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

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सेन्ट्रल माइनिंग रिसर्च इन्स्टीच्यूट (सी.एम.आर.आई.), धनबाद, ने अवतलन संचलन को नियंत्रण करने वाले विभिन्न कारकों के मध्य संबंध, विभिन्न सतह (सब सर्फेस) लक्षणों एवं संरचनाओं के लिए अवतलन संचलन की सुरक्षित सीमाओं एवं अवतलन के नियंत्रण हेतु उपायों की जानकारी के लिए 1964 में अवतलन अन्वेषण प्रारंभ किया था। पहली विस्तृत रिपोर्ट ''सर्फेस सब्सिडेन्स इन माइनिंग एरियाज'' के रूप में 1991 में बनाई गई (1) जिसमें सी.एम.आर.आई. द्वारा 1964 से 1990 तक के किये गये अवतलन अन्वेषणों को सम्मिलित किया गया था। यह रिपोर्ट मल्टी-सीम परिस्थितियों के कुछ डाटा के साथ प्रमुख रूप से केवल सिंगल-सीम कार्यप्रणाली के लिए थी। इस रिपोर्ट में वर्णित अवतलन के विभिन्न परवर्त्तियों के बीच सहसंबंध तथा खनन ज्यामिति में काफी बिखराव देखा गया, जिनके कारण सांख्यिकी के रूप में यह रिपोर्ट महत्वपूर्ण नहीं थी, अत: एक नई रिपोर्ट ''एस्टीमेशन ऑफ सब्सिडेन्स ओवर सिंगल-सीम वर्किंग्स इन कोल माइनिंग एरियाज'' सामने आई, जिसे पुरानी रिपोर्ट में वर्णित प्रासंगिक आँकड़ों को पुन: विश्लेषण द्वारा बनाई गई थी (2)। यहाँ भारत के एकल सीम निष्कासन परिस्थितियों के अवतल अनुमान के लिए नया विश्लेषण भी किया गया। 19 बहुल सीम खनन केव्ड पैनलों पर आधारित (उपरी सीम निष्कासित केव्ड एवं निर्धारित) सी.एम.आर.आई. द्वारा एक नया प्रोजेक्ट (जो कि मंत्रालय द्वारा ग्रान्ट-इन-एड प्रोजेक्ट था) लिया गया तथा अवतलन अनुमान करने वाले मॉडेल विकसित किये गए। एकल तथा बहुल सीम दोनों प्रकार के मामलों के लिए प्रभावी कार्यविधि आधारित एक कम्प्यूटर-सहायता प्राप्त (एडेड) अवतलन अनुमान के मॉडेल का सुझाव दिया गया (3)।

अवतलन पर पहले किये गए अध्ययनों के आधार पर तथा पिछले दशकों में सी.एम.आर.आई. द्वारा संचालित दो ग्रान्ट-इन-एड परियोजनाओं के कारण एकल सीम तथा बहुल सीम वर्किंग्स के लिए अवतलन पैरामीटरों एवं पूर्वानुमेय मॉडलों के बीच मानक तथा संबंधों के बारे में सुझाव देना अब संभव है। लेकिन इन मानकों के विकास के दौरान एस.ई.सी.एल. (साउथ ईस्टर्न कोलफील्ड्स लि0) खदानों के आँकड़ों को निम्नलिखित कारणों से छोड़ देना होगा:-

* एस.ई.सी.एल. के अवतलन प्रेक्षण की न्यूनता।
* दूसरे कोयला क्षेत्रों की तुलना में असंगत रूप से कम मान के अवतलन गणक।
* एस.ई.सी.एल. से प्राप्त अधिकतम आँकड़ें स्टोईंग की परिस्थितियों के थे, जबकि एकल पैनेल में केविंग की परिस्थितियाँ ही अवतलन होने के लिए सबसे खराब होती है।

इस प्रकार एस.ई.सी.एल. कोयला क्षेत्र की परिस्थितियों में एकल सीम निष्कर्षण के लिए अवतलन पुर्वानुमेय, जैसा कि पहले बताया गया है, सही छवि प्रकट नहीं कर सकता है तथा अवतलन का बहुत अधिक मान बता सकता है, जबकि वास्तव में इसका मान बहुत ही कम है।

इन विषयों को ध्यान में रखते हुए जुलाई 2000 से अगस्त, 2004 के बीच कोयला मंत्रालय द्वारा ग्रान्ट-इन-एड फंडिंग के अन्तर्गत अलग से अवतलन अन्वेषण अध्ययन इस उद्देश्य के साथ किये गए कि भविष्य में एस.ई.सी.एल. खदानों के लिए अनुमेय अवतल मॉडलों के बारे में सुझाव दिया जा सके।

इन अध्ययनों ने अवतलन अभियांत्रिकी के लिए पूर्ण रूप से नया परिदृश्य खोल दिया है, जिसका एक स्पष्टीकरण इस आलेख में भी दिया गया है।

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 a 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 normalising 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

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

Where

c_1, c_2 and c_3 are constants

$x = \dfrac{W / H}{NEW}$, W = width of the panel

h = height of extraction

e = percentage of extraction, taken as the ratio

a = subsidence factor = S/h.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:

$$S = 0.33[1 + 1.1 \tanh(1.4(x - 1.8))] \text{ -------------- } (2)$$

After the recently-concluded scientific subsidence monitoring studies, the formulae for subsidence prediction is suggested for SECL mines, as [5],

$$S = 0.3[1 + 0.8 \tanh(1.6(x - 1.5))] \text{ -------------- } (3)$$

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).

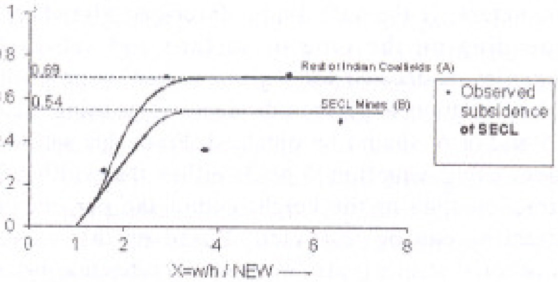

Figure 1: The general trend of subsidence trough occurrence in a single-seam extraction situation. Curve(A) plotted based on 85 caved cases in Indian coalfields [1, 2]; curve(B) plotted with selected caved cases (only continuous) from SECL, marked [5].

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 :

$$G = K_1 \frac{S}{H} \quad \text{--------------} \quad (4)$$

$$E_{(-)} = K_2 \frac{S}{H} \quad \text{------------} \quad (5)$$

$$E_{(+)} = K_3 \frac{S}{H} \quad \text{------------} \quad (6)$$

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,

$H/(h.e) < 0.3$ -------------- (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

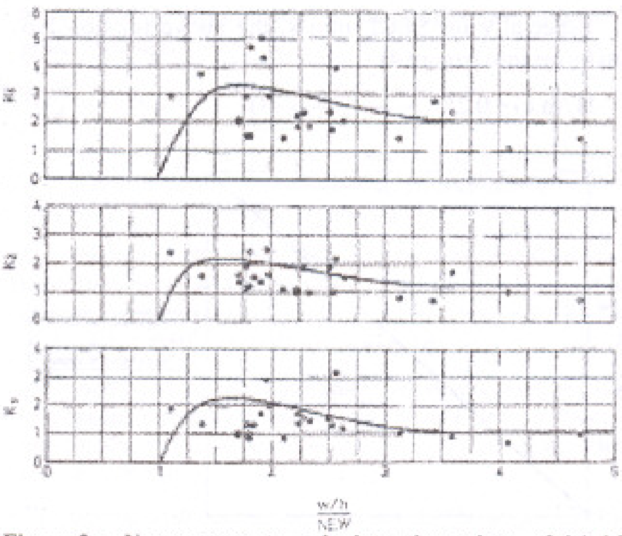

Figure 2 : Nomograms to calculate the values of k1, k2 and k3 in a single-seam extraction situation. Depending on the value of $x = \frac{w/h}{NEW}$, subsidence observation case-studies have been marked.

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.

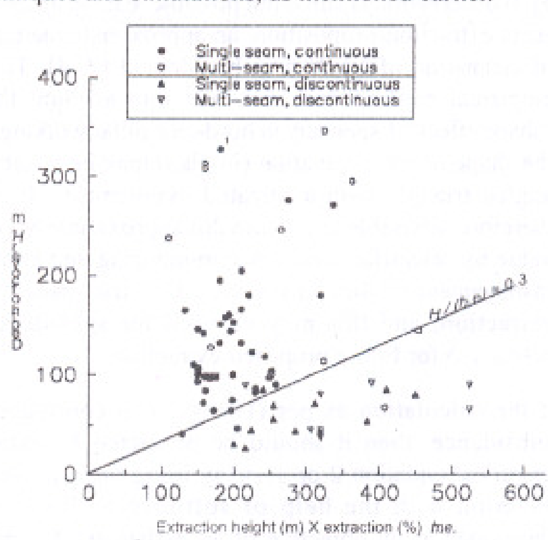

Figure 3 : Showing the line of demarcation to know the nature of likely subsidence. Continuous or dis-continuous, the study-sites marked cover all the Indian coalfields except SECL areas.

Especially for SECL mines, the above relationship transforms into [figure 4]:

$$H/(h.e) < 0.25 \quad \text{--------------} \quad (8)$$

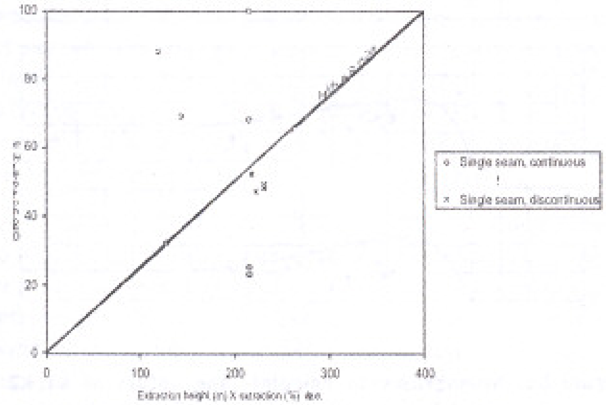

Figure 4 : Showing the line of demarcation to know the nature of likely subsidence:continuous or discontinuous, the study sites marked are those of SECL mines only.

Steps to predict subsidence parameters for given geo-mining 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 below-ground void-created dimension vis-à-vis the onset of measurable subsidence as elaborated elsewhere [1,2, 5]. 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 (I) 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 (I) 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.

(Bejdih colliery, Dubeswari colliery, Methani colliery / Sodepur Area Manoharbahal colliery, Salanpur Area / ECL; West Jhagrakhand colliery / Hasdeo Area / SECL; Murulidih 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 , Dhemomain colliery, Sodepur colliery / Sodepur Area / ECL; Banki colliery, Balgi 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).

(Sheetaldhara-Kurja underground project, Kapildhara underground mine / Hasdeo Area / SECL; Ketki underground mine / Bisrampur Area /SECL; Rajgamar 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 sane subsidence engineering as discussed in this paper. For example, splitting with bolting for final extraction is wisely used worldwide.

If a trial panel with bolted-splitted 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.

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