rate.

g. Each rate of flow has a meandering pattern of its own and, the radius and cross-sectional area of the bends in flow channels increases with flow rate.

h. It is the bed load fraction of the total load, moving along the bed and depositing in layers, gets directly involved in the meandering process. However, the suspended load indicates the transport capacity of channel. For higher transport rates, grater turbulence causes higher amount of suspended load.

i. When a meandering channel reaches any one side of the roadway, the side walls being highly resistant to erosion, the unbalanced erosive power causes the channels to be deeper, thereby increasing its mean hydraulic radius. So, deeper and straight channels have least path resistance and hence, the path remains straight for a longer duration.

5. Flow Velocity and Hydraulic Pressure Loss

Transport of sand along the channel bed is due to the process of rolling, sliding and hoping or saltation. With low flow rates just above the incipient motion condition, bed load motions are intermittent and there is continuous exchange of sand particles between moving bed-load and suspended load. Although there is no generally accepted bed load equation for channel beds, several bed load equation for sand bed streams like, Einstien's bed load equation, Mayer-Peter and Mullar equation, Bagnold bed load equation etc. are very popular in sediment transport along river beds.

The total flow resistance can be separated into skin-frictional and form resistance. Components from both field and laboratory data of channel flow the Darcy-Weisbach form resistance factor, is directly related to bed load transport rate. Fig. 3 shows the relationship between hydraulic pressure loss with sand transport rate for hydro-pneumatic method and Fig. 4 indicates the same for pumped-slurry backfilling method. It may be seen that the hydraulic pressure loss per unit length of channel increases linearly with the sand transport rate for both hydro-pneumatic method and slurry pumping method. Two important observations can be made from these figures:

The increase in total volume flow rate of slurry reduces the hydraulic pressure loss. This is in contradiction with the general concept of pipe flow, where unit pressure loss will increase in total volume flow rate of slurry through the pipe. Thus, on critical observation it was revealed that with increase in total slurry flow rate the area of flow increases through bed scouring. These assumptions were supported by the fact that the measured average velocity of slurry in the channel also decreases with higher slurry flow rate. Hence with lower velocity through larger area of flow the hydraulic pressure loss reduces.

The introduction of air bubbles in the meandering channels reduces the hydraulic pressure loss due to the assistance of buoyant force of air bubbles in sand movement along the channel. Best results were obtained by adjusting the air flow rate to the bullet flow domain. Fig. 5 shows the variation of hydraulic pressure loss with increase in air

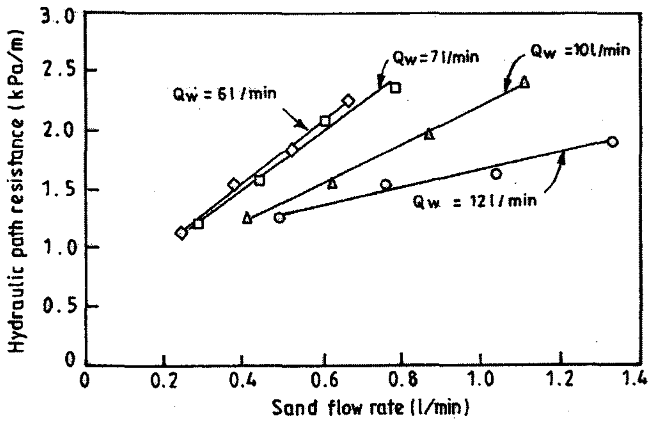

Fig. 3. Variation of hydraulic pressure loss with sand transport rate for hydro-pneumatic method.

to water ratio. The approximate ratio of air to water flow rates which optimises the unit hydraulic pressure loss is in the range 1.8 to 2 as indicated by the flattening of the hydraulic pressure loss values in this zone. It may be recommended that at 7% sand concentration the ratio of air to water should be kept at 1:1 because at such small channel lengths introduction of higher quantity of air may cause its backflow through the inlet pipe. At later stages of filling the air to water ratio may be increased gradually and at final stage a ratio of 2:1 should be sufficient. In field trials the above recommendations have produced a remarkable increase in the maximum amount of sand throughput from a single borehole.

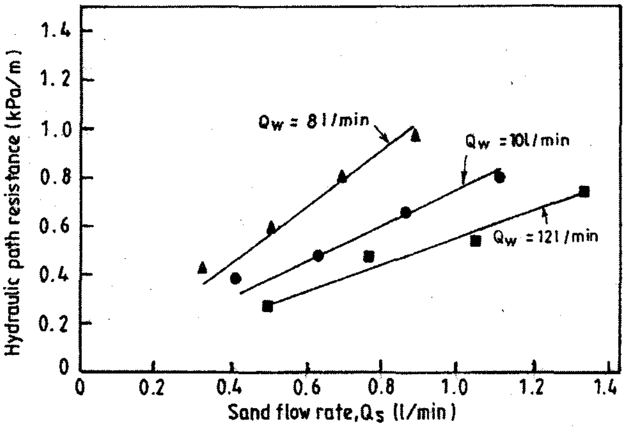

Fig. 4. Variation of hydraulic pressure loss with sand transport rate for pumped-slurry method.

The peak pressure for required for puncturing a new route is 1.5 to 2 times the average pressure value during initial phase of filling, but it went up to more than 3 at later stages of filling. In such case the reduction in sand concentration can prolong the life of the borehole and can maximize the total amount of sand throughput. The maximum area coverage during filling from one borehole was found to be dependent on the slurry flow rate and sand concentration. For the present size of the models it was computed from principles of similitude that the total slurry flow rate should not be more than 20 litres per minute.

With slurry pumping method the maximum allowable volumetric sand concentration for a smooth, undisturbed filling was decided to be 10%. The maximum area coverage A in m^2 for a given slurry flow rate Q_m in litres/ minute are related as

$$A = 0.066 Q_m^{1.3} \tag{1}$$

The approximate shape of the deposit is a scallop having longer length in the rise side of the inlet. Equation 1 may be used by the practicing engineers to actually decide upon the spacing between feeder boreholes for a given capacity of the slurry pump.

The volume of sand V_s in litres that may be sent underground through a single inlet is dependent on the water flow rate Q_m in litres/minute for a fixed concentration. For 10% sand concentration V_s and Q_w were found to be related as

$$V_s = 2.8 Q_w^{1.8} \tag{2}$$

Equation 2 seems to be valid only in the small size scaled models and its validity in the field application is yet to be verified.

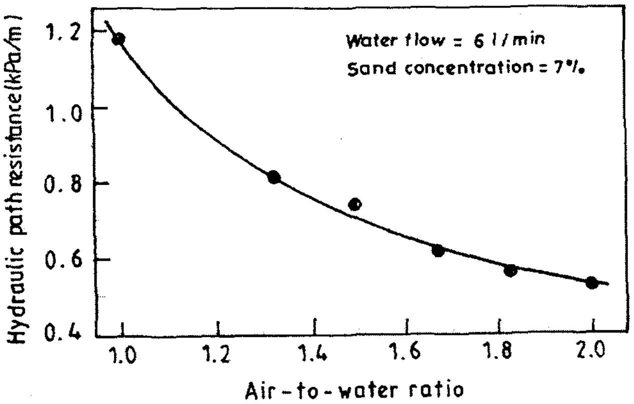

Fig. 5. Influence of air-water ratio on the hydraulic pressure loss in hydro-pneumatic method.

6. Variation of Inlet Pressure

During slurry pumping and gravity filling methods, continuous variation of inlet pressure was recorded using a chart type recorder. Fig. 5 shows variation in the nature of pressure signatures during initial and final stages of filling. Minute analysis of the pressure signatures revealed that path changes by puncturing a new route were always indicated by small peaks followed by sharp falls or valleys. A deeper valley followed by a continued lower pressure for some time indicated a major breakthrough leading to a much shorter new path. The mean pressure level increased gradually as the filling progressed. During the final stages, frequent pressure fluctuations of high amplitudes were observed. But a generalised trend or characteristic to anticipate imminent jamming conditions could not be detected. However, during the rough variations in pressure signature at the final stage, another attempt was made to prolong the life of filling from a single feeder pipe. In this trial, an additional amount of fresh water at high pressure was allowed to enter the feeding pipe as and when a sharp pressure rise was observed. Points S_1, S_2, S_3 and S_4 indicate the moments of opening of the additional water supply valves. The valve was closed as soon as pressure falls to normal working level. Thus, in field trials, life of a single feeder hole may be increased if a proper automated arrangement of fresh water injection at steep slope conditions of the pressure signatures can be made.

7. Multi-variable Regression

Empirical relationships connecting unit hydraulic pressure loss $\frac{\Delta P}{L}$ with the air, water and sand flow rates i.e., Q_a , Q_w and Q_s , developed using multi-variable regression analysis with the help of SPSS software package. In the case of hydro-pneumatic system, the logarithmic fit produced highest regression co-efficient of 0.98 and the relationships is given by

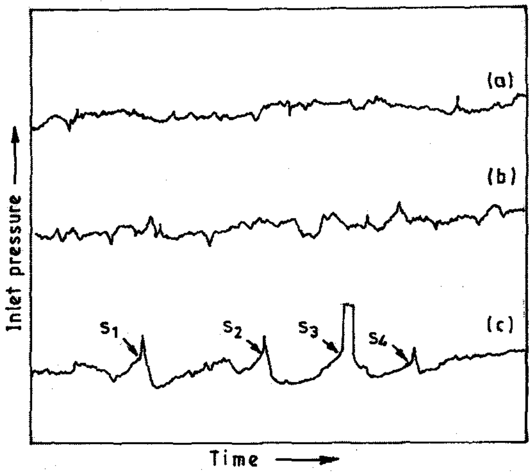

Fig. 6. Typical pressure charts for (a) normal filling during initial and intermediate stages, (b) normal filling during final stage and (c) jamming indication and its avoidance during filling.

$$\frac{\Delta P}{L} = \ln(Q_s^{5.94} Q_a^{-1.09} Q_w^{-3.77}) + 15.08 \tag{3}$$

For pumped-slurry backfilling a simplified power law was found to have a highest regression co-efficient and the corresponding empirical equation is

$$\frac{\Delta P}{L} = 28.5 \frac{\sqrt{Q_s}}{Q_w} \tag{4}$$

The hydro-pneumatic filling method was found to be suitable for sand concentrations up to 7% by volume. Using the Equations 3 and 4 it may be computed that the maximum possible channel lengths that may be sustained for a given hydraulic head will be nearly 50% longer in hydro-pneumatic method as compared to pumped slurry method. For filling with 10% sand concentration the hydro-pneumatic method tends to produce higher hydraulic pressure loss unless air to water ratio is increased to more than 3.5 which is considered as a forbiddingly high value for field trials.

8. Conclusion

Although lower values hydraulic pressure loss were observed in hydro-pneumatic method during laboratory experimentation, a few important points should be considered before its field implementation.

- As no control over the introduced air bubbles can be exerted, the bubbles tends move rapidly towards the rise directions, thus creates an upward bias for the meandering channels and hence the deposits cannot spread much in the strike or horizontal direction.

- Several air release boreholes should be kept in the rise side of the inlet borehole. Even then the complete removal of the introduced air may not be feasible.
- Turbulence of high volumes of rapidly moving air can disturb the stability of the old, weak roof of the subsurface excavations. It may cause local roof falls or create new cracks in the roof for the escape of air to the surface. Unwanted escape of air through old existing cracks will reduce the buoyant motive force for sand transport in the meandering channels.

As a general rule, it may be approximated that the introduced air may create ground puncturing if an existing crack lies extended up to a depth h from surface such that

$$h \leq \frac{H}{\gamma}$$

where, H = depth of the subsurface excavation,
and γ = Mean specific gravity of the overlying strata.

Compared to the hydro-pneumatic method the pumped-slurry backfilling technique was found to suit higher filling rate up to 20 l/min at 10% sand concentration, and thus, it can accomplish quicker filling of the voids. But it requires elaborate and complex surface arrangements which demand high maintenance and frequent shifting. Keeping in view all the above difficulties the author feels that simple gravity filling technique will prove to be a useful method in India. It requires least expenses on equipment and surface arrangements and hence it can be easily used to fill underground excavations below densely populated areas like Jharia and Ranigunj townships in India. The present experiments indicated that with proper control on input parameters simple gravity backfilling technique can prove itself to be an equally efficient one as compared with pumped-slurry backfilling method.

The inlet pressure variation acts as the life-line of a filling system and continuous recording of the same should be done so as to monitor the general health of the filling process. The nature of variation of the injection pressure can also be influenced by the nature of filling material and its grain size distribution. Filling with high slurry flow rate should be preferred as it can fill sufficiently large area without much rise in the injection pressure even at the final stage of filling. Although large amounts of experimental work and field trials have been done for several years no scientific theory has yet been formulated for the transport of filling material along the meandering channels.

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