This paper discusses different causes and remedial measures of pot-hole subsidence due to underground coal mining. Pot-hole subsidence is an abrupt local surface depression due to sudden collapse of overburden into the void created following the extraction of coal. This can be hazardous to life and property as it occurs without any prior indication. Shallow depth of coal extraction, weak overburden, and geological discontinuities are the main causative factors. Rainfall, removal of hydrostatic support, and earthquake aggravate the occurrence of pot-hole subsidence. Pot-holes subsidence can be controlled to some extent by using proper design of support and construction of walls to create a barrier around an area prone to pot-hole subsidence in board and pillar development. Back-filling and grouting can be used to stabilise unapproachable underground abandoned workings.

### Causes of Pot-hole Subsidence

The main causes of pot-hole subsidence are a shallow depth cover, weak overburden, and geological discontinuities.

<table>
<thead>
<tr>
<th>S No</th>
<th>Location</th>
<th>Maximum depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Western Pennsylvania*</td>
<td>47.7</td>
</tr>
<tr>
<td>2</td>
<td>Hanna Area, Wyoming†</td>
<td>73.2</td>
</tr>
<tr>
<td>3</td>
<td>Beulan Area, North Dakota*</td>
<td>24.4</td>
</tr>
<tr>
<td>4</td>
<td>Sheridan Area, Wyoming‡</td>
<td>17.7</td>
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<tr>
<td>5</td>
<td>Illinois Coal Basin†</td>
<td>50.3</td>
</tr>
<tr>
<td>6</td>
<td>Colorado Springs Area†‡</td>
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</tr>
<tr>
<td>7</td>
<td>Superior &amp; Glenrock, Wyoming†,‡</td>
<td>30.5</td>
</tr>
<tr>
<td>8</td>
<td>Rock Springs, Wyoming†‡</td>
<td>101.5</td>
</tr>
<tr>
<td>9</td>
<td>Handidhua &amp; Deulbera collieries, Orissa‡</td>
<td>40.0</td>
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<td>10</td>
<td>Scranton, USA†</td>
<td>88.0</td>
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<td>11</td>
<td>Indiana, USA†</td>
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<td>12</td>
<td>Humberside &amp; Lincolnshire, UK‡</td>
<td>90.0</td>
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<td>13</td>
<td>Eastern US Coalfield†‡</td>
<td>30.0</td>
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<tr>
<td>14</td>
<td>Mithapur colliery, West Bengal‡</td>
<td>25.0</td>
</tr>
<tr>
<td>15</td>
<td>Jamuna &amp; Kotma Area, MP‡</td>
<td>43.0</td>
</tr>
</tbody>
</table>

*Indicates data from India
†Indicates data from the United States
‡Indicates data from the United Kingdom
discontinuities. Rainfall, removal of hydrostatic support and earthquakes aggravate their occurrence. A brief description to each causative factor is given below:

**Shallow Depth**

Shallow depth of working is a very important factor, which controls the pot-holing phenomenon in different part of the world. The depth of workings for the occurrence of pot-hole subsidence varies from 8 m to 101.5 m under different coal measure strata of the world (Table 1). Piggott and Eynon have defined shallow depth as a maximum of 10-times the height of the original roadway excluding surface unconsolidated layers. A correlation was developed between pot-hole subsidence and overburden thickness (h) to mining height (m) ratio. When the ratio is less than 5, there is a strong possibility of the occurrence of pot-holes which decreases when the ratio is between 5 and 11. It was reported that 90 per cent of total pot-holes occurred when h/m ratio was 6 and the upper height of migration of void was 8- to 12-times the height of mining. Caving height could reach to 7- to 10-times the mining height in the presence of the overlying aquifer in room and pillar mining. Hunt has developed a correlation between the depth of the workings and the soil thickness/rock thickness ratio of the overburden in Illinois. He concluded that soil thickness/rock thickness ratio in the overburden for the pot-holes was 0.1 to 1.0.

Analysis of recorded pot-holes of the Jamuna and Kotma Area of the SECL in Shahdol district of Madhya Pradesh showed that pot-holes occurred between 16 to 63 m depth. The soil thickness/rock thickness ratio in the overburden for these pot-holes is 0.14 to 0.32. The ratio of overburden thickness to mining height for the most of the pot-holes of the Jamuna and Kotma Area is between 6 and 40 (Figure 1). A linear equation is developed between overburden thickness and overburden thickness/mining height ratio which is given below:

\[ y = 1.4004x + 9.554 \quad \cdots (1) \]

where, \( y \) = overburden thickness, \( m \) and \( x = \) overburden thickness/mining height ratio.

Index of determination for Eq. (1) is 0.9334. Equation (1) can, also, be used by the coal mining industry for the prediction of pot-hole in advance under similar geo-mining condition.

**Weak Overburden**

Whenever an underground opening is created the strata immediately above the opening become de-stressed. The opening remains stable as long as the stresses do not exceed the strength of the roof rock. Over a period of time, roof stability may be jeopardized by the change in the stresses and strength of the roof rock. These changes may be due to groundwater inflow and creep up to great extent. The presence of water in the overburden also deteriorated the strength of the rock mass. Pot-holes occurred in the zones of weak overburden in Western Pennsylvania and Colorado Springs Areas. Caving of 10 to 15 m of a weak rock mass with an equal amount of sub-soil led to pot-hole formation (Figure 2) at Handidhua and Deulbera collieries in Orissa. The coarse grained sandstone in the overburden had 3 to
4 kg/cm² tensile strength \(^{14}\). These sandstone tended to flow in like sludge in saturated conditions. Two pot-holes occurred at Govinda colliery of Jamuna and Kotma Area, where saturated and weathered sandstones in the overburden was friable and had 60 kg/cm² compressive strength.

**Geological Discontinuities**

Geological discontinuities, particularly closely spaced joints and faults, play an important role in the formation of pot-holes. When a roof is formed from blocks bounded by joints, it may fail by shearing along planes of weakness when the vertical stress exceeds the shear resistance along the joints. Extensive rock fracturing caused pot-holes in Superior, Wyoming \(^{11}\). All the recorded pot-holes of the Jamuna and Kotma Area of the SECL occurred above developed and abandoned bord and pillar workings lying close to the incrop of the coal seams and Kewa River. A pot-hole at Meera Incline formed following the exposure of a fault between 11 and 12 levels in the main dip (Figure 3). Abnormally heavy water seepage was recorded through the fault plane along with sand and soil before formation of the pot-hole. Handihiua and Deulbera collieries also witnessed similar phenomenon along the fault planes.

**Rainfall**

Recharge of the overburden during the rainy season increases the pore pressure, which can trigger roof fall. A relationship was established between cumulative precipitation and cumulative pot-hole development \(^{21}\). It was found that pot-hole development reflected the quantity of precipitation experienced in the preceding 3 to 8 months. Esaki et al. \(^{22}\) have reported that the number of pot-holes increased rapidly during the rainy season in the Chikuku district in Japan. Rainstorms caused pot-holes on the surface in St David, Illinois \(^{9}\). Jamuna and Kotma Area witnessed the occurrence of 11 pot-holes during rainy season whereas occurrence period of 15 cases were not recorded. Remaining three cases of pot-holes occurred in dry period.

**Removal of Hydrostatic Support**

Removal of hydrostatic support to the roof in the old waterlogged workings is also a causative factor for the appearance of pot-hole \(^{20}\). Old waterlogged workings in the Searsole seam have been standing on the small stooks at 8 to 22 m depth since 1928 at Mahabir colliery in Burdwan district of West Bengal in Eastern Coalfields Limited (ECL). Removal of water from the upper old waterlogged workings of the Searsole seam into the lower active workings of Niga seam caused removal of hydrostatic support to the overlying strata. This resulted in the failure of the small stooks left in the Searsole seam and as many as 40 pot-holes appeared on the surface.

**Earthquakes**

Earthquakes can suddenly increase the number of pot-holes. The Tohoku district of Japan witnessed 15 to 20 pot-holes every year between 1947-1987 except in 1987 when an earthquake of 7.4 magnitude caused 219 pot-holes \(^{22}\). Underground blasting can also induce pot-holing phenomenon by way of loosening/opening of joints and faults. This causes roof failure and inflow of washed out overburden materials which ultimately result in the formation of pot-holes.

**Mechanism of Pot-hole Subsidence**

Pot-hole subsidence results from the intermittent, sequential collapse, and unraveling of underground mine roof in localized area, whereby caving migrates through the overlying strata until the fracture zone intercepts the unconsolidated overburden. Generally the roof may fail in two basic modes, i.e., tensile and shear \(^{31}\). After the initial tensile or shear failure of the roof, caving will continue to propagate upward until it is arrested by more competent roof layer or by bulking of the roof debris. The expression of the feature at surface depends on the physico-mechanical properties of the unconsolidated overburden.
The mechanism of a pot-hole occurred at Meera Incline of Jamuna and Kotma Area of the SECL is different. The overburden comprises saturated (water bearing) sandstone and alluvium. The upper portion of the sandstone lying just below the alluvium is weathered and friable. When the face advanced 10 m ahead of the Main Dip-II Level junction in the Upper Kotma (top section) seam, a fault was intersected (Figure 3). Thereafter, heavy inflow of water with sand and soil was noticed along the fault plane. The magnitude of water inflow increased to 9000 l/min. The inflow of water was measured by installing V-Notch across the water flow close to exposed fault plane. The sand and soil were eroded from the weathered, weak and friable sandstone which resulted in the formation of the cavities in the overburden (Figure 4). Thus, a pot-hole appeared on the surface within 7d after the intersection of the fault plane in the heading, following the collapse of the cavities.

Preventive Measures

It has already been mentioned that pot-holing phenomenon creates very serious problems due to the absence of any prior indications. Therefore, it is necessary to know the preventive measures to avoid this phenomenon. The important preventive measures include: designing of proper stiffness of support, construction of walls, grouting of voids, back filling, filling of cracks, etc. A brief description to each preventive measure is discussed below:

Support

Designing proper supports should support the area prone to the occurrence of pot-holes in the board and pillar workings. It is advised to design support based on CMRI geo-mechanical classification of Indian coal measures. This classification is based on statistical study on exposed roof with respect to layer thickness, structural discontinuities, weatherability, compressive strength and ground water seepage. These factors allocated 30, 25, 20, 15, and 10 per cent ratings on the basis of statistical analysis of Indian coal measures. The individual rating is added to know Rock Mass Ratings (RMR). The Indian coal mine roof is divided into five classes. The roof support is designed based on the above classification following the computation of rock pressure as given in Eq. (2).

\[ P_r = B \cdot \gamma \cdot \text{rock load factor}, \]
\[ P_r = B \cdot \gamma \cdot (1.7 - 0.037 \text{ RMR} + 0.0002 \text{ RMR}^2), \]

where, \( P_r \) = rock load, t/m², \( B \) = roof span, m, and \( \gamma \) = rock density, t/m³.

Construction of Walls

When a collapsed roof and inflow of sand and soil with water along a fault pose a significant risk for pot-holes at the surface in the development headings, suitable walls can be constructed to form a barrier around the collapsed area and zone of inflow of sand and soil with water. Underground volume of void is reduced by erecting the suitable walls. Inflow of eroded soil and sand automatically be stops after filling of this reduced void and thus, void formation in the overburden can be avoided. This has been highly successful in the pot-hole prone areas of British coalfields and Jamuna and Kotma area of the SECL.

Grouting of Voids

This approach can be applied as a local area stabilisation technique to support buildings, highway, school, religious buildings, etc. There are two commonly used grouting techniques. One utilizes a sand grout mixture, which is injected into rubblized zones of roof failure and small void to support the roof and eliminate the available space for continued downward movement of the overburden (Figure 5). Another approach can be used in the areas of large voids. This employs gravel-grouted columns to provide direct support to the mine roof (Figure 6). Several pot-holes occurred over abandoned bord and pillar workings in Glenrock, Wyoming which created danger to highway, residential and commercial complexes. These surface structures were successfully stabilized by using 6670 m³ grout mixture.

Back-filling

Normally hydraulic back-filling technique is used to stabilize abandoned workings on a regional basis. Sand, fly ash, crushed rock, and coal mine refuse are used as a fill materials. The stiffer the fill the sooner the
passive resistance will be mobilized and limit deformation and restrict the progression of failure. The entire city of Rock Springs spreading over 13.5 ha, Wyoming lied over abandoned underground coal mine. High pillar extraction and robbing caused 78 subsidence events wherein large majority of them were pot-holes. Hydraulic back-filling to abandoned underground workings using abandoned surface coal mine spoils saved the entire city. The total quantity of back-fill material was 200,000 tones and the cost of back-filling was US $ 55,403/ha.

**Filling of Cracks**

Soil and Sand – Cement mixture above alluvium and rocks, must fill in cracks formed due to ground movements, respectively. However, if the cracks have developed in river or rivulet beds, they 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 pot-hole formation.

**Conclusions**

Pot-hole subsidence caused due to underground coal mining poses serious threat to life and property due to the lack of any surface indications prior to their formations. They occurred up to 63 m depth in Jamuna and Kotma area of the SECL in India. The pot-holes occurred where the soil thickness to rock thickness ratio in the overburden was 0.14 to 0.32. A linear equation was developed between overburden thickness and overburden thickness/mining height ratio. Fault created a direct path between the underground workings and weak weathered water bearing overburden in which cavity is created. This cavity caved in and thus pot-hole appeared on the surface. Pot-holing phenomenon can be controlled to some extent by using proper support and providing a barrier to restrict inflow of weathered material by erecting competent walls in the development workings. Grouting and back-filling can be used to stabilize overburden lying above unapproachable abandoned workings.

**Acknowledgement**

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**References**


24 Anonymous, Geo-mechanical Classification of Coal Measures Roof Rocks via-a-via Roof Support, Published Report (Central Mining Research Institute, Dhanbad) 1987, 125 pp.