NEW INITIATIVES IN SUBSIDENCE ENGINEERING: ENVIRONMENTAL ISSUES AND PRODUCTION CHALLENGES IN COAL MINING

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INTRODUCTION

It is estimated by mining experts that large reserves, more than 2500 million tonnes (MT) of mineable coal in India are locked up in developed bord-and-pillar workings, including multiple and thick seams. Most often, proposed coal extraction in such situations is associated with a technical risk of subsidence damage to the overlying important surface or sub-surface properties. To ensure the co-existence of profitable coal winning and desired surface (or sub-surface) activities or existence, possible subsidence damages should be minimised (in other words, controlled).

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or sometimes, completely prevented. For important surface properties, such as built-up areas, etc., absolutely no subsidence damage is desired. In the case of overlying waterlogged workings, the plane of reference, where no subsidence damage is desired, will be the floor of the waterlogged workings instead of the surface. The pattern of extraction should ensure no crack development on this floor and hence, no inundation-threat to the proposed working (extraction) in the seam below. The pattern of extraction in such situations has to be worked out, keeping in view the concept of non-effective width (NEW).

NEW is defined as the maximum width of extraction up to which no significant symptom of subsidence (i.e., 5mm or more) takes place on the surface or on the plane of reference [1]. NEW is expressed as w/H ratio, where w = width of extraction-span and H = depth of cover. In case of sub-surface properties, e.g., waterlogged abandoned workings in an overlying seam, H is taken as the rock parting between the waterlogged seam and the seam under extraction. An important observation in subsidence engineering is that a harder strata (of all types, not only sandstones) overlying the proposed extraction will give a higher value of NEW [4]. The concept of NEW is simplified to be two-dimensional, although subsidence is associated with three-dimensional (rock) movements. Besides its wide application in selecting a feasible pattern of extraction with the objective of attaining subsidence control on the plane of the reference - the surface or the sub-surface, it is an important parameter in the subsidence prediction norms developed for Indian coalfields [2, 3, 5, 6 and 7].

There are two types of mining subsidence, depending on its extension:

- Localized subsidence or potholing, which is concentrated in areas in the proximity of the excavated area and takes the form of a highly localized abrupt depression that is limited in extension; and

- Extensive or trough subsidence, which results in the formation of topographic depression on the surface (subsidence trough) that is more or less regular in shape and which is directly related to the width-to-depth ratio of the excavated areas below ground. In these cases, the subsidence is large in the central area and decreases progressively towards the sides, the said subsidence being accompanied by horizontal displacement.

The first type of subsidence is not considered for analysis in this paper, as it requires separate treatment. This type of subsidence can only be predicted using numerical modelling techniques, and need to be undertaken on case-by-case basis. The prediction methodology of this type is kept out of the scope of this paper. Discontinuities in a subsidence trough may occur in the second case also. A methodology to predict discontinuous or continuous subsidence is suggested empirically in this paper.

Henceforth, wherever in this paper the word 'surface' appears in the context of subsidence impact due to extraction belowground, it may be understood also as 'the plane of reference' - that may be the floor of a overlying goaved-out seam or other sub-surface properties, with the understanding as mentioned above.

**SUBSIDENCE ENGINEERING**

In order to predict the maximum subsidence versus the width-to-depth ratio, it was necessary to eliminate the variation in NEW, so as to get a rational prediction formula. This is done by normalizing the ratio w/H ratio by NEW, which indirectly takes into consideration the changes of the overlying rockmass case-by-case. Only those cases in which NEW was actually measured, have been selected for developing the prediction formula for subsidence parameters. The statistical best-fit curves are expected to have two inflexion points [2] and must become asymptotic beyond the critical width. A hyperbolic tangent function is logical for such curves. The general equation, which would fit such plots, has thus been chosen in the form

$$S = c_1 \cdot e \left[ \frac{1 - \tanh c_2 (x - c_3)}{\tanh c_2 (1 - c_3)} \right]$$

(1)

Where

- $c_1$, $c_2$, and $c_3$ are constants

- $x = \frac{W}{H}$, $W =$ width of the panel

- $h =$ height of extraction

- $e =$ percentage of extraction, taken as the ratio

- $a =$ subsidence factor $= \frac{S}{h \cdot e}$

- 0.69 (maximum) for caving and 0.05 (average), taken 0.1 for design purpose for stowing.

It is to be noted that the subsidence trough over coal measures is asymmetrical, but the general world trend is to fit a symmetrical equation to the trough. Keeping this in mind, equation (2), as mentioned below, is chosen.

Equation (1) is not convertible-to-linear for the purpose of regression. A non-linear regression analysis was therefore programmed, employing the "search method" of solution, which would satisfy the law of least squares. This led to the following relation for single-seam extraction-proposition [2] (Figure 1) which fits the general trend of subsidence trough occurrences:

$$S = 0.33[1 + 1.1 \tanh(1.4(x - 1.8))]$$

(2)

After the recently-concluded scientific subsidence monitoring studies, the formula for subsidence prediction is suggested for SECL mines, as [3].

$$S = 0.3[1 + 0.8 \tanh(1.6(x - 1.5))]$$

(3)
It may be noted that subsidence factor 'a' for SECL areas should be taken as 0.54, instead of 0.69 which is what is taken for the rest of Indian coalfields (figure 1). The average value of NEW is taken as 0.5-0.6 (instead of the average value 0.4-0.5 for the rest of Indian coalfields).

Figure 1: The general trend of subsidence trough occurrence in a single-seam extraction situation. Curve(A) plotted based on 85 caved cases in Indian coalfields [1, 2]; curve(B) plotted with selected caved cases (only continuous) from SECL, marked [5].

Relationships among subsidence, strains and slope

The standard relationship for maximum slope and strains in relation to the maximum subsidence, as given in Subsidence Engineers' Handbook [8] and as developed in the earlier grant-in-aid project [3] should be used. They are as follows:

\[ G = K_1 \frac{S}{H} \]  \hspace{1cm} (4)

\[ E_{(-)} = K_2 \frac{S}{H} \]  \hspace{1cm} (5)

\[ E_{(+)} = K_3 \frac{S}{H} \]  \hspace{1cm} (6)

After many attempts at trying out different forms of equation, it was observed that regression analysis to obtain the best-fit curve was virtually insurmountable. It was suggested, therefore, to use nomograms (figure 2) as developed earlier to know the value of \( K_1, K_2 \), & \( K_3 \) [2, 3, 5, 6, 7]. It is to be noted that 'S' should be calculated using equation (2) or (3) respectively for the rest of Indian coalfields or for SECL mines, as the case may be.

Procedure for subsidence prediction

Discontinuous subsidence badly damages the surface or has an adverse effect on the plane of reference under consideration. With the help of scientific subsidence observations with varying geo-mining details, the line which envelops discontinuous cases is defined as

\[ H/(h.e) < 0.3 \]  \hspace{1cm} (7)

Where \( H \) is the depth of cover, \( m \)

\( h \) is the working height, \( m \)

\( e \) is the % of extraction in the panel, taken as the percentage value

Figure 2: Nomograms to calculate the values of \( k_1, k_2 \) and \( k_3 \) in a single-seam extraction situation.

Depending on the value of \( s = \frac{W}{h} \cdot \frac{1}{17.5} \), subsidence observation case-studies have been marked.

Figure 3 shows a line of demarcation between continuous and discontinuous subsidence cases, which covers both single and multi-seam mining conditions. For \( H/(h.e) < 0.3 \), there is the likelihood of occurrence of discontinuous subsidence. If so, we may try to either decrease the height of extraction or decrease the percentage of extraction, or both, such that this ratio is more than 0.3; the subsidence then is likely to be a continuous one. Only in such a continuous type can a prediction of the subsidence parameters like subsidence, slope and strains be done, using the above equations. On the other hand, if it is not possible to obtain the likely continuous subsidence profile, the suggestion is to go for prediction of discontinuous subsidence/potholing, etc. This will require separate treatments like use of numerical modelling techniques and simulations, as mentioned earlier.

Figure 3: Showing the line of demarcation to know the nature of likely subsidence. Continuous or discontinuous, the study-sites marked cover all the Indian coalfields except SECL areas.
Especially for SECL mines, the above relationship transforms into [Figure 4]:

\[ H/(h.e) < 0.25 \] \hspace{1cm} (8)

**Figure 4**: Showing the line of demarcation to know the nature of likely subsidence: continuous or discontinuous, the study sites marked are those of SECL mines only.

Steps to predict subsidence parameters for given geomining details of a proposed extraction in a panel:

I. Using equation 7 or 8, the nature of subsidence as to whether discontinuous or continuous should be predicted with the given H (depth of cover), h (height of extraction) and e (extraction in terms of percentage e.g. 70-80% for B&P working, 95% for longwall working) of the proposed extraction panel.

II. Non-effective width (NEW) need to be assessed for a particular seam of a particular coalfield. The best way is to assess NEW by actual observation of background void-created-dimension vis-à-vis the onset of measurable subsidence as elaborated elsewhere [1, 2, 3]. If observation at site is not possible, e.g., in a virgin seam extraction-proposition, an approximate method of estimation of NEW may be adopted [2, 4]. This empirical method does not take into account the "shape effect". Especially in bord-and-pillar workings, the shape of the excavation (in plan) may be a right-angled triangle with a serrated hypotenuse. It is, therefore, advisable to confirm this approximate NEW value by scientific subsidence monitoring and strata management studies in the very first trial-panel of extraction; and this may be used for subsidence prediction for future proposed extractions.

III. If the calculation as per (1) results in continuous subsidence, then it should be predicted by using empirical equation 2 or 3, or by using the influence function with the help of software SUBSOFT, developed as an objective of an earlier grant-in-aid project [3, 6, 7]. The slope and strains should be predicted using equations (4), (5) and (6) respectively. The values of K1, K2 & K3 should be taken from graphs provided in figure 2.

IV. If the calculation as per (1) results in discontinuous subsidence, numerical modelling exercises are to be resorted to, on case-by-case basis.

For any extraction proposition, the above steps are to be followed in sequence, to predict the subsidence parameters. If the safe limit, described elsewhere [9] depending on the type of surface and sub-surface properties, is decided for a given extraction proposition, back calculation, to get the subsidence value using equation 4, 5 and/or 6, should be obtained. From this subsidence value, using equation 2 or 3, either the width of the extraction-span or the height and/or the percentage of extraction can be restricted. Based on this exercise, extraction strategies (out of many partial extraction methods) can be planned to get the desired level of subsidence impact or no subsidence impact on surface or sub-surface properties [9].

**CASE STUDIES**

Based on actual observations, the study of borehole logs and geo-mining details, the authors could recommend extraction propositions in different Indian coalfields where environmental issues and optimisation of production targets in each case were the primary objectives. Obviously, steps to predict subsidence parameters, as elaborated above, were followed. These case studies, to name a few, may broadly be categorised into:

(i) Working below important surface properties with the objective of no subsidence impact.

(Chinakuri Colliery, Dhemokiri colliery, Methan colliery / Sodepur Area Manoharabha colliery, Salanpur Area / ECL; West Jagatkhanda colliery / Hasdeo Area / SECL; Murudih colliery / Western Jharia Area / BCCL; Hingir Rampur colliery / Orient Area / MCL)

(ii) Working below important sub-surface properties with the objective of no subsidence impact.

(Chinakuri Mine No. 3, Dhemokiri colliery, Sodepur colliery / Sodepur Area / ECL; Banki colliery, Balgiri 3 & 4 Incline / Korba Area / SECL)

(iii) Working below forest area where maximum permissible strain should be less than 20 mm/m as prescribed by Ministry of Environment & Forest, Govt. of India. Here, the software SUBSOFT developed by the second author is being used which takes into account the irregular shapes, multi-seam situations and variation of overlapping of one goaf or goaves of a seam by that/those of the other seam(s).

(Sheetalkaran-Kurja underground project, Kapildhara underground mine / Hasdeo Area / SECL; Ketki underground mine / Bisrampur Area / SECL; Raiganj underground mine / Korba Area / SECL; Nandira colliery, Nataraj underground mine / Talcher Area / MCL; Durgapur Rayatwari colliery / Chandrapur Area / WCL).
CONCLUSIONS

Obviously, two important factors need to be considered for a subsidence engineering exercise:

(a) extraction span to be restricted, based on steps provided in this paper.

(b) the barrier pillars or other left-out pillars between two extraction spans (as per ‘a’) should be long-term stable, i.e., the factor of safety is more than 2.0 in case of caving and should be more than 1.0 in case of full stowing. The factor of safety here is defined as the ratio of strength and the redistributed load, on the left-out pillars/stooks, taking the combined effects of extraction in nearby panels[9].

While the strength calculation can simply be done by using the CMRI-developed strength formula, the calculation of the load is often tricky. Especially in the case of irregular shaped-pillars with extraction nearby or with developed workings to be extracted in future, the calculation of the load by use of the tributary area method may give inaccurate results. In such a situation, the designer has to resort to numerical modelling techniques, where simulation using BESOL 3-dimensional software provides a pragmatic solution. Long-term stability of the left-out stooks (in stowing cases only) or pillars is thus ensured, which is described elsewhere [9]. We should espouse the internationally-used best practices, and safe and efficient mining technologies with same subsidence engineering as discussed in this paper. For example, splitting with bolting for final extraction is widely used worldwide.

If a trial panel with bolted-split pillar-workings below a surface or sub-surface property at shallow depth of cover is undertaken with a suite of noble geotechnical instrumentation under a scientific organisation like CMRI, it is possible to establish this partial extraction method where higher recovery can be obtained. A pattern of side-bolting may be designed to offer similar confinement to the pillars but with higher envisaged factor of safety, 2.0 (and not 1.0 as in stowing) as compared to the confinement offered by good stowing.

References


