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Subsidence control measures in coalmines: A review

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This paper reviews subsidence control approaches adopted in underground coalmines. Subsidence, a sudden depression of the ground, occurs in two forms, trough and pothole subsidence. This can be hazardous to life and property as it occurs without any prior indication. Subsidence can be controlled by using partial extraction methods, stowing etc. in working mines. Backfilling and grouting can be used to stabilize unapproachable abandoned underground mines.

Keywords: Coalmines, Subsidence, Partial extraction, Stowing, Grouting

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Introduction

Surface manifestation of underground coal extraction occurs in two forms, pothole and trough subsidence. Pothole subsidence is a sudden depression of ground surface of small area due to sudden collapse of overburden into the underground void. Trough subsidence is a large area depression of the surface terrain, which is common at greater depth. Pothole subsidence is hazardous to life, as it does not impart any prior indication before its occurrence. Ground movements produce various forms of damage to different surface features and structures. Damage to buildings result from tilting, curvature and linear deformation of the ground built on it. Compression and extension of the surface alter the gradient of structural alignment, which ultimately causes their deformation. Subsidence phenomena, which occurs in abandoned mines to a large extent, continues through years after mining[1]. Abandoned room and pillar mining even two centuries ago may still be causing subsidence, which results in heavy loss of life and property. This paper reviews various subsidence control approaches, which are being adopted in collieries for both working and abandoned coalmines.

Subsidence Control in Working Coalmines

Plane Fitting Method

Conventional method of leveling house superstructure subject to curvature and twisting makes it practically almost impossible when the differential subsidence is large[2], where any attempt to level the superstructure, lifting it by large amount, can invariably lead to damage the structure. To overcome this, a Plane Fitting Method (PFM) was developed[3]. As curvature and twisting are caused by differential subsidence, PFM completely eliminates strain on the superstructure caused by curvature and twisting.

Height adjustment devices (crib-jack assembly) are installed under the superstructure for keeping the superstructure in a time dependent incline plane. Number of crib-jack assembly needed for superstructure is obtained as:

$$N = 1.5\ W/J \qquad \dots (1)$$

where, N = Number of crib-jack assembly; W = Weight of superstructure, tons; J = Capacity of jack, tons.

Locations of crib-jack assembly are selected carefully to cover all corners and area under the beam. Maximum spacing of the crib-jack assembly is limited to less than 3 m. Under heavy portion of the superstructure, crib-jack assembly is densely placed.

Trench Around House

Trenching around house is effective in reducing compressive stresses on the floor and wall. The trench should be at least 0.3 m wide, 0.9 to 2.0 m from the exterior wall and should extend 0.15 m to 0.2 m below the foundation[4]. Plain strain formulation was used to study stress reduction on the basement floor due to different dimensions of trench (Fig. 1).

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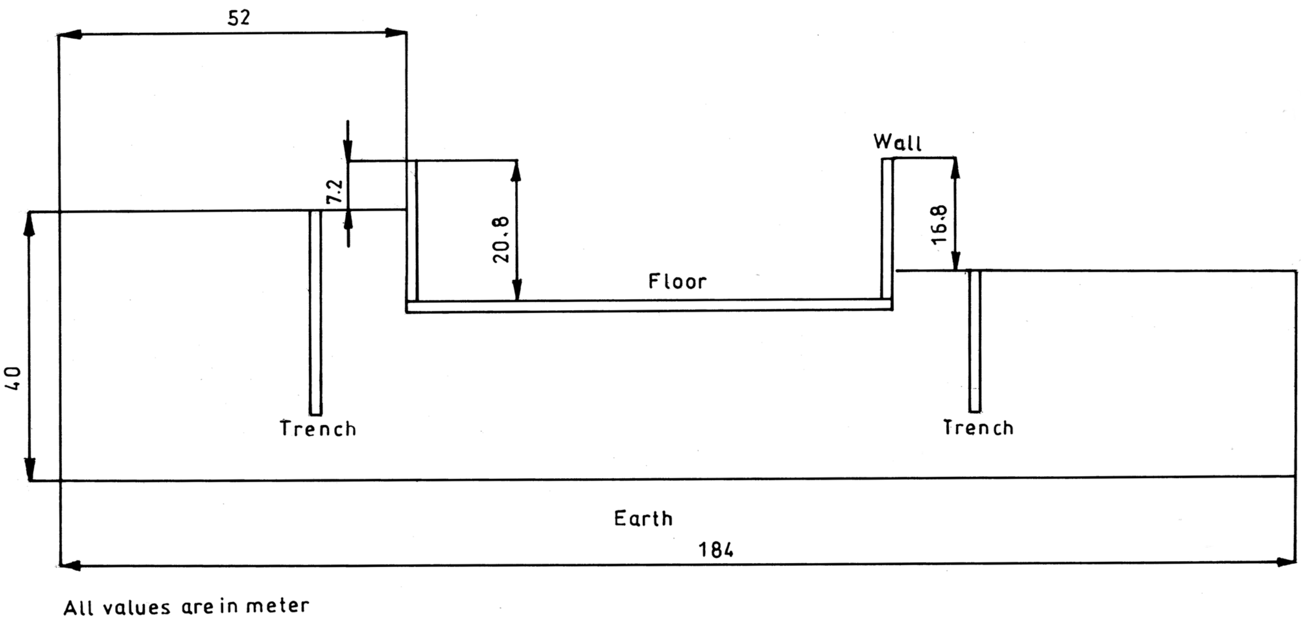

Fig. 1—Finite element model for studying the effect of trench

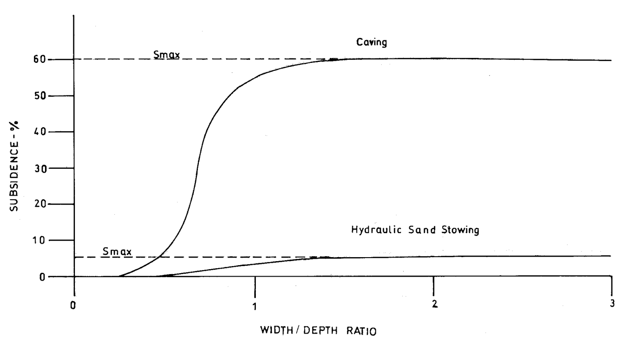

Fig. 2—Relation between maximum subsidence and width/depth ratio

At the boundary nodal points on the ground surface, known vertical and horizontal displacements were assumed. Vertical displacement was selected such that it imposed a constant curvature of 1.5×10^{-5} 1/m throughout the top of the ground surface. Horizontal displacement was chosen such that it imposed a compressive strain of 3×10^{-4} and 7×10^{-4} mm/m throughout the ground surface of the model. These imposed values of curvature and horizontal compressive strain are some typical measured values.

The interaction of basement floor and ground was modeled by using Winkler's sub grade reaction theory[5]. For implementing the sub grade reaction theory, the ground model in plane strain was first run alone (without the wall and floor). Known displacements at the interface nodal points of the ground and floor, and ground and wall were imposed in the ground-alone model; all other boundary points of the ground alone model were fully constrained. By running the ground alone finite element model, reaction forces at the interface nodal points were determined. After this, the combined ground, floor, and wall model was run with known reaction forces at the interface nodal points and known displacements at all other surface boundary nodal points.

Percentage reduction in maximum compressive stress on the floor due to digging a deeper and wider trench was calculated with respect to no-trench situation. Also the percentage gain in reduction of compressive stress on the floor due to digging a large dimension trench with respect to the preceding smaller dimension trench was calculated.

Tension Cable

A tension cable is used to reduce twisting damage to the structure, which has high compressive strength but low tensile strength, for example, concrete block masonry. For proper design, tension in the cable must be determined properly[2].

Hydraulic Sand Stowing (HSS)

In Indian coal mining, stowing plays a vital role for subsidence control. Among different methods of stowing, HSS is very effective in Indian mining (Fig. 2). The maximum subsidence in Indian coalfields with HSS filling is only 5 percent whereas it is 60 percent in case of caving with respect to extraction

Table 1—Maximum subsidence with hydraulic sand stowing

Country	Maximum subsidence %
Ruhr coalfield, Germany[8]	20
Upper Silesia, Poland[9]	12
North & Pas-de-calais coalfield, France[10]	25-35
British coalfield[11]	15-20
Kuho (II) colliery, Japan[12]	19
Kamptee coalfield, India[6]	05

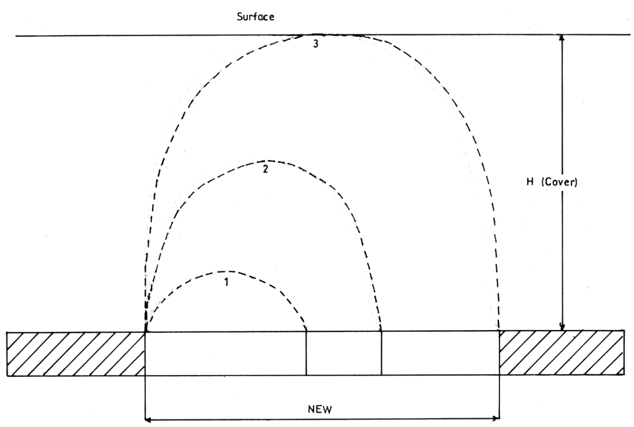

Fig. 3—Non-effective width of extraction

thickness of a single seam extraction[6]. Thus, the maximum subsidence can be reduced 12 times by hydraulic filling of voids with sand with respect to caving. In some stowed panels, the value of subsidence is high due to delay in stowing or old stowed room and pillar working in the overlying or underlying seam. The magnitude of maximum subsidence varies between 05 and 35 percent of the extraction thickness[7]. The maximum subsidence with HSS is high in foreign coalmines in comparison to Indian coalmines (Table 1) due to strong overlying rock in Indian coalmines. Thus, HSS is very effective in India to reduce subsidence in comparison to other countries.

Partial Extraction Methods

Partial extraction methods used to minimize subsidence as well as strain to protect different surface features and structures are as follows:

Non-Effective Width of Extraction

Non Effective Width (NEW) of extraction (Fig. 3) is the underground width of extraction, which does not cause practically any movement on the surface. Whenever an underground opening is made, the equilibrium of the surrounding rock mass is disturbed. This causes stress redistribution around the opening. A pressure arch is formed following the redistribution of stress[13]. The height of caved dome is controlled by: i) Strength of immediate roof; ii) Bulking properties of caved rock mass; and iii) Dimension of the excavation.

The presence of strong bed in the overlying rock mass discourages upward collapse of the roof. With further increase in the width of excavation, the caved dome moves upward and a stage comes when the surface movement starts. It appears that a certain width can be extracted without causing any movement on the surface. This width is termed as NEW and expressed in terms of depth. In India, NEW varies between 0.3 to 1.17 times the depths of extraction. If the extraction width is kept less than NEW, no subsidence occurs on the surface. The percentage of extraction in single seam working with non-effective width of extraction is about 50[14]. Further, the percentage of extraction is reduced in multi-seam mining condition. The value of NEW increases with increasing sandstone and Rock Quality Designation (RQD) in the superincumbent strata.

In this method, row(s) of pillars are extracted in such a way that the width of extraction is always kept less than the NEW and the row(s) of pillars left as barrier between adjacent extracted row(s) of coal pillars have long term stability with safety factor equal to or more than 2.0.

Safety Factor=Strength of pillar (S)/Load on pillar (P) … (2)

The pillar strength estimated using CMRI pillar strength equation[15]:

$$S= (0.27\,\sigma_c\,h^{-0.36}) + ([H/250 + 1]\,[We/h - 1])\ \text{Mpa} \quad \dots (3)$$

where, σ_c = Uniaxial compressive strength of 1 inch coal cube, Mpa; h = Working height, m; H = Depth below surface, m; W_e = Pillar width, m (*for square pillar*); $= 2w_1w_2/(w_1+w_2)$ (*for rectangular pillar*).

Load on pillar is estimated using Wilson's formula[16] as given below:

$$P= [0.025H/W_e^2] * [(W_e + fH)\,(W_e + B)]\ \text{Mpa} \quad \dots (4)$$

where, W_e = pillar width, m; H = depth below surface, m; B = roadway width, m; f = 0.3 for caving; = 0.2 for stowing.

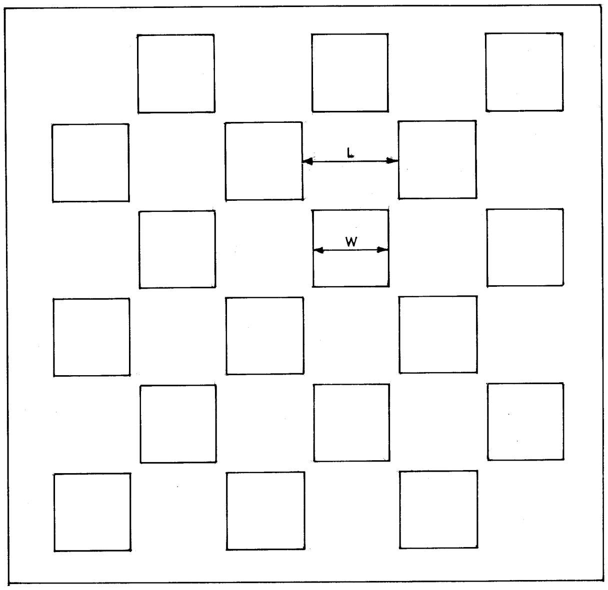

Fig. 4—Chess board method of mining

Chess Board Method

When NEW extraction is not possible, Chess Board method may be adopted. In this method, every alternate pillar in every row is extracted so as to leave a chessboard pattern (Fig. 4). The Percentage of extraction in this pattern comes to 60-65[17].

The safety factor of the pillars left out must be at least 2.0 for long-term stability point of view. The formula[16] used to calculate the load on pillar is:

$$P = 0.025\,[(W_e + B)/W_e]^2\,[2H - (W_e + B)/1.8]\ \text{Mpa} \quad \ldots (5)$$

The strength of pillar is estimated using Eq. 3.

Goaf Pillar Method

When NEW or chessboard method does not give good recoveries, the Goaf Pillar method may be tried. This method consists of leaving pillars systematically in the goaf such that the width of the extracted span around any such pillar is less than NEW and the left out pillars have a long-term stability. The pattern will depend on seam strength, extraction height, depth and pillar size[17]. This method gives the best recovery (60-70%)[18] among all the partial extraction methods.

Wide & Stall Mining

Under surface/subsurface structures, extraction of coal seam at moderate depth cover faces problem of low recovery. Conventional method of mining for optimal coal extraction under such geo-mining conditions is splitting of original developed pillars in which small sized coal pillars (Stooks) are left out to protect the surface structure and overlying coal seam(s). Formation of stook during the optimization of recovery causes considerable drop in strength of the natural support, which is not desirable for long term stability of the underground mining and surface structures[19]. In Indian geo-mining conditions, conventional splitting and stooking method does not provide more than 30 percent coal[20,21] during optimization from a developed thick seam under built up areas. In multisection seam, during the optimization of recovery, pillar strength decreases due to increased height of extraction[22], stability of parting and superimposition of pillars makes the situation more complex from production, productivity and safety point of view.

Matching of gallery size with the strength of immediate roof and strength improvement of the natural support by increasing width/height ratio of pillars are the two basic constituents of the Wide & Stall philosophy[23]. Strength of ultimate pillars and stability of overlying exposed roof span play an important role for long term stability of wide stall under shallow depth cover. The effective bearing capacity of a pillar is comparatively more than a number of stook of the equivalent area. Widths of existing galleries are increased in a particular configuration to improve coal recovery leaving wide pillar in comparison to stook of intact core. Wide & Stall formation accommodates existing galleries of a developed coal seam as well as improves recovery (40-65%)[26] and safety of the ultimate mining structure in comparison to the conventional method. On the basis of extensive laboratory investigations on different simulated models, idea of Wide & Stall mining was conceived and first time implemented in the field at East Bhuggatdih Colliery of the Jharia Coalfield[24]. Taking advantage of the presence of massive sandstone roof and rapid increase of pillar strength with the increase of its width-height ratio[25], splitting and stooking of the pillar was replaced by Wide & Stall formation (Fig. 5).

Splitting of Pillar with Stowing

The Directorate General of Mine Safety (DGMS) generally does not permit splitting of pillars by caving under surface features. But the pillars can be split with stowing. The width and number of splits are decided by pillar strength considerations. A minimum

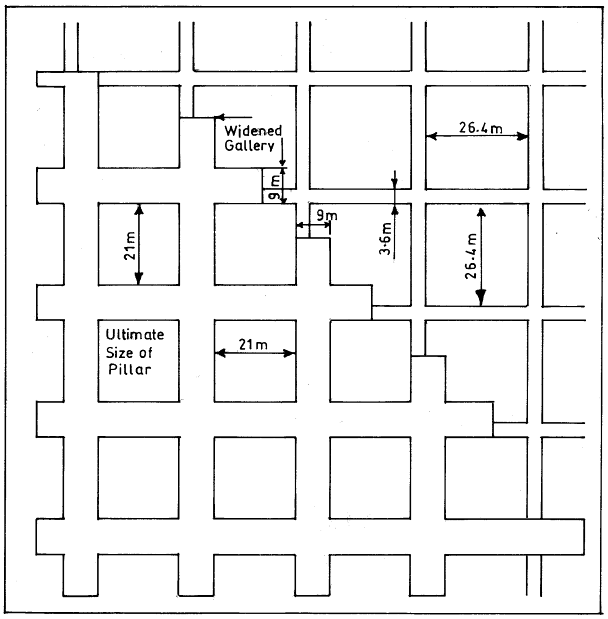

Fig. 5—Wide & stall method of mining

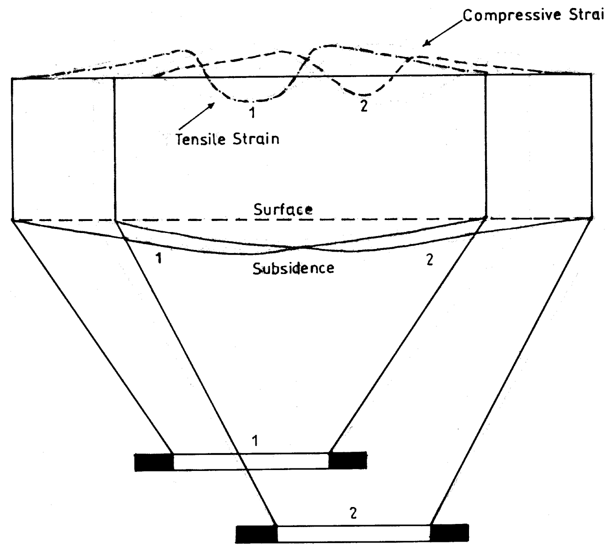

Fig. 6—Harmonic mining

safety factor of 1 is sufficient to ensure long-term stability of stooks with complete stowing.

Splitting of Pillar with Side Bolting

If all the partial extraction methods could not be practiced and also stowing material is not available then the pillar can be split with systematic full column grouted side bolting. The bolted pillar should have long-term stability to ensure zero subsidence at surface.

It was found that the strength of pillar increases with systematic side bolting and the augmented strength[16] is given by:

$$S_b = S[1 + \{20A_s(q-1)\}/(\sigma_c a^2)] \text{ Mpa} \qquad \dots (6)$$

where, S_b = strength of bolted pillars, Mpa; S = strength of unbolted pillars defined by eqn (3), Mpa; A_s = anchorage strength of each bolt, t; q = triaxial strength factor (average 3.5); σ_c = Coal strength, t/m^2; a = Spacing between the bolt, m.

The load on the reduced pillars is estimated using tributary area concept[27] and is given as:

$$P = 0.025H\,[L_1 L_2 / w_1 w_2] \text{ Mpa} \qquad \dots (7)$$

Where, H = depth below surface, m; w_1, w_2 = Pillar widths, m; L_1, L_2 = Centre to centre pillar size, m.

Harmonic Mining

Extraction of a panel causes tensional and compressive strain at the surface. The working in two seams should be so advanced simultaneously to cancel out the balance of strain, caused by one face by the strain induced by another at a different level. This approach is known as harmonic mining, which, however, is not simple as the mine has to be pre-planned, and also problems due to interaction between faces in different seams have to be countered. Another application of the principle is in protection of buildings. The working was laid out so that the building was at the centre of a panel of maximum width. In this, the building was subjected to effects of traveling strains[28]. To counter it, the face was split into two units, which were advanced in steps with a fixed interval between them such that strain induced by two faces cancel each other (Fig. 6).

Subsidence Control in Abandoned Coalmines

Abandoned coalmines also cause surface deformation with time following both pothole and trough subsidence. Two distinctly different subsidence control technologies have been developed for abandoned coalmine[29, 30]: i) Point support method; and ii) Areal backfilling.

Point Support Method

The cost of Point Support method involves a large number of boreholes and the use of expensive material in relatively small quantities. This exists several dozen Point Support method, which operate either to support the underground cavities, controlling subsidence, or to isolate the structure from the effect

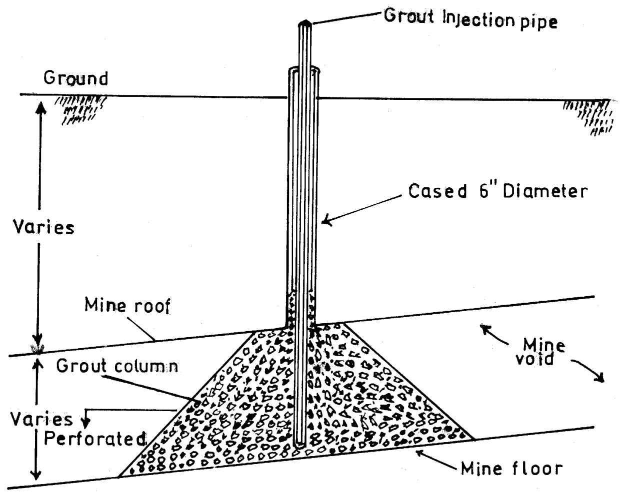

Fig. 7—Grouted column to support the overburden

of subsidence if it should occur. The method usually involves deep foundation through the mine opening supporting the structure on the underlying strata. On the principle of Point Support methods, some other methods are: i) Gravel Column and Associated Method; ii) Fly ash Grout Injection; and iii) Fabric Formed Concrete.

Gravel Column

Gravel column usually placed in the mine opening. Borehole is drilled through the mine strata, and gravel poured down the borehole to form a pile on the mine floor. When the tip of pile contacts the mine roof, it is rodded down to spread the pile and permits additional gravel to be placed (Fig. 7). The objective is to place as much gravel as possible in the mine opening and to achieve firm contact with the mine roof. The filling of a significant fraction of the open mine volume reduced the amount of potential subsidence simply by killing open volume within mine. In effect, the extraction ratio has been reduced by introducing the volume of gravel. The toe of the gravel pile abuts against nearby pillar, providing lateral support and protection against deterioration, in effect the height of the pillar has been slightly reduced by burying their lower portions. Finally, some direct support is provided to the roof strata, reducing the roof span and enhancing the stability.

The method may be used in a variety of applications and with material other than gravel e.g., gravel columns may be placed in a close line around the perimeter of the building to form a continuous gravel wall. The interior of the site may be completely filled with slurry or other material. Alternatively, a lean concrete may be used in place of gravel, so that the piles achieve significant structural capacity.

Fly ash Grout Injection

In a partially subsided mine, it may be difficult to build gravel columns. A highly fluid injection material is desired that will fill small voids and crevices, yet is expensive enough to use in such large openings as may still exist in the mine. It is carried to borehole by pipe and hose, and poured down the borehole in free fall. In large opening, the value of grout injected in each shift is sufficient to create a disk perhaps 10 m in diam and 10 cm tall; by next day, this disk will have set, and another disk will be placed on the top by each day's injection. Eventually, the column of grout will contact the mine roof, the borehole will be filled with grout, and any strata separations in the mine roof will be grouted.

Fabric Formed Concrete

A borehole is drilled from the surface through the mine opening and a short distance into the mine floor. The fabric tube is then placed around a grout pipe, and the assembly lowered into the borehole. Concrete is then pumped from the grout pipe to inflate the fabric tube from the bottom up. Creating a concrete column keyed into the mine floor and roof[28]. Often the grout pipe is left in place to provide some reinforcement. The finished diam of the column depends upon the tensile strength of the fabric and the depth of mine opening. Since the fabric must resist bursting under the hydrostatic pressure of the fluid concrete.

In the design of a subsidence control system such as fabric formed concrete, the interaction among the mine floor, column and mine roof elements must be considered. It is difficult to obtain complete contact. The concrete column is typically stiff and strong in comparison to the mine roof and floor, so that maximum load is limited by bearing strength of floor rather than the strength of the concrete column.

Areal Backfilling

Areal Backfilling involves the filling of mine voids to provide general protection to urban areas that may be measured in sq km. It involved the large quantities of materials such as coal mine refuse or fly ash, which are available locally at low cost. Such materials are not desired on the surface, and backfilling provides an environmentally sound method for their disposal in

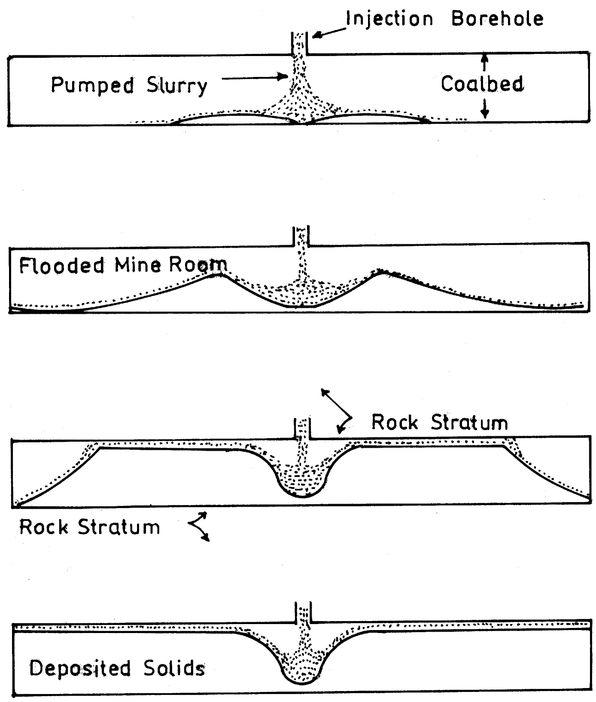

Fig. 8—Sectional view through a flooded mine room at the point of slurry injection showing measurement of particles and growth of deposit

addition to controlling subsidence. In contrast to the point support system, which is typically gravity feed method, Areal Backfilling usually involves pressure injection. On the principle of Areal Backfilling, some other methods are: i) Pumped Slurry Injection; ii) Fly ash Slurry Injection; and iii) Pneumatic Fly ash Injection

Pumped Slurry Injection

Pumped Slurry Injection[4,31] method (Fig. 8) is used in dry or wet mines, but is more successful when the mine is inundated. It offers more effective overburden support than other flushing methods. The objective of using fill material for ground control is to either eliminate or reduce ground movements that can result in surface subsidence.

From the practical standpoint, fill rarely occupies the entire mined-out area and generally does not contact with the roof. Furthermore, a certain delay exists between mining and the placement of the fill consequently, support pillars are already loaded and initial roof convergence has occurred prior to fill placement. The fill material acts initially as a passive support, and being to take on load only when additional deformation of the roof or pillars takes place.

The functions of fills as ground control measures are: (i) To reduce the effective void, thus limiting the propagation of roof caving; (ii) To increase the residual strength, post failure stiffness and to a lesser extent, the effective peak strength of support pillar; and (iii) To provide direct roof support[29]. The geotechnical properties of the fill material under wet conditions are very critical in meeting the design objectives. Consequently, fill materials must be fully characterized to determine their adequacy for use as backfill[32].

Coalmine refuse is crushed and loaded into truck at the mine refuse pile, and traveled several kilometers to a mixing pumping facility. Mixing water is usually obtained from a deep well pump drawing water directly from flooded mine. Coalmine refuse and water are mixed, and pumped through slurry pipeline as much as several kilometers to the injection boreholes currently in use. From a single mixing location, slurry pipelines may be run to a large numbers of boreholes, each of which is backfilled in turn. In locations where multiple seams were mined, lowermost seam is backfilled first, and the remaining seams in sequence from the bottom up.

Fly ash Slurry Injection

Fly ash slurry is injected in abandoned mine using a pumping system. Because of its greater fluidity, fly ash slurry (50-60 % solid) is highly pumpable and travels underground a long distance. At one location, fly ash slurry was deposited more than a kilometer from its injection point, clearly, large areas may be backfilled from each injection borehole, but difficulty may be encountered in determining where the fly ash is traveled.

Pneumatic Fly ash Injection

Some use has been made of pneumatic injection of dry fly ash in dry mines. The process simply involved carrying the fly ash in dry product tankers directly to the injection borehole, and using the tanker's on-board air compressor to blow the fly ash into the mine opening. Such systems have not been developed to the same degree as have effective pumped slurry methods, but certainly could be effective in dry mines where little subsidence has taken place and good connectivity between mines entries exists. In an isolated mine entry, backpressure can rapidly build up, defeating the pneumatic transport mechanism.

In the injection head (Fig. 9), the inner pipe carries compressed air, which impinges on the curve

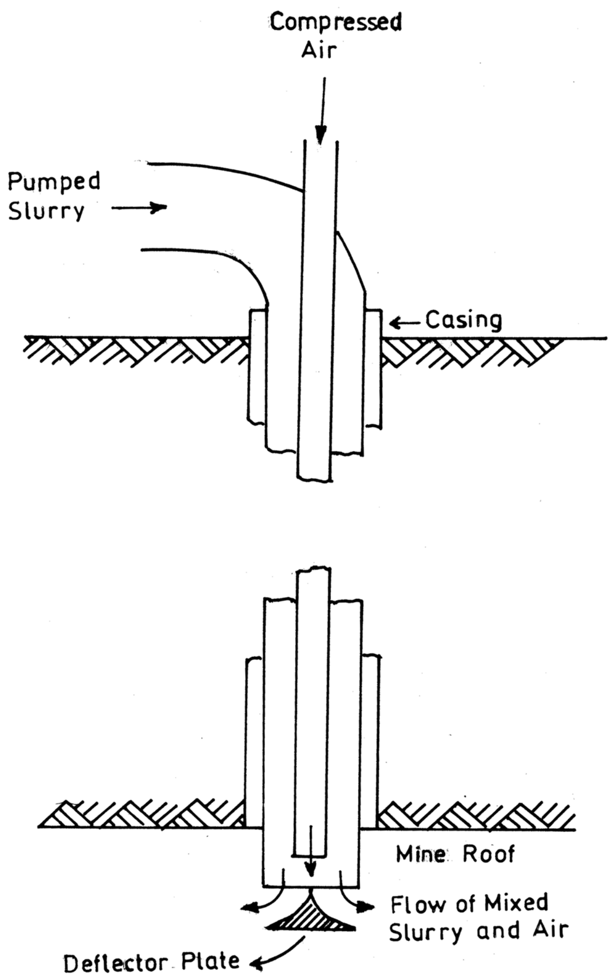

Fig. 9—Pneumatic assisted slurry injection

deflection plate at the bottom of the casing, spraying the wet coal mine refuse horizontally. In open air, the mine refuse would travel up to 15 m in a flat trajectory. In a mine opening, the mine refuse would tend to deposit in a circle around the injection head. As the deposits come near to sealing the mine roof, air velocity through the narrow opening remaining is expected to form a pipe through which slurry would be carried in a pneumatic transport to be deposited at greater distances. As conceived, the system does not have certain obvious faults, nor has it been in operation long enough for this fault to be corrected.

Filling of Cracks

Soil and sand-cement mixture above alluvium and rocks, must be filled in cracks formed due to ground movements respectively. However, cracks, developed in river or rivulet beds, should be in- filled by concrete. This restricts the penetration of surface water through cracks or faults and thereby reduces the erosion of the overburden, thus reducing the possibility of pothole formation[33].

Discussion

Important subsidence control measures in coalmines are summarized as follows:

Methods	Mines condition	Remarks
Plane Fitting	Working mine	Protects the superstructure by eliminating strain.
Trench Around House	Working mine	Trenching around a house absorbs compressive strain.
Tension Cable	Working mine	It is effective in reducing damage to concrete-block masonry basement.
Stowing	Working mine	Hydraulic stowing is very much effective in India as it reduces maximum subsidence by 1/12 times in comparison to caving.
Non-Effective Width	Working mine	This method used to control subsidence completely. The percentage of coal recovery is about 50[14] in single seam condition as is further reduced in multi seam extraction.
Chess Board	Working mine	This method is used for complete subsidence control with 60-65% coal recovery[17].
Goaf Pillar	Working mine	Used where difficult to work by NEW and Chess Board methods. It give best recovery among all partial extraction methods. The extraction percentage comes to 60-70[18].
Wide and Stall	Working mine	Used where cover is shallow for complete subsidence control. The extraction percentage is 40-65[26].
Splitting of Pillar with stowing	Working mine	Splited pillars (stooks) with stowing must have at least 1 safety factor to support the overburden.
Splitting of pillar with side bolting	Working mine	Full column grouted side bolting increase the strength of splited pillars to withstand overburden for complete subsidence control.

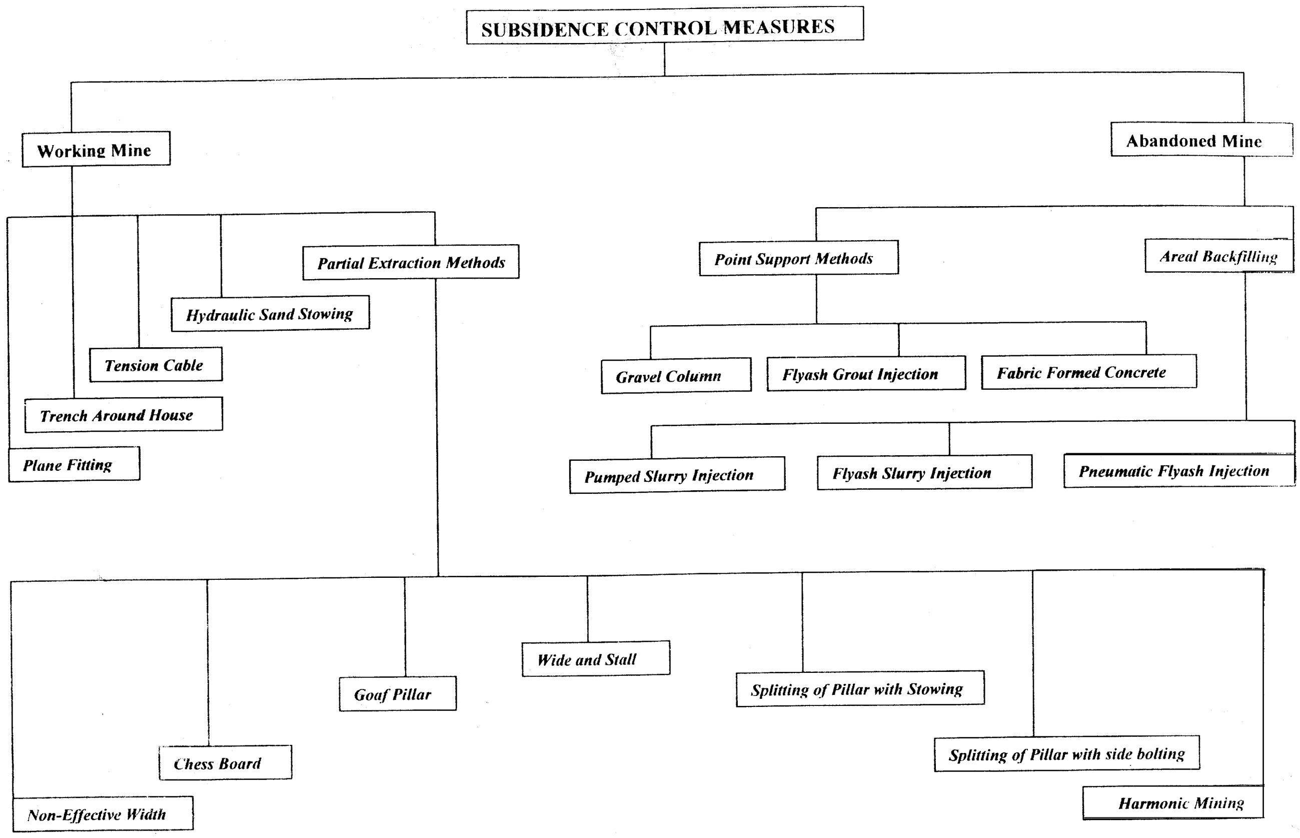

Fig. 10—Different methods for subsidence control

Harmonic Mining	Working mine	Almost strain free mining to control deformation on surface.
Gravel Column	Abandoned mine	Gravel gives a firm contact to the roof and eliminates the ground movement.
Fly ash Grout Injection	Abandoned mine	Fly ash grout injection is effective in partially subsided area to fill small voids and crevices.
Fabric Formed Cement	Abandoned mine	Grouted concretes support the overburden to avoid subsidence movement.
Pumped Slurry Injection	Abandoned mine	Useful in dry and wet condition. Offers more effective overburden support than other flushing methods. It also increases the residual strength and post failure stiffness[31].
Fly ash Slurry Injection	Abandoned mine	A fly ash stowing with 50-60 percent solids travels a great distance to support a large area of overburden.
Pneumatic Fly ash Injection	Abandoned mine	Effective in dry mines where less subsidence has taken place and good connectivity between mines entries exists.

Conclusions

Winning of coal is very important by using suitable method, which gives maximum recovery and safety to life and the property. Goaf Pillar method of partial extraction is best suitable for recovery and safety point of view as this method consists of leaving pillars systematically in the goaf such that the width of the extracted span around any such pillar is less than NEW and the left out pillar have a long term stability. Harmonic mining can be practiced surface structure as it neutralizes the strains without compromising coal recovery. Among all the methods of abandoned mine, Pumped Slurry Injection method is best suitable as this method gives maximum area coverage to support different overlying surface feature and structure and reaches maximum area of mine where the other methods fail to do it.

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