Semi-empirical model for predicting pot-hole depth in underground coal mining

Lokhande D. Ritesh[1,]*, V. M. S. R. Murthy[2] and Singh Kalendra[3]

[1]Visvesvaraya National Institute of Technology, Nagpur 440 010, India
[2]Indian Institute of Technology (ISM), Dhanbad 826 004, India
[3]Central Institute of Mining and Fuel Research, Dhanbad 826 001, India

Pot-hole subsidence can be induced by extracting underground coal seam at shallow depth and is a matter of great concern. This has been the case in some of the coal mines of South Eastern Coalfields Limited, a subsidiary of Coal India Limited. Many of the old underground coal mines developed by bord and pillar method of mining lying at shallow depth are posing stability concerns to the habitat due to pillar collapse and gallery widening under the creep loading and weathering. This requires a systematic study for developing an in-depth analysis on various parameters which influence pot-hole occurrence and also for formulating suitable predictive models. A study was conducted to analyse the pot-hole subsidence data related to 34 pot-hole cases and develop a semi-empirical model for simulating pot-hole depth. This study was carried out in some of the Indian coal mines during different stages of coal extraction, i.e. development and depillaring. Data analysis indicates that height and width of extraction, thickness of soil and rock layers, weighted density and compressive strength are key contributing parameters for the occurrence of pot-hole subsidence. The predicted results match with the actual pot-hole depth measured in the field, validating the model.

Keywords: Bord and pillar method, depillaring, pot-hole subsidence, pot-hole depth, underground coal mining.

MINING, particularly underground mining, is of crucial importance than opencast mining because of environment concerns. As shallow depth coal seams are being exhausted at a rapid pace, it is expected that future focus will be on underground mining because of the negligible impact of deeper excavation on the overlying strata and its environment. However, underground coal mining at shallow to moderate depths can damage the surface and sub-surface strata because of large amount of ground movement. Hazardous environmental damages can be caused by deformation in underground mining on the ground surface. This can be long-term, widely distributed and can lead to large-scale disasters[1].

*For correspondence. (e-mail: riteshlokhande@gmail.com)

Pot-hole subsidence is the most common concern, as most of the underground mines at shallow depth and old mines are surrounded by human habitat. As pot-hole formation never occurs with any prior indication, it can pose a danger to human life and property. Surface features could collapse houses adjacent to it (Figure 1). When there is an inflow of surface run-off into the mine and emission of mine gases, the formation of pot-hole becomes hazardous. Breathing of air in mines through pot-holes electriorate underground conditions[2–5]. Pot-hole prediction model is necessary so that appropriate preventive measures can be taken to arrest pot-hole subsidence.

Mechanism of pot-hole

The main reason for occurrence of pot-hole is falling of overlying strata into the excavated area, especially over

Figure 1. Impact of pot-hole subsidence on surface structure[31,32].

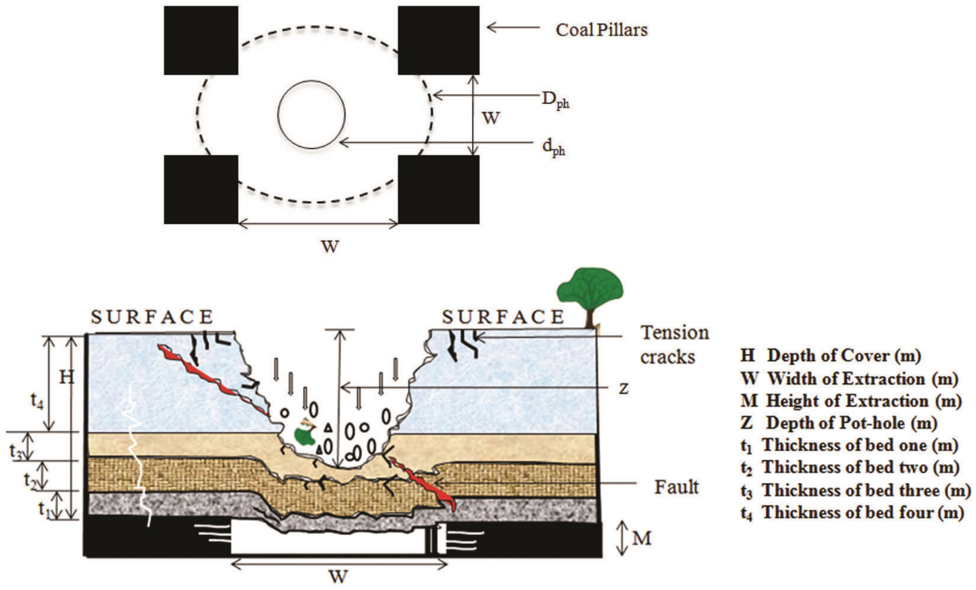

Figure 2. Mechanism of pot-hole subsidence.

mine junctions or flow of material through geological discontinuities such as fault/fractures in the presence of water. The load of overburden after extraction of coal is shifted to nearby coal pillars. As a result, the stress value of the materials above the mined out area gets elevated. Depending on the initial state of stress, tensile stress in the immediate roof and/or high compressive stress at the upper corners of the opening may develop[6]. If the roof contains vertical fractures or joints, tensile stresses will not develop; however, the creation of fractures may occur In each of the cases, there will be a slight downward deflection of roof and a self-supported linear arch will be formed. Finally, pot-hole subsidence may form on the surface. The conceptual model is given in Figure 2.

Field studies

Field parameters like mining conditions and geological discontinuities play an important role in the occurrence of pot-hole subsidence. The field study was done at seven mines located in three different areas of South Eastern Coalfields Limited (SECL), India, namely, Jamuna Kotma, Hasdeo and Bisrampur areas where pot-hole problem is common (Figure 3). This study deals with a total of 34 pot-hole cases which are of different geo-mining conditions[5].

Analysis of reviewed models

Several models were developed for pot-hole subsidence prediction and each of them was utilized pertaining to geo-mining conditions, geometry of extraction, a strength of immediate roof and geometry of pot-hole[2,7–30].

From the literature review, three models were identified which are directly related to the study and can be used to determine the pot-hole depth. These models proposed[16,21,25] were used to understand their suitability in Indian conditions by incorporating the collected field data.

Whittaker and Reddish model

In this model, the amount of volume filling cavity and the volume created due to excavation are main basis for estimation of pot-hole depth. A bulking factor of 1.2 and a 30° angle of repose were assumed for the soft overburden rocks and soil encountered respectively, in the present analysis. The predicted pot-hole depth is given by eq. (1)

$$z=\left(\frac{4}{(k-1)\times\pi\times D^2}\right)\times(2\times w\times M^2\times\cot\varphi+M\times w^2), \quad (1)$$

where k is the bulking factor (1.33 to 1.5); z the height of pot-hole (m); D the diameter of pot-hole (m); w the width of mine rooms (m); M the excavated height of mine rooms (m) and φ is the angle of repose of caved rock within mine rooms adjoining collapse area.

The collected data was analysed to relate the influence of excavated height and pot-hole diameter due to pot-hole depth. Results are depicted in Figures 4 and 5 respectively. It was observed that as the excavated height increases, the void volume also increases which will trigger and accommodate more material from weak overlying strata. Thus, the pot-hole depth tends to increase. Figure 5 shows that the pot-hole depth decreases with an increase in pot-hole diameter, yielding a reasonably good fit

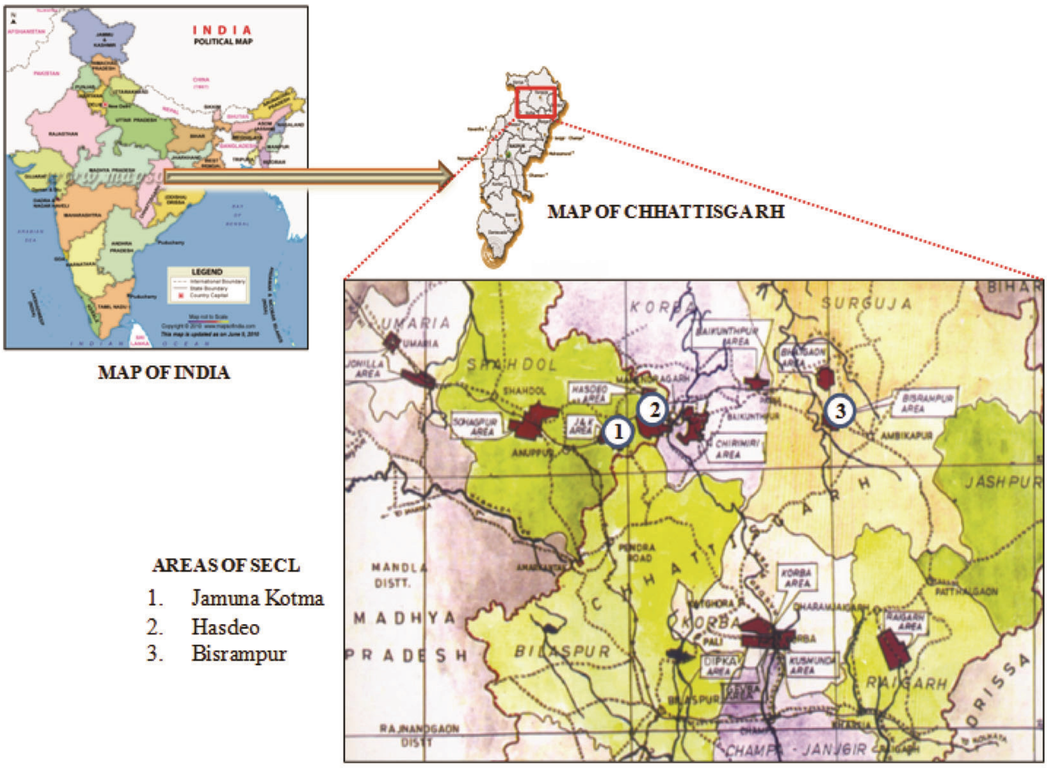

Figure 3. Geographical location of the study areas[33,34].

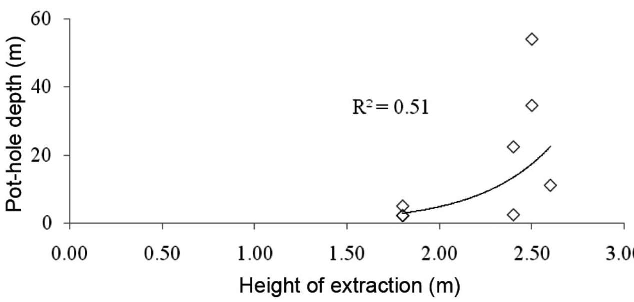

Figure 4. Influence of height of extraction on pot-hole depth in Whittaker and Reddish model.

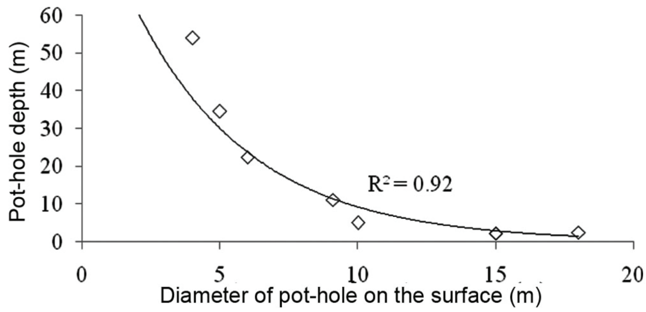

Figure 5. Influence of pot-hole diameter on pot-hole depth in Whittaker and Reddish model.

between the two parameters. The cavity diameter on the surface has been also taken into account in the Whittaker and Reddish model.

Dyne model

Dyne model[21] was exclusively developed for South-western Pennsylvania, where application of the Whittaker and Reddish model was found to be limited. This model was developed for developed workings only. The model used different parameters for estimation of pot-hole depth, namely, excavated height, the diameter of pot-hole at the surface and at the base, the width of extraction and an assumed bulking factor of 1.2 and an angle of repose of 30°. Equation (2) is given by

$$z = 12/\Pi(k-1)(d_{\text{base}^2} + d_{\text{surf}^2} + d_{\text{base}}d_{\text{surf}})\ (\Pi/12t\ (d_{\text{base}^2}$$

$$+D^2 + Dd_{\text{base}}) - ((D-w)/6\tan\theta)(D^2\text{acros}(w/D)$$

$$-D^2/2\sin(2\text{acros}(w/D)) - \Pi D^2/4 + w^2)), \qquad (2)$$

where z is the height of pot-hole (ft); k the bulking factor (1.33 to 1.5); t the excavated height of mine rooms (ft); d_{base} the diameter of pot-hole at base (ft); d_{surf} the diameter of pot-hole at earth's surface (ft); $D = d_{\text{base}} + 2t \cot \theta$; w the width of mine rooms (ft) and θ angle of repose of caved rock within mine rooms adjoining collapse area.

It was analysed by correlating pot-hole depth to excavated height and diameter of the pot-hole. Results are depicted in Figures 6 and 7 respectively. From Figure 6, it was observed that there was no concrete relation between the pot-hole depth and the excavated height. The plot has a poor index of determination (R^2). Also, the estimated depth is on the higher side compared to the measured depth of pot-hole. Similar to the Whittaker and Reddish model, a declining trend was noticed here as well, i.e. pot-hole having higher diameter has lower depth and vice-versa (Figure 6). From Figures 6 and 7, it was found that values obtained by this model are on the higher side than measured values and hence warrant further analysis.

Tajdus K and Sroka A model

Tajdus K and Sroka A[25] model considers the volume of the excavated area, thickness of the strong rock mass, angle of pot-hole slope, the height of excavation and bulking factor. The equations proposed for the ellipse (r_{11}, r_{12}), circle (r_1) radius of pot-hole are given by

$$r_{11} = \sqrt[3]{\frac{3V_p\left(h_g + \frac{1}{2}g\right)}{k_r \pi t_g \alpha}} L/D, \tag{3}$$

$$r_{12} = r_{11} \cdot D/L, \tag{4}$$

where V_p is the volume of excavated area (m^3); h_g the thickness of strong rock mass (m); α the angle of pot-hole slope (the same as the angle of repose); L the width of excavation (m) and D is the length of excavation (m).

Circle radius of pot-hole (r_1)

$$r_1 = \sqrt[3]{\frac{3V_p\left(h_g + \frac{1}{2}g\right)}{k_r \pi t_g \alpha}}, \tag{5}$$

Depth of pot-hole (w_1):

$$w_1 = r_{11}\ t_g\alpha \text{ assuming } w_1 \le h_{n1} + L_p \cdot t_g\alpha,$$

where h_{n1} is the thickness of soft clay (m) and L_p the radius of void (m).

A parametric analysis was carried out separately for developed and depillared cases investigated in this study. The results are discussed below.

Development cases: Under this condition, the extraction height and excavation volume were considered for developing relation a with pot-hole depth as given in Tajdus and Sroka model (Figure 8). Pot-hole depth increases with an increase in excavation thickness. This happens because increasing excavation thickness increases the void volume, thus inviting more material to cave in. This

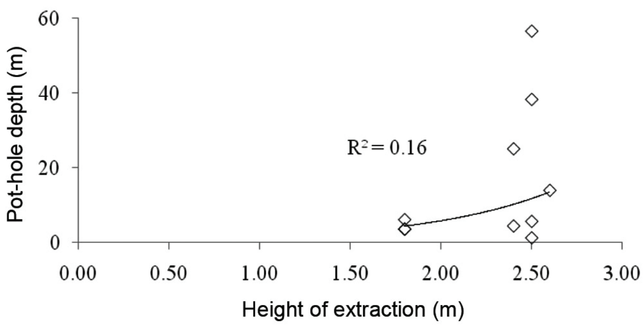

Figure 6. Influence of height of extraction on pot-hole depth in Dyne model.

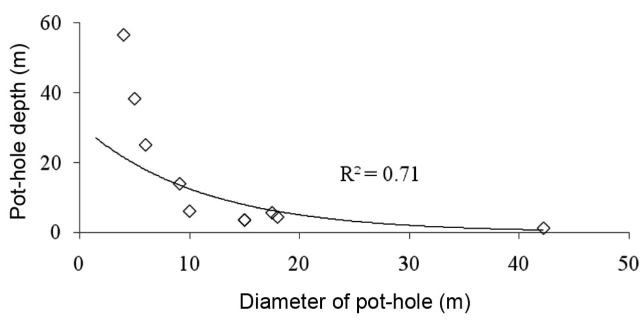

Figure 7. Influence of pot-hole diameter on pot-hole depth in Dyne model.

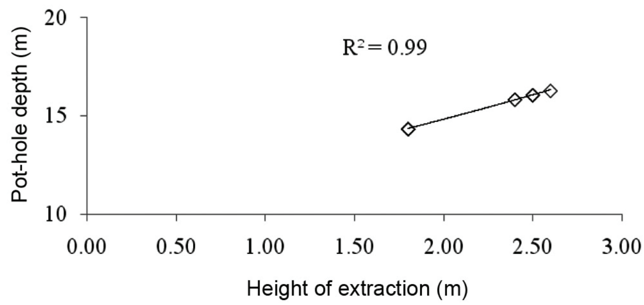

Figure 8. Influence of height of extraction on pot-hole depth of development working in Tajdus and Sroka model.

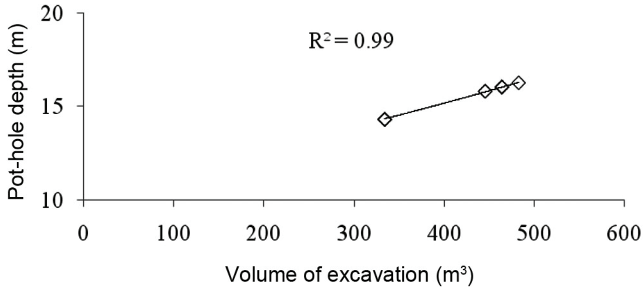

Figure 9. Influence of volume of excavation on pot-hole depth of development working in Tajdus and Sroka model.

curve only supports our conviction in this model when applied to Indian conditions. A relation developed between pot-hole depth and volume of the excavation under development is shown in Figure 9. The curve gives an excellent match of the two parameters (Figure 9). With increase in excavation volume, the pot-hole depth should increase, because higher excavation volume makes the immediate roof vulnerable and causes the material to cave in.

Depillaring cases: To find out the applicability of this model in depillaring condition, analysis was performed using the same parameters and the relationship developed between pot-hole depth and height of excavation is shown in Figure 10.

This model gives an increasing plot with height extraction. This is because increasing height increases the volume of excavated area, thus encouraging more and more material to fill in the area. However, the fit of this curve was poor (Figure 10). The pot-hole depth values obtained using these models were much higher than the actual pot-hole depths measured for the investigated cases. Figure 11 shows an increasing trend in pot-hole depth with the volume of excavation under the same conditions.

With increasing excavation volume the fractures propagate deeper into the immediate roof and the void volume increases, thus encouraging more material to cave in. The volume considered in this case is the total volume of the panel or the goaf area, i.e. a product of length, width and height of extraction.

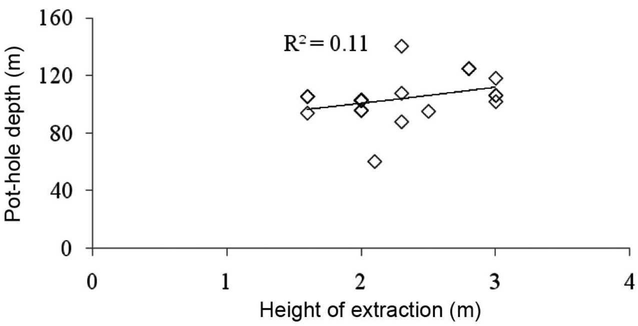

Figure 10. Influence of height of extraction on pot-hole depth of depillaring working in Tajdus and Sroka model.

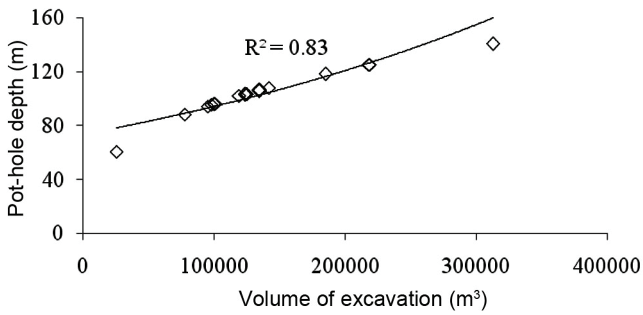

Figure 11. Influence of volume of excavation on pot-hole depth of depillaring working in Tajdus and Sroka model.

It can thus be summarized that the three models discussed above are essentially applicable to development workings only. Therefore, there is a need to develop prediction models involving depillaring workings from the actual field data.

Development of pot-hole depth prediction model

To predict the depth of pot-hole for shallow depth extraction, a model was developed based on the pot-hole subsidence studies and analysis of critical parameters. The parameters were initially recognized from the literature review, current field study and the analysis of relationships. The parameters used for development of pot-hole depth model were height and width of extraction, the thickness of soil and rock layers, weighted density and weighted compressive strength of the rock layers.

For identifying the critical parameters, a thorough understanding is important to develop the prediction model. Also, it is important to note that the depth of the pot-hole also changes with time. Considering that the soil portion will always be converted to pot-hole, the minimum possible pot-hole depth is equal to the thickness of the soil layer. Further, increase in depth will depend on the nature of strata below the soil layer and its competence. To determine the percentage of rock layer that will be converted into pot-hole depth: Let λ is the percentage of rock layer that is converted into pot-hole. With the above assumption, the eq. (6) shows estimation of pot-hole depth

$$Z = S + \frac{\lambda}{100} \times T, \tag{6}$$

where z is the pot-hole depth (m); S the thickness of soil layer (m); λ the percentage of rock layer changed into pot-hole and T is the thickness of rock layer (m).

Now λ is directly proportional to M (height of extraction) and W (width of extraction), also it is inversely proportional to V_d (weighted density) and σ_w (weighted compressive strength).

$$\frac{\lambda}{100} = C * \frac{M^a \times W^b}{V_w \times \sigma_w}. \tag{7}$$

Here a and b are powers of M and W respectively, and C is constant. So eq. (6) becomes

$$Z = S + C \times \frac{M^a \times W^b}{V_w \times \sigma_w} \times T. \tag{8}$$

Now the correlation of this equation with different values of a and b (Tables 1 and 2). The best R^2 was found to be 0.683 with $a = 1$ and $b = 1$.

Table 1. For development case (assume $C = 1$)

V_m (kN/m^3)	σ_w (MPa)	M (m)	W (m)	S (m)	T (m)	Field, z (m)	$a = 1; b = 1$	$a = 1; b = 2$	$a = 2; b = 1$	$a = 2; b = 2$
21.5	5.37	2.5	4.2	27	26	15	29.36456	36.93114	32.91139	51.82786
22.1	6.48	2.4	4.2	3.8	20.1	6	5.214781	9.742081	7.195475	18.061
22.07	5.72	1.8	4.2	9.99	53.01	10	13.16454	23.32308	15.70418	33.98955
22.07	5.72	1.8	4.2	9.99	53.01	9	13.16454	23.32308	15.70418	33.98955
21.71	6.46	2.5	4.2	6	10	10	6.748681	9.144461	7.871703	13.86115
21.71	6.5	2.5	4.2	6	17	3	7.264926	11.31269	9.162314	19.28172
22.13	6.19	1.8	4.2	6.98	25.2	6	8.370754	12.82117	9.483357	17.4941
Index of determination (R^2)							0.683	0.641	0.671	0.595

V_m, Weighted density; σ_w, Weighted compressive strength; M, Height of extraction; W, Width of extraction; S, Thickness of soil layer; T, Thickness of rock layer.

Table 2. For depillaring case (assume $C = 1/40$ to account for large W in depillaring case)

V_m (kN/m^3)	σ_w (MPa)	M (m)	W (m)	S (m)	T (m)	Field, z (m)	$a = 1; b = 1$	$a = 1; b = 2$	$a = 2; b = 1$	$a = 2; b = 2$
22.17	6.8	2.8	160	3.8	27.7	5	5.857895	333.0632	9.562106	925.7369
22.51	6.8	2.8	160	3.8	28	3.7	5.848763	331.602	9.536535	921.6457
22.51	6.8	2.8	160	3.8	28	3.4	5.848763	331.602	9.536535	921.6457
21.71	6.55	3	160	6	14	6	7.18143	195.0289	9.544291	573.0866
21.71	6.55	3	160	6	14	6	7.18143	195.0289	9.544291	573.0866
21.72	6.59	3	198	6	19	12	7.971219	396.3013	11.91366	1176.904
20	6.63	2	240	4	19.5	4	5.764706	427.5294	7.529412	851.0588
20	6.63	2	240	4	20	4	5.809955	438.3891	7.61991	872.7783
20	6.63	2	360	4	16	8	6.171946	785.9005	8.343891	1567.801
20	6.63	2	360	4	14	6	5.900452	688.1629	7.800905	1372.326
20	6.63	2	198	4	16	3	5.19457	240.5249	6.38914	477.0498
20.48	6.66	1.6	380	1.5	22.5	4	4.00739	954.3083	5.511824	1525.993
20.48	6.66	1.6	380	1.5	22.5	3	4.00739	954.3083	5.511824	1525.993
22.3	6.73	2.3	360	3	12.7	5	4.751677	633.6039	7.028858	1453.389
22.3	6.69	2.3	200	3	24.5	5	4.888569	380.7139	7.34371	871.7419
Index of determination (R^2)							0.505	0.003	0.434	0.036

Thus, the formula for development case would be

$$Z = S + C \times \frac{M \times W}{V_w \times \sigma_w} \times T. \tag{9}$$

The formula for depillaring case would be

$$Z = S + C \times \frac{M \times W}{V_w \times \sigma_w} \times T. \tag{10}$$

Now to find out the constants, the following basis is considered.

The average width W in development working is 4.2 m and the average width in depillaring working is 247.73 m. The correction factor to be introduced for the status of working should thus be

$$K_t = \frac{247.73}{4.2} \approx 60.$$

Constant K_s to account for the variation in the properties of soil is given by

$$K_s = C \times V_w \times \sigma_w. \tag{11}$$

Now, considering an average value of field z and calculated z, it is found that using $C = 2/3$ we can get the averages to be same in development case, i.e.

$$K_s = \frac{2}{3} \times V_w \times \sigma_w. \tag{12}$$

Thus, the final equation is

$$Z = S + \frac{M \times W}{K_t \times K_s} \times T, \tag{13}$$

where z is the depth of the pot-hole (m); S the thickness of the soil layer (m); T the thickness of the rock layer (m); M the height of extraction (m); W the width of extraction (m); K_t the constant factor for status of working (for development = 1 and depillaring = 60); K_s the coefficient of rock layer = $2/3 V_w \sigma_w$; V_w the weighted density of the rock layer (kN/m^3) and σ_w is the weighted compressive strength of the rock layer (MPa).

Table 3. Calculated depth of pot-hole for both development and depillaring

V_m (kN/m^3)	σ_w (MPa)	M (m)	W (m)	S (m)	T (m)	z_m (m)	z_e (m)	Status of working
21.02	5.75	2.60	4.2	12.5	18.5	11.9	15.01	Development
22.10	6.48	2.40	4.2	3.8	20.1	6	5.92	Development
22.17	6.80	2.80	160	3.8	27.7	5	5.86	Depillaring
22.51	6.80	2.80	160	3.8	28	3.7	5.85	Depillaring
22.51	6.80	2.80	160	3.8	28	3.4	5.85	Depillaring
24.11	6.80	2.50	4.2	2.28	17.22	6	4.03	Development
22.07	6.62	1.80	4.2	9.99	53.01	10	14.75	Development
22.07	5.72	1.80	4.2	9.99	53.01	9	14.75	Development
22.13	6.19	1.80	4.2	6.98	25.2	6	9.07	Development
21.71	6.55	3.00	160	6	14	6	7.18	Depillaring
21.71	6.55	3.00	160	6	14	6	7.18	Depillaring
21.71	6.50	2.50	4.2	6	17	3	7.89	Development
20.00	6.63	2.00	240	4	19.5	4	5.77	Depillaring
20.00	6.63	2.00	240	4	20	4	5.81	Depillaring
20.00	6.63	2.00	360	4	16	8	6.17	Depillaring
20.00	6.63	2.00	360	4	14	6	5.90	Depillaring
20.00	6.63	2.00	198	4	16	3	5.20	Depillaring
20.40	6.61	2.00	396	4	31.3	6	8.59	Depillaring
20.48	6.66	1.60	380	1.5	22.5	4	4.01	Depillaring
20.48	6.66	1.60	380	1.5	22.5	3	4.01	Depillaring
21.00	7.11	1.60	360	3.8	20.2	2.5	5.75	Depillaring
22.30	6.73	2.10	160	3	19	6	4.06	Depillaring
22.30	6.73	2.30	480	3	29.9	6	8.50	Depillaring
22.30	6.73	2.30	360	3	12.7	5	4.75	Depillaring
22.30	6.69	2.30	200	3	24.5	5	4.89	Depillaring
21.50	5.37	2.50	4.2	27	26	15	30.55	Development

z_m, Measured depth of pot-hole; z_e, Estimated depth of pot-hole.

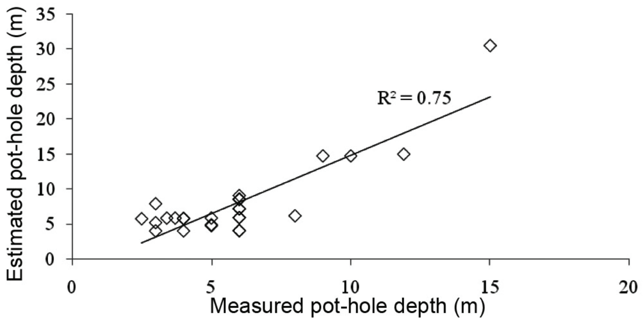

Figure 12. Measured and estimated pot-hole depth for development and depillaring working.

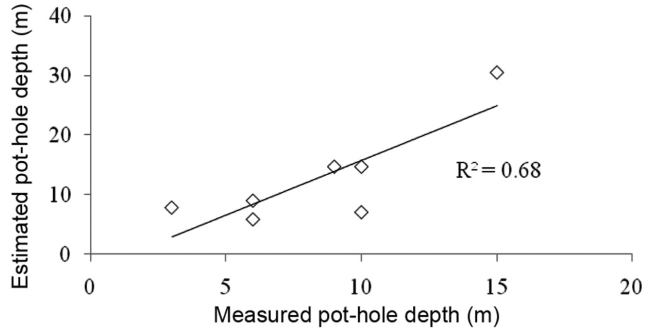

Figure 13. Measured and estimated pot-hole depth for development working.

Model validation

Depth of pot-hole in development and depillaring cases

The developed model (eq. (3)) can estimate pot-hole depth for both development and depillaring conditions. The pot-hole cases studied under these conditions have been compiled and presented in Table 3. The model was validated by regression analysis and is shown in Figure 12. The index of determination (R^2) between the measured and estimated pot-hole depth is 0.75 and is reasonably accurate for future prediction.

Depth of pot-hole for development cases

The investigated development cases have been compiled separately and presented in Table 4. The developed semi-empirical model was validated by comparing the actual and predicted pot-hole depth values as shown in Figure 13. The R^2 between the actual and estimated pot-hole depth using the developed model is 0.68 for development cases.

Depth of pot-hole in depillaring case

Pot-hole cases in depillaring were compiled and presented in Table 5. The developed semi-empirical model

Table 4. Calculation of depth of pot-hole for development cases (with $K_t = 1$)

V_m (kN/m^3)	σ_w (MPa)	M (m)	W (m)	S (m)	T (m)	z_m (m)	z_e (m)
21.02	5.75	2.60	4.2	12.5	18.5	11.9	15.01
22.10	6.48	2.40	4.2	3.8	20.1	6	5.92
22.07	5.72	1.80	4.2	9.99	53.01	10	14.75
22.07	5.72	1.80	4.2	9.99	53.01	9	14.75
22.13	6.19	1.80	4.2	6.98	25.2	6	9.06
21.71	6.46	2.50	4.2	6	10	10	7.12
21.71	6.50	2.50	4.2	6	17	3	7.90
21.50	5.37	2.50	4.2	27	26	15	30.55

Table 5. Calculation of depth of pot-hole for depillaring cases (value of $K_t = 60$)

V_m (kN/m^3)	σ_w (MPa)	M (m)	W (m)	S (m)	T (m)	z_m (m)	z_e (m)
22.17	6.80	2.80	160	3.8	27.7	5	5.86
22.51	6.80	2.80	160	3.8	28	3.7	5.85
22.51	6.80	2.80	160	3.8	28	3.4	5.85
21.71	6.55	3.00	160	6	14	6	7.18
21.71	6.55	3.00	160	6	14	6	7.18
21.72	6.59	3.00	198	6	19	12	7.97
20.00	6.63	2.00	240	4	19.5	4	5.77
20.00	6.63	2.00	240	4	20	4	5.81
20.00	6.63	2.00	360	4	16	8	6.17
20.00	6.63	2.00	360	4	14	6	5.90
20.00	6.63	2.00	198	4	16	3	5.20
20.48	6.66	1.60	380	1.5	22.5	4	4.01
20.48	6.66	1.60	380	1.5	22.5	3	4.01
22.30	6.73	2.30	360	3	12.7	5	4.75
22.30	6.69	2.30	200	3	24.5	5	4.89

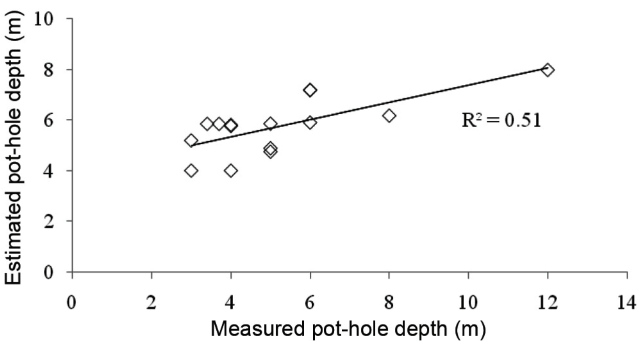

Figure 14. Measured and estimated pot-hole depth for depillaring working.

was validated by comparing the actual and predicted pot-hole depth values as shown in Figure 14. The R^2 between the actual and estimated pot-hole depth is 0.51 for depillaring cases. Thus, the model developed for predicting pot-hole depth for shallow underground coal mining can be used for prediction in future.

Discussion

Pot-hole depth prediction models discussed in the paper are not applicable directly to the cases studied and are constrained by certain boundary conditions. With Whittaker and Reddish model, the pot-hole depth value estimations were greater than the observed values in Indian conditions. The model is made for limited width of extraction and not useful for depillaring conditions.

Dyne model predicts pot-hole depth only for development cases. Further, in development, the results obtained from this model are not in good agreement with the observed field data. In this model, overburden thickness and seam thickness were calculated from the plan and not from actual field conditions. Width of extraction, bulking factor and angle of repose was assumed for development of this model. Tajdus and Sroka's model hold good for developed workings, but in depillaring workings, estimated pot-hole depth is much higher than the value observed in the field. Considering the above limitations, a new model was developed from the present study and the developed model was validated for combined development depillaring, and development, and depillaring separately. The models yielded a reasonable index of determination (R^2) with 0.75, 0.68 and 0.52 respectively, between the measured and estimated pot-hole depth. It was also found that the combined model works well for the estimation of pot-hole depth under various conditions.

Conclusion

The study highlights the problems of working at shallow depth mining related to pot-hole subsidence, especially, at SECL and in similar collieries. The semi-empirical model developed was found to be useful and helps to determine the amount of pot-hole depth. The model yielded good results with a reasonable degree of confidence. The prediction model which was developed for assessing the pot-hole depth will be useful to the mining industry in general and also in areas where these studies were carried out. The developed model does not represent the conditions where fault and water bodies are present or absent. More case studies have to be collected with varied geo-mining conditions, which can be incorporated to the developed models so that it can analyze the complex cases more precisely.

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