

CHAPTER 2

REVIEW OF LITERATURE

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2.1 Mine subsidence

Mine subsidence can be defined as movement of the ground surface due to excavation in underground workings. Subsidence is time dependent deformation, either natural or man induced, in which there is lowering of ground surface in response to removal of gas, liquid, or solid matter. Surface manifestation of underground coal extraction occurs in two forms, i.e., pot-hole (Figure 2.1) and trough subsidence (Figures 2.2 & 2.3). Pot-hole subsidence is an abrupt depression of local ground surface, which occurs due to sudden collapse of the overburden into an underground void. The pot-hole subsidence is very dangerous to lives and properties, as it does not give any prior warning. The main causative factors of pot-hole subsidence are shallow depth of mining, geological discontinuities, weak and saturated overburden (Karfakis 1993; Singh and Dhar 1997; Singh 2007). Trough subsidence is a gentle and large area depression of surface terrain (Figures 2.2 & 2.3), which is a very common form of subsidence in Indian coal mines.



Figure 2.1 Danger to the life and property due to pot-hole (Lokhande et al. 2015)

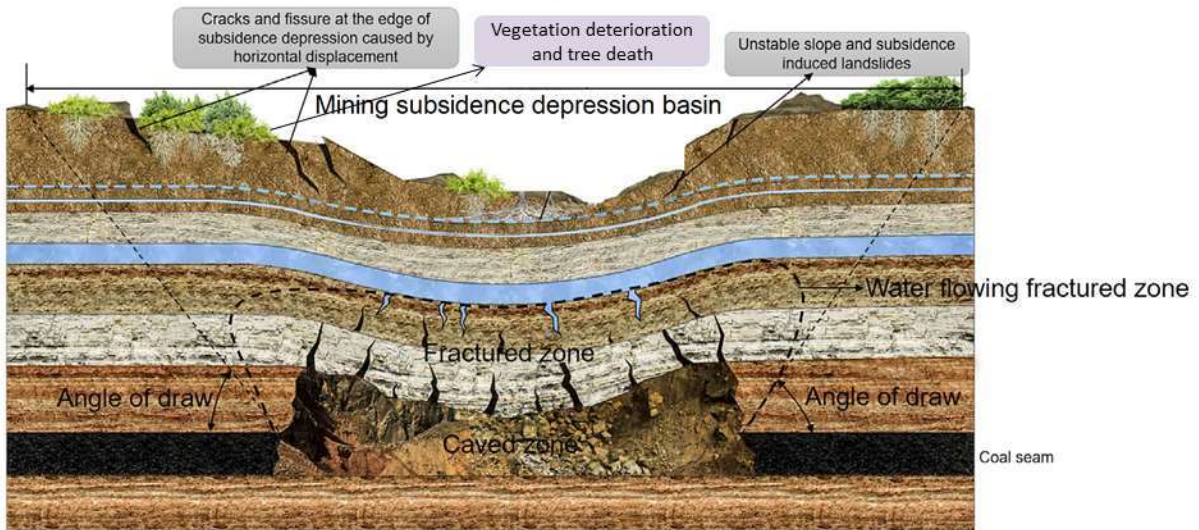


Figure 2.2 The mechanism of underground coal mining on land degradation (Xiao et al. 2020)

2.2 Causes of subsidence movements

Subsidence movements are caused by natural and manmade activities (Reddish and Whittaker 2012, CIMFR 2007). Figure 2.4 presents a schematic diagram showing the natural and manmade causes of subsidence and are briefly described below.

2.2.1 Natural causes

- **Solution of minerals and rocks:** Water dissolves limestone and gypsum and underground cavities are formed. Progressive upward collapse of these cavities results in the formation of pot-holes on the surface.
- **Soil shrinkage:** Removal of moisture from soils as a result of climatic change can lead to appreciable soil shrinkage and accompanying subsidence movements.
- **Tectonic and volcanic activities:** Earthquakes can result in sudden sinkage of relatively large surface area (Esaki et al., 1989). Areas adjacent to major faults can

also experience the effect of subsidence during movement. Surface subsidence also occurs due to collapse of void structures in volcanic deposits.

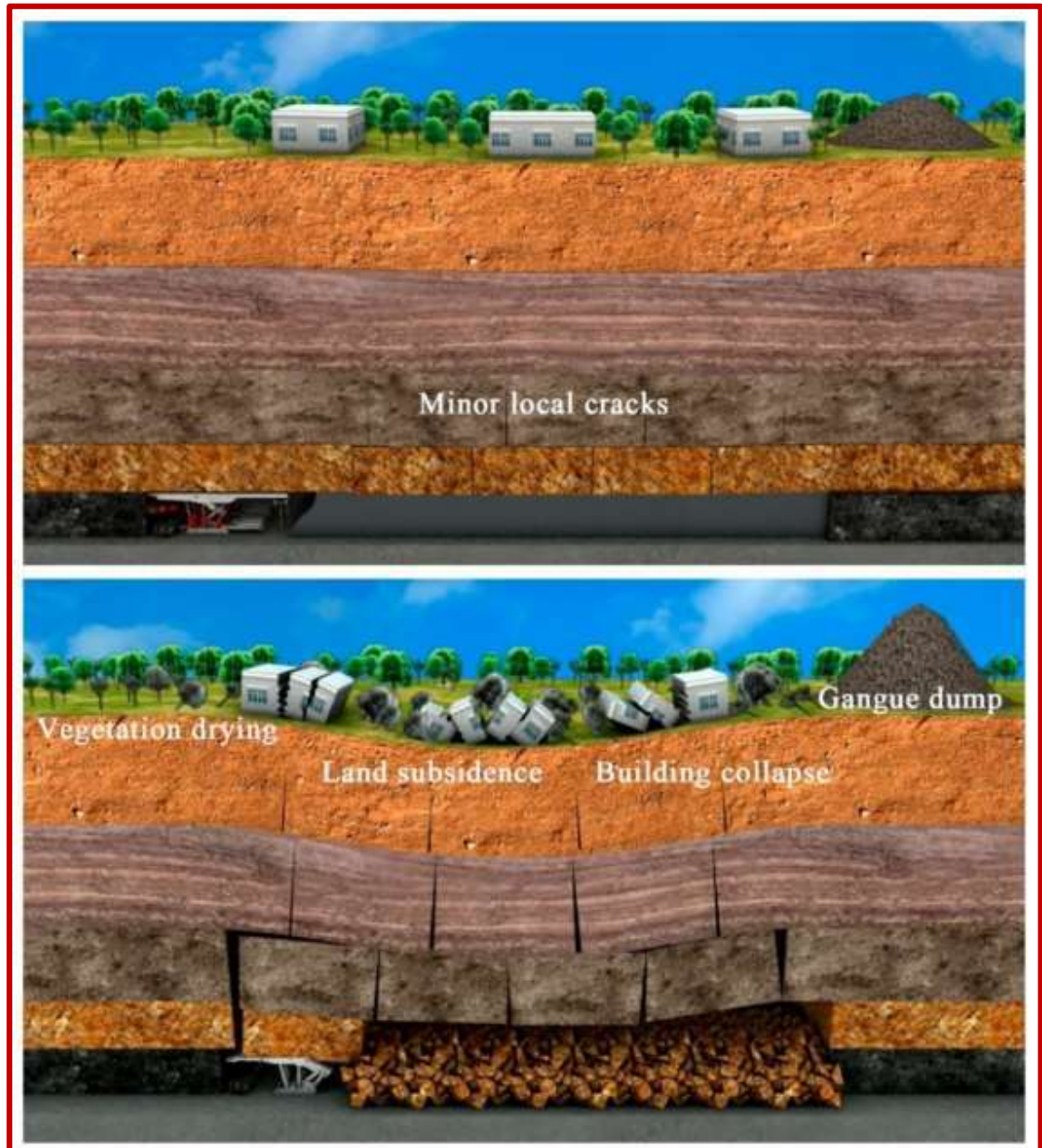


Figure 2.3 Schematic diagrams of the influences of coal mining on the environment (a) Backfilling mining (b) Caving mining (Zhang et al. 2019)

- **Geological cycles:** Denudation, deposition and plate movements can also lead to subsidence movements.
- **Landslide:** Landslide in hilly terrain can lead to subsidence movement, particularly in rainy season.
- **Frosting and defrosting:** Defrosting can cause natural subsidence due to reduction in volume following melting of ice.
- **Rodents:** Rodents construct holes in the ground, which eventually cave in as subsidence phenomenon on the surface.

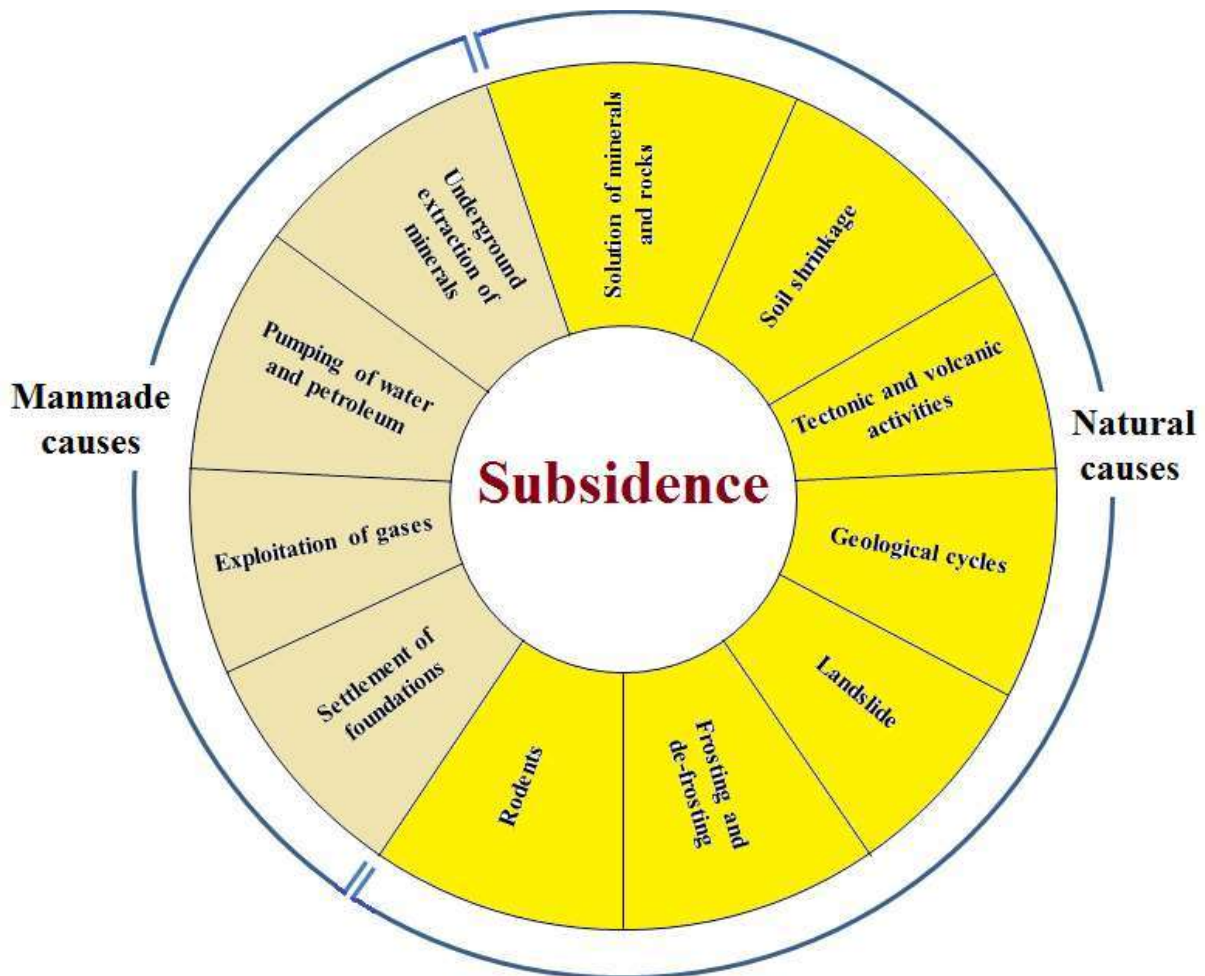


Figure 2.4 Natural and anthropogenic (manmade) causes of subsidence

2.2.2 Manmade causes

- **Settlement of foundations:** Magnitude of settlement is a function of loading intensity and drainage conditions of the loaded material. Settlements are normally greater during early stages and gradually decrease with time as uniformity of foundation loading has a marked influence on reduced differential settlement tendencies.
- **Exploitation of gases:** Exploitation of hydrocarbon from coal seams can lead to downward movement of overburden, causing surface subsidence.
- **Pumping of water and petroleum:** Pumping of water and petroleum also results in compaction of aquifer/reservoir causing subsidence on the surface.
- **Underground extraction of minerals:** Underground extraction of minerals, particularly coal, causes extensive surface subsidence. Overburden depth controls the risk of the pot-hole and trough subsidence (Karfakis 1993) due to coal mining. Subsidence movements are not very common in metal mining as the overburden is strong.

2.3 Mechanism of coal mine subsidence

When an underground opening is made in a coal seam by excavation of coal, the stresses are redistributed in the superincumbent strata around the opening. Rock mass around the opening tends to move into the opening, creating a zone of influence around the opening. The extent of zone of influence depends upon the nature of overlying rock mass, size of opening, nature of coal and depth. As the size of opening is enlarged in the process of coal extraction, the zone of influence around the opening also enlarges. The process of enlargement of zone of influence continues with increase in the size of opening and a stage

is reached when the zone of influence reaches the surface causing subsidence movements on the surface. Figure 2.5a shows the zone of influence at various stages of coal extraction around the opening. At the initial stages of coal extraction (stage 1 to stage 6), no impact is visible on the surface due to the smaller size of opening. With further increase in width of extraction, a stage is reached (stage 7), where zone of influence reaches to the surface, causing subsidence of overlying strata. Figure 2.5b shows a schematic diagram of the strata disturbance caused by mining subsidence.

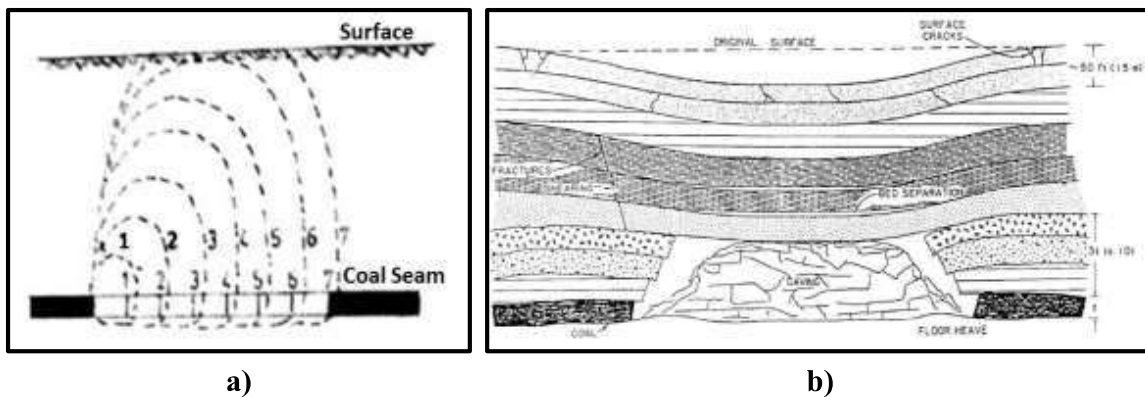


Figure 2.5 a) Zone of influence around an opening b) Strata disturbance and subsidence caused by mining (Singh and Kendorski 1981)

2.4 Factors influencing subsidence movements

Factors that influence the subsidence movements can be mainly categorized into two categories. These categories are (1) Geological factors and (2) Mining factors. Figure 2.6 represents the schematic diagram of various factors influencing the subsidence movements.

2.4.1 Geological factors

- **Seasonal shrinkage:** Moisture changes of clay deposits at the surface causes shrinkage and expansion depending on loss or gain of moisture, respectively. This

leads to volume change resulting in differential horizontal movements causing surface cracks to open and close periodically (Singh and Singh 1998).

- **Hydrogeology:** Groundwater plays an important role in the process of surface subsidence. Localized drainage significantly lowers the water level through mining induced cracks which lead to surface subsidence. This is due to compaction of the overburden following removal of groundwater from inter-granular spaces/voids (Singh et al. 1990). Localized erosion in the saturated overburden through fissures can develop pot-hole subsidence on the surface (Whittaker and Reddish 1993).

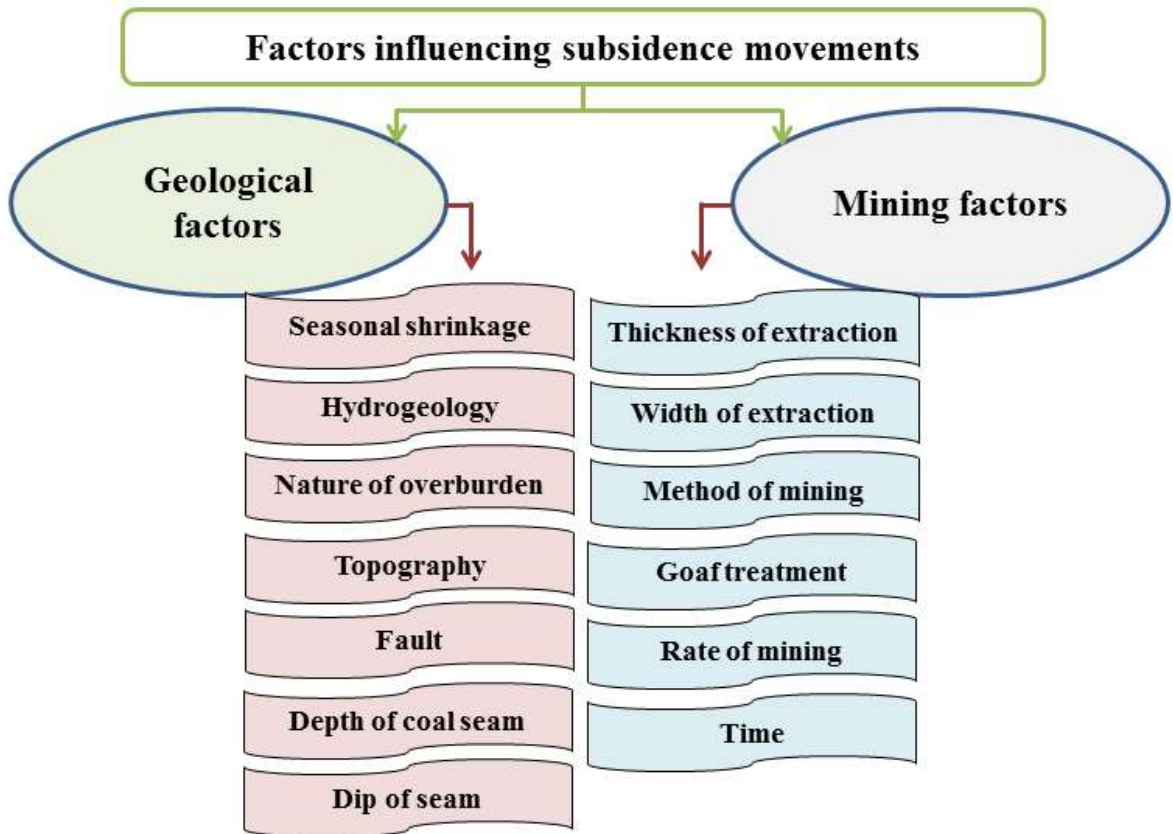


Figure 2.6 Schematic diagram of the various factors influencing subsidence movements

- **Nature of overburden:** Nature of overburden rocks also influences the magnitude and limit of subsidence on the surface. Several European Coalfields including British coalfields (NCB 1975), Ruhr coalfield, Germany (Schulte 1957), North and Pas de Calais coalfields, France have 90% maximum subsidence in terms of extracted height, whereas Indian coalfields recorded a maximum subsidence of 69% and 81% of extraction height for single and multi-seam mining conditions respectively (Anon 1999; Singh et al. 2006; Chekan and Matetic 1990). This difference is attributed to dominance of weak clayey and strong sandstone overburden in European and Indian coalfields, respectively. The weak bed in the overburden increases the area of subsidence, whereas strong bed tends to decrease the extent of subsidence (Yao et al. 1991).
- **Topography:** Surface topography can influence the nature of the resulting surface subsidence. The increased zone of tensile strain on the up-slope side of the mined-out area can be of importance in encouraging the opening of natural and induced fissures/weaknesses (Reddish and Whittaker 2012). Khair et al. (1988) reported a significant increase in tensile strain when mining in an uphill direction. On the downslope, an extremely large zone of compression and heaving at the foothill was observed at a site in the north-central region of West Virginia.
- **Fault:** Faults may cause stepping on the subsidence profile and reduce or increase the extent of trough depending upon their position with respect to underground workings (Hellewell 1988). It can also trigger pot-hole subsidence by allowing movement of eroded weak overburden with water into the underground void (Singh 2000).

- **Depth of coal seam:** Depth of extraction is directly controlled by depositional characteristics of coal seam. Subsidence factor, a ratio of maximum possible subsidence to mining height, decreases with increasing mining depth (Peng 1992). The maximum subsidence and strains decrease with increase in mining depth (Singh et al. 1990).
- **Dip of seam:** Dip of seam influences the profiles of subsidence, strains and angle of draw. The position of maximum subsidence is generally shifted towards dip side of extraction from center of the panel (Kratzsch 2012; Singh and Singh 1998). The Magnitude of dip side tensile strain and angle of draw is more in comparison to rise side.

2.4.2 Mining factors

- **Thickness of extraction:** The magnitude of subsidence movements is directly proportional to thickness of extraction. When the ratio of mining depth to mining height is large, the surface deformation will be small and the subsidence basin will be mild (Peng 1992). Conversely, when the ratio is small, the surface deformation will be large and the subsidence basin will be sharp and in extreme cases, there may even be cracks, steps, or pot-hole on the surface (Singh 1990).
- **Width of extraction:** At a constant depth, the wider the opening, the larger is the maximum subsidence at the center and wider the subsidence basin (Kratzsch 2012). Stated differently, an opening of fixed width in critical or even supercritical condition in shallow depth becomes sub-critical in larger depths. Under similar mining height, all openings with the same width-to-depth ratio will have a same amount of maximum subsidence.

- **Method of mining:** The method of mining, particularly percentage of extraction, plays an important role in subsidence movements (Kumar 1991). In longwall panel, the percentage of extraction is 100, whereas, in bord and pillar and partial extraction methods, the percentages of extraction are 70-90 and 50-70, respectively. Percentage of extraction/method of mining is directly proportional to the amount of surface subsidence.
- **Goaf treatment:** The stowing of void created due to mining can reduce surface subsidence effectively. Filling of voids can reduce the volume of underground voids and thereby the subsidence on the surface.
- **Rate of mining:** The underground mining rate influences the rate of surface subsidence. When the face is stopped, the subsidence at the surface continues with slow rate (NCB 1975). In case of slow advancing face, the angle of draw at the face would be more than in case of rapidly advancing face.
- **Time:** Subsidence movement over an underground extraction continues for a certain period which is called residual or creep subsidence. The magnitude and duration of residual subsidence is about 5-22.4% of maximum subsidence and 6-15 months, respectively (Singh and Singh 1998; Whittaker and Reddish 1993). The parameters controlling the duration of residual subsidence, i.e., time taken for complete stabilization of surface after completion of extraction in the panel, are depth & method of mining, the nature of overlying rock mass, goaf support, presence of geological disturbances, etc.

2.5 Impact of subsidence movements

There are various impacts of mine subsidence on surrounding environment (Figure 2.7). Damage to surface features and structures due to underground coal mining has a serious problem and becoming more widespread as the demand for coal increases. It is also increasing due to population explosion within the mining lease holding area.

Damage from subsidence movements can be caused by change in surface slope due to differential vertical displacement and horizontal strains (CIMFR 2007). Compressive strains with concave curvature of the ground surface result in crushing, over-thrusting and horizontal openings in brick-wall. Tensile strain accompanying convex curvature of the ground resulting in fractures tapering from the ground upwards. Differential vertical ground movement can adversely affect surface drainage, tall structures, factory plant and machinery. Sewerage pipes may be broken or cracked due to vertical movement, which results in malfunctioning of the system. Subsidence troughs can give rise to potential ponding and flooding. Tilting of factory machines and plants results in inoperative equipment.



Figure 2.7 Various impacts of land subsidence

Mining subsidence cause decrease in slope stability, contamination of groundwater by acid drainage, increased sedimentation, bank instability and loss, creation or alteration of riffle and pool sequences, changes to food behavior, increased rates of erosion with associated turbidity, impacts and deterioration of water quality due to a reduction in dissolved oxygen and to increased salinity, iron oxides, manganese, and electrical conductivity (Choubey 1991; Booth and Bertsch 1999; Sidle et al. 2000; DLWC 2001; Gill 2000; Stout 2004; Ma et al. 2014a, Ma et al. 2014b).

Pumping of aquifers associated with underground mining areas can interrupt flow to surface water. The hydrologic regime of alluvial systems and wetland ecosystems can be affected by underground mine dewatering, which may impact productivity, wildlife habitat, and ecosystem functions. Surface land uses that may be affected by mining subsidence include crop production and grazing land areas which serve for public use.

2.5.1 Structural damage

Damage to surface structures and facilities is the most commonly recognized and observed environmental impact from mine subsidence (Figure 2.8) because they are typically a part of the mining operations or because towns and other industries are built close to mining activities. Gray et al. (1977) found that out of 354 incidents of subsidence examined in western Pennsylvania, nearly 1 in 3 involved damages to properties. Singh (2000) noted that the earliest motivation for the study of subsidence was severe damage to structures and other surface facilities.

Damages to structures are generally classified as cosmetic, functional, or structural. Cosmetic damage refers to slight problems where only the physical appearance of the structure is affected, such as cracking in plaster or drywall. Functional damage refers to situations where the structure's use has been impacted, such as jammed doors or windows. More significant damages that impact structural integrity are classified as structural damage. This would include situations where entire foundations require replacement due to severe cracking of supporting walls and footings.

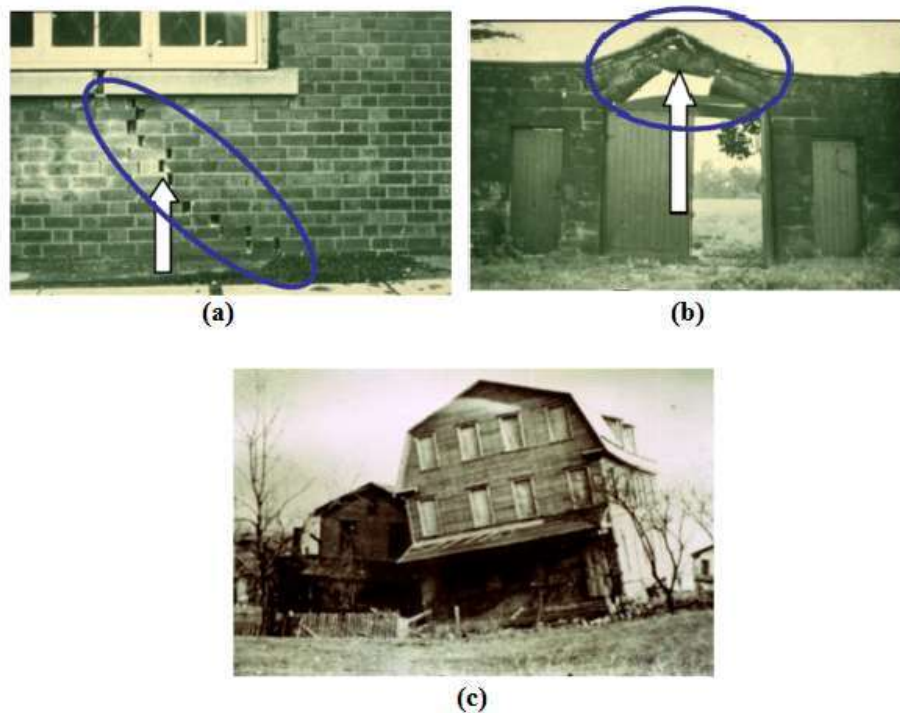


Figure 2.8 Effects of subsidence on surface structures (a) Tensile area (b) Compressive area (c) Maximal dip effect (Didier et al. 2009)

The structures like bridges, roads, etc., may experience movement towards or away from each other depending upon the nature of ground strains. Buildings and roads are frequently damaged by subsidence events. In buildings, the structural damage may include cracking or failure of foundations, vertical displacement, buckling, misalignment of doors, and complete structural failure. Damage to sewage and drainage systems and water and gas lines is also possible. Gas lines may catch fire and explode if ruptured (Lee and Abel 1983).

The impacts to structures are based on tensile stresses, compressive damage, angular distortion and differential tilting or bending. These may act in a single deformation mode, but typically several of these forces work together to produce complex impacts on buildings and other structures, including bridges, railways lines, roads, communication and power systems. Most of the observations in literatures are based on coal-mining subsidence

impacts to surface structures and facilities. These impacts have also been noted where hard-rock mines have been located in close proximity to dwellings and other structures. Buildings and other engineered structures may be damaged or destroyed, and land may be removed from productive use by such ground failure.

2.5.2 Impact on soil properties

Surface topography of landscape in mining areas is affected by underground subsidence (Vishwakarma et al. 2020a). Landscapes with erosive soils on long slopes may be subject to increased erosion potential because of slope increase or displacement of erosion control structures (such as tree, grass, shrubs, etc.).

Kundu et al. in 1994 performed studies on the topsoil of an underground coal-mining project of Raniganj Coalfield in Eastern India. A fact-finding survey was made to assess the impact of mining on the topsoil. Soils were deficient in nutrients at the subsided zone. They concluded that underground mining activity creates land subsidence and disturbs the water table, finally having a negative impact on the topsoil of the area.

In a study performed by Hu et al. (1997) on impact of coal mining induced subsidence on farmland in eastern China (Hu et al. 1997), they found that the soil physical properties such as bulk density, moisture content and hydraulic conductivity deteriorated from top to bottom towards the center of the trough. Except for soil electrical conductivity, the tested soil chemical properties were not so sensitive to mining subsidence. Based on the soil analysis of the subsided land, soil erosion was identified as a serious problem, most severe in the middle of the prone land. In low areas with high water tables, ponding is a particular problem. In some situations, ponding might be viewed in a positive way because it creates wetlands beneficial to wildlife but negatively when it reduces net returns to a food

or fiber producer. In Southern Illinois landscape, subsidence from underground longwall coal mining creates wet or ponded areas that delay and disrupt farming practices, cause low seed germination, and reduce crop growth and grain yields.

Tripathi et al. (2009) conducted a research on the assessment of the impact of post-mining land subsidence due to underground coal mining operations on plant available nutrient status and nitrogen mineralization rates. They quantified the changes in all the three (rainy, winter and summer) seasons, in slope and depression microsites of the subsided land and an adjacent undamaged forest microsite. They found that the physicochemical characteristics of soil were altered after subsidence, showing a positive impact on total nitrogen and total phosphorus in depression microsites. While in slope microsites, the values were lower. Soil nitrate-nitrogen and phosphate-phosphorus concentrations were also found higher in depression microsite, showing an increase of 35.68% and 24.74%, respectively. Net nitrification and net nitrogen-mineralization were increased in depression microsite by 29.77% and 25.72%, respectively.

Li et al. (2010) revealed the effects of mining subsidence on physical and chemical properties of soil in slope land in Hilly-Gully region of loess plateau. The objective of the study was to reveal the influence of mining subsidence on soil properties. The physical and chemical properties of soil in sunken slope land in Shuangliu mining area in Lishi were studied. The study showed that mining subsidence destroyed the soil structure, promoted soil leaching and deteriorated the physical and chemical properties of soil.

Singh et al. (2010) studied the impact of underground coal mine subsidence with respect to physicochemical characteristics and inorganic nutrients (plant available nutrients) in forest soil ecosystems of Singareni Coalfields area. They observed that forest soil texture (with respect to coarse sand content) was higher in fresh subsided site as compared to the

old subsided site, while the fine textured soil was maximum in old subsided site. After subsidence, total nitrogen and phosphorus were found to increase by 0.45% and 5.6% in subsided site, respectively.

Wang et al (2014) focused on the investigation of the vegetation in the coal mine subsided areas of Shenfu-Dongsheng coal mine region in the geomorphic type of windy desert. Based on the data obtained from the field survey, they measured the correlations between species diversity and soil properties with the slope. The correlation they have reported on species diversity and soil properties of windy desert area slope was that the soil properties (i.e. soil water content and soil nutrient) and the species diversity increased at the bottom of the slope. Significant positive correlation was observed of species diversity with soil water content. As plant-soil is a very complex system, many ecologist reported soil moisture and organic carbon content as the main gradients for variation in species diversity and their distribution (Ru and Zhang 2012; Kirsch et al. 2012; Chaturvedi and Raghubanshi 2014, Sarvade et al. 2016). In windy desert area of Shenfu-Dongsheng coal mine region, water content increases the availability of nutrients to the vegetation and acts as the main gradient for the change in species diversity.

Impact of coal mining subsidence on soil physical qualities was assessed by Dejun et al. (2016) in a case study performed in Western China. They proved that coal mining can reduce the average value of soil water content, cohesion and organic matter, and increase the average value of internal friction angle, while in comparison; it did not influence soil bulk density, dry density and porosity very much. The relationship among soil physical quality index was also influenced by the subsidence induced by coal mining influences. Although the statistical analysis showed that the average values of soil water content, organic matter and cohesion were greatly affected by coal mining subsidence, the same

phenomenon may not always happen in every sampling location due to soil spatial and temporal variability.

Li et al. (2018a) tried to draw an attention about the subsidence impact on spatial distribution of potentially toxic metals in farmland tillage soil. They collected 103 samples of farmland tillage soil surrounding a coal mine in southwestern Shandong province, China and monitored the heavy metal concentrations of each sample by inductively coupled plasma mass spectrometer (ICP-MS). Statistics, geostatistics, and geographical information systems (GIS) were used to determine the spatial pattern of the potentially toxic metals above in the coal mining area. The results showed that the contents of soil toxic metals were influenced by coal mining activities. The average concentrations of toxic metals (Cr, Ni, Cu, Zn, Cd and Pb) were mostly exceeded the natural soil background contents of Shandong Province.

Ma et al. (2019) investigated the effects of land subsidence induced by underground mining on the soil quality in western China. Soil samples were collected at 0–15 cm and 15–30 cm from control and subsidence areas in three coal mines. The results showed that the clay and silt percentage, total nitrogen, ammonia nitrogen ($\text{NH}_4^+\text{-N}$), nitrate-nitrogen ($\text{NO}_3^-\text{-N}$), available phosphorus, and available potassium of the subsidence areas were significantly lower than those of the control areas. The sand percentage of soil tended to increase. These results indicated that land subsidence induced by coal mining caused losses in surface soil water and nutrients and ultimately led to soil quality degradation.

2.5.3 Impacts on agricultural lands

Surface land that may be affected by mining subsidence includes crop production and grazing, areas serving as aquifers, areas of recharge for underground waters and areas

with surface waters that support aquatic life or supply water for public use. Subsidence impacts agricultural lands in ways that include formation of surface fissures, change in ground slope, changes to surface drainage, disruption of groundwater hydrology, deterioration of surfaces and groundwater quality, and occurrence of subsidence areas (Darling 2011). Subsidence-caused damage to surface land use is generally characterized by either a diminishment or loss of use or productivity (Vishwakarma et al. 2020b). The amount of impact is site-specific and may be based on perception as well as measurable quantification. At a “moderate” level of damage, a particular surface land use may decrease the benefits or suitability of that use. At a “high” level of damage, a particular surface land use may become uneconomic, impractical, or in some cases may be lost. Impacts on agriculture might be due to various interactions taking place in between and among many factors. There are two major types of impact: one is impacts on crop productivity and the other is impacts on soil functions.

2.5.3.1 Impacts on crop productivity

Variations in crop productivity after mining subsidence are mainly due to changes in the hydrological properties of native soil and agricultural landscapes (Bauer 2008). The occurrence of subsidence leads to formation of subsidence basin in the agricultural fields (Figures 2.9 and 2.12).

An anoxic condition may arise due to water ponding caused by flooding, resulting into the hampered crop growth (Vantoi et al. 1995). This effect is more prominent if cropping occurs in summer when higher temperatures increase soil breath rates and intensify the threat of anoxia initiation (Bacon 2013). Water ponding may also result in

interference in farming practices and low crop productivity. Soil compaction at the subsidence compression zones may also affect the crop productivity (Ishaq et al. 2001).



Figure 2.9 Subsidence basin observed in an agricultural field in the Witbank area, South Africa (Engelbrecht, 2013)

Darmody et al. (1989) found a 4.7% average reduction in overall corn yields in subsidence affected land in southern Illinois. In the same study, areas classified as moderately and severely affected by subsidence represented 2.3% and 5.3% of the mine land area and registered 42% and 95% corn yield reductions, respectively. These severe yield reductions were in unmitigated portions of the subsided landscape.

According to the study performed by Darmody (2000) and Darmody et al. (2014) in Illinois Basin on four-year corn crops, yield reductions were observed in the years with above-average rainfall. This was because of water ponding at the near-level grounds and at the bases of the troughs. The study focused on low inclined plain surfaces where the significant effect of the subsidence is likely to be related to changes to water drainage and topography.

The subsidence affects the agriculture productivity and drainage patterns of the area. Water accessibility and water loggings are likewise influenced by the crop type, sensitivity, and farming practices. Subsidence may altogether modify or destroy these water system frameworks. It may also influence the shape and efficiency of the management workings that are utilized to control soil erosion. Productivity of agricultural lands is a function of many interrelated factors like soil properties, plant-available water, climate and genetics. Furthermore, the cropping system and management of crop variety, fertilizer application and use of herbicides or pesticides influence the crop productivity (Figure 2.10).

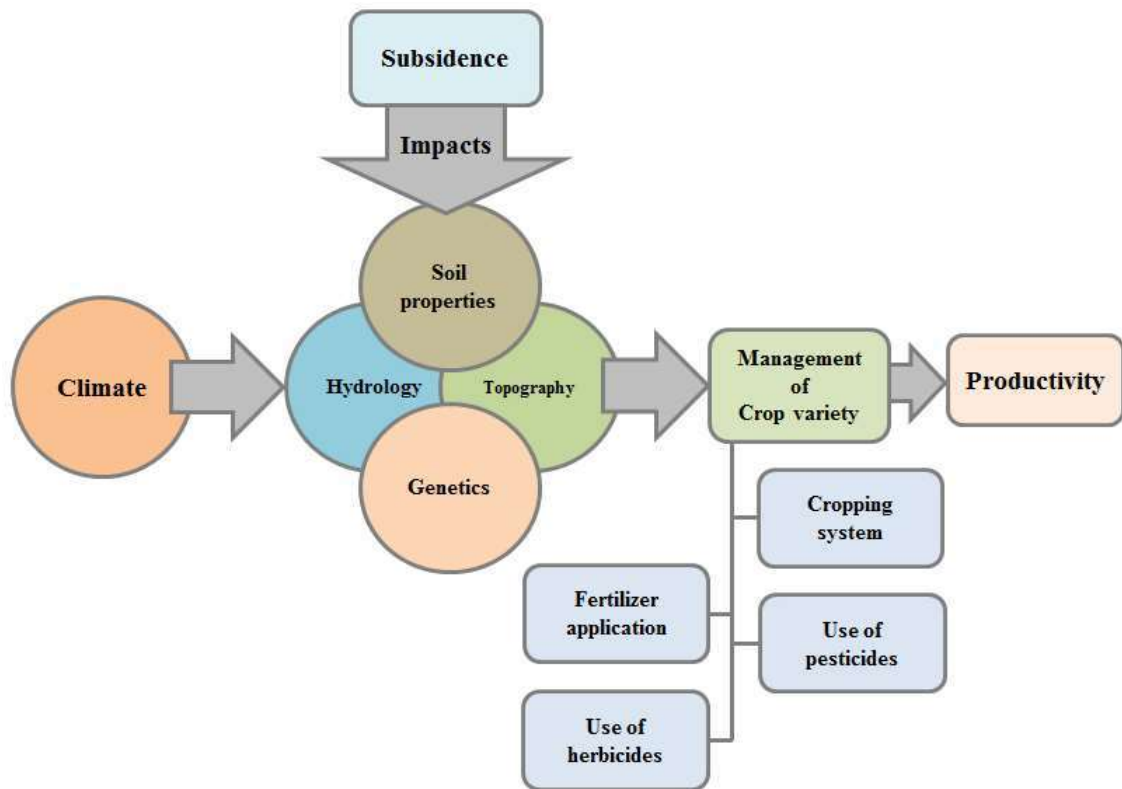


Figure 2.10 Schematic diagram showing the various ways of impacts of coal mining subsidence on agricultural productivity (modified from Lechner et al. 2016; Yao and Cui 2021)

A field investigation experiment was conducted by Zhang et al. (2017a) in subsided area of Zhaogu coal mine of Jiaozuo Coal Group, Henan Province, China, to explore effect of surface cracks caused by coal mining on the soil characteristics. They concluded that surface cracks resulted in loss of water and nutrients and reduction in crop yield, which were more serious with larger cracks.

Xiao et al. 2021 examined the relationship between coal mining subsidence and crop failure in plains with a high underground water table. They reported that the coal mining leads to stretching and deformation of the ground, land subsidence, and changes the physicochemical properties of the soil. In their case the yield of aboveground crops was poor, but under the influence of external factors such as irrigation and breeding, the threat of coal mining to crop growth was reduced.

Yields from crops such as chickpea and wheat are susceptible to changes in density (Gan et al. 2003; Lemerle et al. 2004, Lechner et al. 2016). In an experiment performed by Lemerle et al. (2004) for three wheat cultivars (*Lolium multiflorum*; *Lolium rigidum*; *Triticum aestivum*), a decrease in average yield by 4-5% was observed by increasing the crop density from 200 crops/m² to 425 crops/m². In contrast, effect of subsidence on percent yield has not been observed at some places with different cropping and irrigation systems. This has been shown in an experiment performed by Thompson et al. (2010), where visible impacts of subsidence on vineyard yields could not be seen. This was due to the presence of slope, which had maintained a proper water drainage system.

Chen et al. (2014) used the theory of niche to construct the niche suitability evaluation model of farmland in mining subsided area. They also concluded that surface subsidence caused by coal mining had an influence on the normal production of cultivated land.

2.5.3.2 Impacts on soil functions

Areas exposed to underground mining gradually result in subsidence of the aboveground surface, which can affect the soil structure in various ways. Underground mining induced surface subsidence may result into the formation of tensile and compressive strain zones at the subsidence areas. Tensile strain appears as cracks on the surface (Figure 2.11). The impacts of surface subsidence on the soil depend upon the type of the soil and its position in relation to subsidence areas. Soil particles at the pre-mining stage remain in a compact & tightly bound condition, but after mining, due to subsidence, it results in the soil's loose binding; consequently, the soil particles are left with very little compaction effect on the crop roots.

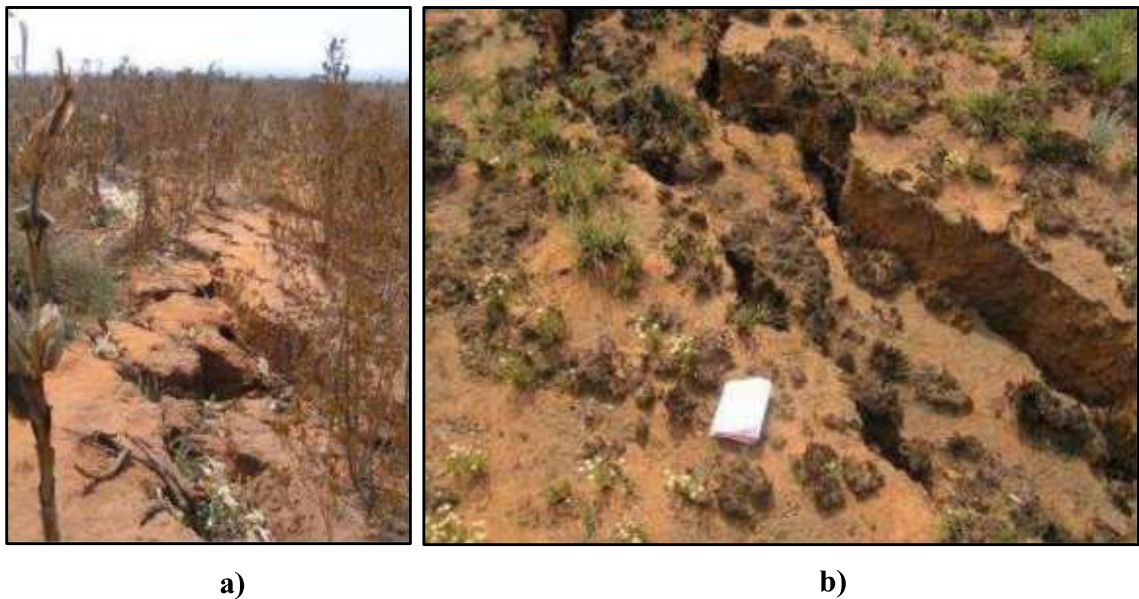


Figure 2.11 (a) Tension cracks associated with subsidence basin formation developed in an agricultural field in the Witbank area, South Africa **(b)** Tension cracks representing secondary features of surface subsidence (Engelbrecht 2013)

Due to the tensile strain, binding of roots in the soil is adversely affected by the subsidence process. It becomes very poor and hence, roots are unable to take the sufficient amount of nutrients from the soil. The reason can also be attributed to the lesser contacts of soil particles to the roots. The insufficient supply of nutrients adversely affects the major physiological processes of the crops like photosynthesis, chlorophyll synthesis, etc. and thus, consequently, impaired chlorophyll synthesis results in improper growth of the plants.

The compact soil may also hinder normal root growths, water and nutrient use efficiencies (Ishaq et al. 2001) by changing soil structure and hydrology through change in bulk density, infiltration, soil porosity, aeration, etc.



Figure 2.12 Subsidence basin observed at the agricultural field of Hanwang coal mine, China (Guo et al. 2018)

While working on silty clay loam soils in Illinois, Seils et al. (1992) reported that there is formation of cracks at the edge (tensile zones) and these cracks may increase the hydraulic conductivity along and through the cracks due to preferential flows. Large surface cracks resulting due to mine subsidence generally do not spread over the mined

area, but rather, associated with the edges where tension cracking occurred, was reported by Darmody (2000).

Principal Component Analysis was performed to evaluate the effect of slope position formed due to coal mining subsidence on the agricultural soil quality by Guo et al. (2018) at the agricultural field of Hanwang coal mine, China (Figure 2.12). Soil samples were collected from different positions in the subsided farmland. The analysis results of the samples were subjected to principal component analysis and soil quality indexes of different positions were determined. The study suggests that the slope position because of coal mining subsidence strongly affected the soil quality and crop yields.

2.5.4 Hydrologic impacts

Subsidence can cause both surface water and groundwater impacts. The degree to which those impacts change the land use typically depends on the unaltered (pre-mining) surface water and groundwater characteristics. Mining subsidence influences hydrologic systems in ways that cause changes to both water quality and quantity.

Subsidence can cause the formation of open cracks, fissures, or pits if it is connected either directly or indirectly to surface water (streams, lakes, ponds), which may lead to partial or complete loss of water that is drained to lower strata or mine workings. Depletion of water resources in this manner can impact their suitability (quality and quantity) as well as aquatic life forms (Darling 2011) and other life, which may depend on surface water systems.

Groundwater can be affected by mine subsidence in various ways, including lowering of groundwater levels, changes in flow rates, and impacts on water quality. Lowering of groundwater levels may decrease the groundwater supply and result in the

decrease or loss of well water and decreased surface transmission to springs, seeps and other surface water sources (streams, lakes and ponds). Increase in flow may be brought about by faster movement through fractured strata, accumulation of water, and reduced evapo-transpiration. Decrease in flow may be brought about by water diversion caused by mining and mine subsidence. Alteration of water quality is caused by changes in the chemical reactions and reaction rates with the minerals or surrounding strata (Darling 2011). The high rate of occurrence of acid drainage and associated metals contamination accompanying with mining operations is well documented and is recognized as a major adverse consequence of many hard-rock metal mining operations.

Fractures, fissures, and pits on the earth's surface provide a means for contaminants to seep through down to the aquifers that lie above the mined zone. Such contaminants may react chemically with each other or with the rocks. According to Mead et al. (1978), the underground coal gasification process and in situ retorting of oil shale can also affect ground-water supplies.

Darmody et al. (1989) proposed that the highest effect from an underground mine subsidence is on hydrology. According to Ham (1987) and Darmody (2000), changes to surface topography and soil compaction can result in disturbances to surface water runoff patterns and thus influence soil infiltration and porosity. The cracking and widening of joints and bedding planes (due to subsidence) raise the permeability as well as porosity and may likewise increase hydrologic associations between aquifers (Booth and Spande 1992).

The effects of land subsidence and rehabilitation on soil hydraulic properties were studied by Wang et al. (2017) in a mining area in the Loess Plateau of China. An underground coal mine was selected to conduct the field plot experiment. Four plots were designed, including one unmined plot, two subsided plots and one rehabilitated plot, and

samplings were carried out at each plot. The soil moisture retention curve, field capacity, saturated hydraulic conductivity at the depths of 0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm at each sampling point were measured. The correlation analysis among soil hydraulic properties and the path analysis of effects of subsided cracks on the hydraulic properties were carried out. The results showed that the land subsidence increased the variability of soil hydraulic properties; whereas, they became relatively uniform after land rehabilitation. It also showed that the land subsidence significantly altered the soil hydraulic properties, increasing the hydraulic conductivity and decreasing the field capacity. However, land rehabilitation can improve soil hydraulic properties and increase the use efficiency of soil water, decreasing the hydraulic conductivity and increasing the field capacity. The cracks related to subsidence and vegetation had significant effects on the soil's hydraulic properties.

In a study performed by Liu et al. (2020), O–J–I–P chlorophyll a fluorescence analysis was used to diagnose the disturbance mechanism of typical individual plants by coal mining subsidence in a semiarid area. The results showed that the groundwater level and soil water content decreased due to the disturbance of coal mining subsidence and the plant growth was affected by drought stress. Stomatal conductance, photosynthetic rate, and transpiration rate decreased significantly. The spatial heterogeneity of soil water content after mining subsidence was the main reason for the differing degree of plant drought stress in different subsidence areas.

Soil water contents and isotopically labeled water (^2H) information were used by Chen et al. (2022) to detect the effects of soil structural differences due to coal mining subsidence on soil water infiltration and plant water uptake patterns in the non-mining zone, subsidence fracture-free zone, and subsidence fracture zone. Based on soil water

content measurements of soil profiles, soil water content in the subsidence fracture zone was the lowest among the three zones.

2.5.5 Coal mine fires

Sometimes coal mine fires may occur due to underground coal mine subsidence. According to Dunrud and Osterwald (1980), coal mine fires seem to start by spontaneous ignition when air and water enter through subsidence cracks and pits. The drawing in of oxygen and the exhaustion of smoke, steam, and noxious gases through these cracks helps support combustion. As the coal burns, more cavities are created, causing more cracking and collapse, which allows greater access for air, thereby accelerating coal burning. This process not only destroys the valuable commodity but it pollutes the air and kills nearby vegetation.

According to Pandey et al. (2016), coal mine fire has led to degradation of land in the form of undulating surfaces caused by subsidence and affects vegetative land by degrading the fertility of the soil. Over 6025 hectare of land had degraded due to coal fire and other mining activity in Jharia coalfield. The forest cover has decreased sharply and native natural vegetation is being replaced by exotic species (Pal et al. 2011). Aesthetic look of Jharia coalfield is drastically damaged due to mass deforestation and subsidence.

Changes in the thermal properties have an effect on the plant growth. The thermal properties are the primary factors that affect the rate of plant growth and development (Hatfield and Prueger 2015; Onwuka and Mang 2018). Soil temperature has a great effect on plant growth by influencing water and nutrient uptake (Onwuka and Mang 2018; Toselli et al. 1999), root and shoots growth (Weih and Karlsson 1999). Water uptake decreases with low temperature. This is due to the increased viscosity and decreased absorption rate

of water at low temperature (Toselli et al. 1999). Decreased water uptake reduces the rate of photosynthesis. The metabolic activities of micro-organisms play an important role in the cycling of nutrients in the soil and ensuring the nutrients are in a form available to the plants. Therefore increased metabolic activities of micro-organisms as a result of increase in soil temperature will stimulate the availability of nutrients for plants. Soil temperature also affects nutrient uptake by changing soil water viscosity and root nutrient transport (Grossnickle 2000). Lahti et al. (2002) observed that at low soil temperature, nutrient uptake by plants reduce as a result of high soil water viscosity and low activity of root nutrient transport. Increase in soil temperature improves root growth because of the increase in metabolic activity of root cells and the development of lateral roots (Repo et al. 2004). Extreme heat stress can reduce plant photosynthetic and transpiration efficiencies and negatively impact plant root development (Irmak 2016). In controlled environment studies by Hatfield and Prueger (2015), warm temperatures increased the rate of phenological development. Thus, the warmer temperatures expected with climate change and the potential for more extreme temperature events impact plant productivity.

2.5.6 Dissolved organic matter and organic carbon

Li et al. (2014) performed a study on change characterization of dissolved organic matter in different subsidence land of a coal mine, China. The results showed a decrease in protein-like materials and an increase in humic acid materials with the formation of subsidence wetland. The structure of dissolved organic matter became more complex and the degree of humification of dissolved organic matter increased. The correlation analysis indicated that changes had significant influence on the bioavailability of metals.

In another study, soil nutrients of different utilization types (for example, greenhouse reclamation area, cropland reclamation area and forest reclamation area) in coal mining subsidence area had been analyzed by Zhou et al. (2015). Results showed that in greenhouse reclamation area, the content of organic matter and elements was higher, followed by cropland reclamation area, but in forest reclamation area, soil fertility was improved with the prolongation of the cropping and reclamation.

Xu et al. (2019) investigated the effects of underground coal mining on regional soil organic carbon pool in farmland in the Jiuli mining area of Xuzhou city in China as a typical coal-mining region based on field sampling, chemical analysis, model construction, and spatial analysis using the ArcGIS software. The results showed that in the mining subsidence area, spatial variation in soil organic carbon content was mainly caused by structural factors (mining subsidence, subsidence waterlogging, and other structural factors due to coal mining) at a regional scale.

2.5.7 Economic impacts

Economic impacts of subsidence may include direct structural damage, loss of the value of renewable resource lands (i.e., farmland), land value depreciation, loss of sterilized resources where underground resources must be left to support surface development, and adverse effects on economic growth (Stingelin 1975; Dyne 1998). The Bureau of Mines estimated that underground coal mining would cause surface damage costs in excess of one billion dollars from 1973 to 2000 (Comptroller General of the United States 1979).

2.5.8 Other impacts

Fractures in subsidence features allow methane and other dangerous mine gases to leak out, causing trees and plants to die. These same gases could present a hazard to animals or people on the surface.

Mining-subsidence impacts related to wildlife and human recreational use are generally characterized by either a diminishment of the actual or perceived value for such use or, in some cases, by the total loss of such use. Direct impacts on a particular aquatic species or for a particular recreational use might be measurable, whereas indirect impacts on a particular species or recreational use for an area are more difficult to evaluate and, to some extent, may be subjective. For example, one species of aquatic insect may be unique to a particular hydrological system that is threatened by mining. In an indirect manner, any mammalian wildlife, which depends on that species of insect for food, would also be impacted. Similarly, recreational activities like fishing or hiking could be impacted by mining subsidence.

Mining subsidence also affects the use of lands by wildlife or for human recreation. Additional consideration is required where lands are intended to support threatened or endangered wildlife species or in wilderness areas that are intended to retain certain undisturbed or natural characteristics.

2.6 Subsidence impact assessment using remote sensing technique

2.6.1 Remote sensing

Remote sensing is the science of acquiring information about the Earth's surface without actually being in contact with it. This is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information. Remote sensing

technologies can be applied efficiently to distinguish and evaluate the past, present as well as the future trends of land use land cover (LULC) (Dadhich and Hanaoka 2011; Mishra et al. 2014). These techniques have been recognized as potential and effective tools for the assessment of land, water, and other natural resources (Mundia and Aniya 2005). A number of studies have been attempted to elucidate the efficacy of these tools for assessment of LULC changes (Kilic et al. 2006; Raju and Kumar 2006) as well as the changes occurring in vegetation growth patterns (Gu et al. 2014, Vishwakarma et al. 2018, 2021). The use of these techniques also provides the benefit for speedy data acquisition, often at a lower cost than traditional ground inspection methods (Mishra and Rai 2016). Figure 2.13 shows a schematic diagram of the important stages in remote sensing technique.

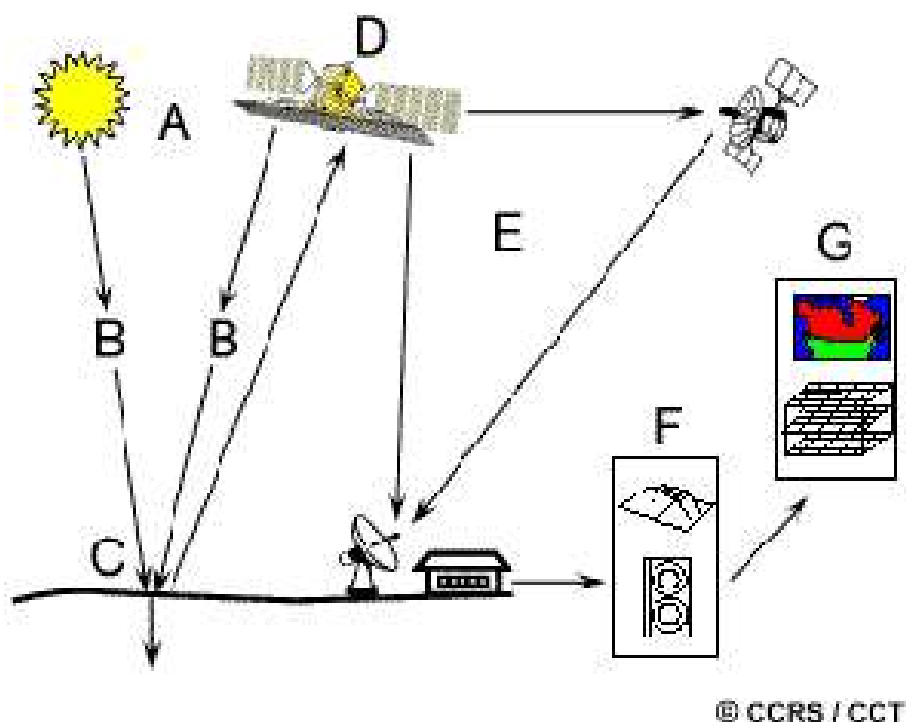


Figure 2.13 Important stages in remote sensing (CCRS; Canada Centre for Remote Sensing)

Where A is the energy source, B denotes the radiation and the atmosphere, C denotes interaction with the target, D is the recording of energy by the sensor, E is the transmission, reception, and processing, F denotes the interpretation and analysis, and G denotes the application.

The fundamental of these terminologies have been discussed below:

- i. **Energy source or illumination (A)** – The first requirement for remote sensing is to have an energy source that illuminates or provides electromagnetic energy to the target of interest.
- ii. **Radiation and the atmosphere (B)** – As the energy travels from its source to the target, it will come in contact with and interact with the atmosphere it passes through. This interaction may take place a second time as the energy travels from the target to the sensor.
- iii. **Interaction with the target (C)** - Once the energy makes its way to the target through the atmosphere, it interacts with the target depending on the properties of both the target and the radiation.
- iv. **Recording of energy by the sensor (D)** - After the energy has been scattered by or emitted from the target, we require a sensor (remote - not in contact with the target) to collect and record the electromagnetic radiation.
- v. **Transmission, reception, and processing (E)** - The energy recorded by the sensor has to be transmitted, often in electronic form, to a receiving and processing station where the data are processed into an image (hardcopy and/or digital).
- vi. **Interpretation and analysis (F)** - The processed image is interpreted, visually and/or digitally or electronically, to extract information about the target which was illuminated.

- vii. **Application (G)** - The final element of the remote sensing process is achieved when we apply the information we have been able to extract from the imagery about the target in order to better understand it, reveal some new information, or assist in solving a particular problem.

2.6.2 Radiation-target interactions

Radiation that is not absorbed or scattered in the atmosphere can reach and interact with the Earth's surface. There are three forms of interaction that can take place when energy strikes or is **incident (I)** upon the surface. These are: **absorption (A)**; **transmission (T)**; and **reflection (R)**. The total incident energy will interact with the surface in one or more of these three ways. The proportions of each will depend on the wavelength of the energy and the material and condition of the feature.

Figure 2.14 shows the example of three forms of interaction of the incoming incident energy. A chemical compound in leaves called chlorophyll strongly absorbs radiation in the red and blue wavelengths but reflects green wavelengths. Leaves appear greenest to us in the summer, when chlorophyll content is at its maximum. In autumn, there is less chlorophyll in the leaves, so there is less absorption and proportionately more reflection of the red wavelengths, making the leaves appear red or yellow (yellow is a combination of red and green wavelengths). The internal structure of healthy leaves acts as excellent diffuse reflectors of near-infrared wavelengths. If our eyes were sensitive to near-infrared, trees would appear extremely bright to us at these wavelengths. In fact, measuring and monitoring the near-infrared reflectance is one way that scientists can determine how healthy (or unhealthy) vegetation may be. For example, vegetation may reflect somewhat similarly in the visible wavelengths but are almost always separable in the infrared.

Spectral response can be quite variable, even for the same target type, and can also vary with time (e.g., greenness of leaves) and location. Knowing where to look spectrally and understanding the factors which influence the spectral response of the features of interest are critical to correctly interpreting the interaction of electromagnetic radiation with the surface.



Figure 2.14 Three forms of interaction of the incoming incident energy (CCRS)

NDVI is the most common index that quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs). Healthy vegetation (chlorophyll) reflects more near-infrared (NIR) and green light compared to other wavelengths. But it absorbs more red and blue light. NDVI uses the NIR and red channels in its formula, which is given by –

$$NDVI = \frac{NIR-R}{NIR+R}$$

Where NIR = Near-Infrared Band value and R = Red Band value recorded by the Landsat 8 OLI imageries. Figure 2.15 illustrates the basic concept behind the calculation of NDVI.

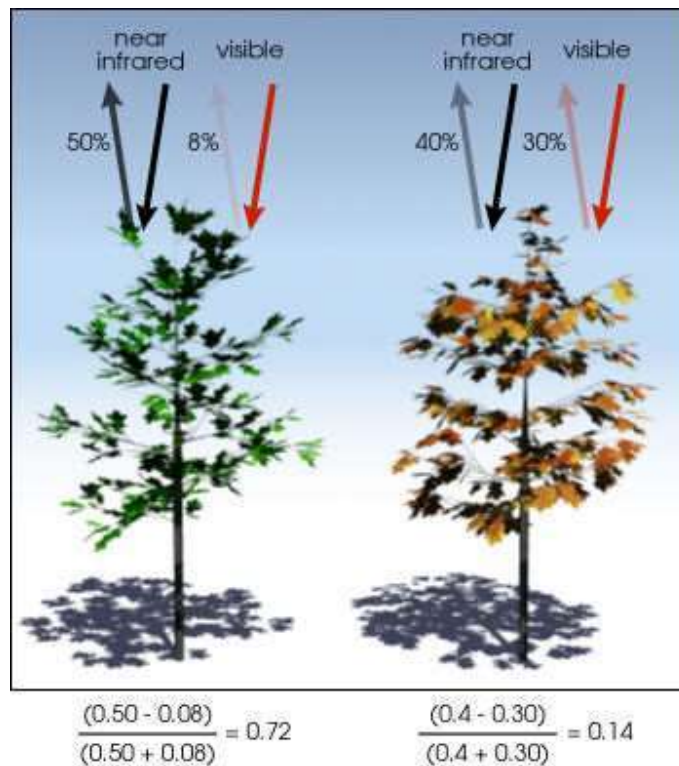


Figure 2.15 A schematic diagram showing the basic concept behind the calculation of NDVI (NASA; National Aeronautics and Space Administration)

The result of this formula generates a value between -1 and +1. Low reflectance (or low values) in red channel and high reflectance in NIR channel will yield a high NDVI value and vice versa. Overall, NDVI is a standardized way to measure healthy vegetation. High NDVI values mean healthier vegetation and lower NDVI value means less or no vegetation.

There are no two remote sensing images that are the same. The problem is same with the NDVI products too. For local-scale vegetation management purposes, NDVI is commonly used as a direct indicator of vegetation health and growth (Coops and Stone 2005; McVeagh et al. 2012); for large-scale vegetation monitoring purposes, NDVI is often used as a dependent variable to predict other vegetation attributes that cannot be

detected directly with remote sensing imagery. In either case, it is possible to validate the visual or quantitative predictions (Box et al. 1989; Loranty et al. 2018). This validation is necessary to evaluate the effectiveness of NDVI data used.

2.6.3 Image analysis

Interpretation and analysis of remote sensing imagery involve the identification and/or measurement of various targets in an image in order to extract useful information about them. Targets in remote sensing images may be any feature or object which can be observed in an image and have the following characteristics:

- Targets may be a point, line, or area feature. This means that they can have any form, from a bus in a parking lot or plane on a runway, to a bridge or roadway, to a large expanse of water or a field.
- The target must be distinguishable; it must contrast with other features around it in the image.

When remote sensing data are available in digital format, digital processing and analysis may be performed using a computer. Digital processing may be used to enhance data as a prelude to visual interpretation. Digital processing and analysis may also be carried out to automatically identify targets and extract information completely without manual intervention by a human interpreter.

2.6.3.1 Digital image processing

Digital image processing may involve numerous procedures, including formatting and correcting of the data, digital enhancement to facilitate better visual interpretation, or even automated classification of targets and features entirely by computer. In order to

process remote sensing imagery digitally, the data must be recorded and available in a digital form suitable for storage on a computer tape or disk.

For discussion purposes, most of the common image processing functions available in image analysis systems can be categorized into the following categories:

- a) **Preprocessing** functions involve those operations that are normally required prior to the main data analysis and extraction of information and are generally grouped as **radiometric or geometric corrections**. Radiometric corrections may be necessary due to variations in scene illumination and viewing geometry, atmospheric conditions, and sensor noise and response. Each of these will vary depending on the specific sensor and platform used to acquire the data and the conditions during data acquisition.
- b) **Image transformation** typically involves the manipulation of multiple bands of data, whether from a single multispectral image or from two or more images of the same area acquired at different times (i.e., multitemporal image data). Either way, image transformations generate "new" images from two or more sources that highlight particular features or properties of interest better than the original input images. Basic image transformations apply simple arithmetic operations to the image data. Image subtraction is often used to identify changes that have occurred between images collected on different dates.

One widely used image transform is the Normalized Difference Vegetation Index (NDVI) which has been used to monitor vegetation conditions on continental and global scales using the advanced, very high-resolution radiometer sensor onboard the NOAA series (national oceanic and atmospheric administration) of satellites

c) **Image Classification and analysis:** Digital image classification uses the spectral information represented by the digital numbers in one or more spectral bands and attempts to classify each individual pixel based on this spectral information. This type of classification is termed as spectral pattern recognition. In either case, the objective is to assign all pixels in the image to particular classes or themes (e.g., water, coniferous forest, deciduous forest, corn, wheat, etc.). The resulting classified image is comprised of a mosaic of pixels, each of which belongs to a particular theme and is essentially a thematic "map" of the original image.

2.6.3.2 Data integration and analysis

Most data is available in digital format from a wide array of sensors. Data integration is a common method used for interpretation and analysis. Data integration fundamentally involves the combining or merging of data from multiple sources in an effort to extract better and/or more information. This may include data that are multitemporal, multiresolution, multisensor, or multi-data type in nature.

2.6.4 Studies based on the effect of mining induced subsidence on the plants using remote sensing techniques

Various studies have been carried out by many authors on subsidence prediction and impact using remote sensing techniques. The present study is focused on the effect of coal mine subsidence on the plants using remote sensing techniques.

Thompson et al. 2011 reported on the design and implementation of a program to monitor the surface effects of longwall mining-induced subsidence on wine grape yields within vineyards of Australia's Hunter Valley. It was a multi-scale, multi-temporal, sliding window monitoring design synchronized with the progression of longwall panels. On the

vineyard-block scale, individual vine panels were sampled for grape yield. On the regional scale, measures of vine photosynthetically active biomass were obtained from remotely sensed, Quickbird satellite imagery. All data were analysed in conjunction with three identified subsidence “zones”: minimum subsidence associated with chain-pillars, maximum subsidence associated with the longwall, and a zone corresponding to the transition between them. Visual observations conducted throughout the campaign confirmed the occurrence of isolated localised surface cracking, particularly in areas of maximum soil tension. However, both vineyard and block-scale data indicated no obvious, systematic mining-induced viticultural effects in the study site investigated during the study period.

The ecological environment has been affected by coal mining. Vegetation index is often used as an important indicator for monitoring changes in the ecological environment. Ma et al. (2013) investigated the spatial-temporal variation of vegetation index caused by mining subsidence in semi-arid mountain regions. The results showed that spatial connections between NDVI (normalized difference vegetation index) change and surface mining disturbed area were significantly different. The maximum of forest canopy NDVI average in non-mining area increased year by year (0.619451 (2004), 0.637263 (2005), 0.662735 (2006), 0.739987 (2007)), and its average annual net increased by 6.18%. The maximum of mean NDVI in subsidence areas, however, tended to increase before mining. In mining year, the values decreased with an average annual decrease of 11.91. The NDVI mean variation before and after the mining subsidence in eight experimental faces of Lu'an mining area were also extracted from 2004-2007 by seven temporal remote sensing images. They observed that the coal mining caused an annual decline of -14.83% of the NDVI maximum in the eight experimental faces. This decline lasted about one to two years. This

indicated that NDVI change had a temporal correlation with mining activities in the experimental faces, and the damaging of plants growth and the weakening of biomass accumulation in mining disturbed areas were mainly caused by the mining subsidence. Tao et al. (2016) studied the temporal characteristics of response of vegetation to disturbance of mining and subsidence in semi-arid coal mining area. They found that coal mining had some negative impacts on vegetation NDVI.

A gradual comprehensive analysis of the impact of coal exploration on vegetation growth was performed by Gu et al. (2014). Chongqing Songzao Mining was selected as the study area. Changes in NDVI of the past decade were analyzed from a macro perspective using three remote sensing data. They concluded that Songzao mining exploitation of coal resources affected the local forest and grassland vegetation, but not on a wide range of forest and grassland ecosystems adversely affected. The area of forest and grassland ecosystems carried local failure, and through the self-healing approach ultimately made forest grass ecosystem to stabilize.

Mining for resource extraction may lead to several geological and associated environmental changes due to ground movements, collision with mining cavities and deformation of aquifers. Padmanaban et al. (2017) studied the landscape dynamics in Kirchheller Heide, Germany, which experienced extensive soil movement due to longwall mining without stowing, using Landsat imageries between 2013 and 2016. The changes in vegetation health using NDVI were analyzed. NDVI values indicated that 66.5% of the vegetation of the study area was degraded due to mining subsidence.

A combination of field assessments with remote sensing was used by Yang et al. (2018) to examine vegetation patterns and responses to underground mining, located on the southern edge of Inner Mongolia in China. After mining started, the vegetation community

index based on plant density and coverage in areas affected by subsidence fractures decreased by 0–21.5%. Nevertheless, the average NDVI at the entire watershed scale increased by 15% from 2001 to 2016, although this change appeared to be primarily related to rainfall. This study confirmed that underground coal mining in the watershed had not caused extensive vegetation degradation as feared.

In India, there is scanty of information regarding the changes in forest and soil due to mine subsidence and the study of subsidence on forest cover and soil characteristics is limited. This study would be helpful for understanding the various aspects of the effects of mining induced subsidence on soil, forest land and flora using laboratory model, physical and chemical analysis of the samples collected from the study area through field visit and by geospatial techniques using the remote sensing technology.