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# An Investigation of Sinkhole Subsidence and its Preventive Measures in Underground Coal Mining

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**Abstract**

Subsidence is a depression of the ground on the surface due to extraction of minerals from underground coal mines. It occurs in two forms, namely, trough and sinkhole subsidence. Trough subsidence is a depression covering a large surface area whereas sinkhole subsidence is a localized phenomenon occurring due to sudden collapse of overburden into the underground voids.The impact of sinkhole subsidence on the environment can occasionally be very catastrophic, destroying property and even leading to the loss of life. The environmental components can be defined as public health and safety, social relationships, air and water quality, flora and fauna. The paper discusses the causes and Impact of sinkhole subsidence on various environmental aspects. The paper also highlights the researchers who work on different models for risk assessment of sinkhole subsidence, this has been done by using various methods, namely, empirical, semi-empirical, remote sensing & GIS, numerical method and geophysical method to save human life, environment and prevent the loss to property.


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*Keywords:* Subsidence; Sinkhole; Environment

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## 1. Introduction

Several underground coal mines in India are located near urban areas. There is also a growing trend of human occupation near mining sites due to foreseen benefits of employment and lively hood. Sinkhole formation in such locations can be dangerous to life and property as it does not give any prior indication of its occurrence. It causes increased costs, and delays to new development; damage to existing development and infrastructure; and, in the worst cases, injury or loss of life. It may give rise to derelict land, loss of industrial production and loss of homes (Fig. 1). Numerous damaging subsidence events occur each year often because past development has taken place in subsidence prone areas. The economic impact of sinkhole subsidence, in the form of loss of surface and underground property, disruption of work, production loss, cleaning of the sinkhole in affected areas and filling of the sinkhole, is also significant in many cases.


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Fig. 1. Sinkhole Subsidence[1]

Underground excavations created for coal mining purpose may create cavities in the subsurface due to deformations and displacements of the overlying strata, the extent of which depends on the magnitude of the in-situ stresses, mining induced stresses, void size, immediate roof characteristics and presence of geological discontinuities. With time, these cavities may enlarge as remnant pillars left to support immediate roof deteriorate and the superjacent strata moves into the voids, resulting in instability of underground workings[2]. Gradually, these movements work up to the surface to form a depression on the ground surface which is commonly referred to as subsidence (Fig. 2). Surface subsidence generally entails both vertical and lateral ground movements. It manifests in three major ways, namely, cracks, troughs or sag and sinkhole subsidence.

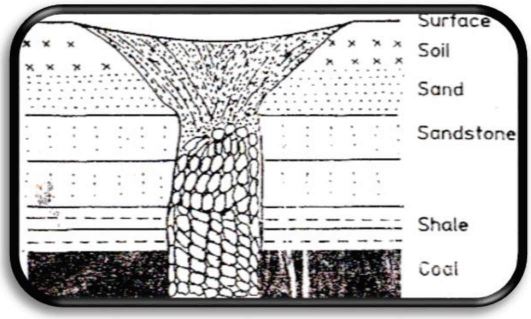


Fig. 2. Formation of Sinkhole Subsidence[3]

In this paper, authors discusses the causes and Impact of sinkhole subsidence on various environmental aspects and also highlights the researchers who work on different models for risk assessment of sinkhole subsidence, that has been done by using various methods, namely, empirical, semi-empirical, remote sensing & GIS, numerical method and geophysical method to save human life, environment and prevent the loss to property. Sinkhole phenomena can be controlled by design of proper stiffness supports, construction of wall, Grouting of voids, Areal backfilling and Fillings of crack.

## 2. Factors affecting sinkhole subsidence

The sinkhole subsidence occurs depends upon various factors. The main factors which are governing for sinkhole subsidence are method of working, multiple working seam and depth of extraction, thickness of seam, presence of geological disturbances, in situ stresses, surface topography, nature of overburden, lowering of ground water, rainfall and earthquakes. Brief descriptions of each important factor are given below:

### *2.1. Method of working*

Bord-and-pillar, longwall, and in situ extraction techniques will affect the surrounding rock differently; pillar layout, cavity shape and the volume of material removed govern the timing and configuration of surface expressions. For example, longwall mining generally produces contemporaneous subsidence, whereas bord-and-pillar mining in the eventual collapse of pillars may lead to trenching or sagging of the surface [4].

*2.2. Multiple working seams*

Where multiple worked-out mining horizons exist, collapse could be initiated from any one of several levels, thereby increase the subsidence events, because the adjacent strata are disturbed[5]. Mining beds from top to bottom generally is safer and more efficient[6].

*2.3. Depth of extraction*

It is generally agreed that the deeper the excavation, the less is the subsidence at the surface. In deeper depth of workings, chances of sinkhole are less as compared to shallow depth working. Deeper working excavations always have trough type of subsidence, whereas in shallow depth chances of sinkholes are more[7].

*2.4. Thickness of seam*

Thick seam extraction may lead to higher amount of surface subsidence. In thick beds, the height-to-width ratio of the pillars is higher for a given exaction ratio. Slender pillars are normally more prone to failure. In some mining areas the relationship of seam thickness and overburden depth to vertical displacement of the ground surface is well established[5].

*2.5. Presence of geological disturbances*

The existence of faults, folds, fissures and joints may increase sinkhole subsidence potential. Mining disturbs the equilibrium of force in the strata and movement along a fault plane, due to ease of slippage, causing either settlement or up thrust at the surface, which may appear as a series of step fractures. Fault planes structures tend to be dangerously damaged but nearby buildings remain relatively intact[8].

*2.6. In situ stresses*

High horizontal stresses which are common in many shallow crustal rocks, act to inhibit the development of a surface depression by maintaining a strong ground arch in the immediate mine roof. The arch height and stability are sensitive to the ratio of vertical to horizontal stresses. A highly stressed arch may fail violently as a result of progressive thinning as happened at the Urad Mine in Colorado[9]. Roof instability and floor heave, resulting from high horizontal stresses and their orientation, need to make mining layout coal mines in the Allegheny Plateau[10].

*2.7. Surface topography*

Several investigators have noted the complicating effects of topographic variations on subsidence development. Sloping ground tends to emphasize downward movements because of gravity. In contrast to a level ground surface where the stresses produced by overburden on subsurface rocks are uniform, regions with irregular topographic relief will have irregular stress distributions that vary with the height of the column of rock above a particular underground point[4].

*2.8. Nature of overburden*

Strong massive beds above the mine level tend to prop the overburden for a prolonged period and defer the occurrence of sinkhole subsidence[5] (Fig. 3).

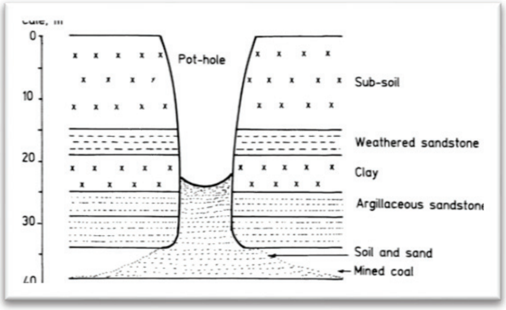


Fig. 3. Sinkhole formation in weak overburden[11]

*2.9. Lowering of ground water*

Sinkholes may form as a result of lowering the water table by excessive water for human use. This appears to be responsible for sinkhole formation. Caverns that are forming just below the water table are filled with water. The water table was lowered over the years resulting in the level of groundwater in the caverns to become lower. While the water table was high, the water in the cavern helped to support the roof of the cavern. This support is removed when the water table is lowered, and thus the unsupported roof eventually becomes unstable and collapses to form a sinkhole[3].

*2.10. Rainfall*

Rainfall recharges the overburden strata, which decreases the strength of the rocks. This phenomenon increases the pore pressure, which can trigger roof fall. The roof fall may propagate upward resulting in the formation of sinkholes on the surface. Recharge of the overburden can also increase erosion of the weak and weathered sandstones due to movement of water along closely spaced joints and faults which can also result in the formation of sinkhole on surface[12].

*2.11. Earthquakes*

Earthquakes can also suddenly increase the frequency of the occurrence of sinkholes. Earthquakes initiated significant liquefaction that drastically changed the ground surface. This is one of the major effects of earthquakes. Sinkhole subsidence can occur in various ways during an earthquake. Movement that occurs along faults can be horizontal or vertical or have a component of both. As a result, a large area of land can subside drastically during an earthquake[13].

## 3. Impact of sinkhole subsidence on environment

Damage from sinkhole subsidence over underground coal mines has been a serious problem. Economic impacts of subsidence in rural areas can also be significant, changes in surface slope, differential vertical displacements and horizontal strains. Some impacts of sinkhole subsidence are discussed below:

a. Surface Structures
b. Hydrogeology
c. Vegetation and Animals
d. Coal Mines
e. Social-Life
f. Water and Streams
g. Agricultural

### *3.1. Impact on surface structures*

Buildings, bridges and roads are frequently damaged by sinkhole subsidence. In buildings, the structure damage may include cracking or failure of foundations, vertical displacement, buckling, misalignment of doors, tilt, angular distortion and bending, and horizontal strain, complete structural failure and deformations from ground movements usually begin at foundation level and propagate upward through the basement to the superstructure[14]. Bridges are formed by horizontal ground strain resulting in the movement of the supports of piers either towards or away from one another. Roads that are damaged must be regarded or backfilled. Damage to sewage and drainage systems, water and gas lines is also possible. Gas lines may catch fire and explode if ruptured[4]. Grey et al[15] studied 354 incidents of subsidence in western Pennsylvania. Structures like dams, embankments, reservoirs, canals, sewers are also affected by sinkhole subsidence (Fig. 4).

Fig. 4. Structural Damage due to Sinkhole Subsidence[16]

### *3.2. Impact on hydrogeology*

Sinkhole subsidence can alter the hydrological balance and affect both ground and surface water flow, in turn leading to the scarcity of water to the people. In the dry areas that typically overlie western energy resources, the loss of springs and other surface water is especially critical. In addition to conventional coal mining, the underground coal gasification process and in situ retorting of oil shale can also affect ground-water supplies. When ground water reenters a gasified coal bed, the residual reaction products (coal ash, tars, and gases) may undergo leaching, dissolution and hydrologic transport[17]. As a consequence of the sportive properties of the rocks associated with coal, the contaminants may move more slowly than the ground water and they may react chemically with each other and with the rocks, potentially lengthy and poorly understood processes[4] (Fig. 5).

Fig. 5. Effect of Sinkhole on groundwater development[18]

### *3.3. Impact on vegetation and animals*

Cavities, crakes may induce tension fractures in nearly overlying beds and allow methane and other dangerous mine gases may leak out on the surface resulting in loss of trees, woody plants, animals or people. Garner[19] examined that certain bacteria in the soil use methane to produce hydrogen sulphide and nitrous oxide. These gases disrupt the root transpiration of woody plants, ultimately killing them. Noxious or toxic gases may also overcome animals grazing on the surface. Collapse pits and open fractures may trap animals or interrupt their migration patterns. Losses of soil water or water in deeper aquifers through fractures created by sinkhole subsidence could be equally harmful to plant and animal life, especially in semiarid areas[4] (Fig. 6).

Fig. 6. Effect of Sinkhole on vegetation [20]

### 3.4. Impact on coal mines

Coal mine fires are an indirect result of coal extraction and leads to long-term subsidence. According to Dunrud and Osterwald[21] coal mine fires appear to have been started by spontaneous ignition when air and water were introduced with sinkhole subsidence.

Fig. 7. Coal mine fires due to Sinkhole[22]

As the coal burns, more cavities are created causing more cracking and collapse which allows greater access for air, thereby accelerating coal burning. This uncontrolled "in situ gasification" process is destroying a valuable resource. In addition, gaseous combustion products locally pollute the air; soil changes are produced and kills nearby vegetation[4] (Fig. 7).

### 3.5. Impact on social –life

Sinkhole subsidence has decreased the capacity of the environment to support some life forms. Sinkhole causes damage to bridges, roads, railroads, storm drains, sanitary sewers, canals, damage to private and public buildings and failure of well casings from forces generated by compaction of fine-grained materials in aquifer systems. Sinkhole subsidence and the general lowering of the ground surface may also change the normal drainage pattern causing local surface flooding[8] (Fig. 8).

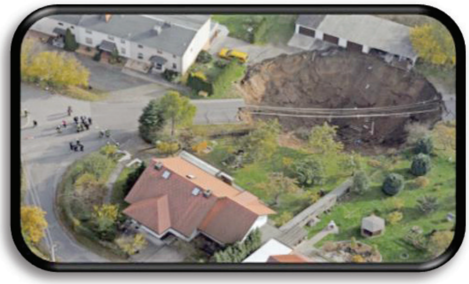

Fig. 8. Effect on Social life[23]

*3.6. Impact on streams and surface waters*

The formation of sinkhole at the bottom of or adjacent to, surface water bodies, such as streams, ponds and lakes can lead to complete or partial loss of water due to leakage to the underlying strata. The resultant changes in surface slope can adversely impact drainage along irrigated fields, canals, sewers and natural streams. Dewatering impacts under these conditions can reach to a few hundred feet above the mine collapse areas[24].

*3.7. Impact on agricultural*

Sinkhole subsidence may cause differential soil settlements of buildings and shrinking/swelling of soils. When soils shrink or swell due to the influence of water, damage may occur in surface structures that appear to be similar to subsidence damage. In cold areas, freezing and thawing effects may also cause expansion and contraction of poor drainage fine-grained soils[5] (Fig. 9).

Fig. 9. Effect of Sinkhole on agriculture[25]

## 4. Sink-hole risk assessment

Several underground coal mines in India are located near urban areas. There is also a growing trend of human occupation near mining sites due to foreseen benefits of employment and lively hood. Sinkhole formation in such locations can be dangerous to life and property. Sinkholes often lead to severe damage to surface features by causing collapse of houses with development of severe cracks on walls and floors.

In globe, several models were developed for risk assessment and prediction of sinkhole subsidence. This is to understand the exact nature of sinkhole and its intensity. Some methods which are available to predict the risk of sinkhole subsidence are;

a. Empirical method
b. Semi-empirical method
c. Remote sensing & GIS
d. Numerical modelling
e. Geophysical method

*4.1. Empirical methods*

On this type of method, different researchers were carried out on work for risk assessment and prediction of sinkhole [26-28, 30-35, 38, 40-43, 44-47].

The model developed by Whittaker Reddish[40], predicts the depth of the sinkhole by equating the volume of caved material to the volume generated by rock excavation. In this model the rock density and bulking characteristics of the immediate roof are assumed to be unaffected by increased loading due to caving.

Dyne[33] developed a model for South-western Pennsylvania after due modifications in shape and dimensions of collapse chimney that was assumed in Whittaker Reddish model[40]. This model accommodates the possibility of sinkholes with a wider base and also considers the shape of the fallen material to be that of truncated cone rather than truncated pyramid. Applicability of this model was limited to development cases only.

Singh[35] developed a rating approach for sinkhole prediction utilizing, depth of cover, uniaxial compressive strength, geological discontinuity and water seepage. The preliminary risk of sinkhole occurrence can be understood using this model. However, the model cannot predict sinkhole depth.

Lokhande et al.[36] has developed Pot-Hole Subsidence Rating (PHSR) for assessing the risk of Pot-

Hole subsidence. Pot-hole can also be called as sinkhole. This was mainly to make the sinkhole subsidence prediction more holistic by considering relevant causative parameters and applying suitable corrections for fine tuning the same. In this approach, the range of four critical parameters is first identified and based on the frequency of occurrence of pot-holes, suitable ratings were assigned. The sum of the ratings of the four parameters is termed as PHSR. To consider the influence of certain qualitative parameters correction factors were proposed. For estimating the sinkhole risk involved, PHSR values are categorized into five classes as given in Table 1.

Table 1. Categorization of Sinkhole Risk

| Pot-hole rating | Class | Risk of pot-hole occurrence |
|---|---|---|
| 80 – 100 | V | Very low |
| 60 – 80 | IV | Low |
| 40 – 60 | III | Medium |
| 20 – 40 | II | High |
| 0 – 20 | I | Very high |

Lokhande[39] was also developed in empirical model which estimates pot-hole depth (PHD) as given in Equation 1.

$$z = [50 + \left(0.5 * \frac{H}{M}\right) - \left(0.14 * \left(\frac{t2+t3}{t1}\right)\right) + (0.64 * \text{v}) - \left(5.4 * \frac{\sigma c}{\sigma t}\right) \;] \qquad \text{(Equation 1)}$$

where,

H is the cover depth (m)

M is the extraction height (m)

z is the pot-hole depth (m)

t1, t2 and t3 are the layer thicknesses of the strata of different lithological sequence above the working.

σc1, σc2 andσc3 are the compressive strengths of different lithological sequence respectively,

### 4.2. Semi-empirical methods

Brown and Ferguson[29] developed model using parameters such as slope of the ground surface and groundwater pressure in the tension cracks and on the shear plane. The model suggested by Brown and Ferguson is bit complicated due to the large numbers of parameters considered.

Lokhande[37] developed a model for predicting the sinkhole depth and diameter for shallow underground coal mining. The expressions developed for predicting the depth and diameter of sinkhole are given in Equation 2 and Equation 3 respectively are given as follows,

$$\mathrm{z} = \mathrm{S} + \frac{\mathrm{M*W*R}}{\mathrm{Kt*Ks}} \qquad \text{(Equation 2)}$$

$$d = \sqrt{\frac{W}{Kt*M}} * \mathrm{z} \qquad \text{(Equation 3)}$$

where,

z = Depth of the sinkhole (m)

d = Diameter of sinkhole at the surface (m)

S = Thickness of the soil layer (m)

R = Thickness of the rock layer (m)

M = Height of extraction (m)

W = Width of extraction (m)

Kt = Constant for stage of working

(for development = 1 and depillaring = 60)

Ks = Coefficient of Rock Layer = $\frac{\;}{3} * WD * WC$

WD = Weighted density of the rock layer (kN/m3)

WC = Weighted compressive strength of the rock layer (MPa)

### *4.3. Remote sensing and GIS*

This method has been developed by different researchers on an assessment of risk of sinkhole subsidence[48-52].

Ki-Dong-Kim et al.[48] was used as a probability model, a statistical model and GIS to evaluate the factor related to sinkhole subsidence using the frequency ratio and logistic regression model, the spatial relationship between sinkhole subsidence area related factor, such as topography, depth of the mined tunnel, borehole data, geology and land use.

Hyun-Joo oh et al.[49] analyzed sinkhole subsidence on discontinuous residual subsidence for hazard mapping in an area by using a sensitivity analysis and GIS.

Saro Lee et al.[50] considered 824 cases of abandoned underground coal mines for the study of subsidence based on the trough and sinkhole formation. They analyzed ground subsidence susceptibility (GSS) around abandoned coal mines in Jeong-am, Gangwon-do, South Korea, using artificial neural network (ANN) and geographic information system approaches. Spatial data of subsidence area, topography and geology, as well as various ground-engineering data, were used to create a raster database of relevant factors for a GSS map.

Ling Chang and Raman F. Hanssen[51] was been used to investigate deformation of sinkhole occurrence by using the SAR data.

### *4.4. Numerical modelling*

Parise & Lollino[52] observed in their model that natural caves represent a potential hazard for the built environment, due to the occurrence of instability within caves, which may propagate upward and eventually reach the ground surface, inducing the occurrence of sinkhole. They analyzed the failure mechanisms observed in the field for such underground instability processes and the factors that seem to influence the processes. Numerical analyses were done using both the finite element method for geological settings represented by continuous soft rock mass and the distinct element method for jointed rock mass conditions. Both the effects of local instability processes occurring underground and the effects of the progressive enlargement of the caves on the overall stability of the rock mass were investigated along with the consequent failure mechanisms.

Lokhande[37] developed numerical models using FLAC3D and 3DEC to understand the mechanism of the sinkhole subsidence under development and depillaring conditions. Parametric analysis work was carried out by varying the geometry, properties of the rocks and the sequence of extraction.

Kanaan Hanna & Keith Hesely[53] was modelled using La Model, a non-linear boundary- element displacement –discontinuity program, to estimate pillar safety factor, area of potential present or future sinkhole subsidence due to the time-dependent deterioration of the coal pillar.

### *4.5. Geophysical methods*

Michael Trevits et al.[54] worked on sinkhole subsidence by using GPR geophysical method. Hanna Kanaan & Hesely Keith[55] studies risk assessment by using integrated engineering geophysical using a multi-phase approach with a surface seismic multi-channel analysis of surface waves (MASW) and seismic reflection techniques.

## 5. Preventative measures

Different preventive measures may be adopted to control sinkhole subsidence damage:

a. Design of proper stiffness Support
b. Construction of a wall
c. Grouting of voids
d. Areal Backfilling
e. Filling of cracks

### *5.1. Design of proper stiffness Support*

The areas prone to the occurrence of sinkholes should be supported by designing supports to have the required stiffness[8].

### *5.2. Construction of a wall*

When a collapsed roof and inflow of sand and soil with water along a fault is significant risk for sinkholes at the surface in the development headings, suitable walls can be constructed to form a barrier around the collapsed area and the zone of inflow of sand and soil with water. This has been highly successful in the sinkhole prone areas of the British coalfields[56] and the Jamuna and Kotma Area of the SECL[3].

### *5.3. Grouting of voids*

This approach can only be used as a local area stabilization technique. It has been used to support buildings, highways, schools, churches, etc. located over goaves. There are two commonly used grouting techniques. One utilizes a sand–grout mixture which is injected into rubblized zones of roof failure and small voids to support the roof and to eliminate the available space for continued downward movement of the overburden material (Fig. 10). Another approach can be used in areas of large voids. This employs gravel–grouted columns to provide direct support to the mine roof (Fig. 11). Karfakis[57] describes how an area of approximately 7 ha lying over abandoned coal mines in Rock Springs, Wyoming, was treated by grouting. Over 250 structures in the same town have been stabilized using grouting so far.

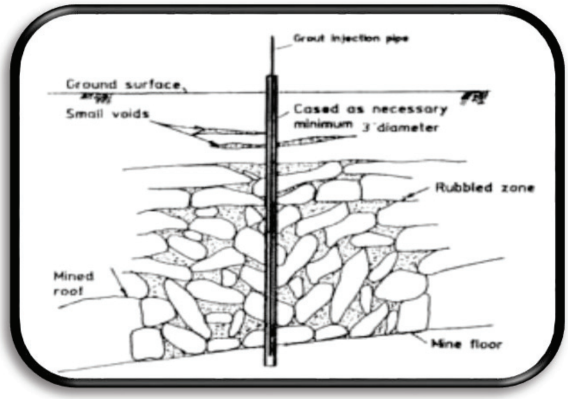


Fig. 10. Rubble and small void grouting[57]

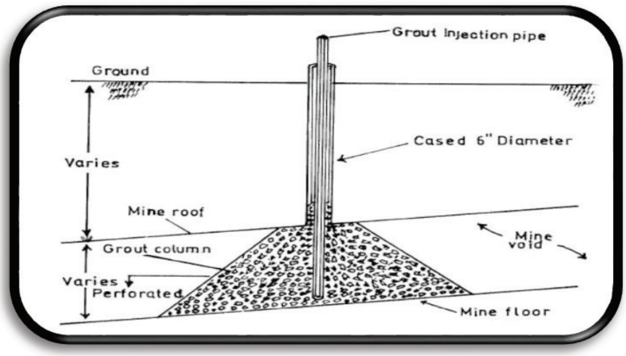


Fig. 11. Gravel and Grout Column[57]

### *4.4 Areal backfilling*

Areal backfilling includes the filling of mine opening or voids to provide the protection to urban areas that may be measured in sq km. normally large quantities granular fill materials, e.g. sand, crushed rock, fly ash or coal mine refuse and are used to fill the voids[57]. A total of 800 000 tones of material was placed beneath the town and it was found that 100% of the void was filled with granular backfill material. Lokhande[43] gives some other methods based on the principle of areal backfilling are Pumped slurry injection, Fly ash and Slurry injection, and pneumatic fly ash injection.

### *4.5 Filling of cracks*

Cracks formed due to ground movements must be filled in by soil and a sand–cement mixture above alluvium and rocks respectively. However, if the cracks have developed in river or rivulet (nallah) beds, they should be in-filled by concrete. This restricts the movements of surface water through cracks or faults and thereby reduces the erosion of the overburden, thus reducing sinkhole to some extent [3].

## 6. Conclusions

The potential sources of sinkhole subsidence in underground coal mining are method of working, shallow depth of extraction, thickness of seam, multiple working seams in one mine, overburden thickness, hydrology and geological disturbances parameters. The impacts of sinkhole subsidence on surface structure, hydrology, vegetation & animals, coal mines, water & stream and agricultural are affected more and due to this social life may get disturbed as it does not give any prior warning before its occurrence. Sinkhole subsidence can be prevented by using various measures, namely, design of proper stiffness Support, construction of wall, grouting, areal backfilling and filling of cracks may help in protecting the damages on the surface over the affected areas. In total sinkhole subsidence due to underground coal mining creates problem on social environment and by using different models developed by various researchers may help in predicting the sinkhole subsidence in advance which helps the society to save the loss of life and property.

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