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Subsidence

Occurrence, Prediction and Control

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CHAPTER 15

SUBSIDENCE ARISING FROM GROUND-WATER WITHDRAWAL, OIL AND GAS FIELD ACTIVITIES AND UNDERGROUND COAL GASIFICATION

Several underground processes are operated remotely as with ground-water withdrawal, oil and gas field operations and the underground gasification of coal. The fact that fluid and/or gas are removed from significant depths results in a measure of uncertainty arising regarding the full extent of the surface area affected by subsidence. Unless a distinct boundary exists in part or in full as can occur by virtue of geological structure, then the limits of fluid withdrawal may decrease gradually owing to the flow properties of the reservoir rocks/sands.

This chapter examines a number of aspects involved with the nature of surface subsidence as often occur with these forms of underground processes.

Subsidence arising from ground-water withdrawal

Poland (1972) has drawn attention to particular problems and their control in matters of land subsidence associated with ground-water withdrawal. An extension of Poland's work has been reported by Helm (1984) who examined field-based computational techniques with special reference to predicting subsidence due to fluid withdrawal. Helm suggested that the choice of predictive technique should be based on the availability of appropriate data from the field. In those cases where only estimates of the depth and thickness of compressible formations are possible, then simplified calculations for many situations have proved to be adequate.

Subsidence relates to vertical movement, and associated effects, of the land surface. Compaction in geological terminology refers to the decrease in thickness of sediments following the application of vertical stress. Consolidation in soil mechanics terminology relates to decrease in thickness of a laboratory sample subjected to compressive loading. The subsidence arising from withdrawal of ground-water is essentially a surface response to sediment compaction at depth, Helm (1984).

A small change in effective stress of an engineering soil at depth is accompanied by a small change in volume when considering a column of soil. The application of a sustained constant head of drawdown to a ground-water regime triggers a subsidence process which does not occur immediately. The response of the porous sediment forming the aquifer is to behave in accordance with time-consolidation theory which means that the subsidence rate will taper off gradually and can take many years. The magnitude of the drawdown head will influence the time of subsidence duration and also the limits of subsidence although the ground-flow properties also play a role. Helm (1984) suggests that empirical methods allow observed subsidence to be plotted against time so that extrapolation is possible for predicting future subsidence simply by selection of an appropriate curve fitting technique.

General surface behaviour to ground-water withdrawal. Two principal mechanisms have been advanced to explain ground behaviour following ground-water withdrawal:

1. The phenomenon of localised differential compaction.
2. The resulting horizontal contractions which arise owing to capillary effects in the zone above a lowering water table.

Holzer (1984) considers that based on US experience these particular points appear to be of significance to ground movement behaviour, although the second seems only of relevance in areas where surface fissures exhibit polygonal patterns. Earth fissures appear to mainly form in those zones where the near-surface aquifer system experiences thinning over ridges or even steps at the bedrock surface. Field evidence indicates that such fissures occur in those zones of maximum tension, ie curvature convex-upward. Fissure systems forming complex polygonal patterns appear to be essentially large contraction cracks.

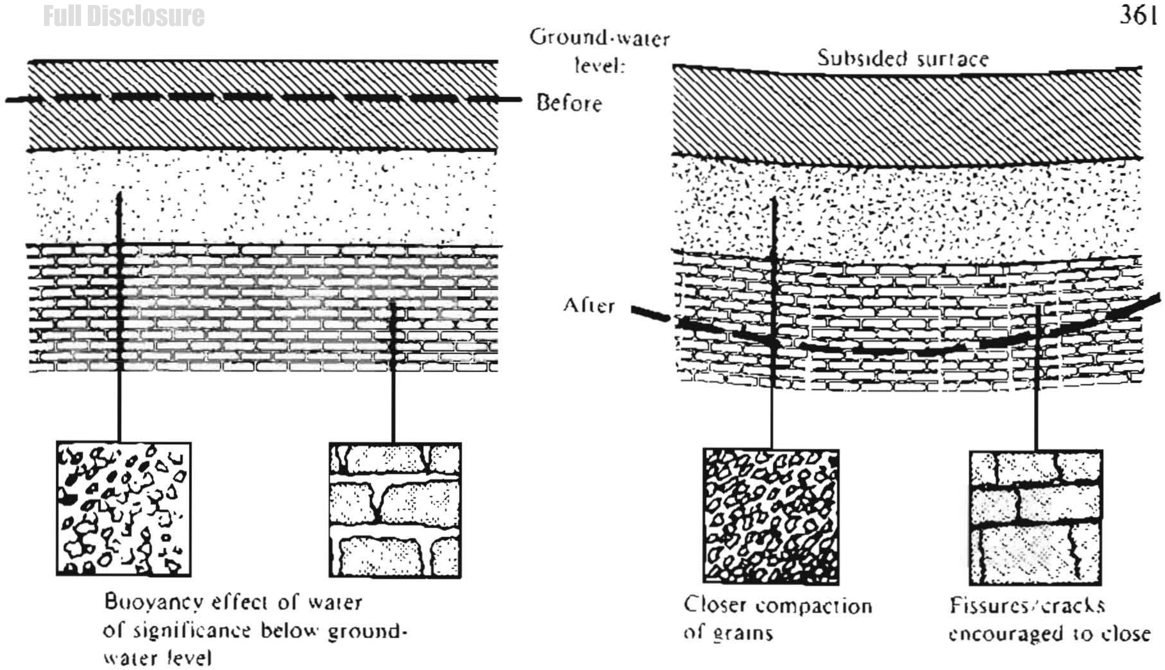
Figure 201 illustrates the principal mechanisms of ground behaviour as based on US observations following the withdrawal of ground-water.

Nature of surface failure and subsidence resulting from ground-water withdrawal: US experiences

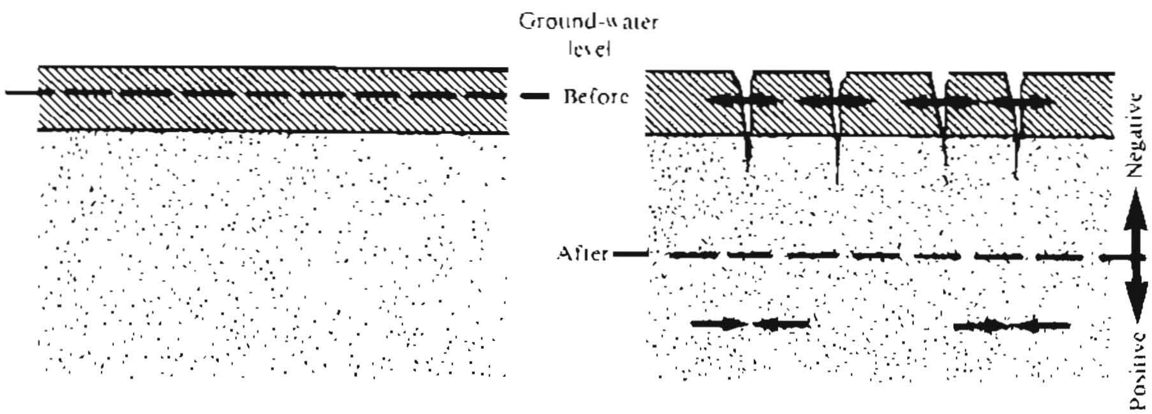
An interesting and comprehensive account of the nature of surface ground failures above unconsolidated sediments which have been subjected to ground-water withdrawal has been given by Holzer (1984). He reported that observed failures included long tension cracks or fissures at one end of the range through to surface faults (significant steps) at the other. These failures are a feature of land subsidence resulting from underlying unconsolidated sediment experiencing compaction during ground-water withdrawal. The fissures can range in length from tens of metres to kilometres, but generally open of the order of centimetres. Later erosion of such fissures commonly results in gullies of dimensions 1-2m width and 2-3m depth. Some fissures have been measured to depths of 5 to 10m using a weighted line lowered into the fissure. A fissure was logged as having a depth of 16·8m when logging terminated at the water table. The surface fault (step) features commonly exhibit scarps of 0·5m height with lengths of the order of a kilometre or so; some surface faults attain heights of 1m and a length of 16·7km has been observed. Scarp growth has been reported to be in the range of 4 to 60mm/year with most movement correlating with seasonally wet periods. Major step development has resulted in extensive surface damage at Houston - Galveston, Texas, metropolitan region.

Holzer (1984) has estimated that surface subsidence effects relating to ground-water withdrawal from underlying unconsolidated sediments has affected a total area of around 22 000km^2 in the United States. The main feature is that of loss of elevation namely subsidence, and has exceeded 1m in several areas whilst at the San Joaquin Valley, California the maximum subsidence has attained 8·5m. Holzer points out that fissures are generally first noticed after erosion along the line of the fissure particularly following rainstorms. The early stage of development would typically show collapse features along the line of the fissure, and such features would be generally connected by minor to hairline cracks. There is an indication of hydraulic connection between these surface features in most situations. A further important aspect drawn attention to by Holzer is that scarps formed by faults due to ground-water withdrawal usually appear similar to fault scarps of natural origin and that confusion can arise in differentiating between them. The following points are made in this respect:

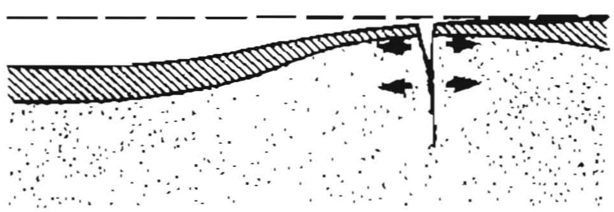
1. ground-water fluctuations have been observed to relate to surface fault movement, although seasonal fault movements also occur,



(a) Effect of ground-water withdrawal on localised differential compaction resulting in surface subsidence.



(b) Surface tension and capillary attraction creating horizontal tension forces in near-surface soils and giving rise to complex polygonal patterns of fissure systems



(c) Occurrence of large surface fissures/faults in zones of maximum tension as created by ground-water withdrawal

Figure 201 Illustrating the principal mechanisms of ground behaviour following withdrawal of ground-water. Based on observations reported by Holzer (1984).

2. ground-water withdrawal appears linked with temporal and areal manifestation of localised fault occurrence,
3. earth fissures arising through water-withdrawal pose distinct hazards, namely *(a)* the displacements accompanying their formation, and *(b)* the resulting deep gullies which are modified by erosion,
4. most of the observed earth fissures occur above ridges in the bedrock surface which may be buried. The fissures appear to be controlled by bedrock conditions.

Holzer refers to land subsidence in the Picacho Basin, Arizona where water withdrawal has taken place over several years. Between the period 1963/64 to 1977 subsidence was observed to take place over the basin and spanning a distance of some 12km approximate diameter with maximum subsidence of 1·25m. Subsidence movements concentrated around the Picacho Fault which extends some 15km along the edge of the basin and bordering the Picacho Mountains. Fissuring was also observed to occur in the vicinity of this surface fault, which was first formed as a fissure in 1949 and had since developed relative vertical displacements (steps) of 0·2 to 0·6m. The fault scarp began to form in 1961. Creep rate across the scarp was around 60mm/year during the early stages but decreased to around 9mm/year by the period 1975-80. Holzer reports that the creep rate varies seasonally and that there is a correlation with water-level fluctuations. Field investigations indicate that the Picacho Fault is in the main associated with a pre-existing fault and this acts as a partial barrier to ground water flow in the alluvial aquifer.

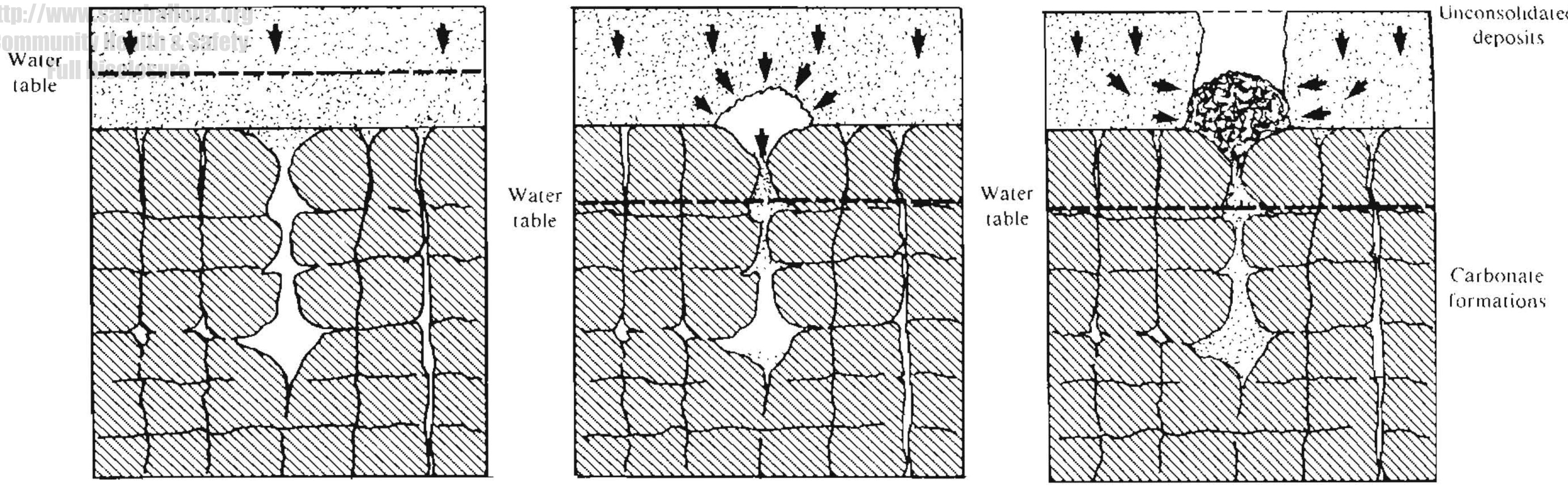
Land subsidence at Houston - Galveston, Texas is also discussed in detail by Holzer. More than 160 surface faults of total length greater than 500km have been observed to be associated with subsidence attaining a maximum value of more than 2·7m with a subsidence affected area of some 90km or so approximate diameter. The land subsidence referred to here has been observed from 1906 to 1978. The surface faults tend to predominate in an approximate north-east direction, and their intensity is greatest around the central area of the subsidence basin. Although oil and gas production is fairly extensive in this region, it is considered that the land subsidence is due almost exclusively to ground-water withdrawal, with minor contributions from oil and gas production.

Detailed surveying observations made by the Nevada Department of Transport in the Las Vegas Valley are also referred to by Holzer, and these results indicate the formation of a localised subsidence depression in association with a fault. As no pumping wells were located in the area of the depression, this localised subsidence was attributed to sub-surface conditions rather than lowering of the water level.

Special problems arising from ground-water withdrawals above sink-hole prone carbonate bedrock conditions

Lowering of the water-table by ground-water withdrawal above carbonate rocks such as limestone and dolomite has given rise to particular sink-hole problems developing at the surface. Where such rocks occur at the surface, it is not uncommon to see pock-marked features of earlier erosion. The extent of such erosional features depends upon the sensitivity of such rocks to dissolution by surface- and ground-waters in addition to climatic conditions, vegetation, topography and the general character of structural weaknesses within the rock mass. Chapter 1 has discussed sink-hole development as a natural phenomenon in limestone country. Attention is drawn here to particular problems encountered when lowering the water-table over sink-hole prone carbonate bedrock conditions.

Effect of lowering the water-table. Figure 202 illustrates the main principles governing the effect of changed water-table conditions on the development of a sink-hole at the surface.



Stage 1

1. Water-table above carbonate bedrock subjected to steady state conditions and virtually in equilibrium.
2. Downward percolation of water into carbonate bedrock "controlled" by infilling of clays, silts, gravels etc within immediate bedrock fissures.

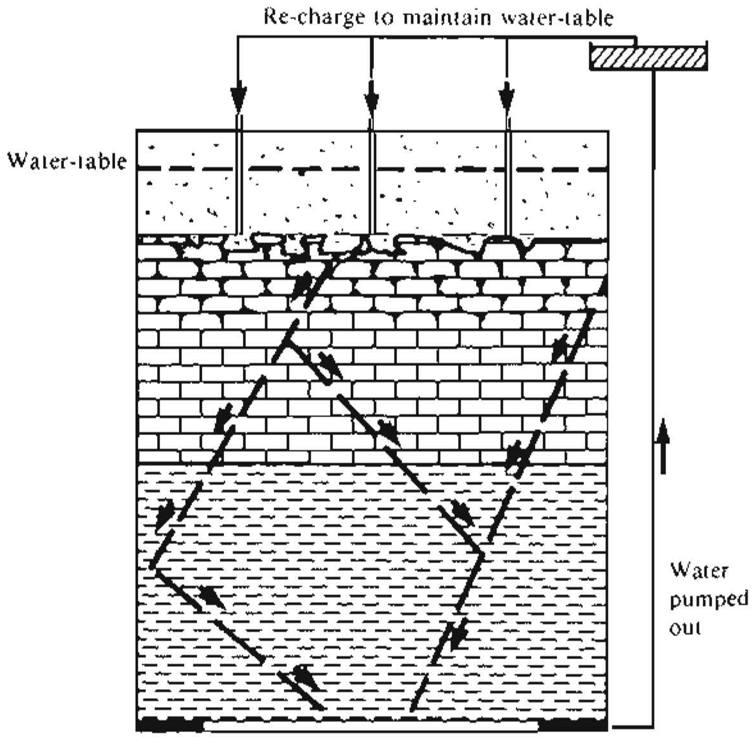
Stage 2

1. Water-table lowered to below carbonate bedrock.
2. Drainage of surface waters through to water-table line attempts to seek lines of least resistance. Large pre-existing erosion-widened fissures in bedrock form natural drainage attraction points.
3. Localised attraction of drainage above major fissured feature creates potential for surface deposit materials to wash down and trigger onset of a sink-hole development.
4. Lower connecting ground-water courses allow loose material to be washed down and transported underground.

Stage 3

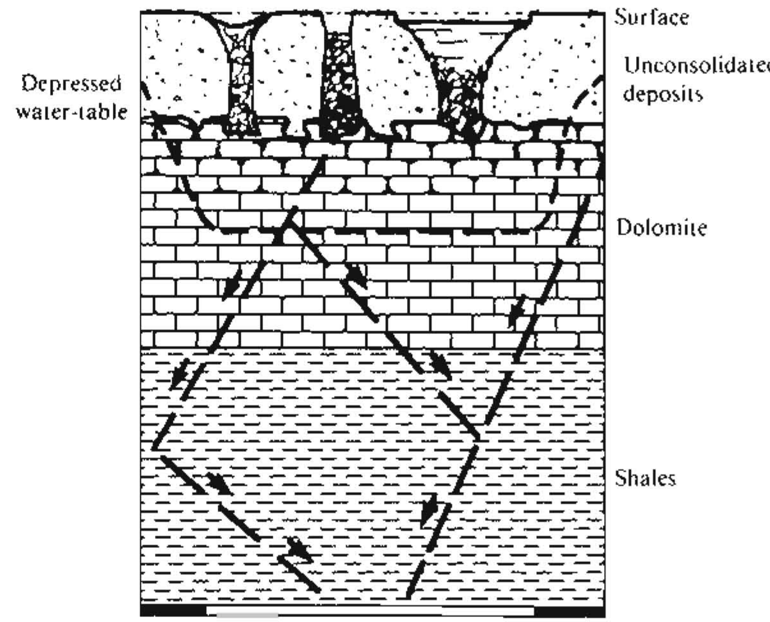
1. Sink-hole develops to surface if material can be washed down into lower cavities — otherwise it could choke naturally before reaching surface if sufficient depth of cover exists.

Figure 202 Illustrating effect of ground-water withdrawal above sink-hole prone carbonate bedrock conditions.



(i) Re-charging water-table during mining

1. Mining progressively results in increased inflow of water into mine, particularly via disturbance to connecting faults.
2. Water pumped out is used to re-charge the water-table and prevent, or control, formation of sink-holes.



(ii) Effect of de-watered compartment on the surface

1. Water-table is lowered locally to create de-watered compartment in order to reduce inflow of water into mine.
2. Changed hydrogeological conditions at interface between unconsolidated materials and dolomite encourages development of sink-holes which can be of:
   (a) Local saucer-shaped, or funnel-shaped depression generally affecting small area.
   (b) Clearly defined subsidence hole with near vertical or even overhanging sides which is again localised.
   (c) Depression, usually circular, with stepped edges; the step can be of a few millimetres but generally of order of centimetres although steps of a few metres are not unknown. The diameter of the depression can be up to 100m or even greater, depending upon the rate at which the water-table is lowered and condition of the bedrock.

Figure 203 Illustrating effect of lowering the water-table below the dolomite bedrock horizon and subsequent effect on sink-hole development.

With the water-table above the carbonate bedrock level and located in the unconsolidated deposits, in effect is in a virtual state of equilibrium. The downward percolation of water into the carbonate bedrock is "controlled" by infilling of the immediate bedrock fissures with unconsolidated materials washed down from the surface deposits. If a flow-path for the waters draining into the carbonate, was suddenly enlarged say by breaking down of a clay plug, then the conditions could arise for the start of a natural sink-hole to develop. However, the latter condition could easily become choked by more material falling into the carbonate drainage cavity, and a state of equilibrium being restored.

Stage 2 of Figure 202 shows the effect of lowering the water-table below the carbonate bedrock horizon. Water draining through the unconsolidated materials will seek the line of least resistance and be attracted to major natural drainage features at the carbonate interface. The result can be to dislodge previously choked fissure systems and allow major drainage paths to come into operation. The water drainage pattern in the unconsolidated materials will encourage the formation of cavities at the contact horizon with the carbonate. As the unconsolidated materials fall into the carbonate fissure system, sufficient water flow now exists as to wash these loose sediments into lower cavities. This process can progress and eventually lead to the formation of a collapse-feature, often a sink-hole, appearing at the surface.

Sink-holes associated with ground-water withdrawals in carbonate bedrock conditions in the US. Newton (1984) has described sink-hole activity in carbonate terranes following ground-water withdrawals and remarked that the problem frequently arises in Alabama, Florida, Georgia, Maryland, Pennsylvania, South Carolina and Tennessee. He draws attention particularly to the problems created by sudden appearance of sink-holes resulting in collapses beneath highways, roads, railways, buildings, pipelines and other surface features. Newton refers to the conditions under which sink-holes develop and they are primarily dependent upon carbonate rock types such as limestone and dolomite being present; these rocks allow the storage and movement of water through interconnected openings created along joint and bedding planes, fractures and faults enlarged by the dissolution action of water. This author reports that thousands of natural sink-holes exist in areas of Alabama where carbonate bedrock is present, and they vary in size from a few metres to as much as 3km in diameter with depths of a few metres to more than 30m. The timing of occurrence can be of short duration after the introduction of man-made effects on the hydrogeological conditions, or in the case of natural sink-hole development may take periods of time involving up to thousands of years. The nature of the underlying bedrock plays a major role.

Sink-holes resulting from ground-water withdrawals in carbonate bedrock conditions in South Africa. The work of Jennings, Brink, Louw and Gowan (1965) has examined the development of sink-holes in the Transvaal dolomites of South Africa where pumpage of water has created cones of depression. These authors demonstrated that sink-hole and surface subsidence problems increased in those situations where the water-table was lowered.

Mining operations beneath the dolomite generally experience a gradual increase in the amount of water gaining access to the mine. Water commonly drains through disturbed fault planes to lower horizons. Water pumped out of the mine is commonly used to re-charge the water-table above the mining area and thus effect a control measure on the development of sink-holes at the surface. However, if the underground pumping operations become excessive, the overall economics of the situation may require other approaches to the problem. Attempts have been made to introduce grouting materials in the dolomite in order to try to control inflow into the mine below; such attempts have met with limited success especially in view of the magnitude of the problem and the general uncertainty as to where such remedial measures should be introduced. De-watering of a compartment above a mining area is generally only resorted to when other methods prove unsuccessful or inadequate. This allows the water entering the mine to be significantly decreased, as no re-charge of the water-table is carried out and consequently re-cycling the water is avoided. However, lowering the water-table results in the dolomite bedrock influencing the state of drainage, so that pre-existing drainage paths and cavities now allow scope for the unconsolidated materials to wash down into cavity systems deeper in the dolomite. Progressive washing down of the sediments and creation of cavities in the unconsolidated materials above the dolomite provides the conditions for sink-hole development at the surface.

The form of sink-hole and surface depression development depends upon the thickness and nature of the unconsolidated materials near the surface, as well as the size and geometry of the underlying cavity, and the rate at which such a cavity is formed by internal erosion and collapse. Clearly defined sink-holes may appear suddenly and be of significant depth and diameter, whilst other surface subsidence features may be that of a large diameter of up to hundreds of metres but with a relatively small step and a central area which has lowered of the order of centimetres. The nature of the surface subsidence feature can differ appreciably. There is a tendency for such surface subsidence features to cluster together in view of tending to reflect particular drainage patterns and cavity development at the dolomite bedrock horizon which promote internal erosion. Additionally areas of high water content within the unconsolidated materials appear to be those zones of importance in attracting near-surface drainage and are thus likely to experience cavity formation. Such saturated or significantly partially saturated zones will be in a weaker state and thus be sensitive to collapse processes.

Organic soil subsidence. Stephens, Allen and Chen (1984) have reported that organic soil subsidence is mainly a feature of drainage and development of peat. The reasons for subsidence are densification, particularly shrinkage and compaction, or from loss of mass through biological oxidation, burning, hydrolysis and leaching, erosion and mining. Densification results shortly after the implementation of drainage. Oxidation and erosion are generally slow with minor losses of mass. Losses due to mining activities depend upon direct removal of peat from the site and consequently has a more localised effect which will vary considerably from site to site.

The English Fens drainage activities began in 1652. These low-lying peat moors experienced alternate cycles of effective drainage which led to increased subsidence and corresponding changes in water tables. As the water-table was lowered by improved drainage, the peat surface subsided and thus created a need for further drainage operations to maintain land usage. Stephens *et al* report that those peat lands have been subjected to an annual subsidence rate in the range of 0·5 to 5cm/year with up to 3·48m of subsidence since drainage began in the 17th century. Several countries experience long-term subsidence effects due to organic soils, and particularly in The Netherlands, USA, USSR, Norway and Ireland.

Subsidence rates are influenced by the nature of the peat, the depth to the water-table, and temperature. The intensity and distribution of peat drainage operations are the main governing factors on the general development of surface subsidence. There appears to be an approximately linear relationship between the average depth to the water-table and the average subsidence according to Stephens *et al*. Subsidence of organic soils is faster in warmer regions than when compared to similar deposits in cooler climates.

Geothermal fluid withdrawal effects on subsidence. The work of Stilwell, Hall and Tawhai (1975) has demonstrated that fluid withdrawal from the geothermal field at Wairakei on the North Island of New Zealand has given rise to up to 4·5m subsidence with accompanying horizontal ground displacements of up to 0·5m. Mixtures of steam and predominantly water are yielded by the geothermal reservoir. Geothermal fluid production began in 1950 and it appears that subsidence affects an area in excess of $3km^2$ essentially over the main geothermal reservoir which has a thickness in the range 370 to 790m.

Narasimhan and Goyal (1984) give a review of subsidence aspects relating to geothermal fluid withdrawal and draw attention to experiences at Larderello in Italy, Cerro Prieto in Mexico, Wairakei in New Zealand, and The Geysers, California in the USA. These authors remark that land subsidence may accompany geothermal fluid withdrawal where favourable hydrogeological and exploitation conditions exist. The cause of subsidence is attributed to volume changes in the reservoir undergoing depletion of geothermal fluid storage although thermal contraction is also considered to play a role. Narasimhan and Goyal examined different bases of subsidence prediction in such conditions but concluded that the best course of action in establishing reliable data is that of comprehensive deformation monitoring of both surface and subsurface responses to fluid withdrawal so as to enable prediction models to be validated. Field evidence indicates that subsidence arising from geothermal fluid withdrawal tends to be in the form of a general depression which reflects the size and position of the underground reservoir, although major faults can have a significant limiting influence on subsidence development at the surface in some cases.

Subsidence over oil and gas fields

The oil and gas production activities at the Goose Creek oil field, Texas, gave rise to the first detailed reports on resulting surface subsidence during the period 1900-1920, Pratt and Johnson (1926). The Bolivar Coast oil fields, Venezuela, also experienced subsidence during the 1920's, van der Knaap and van der Vlis (1967), whilst Gilluly and Grant (1949) refer to subsidence above the Wilmington oil field, Long Beach, California during the 1930's. Subsidence has been reported to be associated with the Groningen gas field, The Netherlands, as discussed by Schoonbeck (1976), in addition to the Huntington Beach oil field of California, as referred to by Martin and Serdengecti (1984), and also oil and gas fields in the USSR, Ilijn (1977).

It is clear from the remarks of Martin and Serdengecti (1984) that subsidence over oil and gas fields has been widely reported and has occurred in several countries. The magnitude of the subsidence observed has been almost 9m at the Wilmington oil field. These authors note that surface subsidence probably occurs over all oil and gas reservoirs where a pressure decline is experienced, even though subsidence seems to have been detected at only a few of the many thousands of oil and gas fields which have been developed. The potential subsidence appears to be insignificant for most oil and gas fields.

Martin and Serdengecti (1984) suggest that where major subsidence occurs over oil and gas fields, then two *in situ* rock failure conditions appear to prevail. Firstly, there is the general weakness of some rock types regarding grain behaviour with accompanying reductions in porosity and the thickness of the reservoir. Secondly, the stress state may result in *in situ* failure and movement along fracture and fault planes. These authors state that the maximum subsidence (S) will be a function of:

(a) the associated one-dimensional compaction,
(b) the stress transfer factor and is related to stress transfer from the surrounding rocks to the reservoir rock,
(c) the subsidence spreading factor which relates the maximum reservoir compaction to that of the maximum surface subsidence.

The one-dimensional compaction is the product of the one-dimensional compaction coefficient, the pressure drop and the reservoir thickness. The stress transfer factor is the ratio of the maximum reservoir compaction to the one-dimensional compaction; this is an indication of the amount of stress transferred to the reservoir rock as a result of the pressure drop. The subsidence spreading factor is the ratio of maximum surface subsidence to the maximum reservoir compaction. This ratio is reported to be about 1·0 for shallow reservoirs of large lateral extent. This factor decreases with increasing depth below surface of the reservoir and for decreasing lateral extent, Geertsma (1973).

A general expression for maximum subsidence (S) has been given by Martin and Serdengecti (1984) as equation (67).

$$S = \begin{pmatrix}\text{one-dimensional}\\ \text{compaction}\end{pmatrix} \begin{pmatrix}\text{Stress transfer}\\ \text{factor}\end{pmatrix} \begin{pmatrix}\text{Subsidence}\\ \text{spreading factor}\end{pmatrix} \tag{67a}$$

$$= \left(C_m \, \Delta p \, h\right) \left(\frac{\Delta h_m}{C_m \, \Delta p \, h}\right) \left(\frac{S}{\Delta h_m}\right) \tag{67b}$$

where,

C_m = one-dimensional compaction coefficient
Δp = the pressure drop
h = reservoir thickness
Δh_m = maximum reservoir compaction

The general conclusions drawn by Martin and Serdengecti are:

1. The majority of oil and gas reservoirs give rise to only small amounts of reservoir compaction and associated surface subsidence.
2. Reservoir rock compaction and resulting surface subsidence exhibit inelastic behaviour of the reservoir rock and possibly that of the surrounding and overlying rocks.
3. The principal factors influencing oil-field subsidence appear to be: reservoir fluid pressure, depth, geometrical setting, and mechanical properties of reservoir rock and surrounding and overlying rocks.

These authors suggest that subsidence arising from reservoir compaction over oil and gas fields can be controlled by fluid injection in order to achieve pressure maintenance. In the case of strong water-drive reservoirs, the restriction of reservoir withdrawals in order to allow the water influx to maintain the reservoir pressure is entirely feasible as a subsidence control measure.

Subsidence over the Ekofisk oil field. The Ekofisk oil field consists of a fractured chalk reservoir located centrally in the North Sea, and subsidence was first recognised towards the end of 1984. Wiborg and Jewhurst (1986) have given subsidence details for the Ekofisk oil field. They reported that some 2·6m of subsidence was observed up to mid-1985 and subsidence rates of 0·4 to 0·46m/year with up to 0·7m/year centrally have occurred since 1979-80. The cause of the subsidence is explained as reservoir pressure depletion by fluid withdrawal as associated with production operations, and these authors argue that for the seabed movement to be arrested necessitates the maintenance of pressure by means of fluid injection (ie water, gas) back into the oil producing formation.

Ekofisk is a major gathering location for gas, oil and condensate produced from wells on the Norwegian shelf, with gas pipelines connecting with Teesside, England and Emden, West Germany.

The chalk reservoir rock at Ekofisk often has porosities greater than 40%, although the matrix permeability is low being of the order of 0·1md. Shales and clays comprise the bulk of the overburden with an estimated coverload pressure of 62 MPa. The original pressure of the reservoir was 48 MPa. Consequently the chalk reservoir rock was required to support the net pressure differential of 14 MPa. Oil production resulted in the reservoir pressure reducing to 24-28 MPa so that the net pressure for support by the chalk increased to 34-38 MPa. Some 65% to 85% of the reservoir compaction at Ekofisk was indicated by testing and measurement to have appeared as seabed subsidence. Surprisingly, effective permeabilities are virtually unchanged even after continuous production of 14 years.

Laboratory investigations by Wiborg and Jewhurst indicated that chalk with porosities less than 30-32% should not undergo significant compaction, even without the maintenance of reservoir pressure. These authors have related laboratory studies and field measurements to the Ekofisk subsidence problem. Table 26 gives five key parameters regarded of significance to evaluating the probability of subsidence.

Key Parameter	Reservoir rock formation	
	Danian Chalk	Cretaceous Chalk
High porosity	48%	35%
Thick reservoir	183m	122m
Large pressure reduction	22 MPa (1985)	24 MPa
Large areal extent	8km × 5km	
Shallow reservoir	3000m	3200m

Table 26 Key parameters of significance for evaluating the probability of appreciable subsidence at the Ekofisk oil field, North Sea. After Wiborg and Jewhurst (1986).

With reference to Table 26, these authors regard reservoir depth to be a parameter of significance at Ekofisk, and point out that at other localities reservoirs with substantial resulting surface subsidence have been producing from about 1500m or less.

At Ekofisk, a bathymetric survey from 1970 (±1m accuracy) and surveys performed during 1984/85 and later in 1985 (±0·7m accuracy) of the seabed provided data which allowed a subsidence depression of 2·6m maximum subsidence to be indicated. The shape of the subsidence depression resembles the size and general shape of the underlying reservoir some 3km below.

The Ekofisk subsidence depression as during 1985 was indicated to be about 6km long (north-south) and 4km wide (east-west).

The subsidence at Ekofisk is of special importance in view of platforms and other structures being located on the seabed at a depth of 70m. Submerging part of the structure further into the sea decreases the margin of safe elevation from wave and sea level action. Tilting of large seabed mounted structures can be highly significant in view of the overall height of such structures. Wiborg and Jewhurst refer to the need to make changes on existing platforms when the subsidence reaches 4m. The Ekofisk tank is located in the subsidence area; it has a storage capacity of one million bbl and is a concrete structure. This tank is planned to be modified so that it can accept up to 6m subsidence. They show results of subsidence predictions and essentially extrapolate the present subsidence data. Assuming no action is taken to control the Ekofisk subsidence, these authors show that for natural depletion of the reservoir subsidence is likely to level out to 6 to 7m beyond the year 2010. Conversely using 350 MMscfd injection into the reservoir should control subsidence immediately and ensure subsidence is kept to not more than about 4m by the year 2010 and thereafter level off to 4 to 5m. These predictions are based on a present subsidence rate of 0·45m/year.

Figure 204 shows a diagrammatic representation of the Ekofisk subsidence depression based on the interpretation of Maury, Sauzay and Fourmaintraux (1987). They draw attention to the problems of safety for seabed mounted structures in respect of wave height and tilting following subsidence. Additionally the seabed can experience changed foundation conditions owing to subsidence, especially regarding movements and behaviour under stress.

Surface subsidence behaviour above oil fields according to influence function prediction methods. Considering the general character of surface subsidence development above oil field operations, due account should be taken of the prediction methods used in conventional mining and in particular the influence function method described earlier in this book. The present authors have considered an oil field situation where the anticlinal structure of the reservoir results in the volume of the oil abstracted region having its maximum thickness in the centre and then tapers to zero at its boundaries. Under these conditions it has been assumed that the oil abstracted has created fissure spaces which can be regarded as equivalent to a mined-out zone and can thus be treated as a mining subsidence calculation.

Figure 205 shows the basic approach adopted for applying subsidence engineering principles to the oil field situation. The fact that there is tapering towards the edges means that subsidence trough development will be more confined than with conventional mining situations. Additionally there is likely to be a large spread of subsidence which is of minor to no significance in view of the edge effect. Under these oil field geometry conditions, the reservoir width to depth ratio will be of much less significance than with conventionally mined-out extractions. The limits of subsidence are likely to be very similar to conventional mining for similar cover rock conditions. The nature of the overlying rocks will be of major significance; strong and competent cover rocks will encourage bridging across oil abstracted areas. The depth of the reservoir coupled with effective width are of course singularly important in reducing subsidence effects at the surface.

Figure 206 presents subsidence predictions using influence function methods for an oil field situation.

Surface subsidence resulting from underground coal gasification

Underground coal gasification (UCG) involves burning coal underground by means of a selected mixture of gases which are injected into the coal seams through boreholes. The product gases of the burning process are extracted through a separate borehole. The underground burning process gradually creates a cavity which is commonly approximately circular within a seam of limited height. Thick coal seams allow roughly spherical or ovaloid shaped cavities to frequently form.

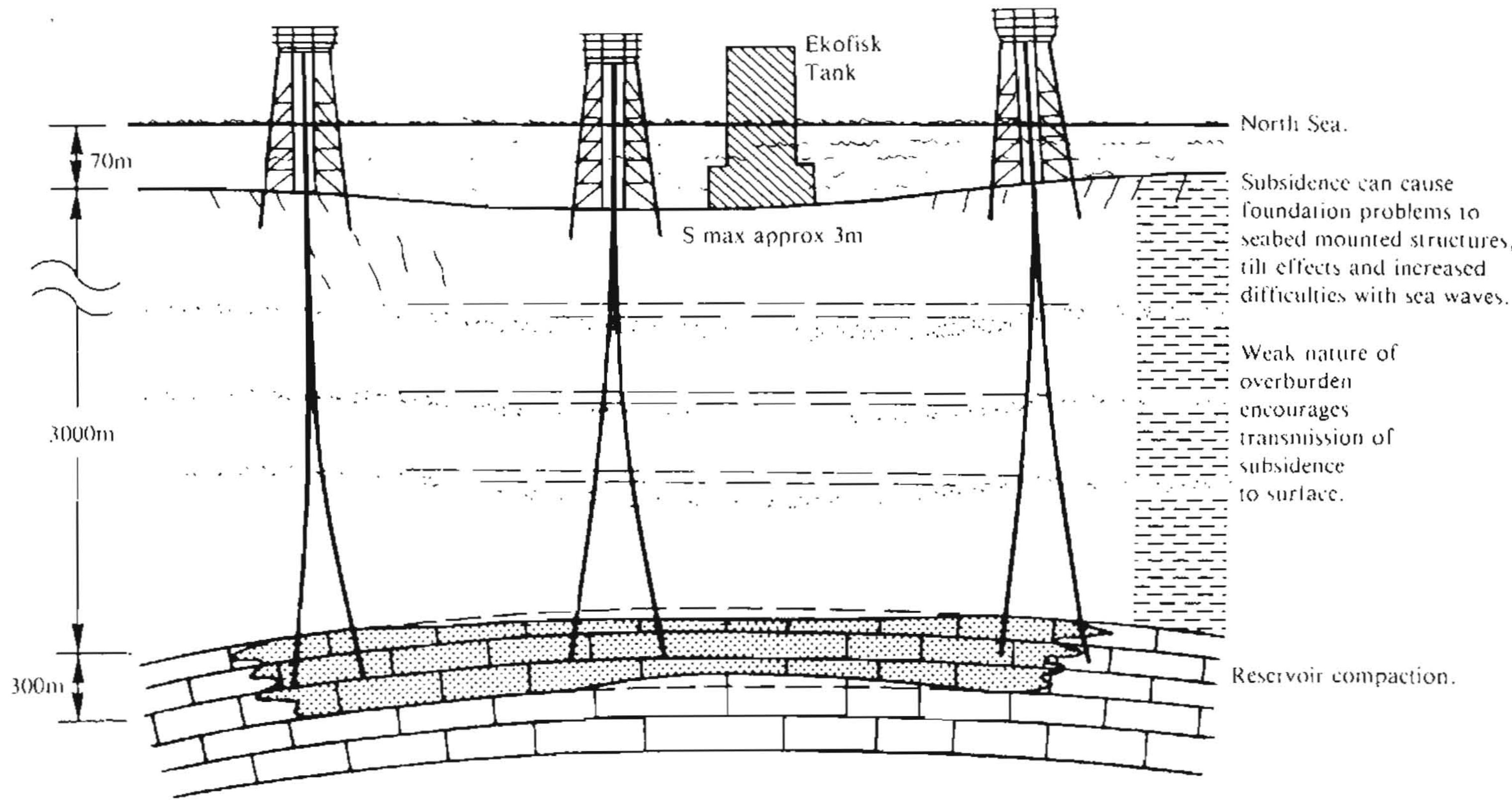
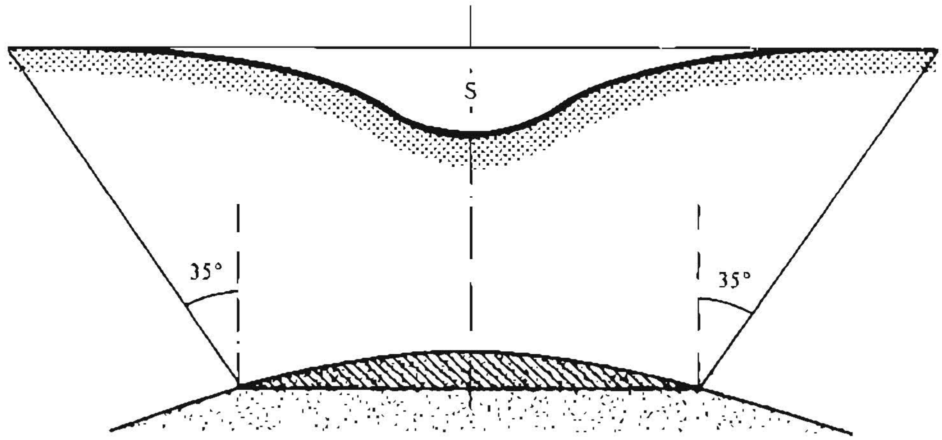
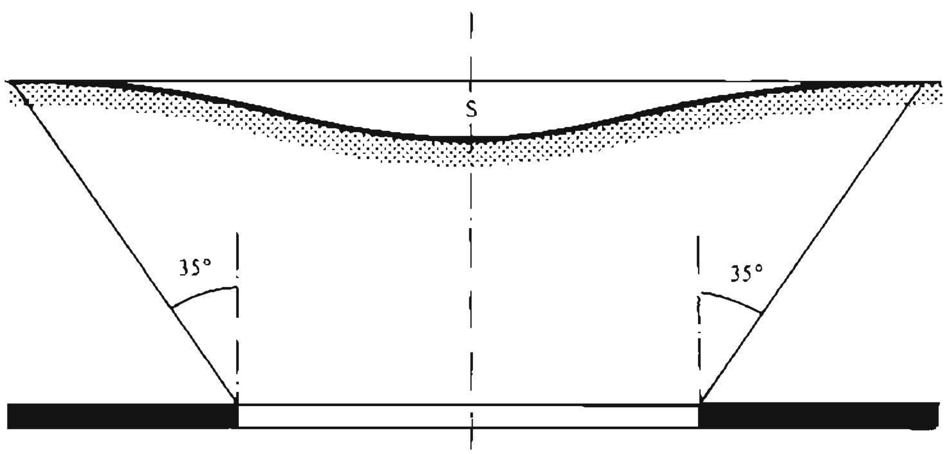


Figure 204 Subsidence of a North Sea oil field. After Maury, Sauzay and Fourmaintraux (1987).
(Diagrammatic representation only and not to scale)

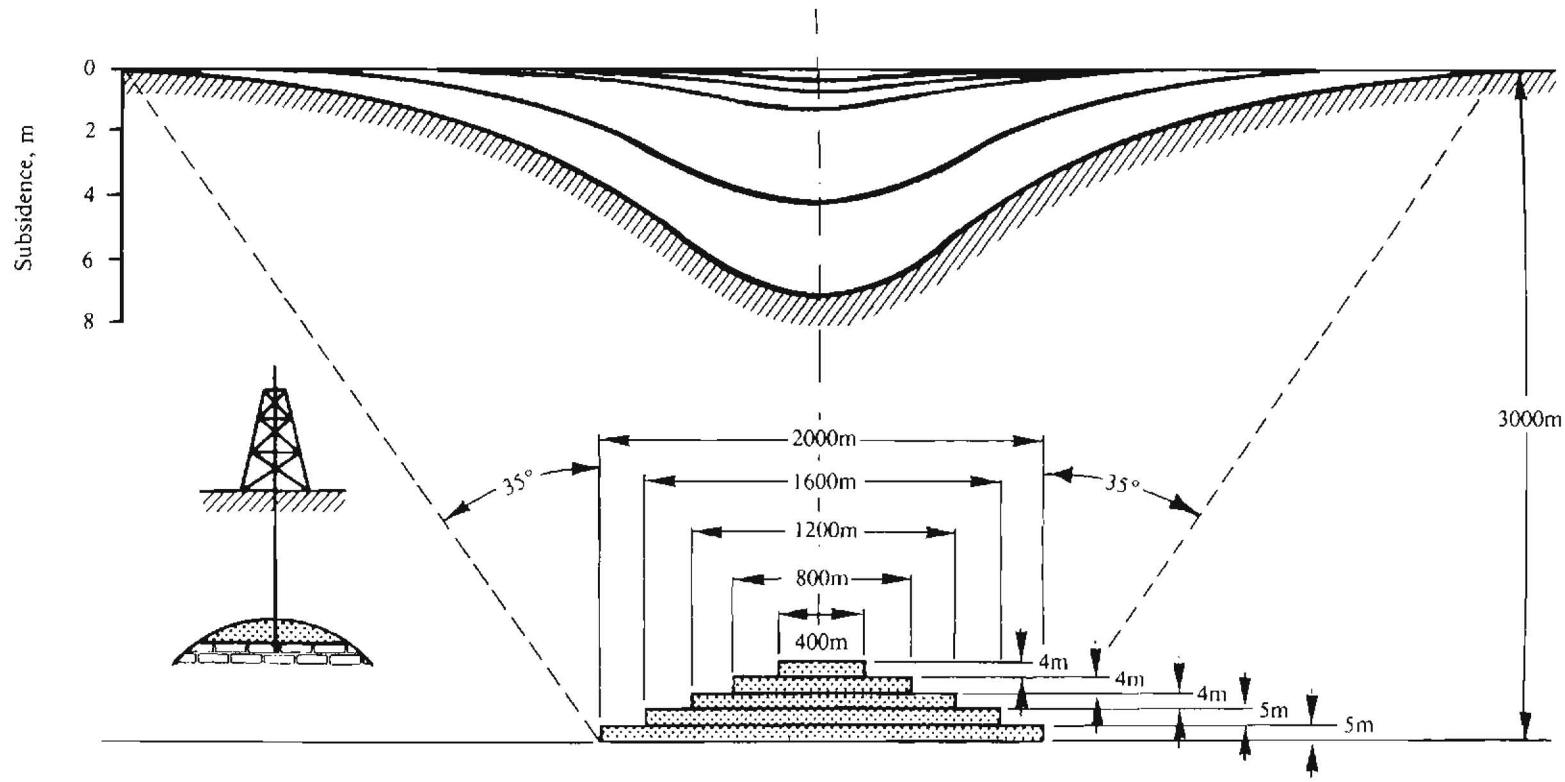


(a) Typical character of oil field subsidence profile



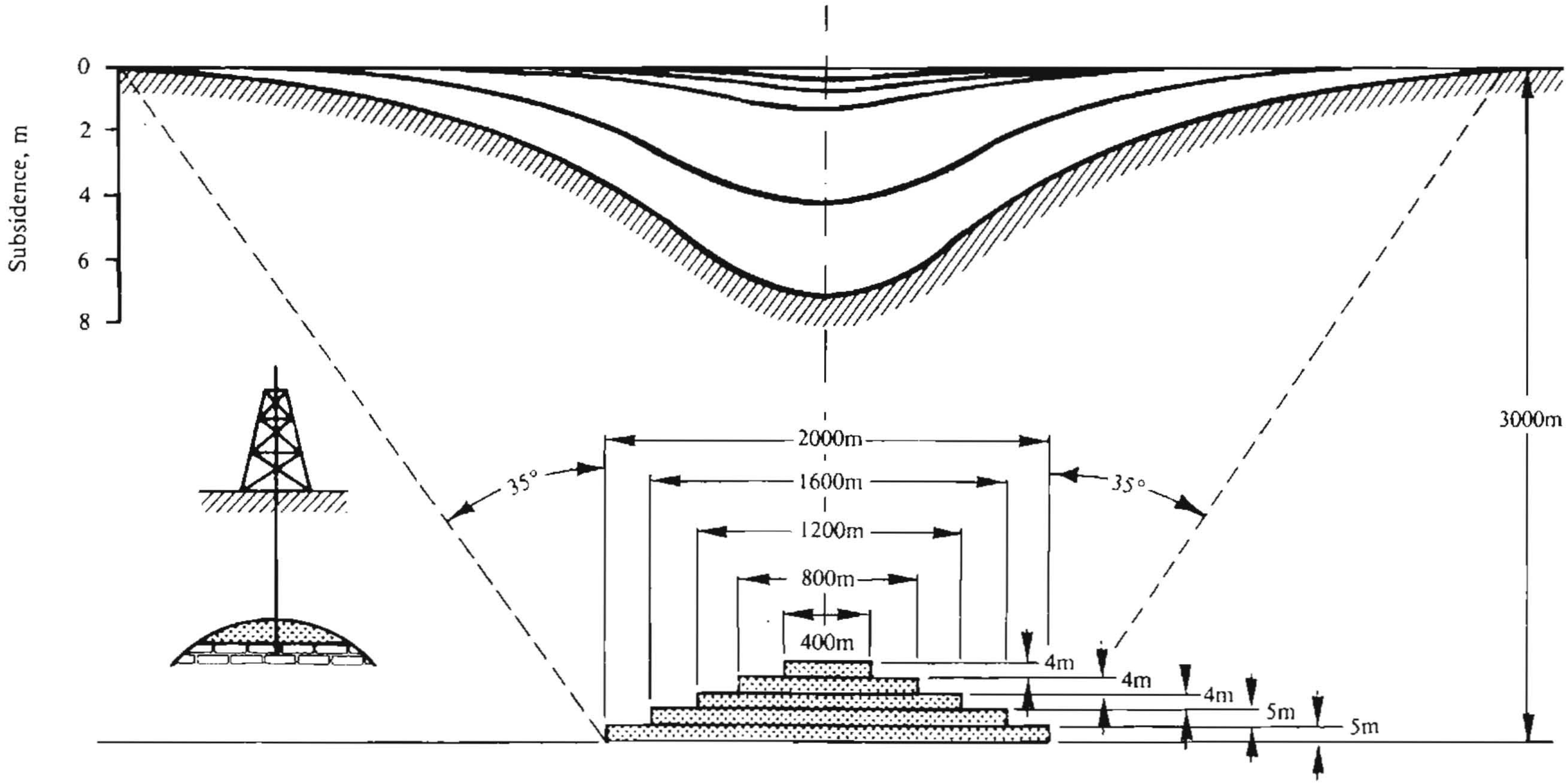
(b) Typical longwall extraction subsidence profile

Figure 205 Comparison of surface subsidence profiles for oil field and longwall mining situations.



Note: Oil withdrawal assumed to create voids which can be regarded as equivalent to a mined-out area for the purposes of subsidence calculation.

Figure 206 Application of influence function method to calculating surface subsidence above oil field represented by several strips of decreasing length.



Note: Oil withdrawal assumed to create voids which can be regarded as equivalent to a mined-out area for the purposes of subsidence calculation.

Figure 206 Application of influence function method to calculating surface subsidence above oil field represented by several strips of decreasing length.

The UCG cavity experiences stress changes due to induced stress redistribution as the cavity increases in size and stress effects due to the thermal response of rocks surrounding the cavity. Experiments carried out by the authors on British Coal Measures rocks at the temperatures encountered in UCG cavities indicated that sandstones did not experience any significant changes in compressive strength. Shales and mudstones did, however, experience appreciable change especially in breaking down to form multiple thin layers. Carbonaceous material within such rocks readily promoted breakdown of the host rock during the burning process. Clay-based materials exhibited a baked characteristic after burning, with increased hardness properties and improved resistance to breakdown by water.

Experimental observations suggest that a coal seam roof comprising of thin carbonaceous shale/mudstone layers would experience detachment of individual layers owing to thermal effects. Their ability to bulk under such conditions would be improved owing to the increased occurrence of voids within the collapsed roof rocks. Rocks in this condition have improved drainage properties.

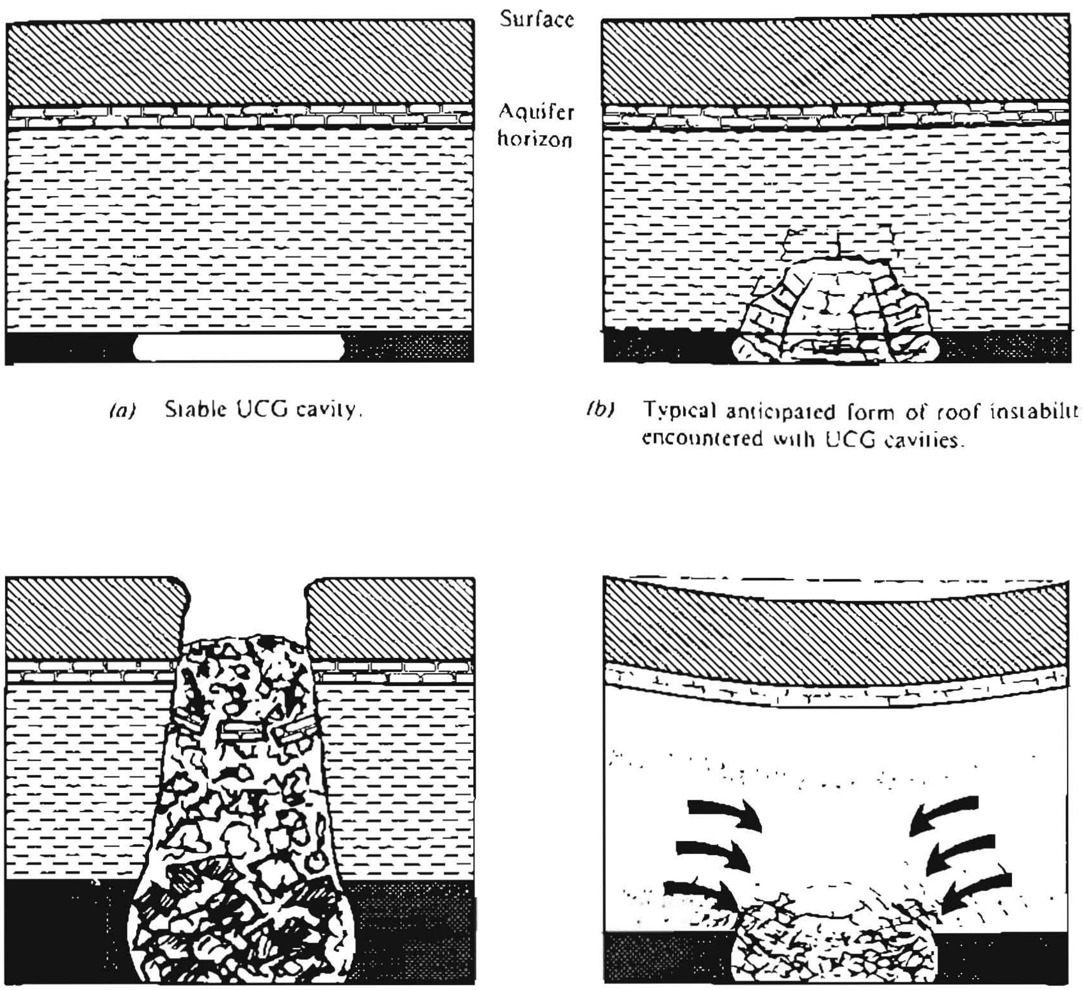
The collapse of UCG cavities can result in possible contamination of aquifers which are within proximity of such effects. However, these cavities can possess surface subsidence potential if the conditions favour their development.

Mode of roof collapse and subsidence development. Figure 207 shows the basic form of roof collapse and subsequent development of subsidence as is generally experienced with UCG cavities. The collapse potential of the roof is of course influenced by the strength and general competence of the immediate rocks overlying the seam and the nature of the overburden to the surface. Well-jointed and thinly-layered rocks will encourage upward collapse of the rocks above the cavity. Consequently aquifers can be disturbed by this form of collapse process. Sink-holes can occur if the depth and extraction conditions favour development. Weak clays may tend to flow towards the collapsed zone and result in a surface depression.

The nature of surface subsidence features resulting from UCG operations will have similarities with those associated with room and pillar operations discussed in an earlier chapter of this book. However, the cavities formed do not have significant inter-connection, and consequently have limited potential for collapsed material to flow into lower unfilled cavities as is the case with room and pillar layouts. The potential height of the collapse zone will be mainly governed by the bulking characteristics of the roof rocks and on the basis of earlier discussions on this aspect in Chapter 8, a height of 3-5 (M) could be expected for a single cavity with limited connections to adjacent boreholes. Where extensive underground cavity development has occurred in association with UCG operations and particularly with wide connections to neighbouring boreholes in the same seam, then a potential collapse height of 6-10 (M) may occur. The symbol M in this context would refer to the average extraction height of the cavity as formed prior to collapse.

Subsidence studies relating to underground coal gasification. An interesting account of subsidence modelling applied to underground coal gasification has been given by Trent and Langland (1983) who reported on finite-element and finite-difference studies. These authors suggested thermal effects to be important and that the finite-difference method appeared to allow more scope for studying such effects. Sutherland, Schuler and Benzley (1983) have reported experimental work using centrifuge simulations. These studies allowed progressive failure of the strata to be demonstrated.

Jegbefume and Thompson (1983) have examined the roles played by temperature and non-elastic behaviour on roof collapse and resulting subsidence development arising from



(a) Stable UCG cavity.

(b) Typical anticipated form of roof instability encountered with UCG cavities.

(c) Collapse of UCG cavity disturbing aquifer and breaking through to surface. Generally considered remote occurrence unless shallow depth and thick seam conditions exist.

(d) Formation of depression at surface over UCG cavity where clays flow from over solid sides into cavity.

Figure 207 Underground coal gasification (UCG) cavities: roof collapse and subsidence features.

underground coal gasification. The influence of drying of the surrounding rocks was considered to be an important factor in reducing subsidence, although they suggest that such effects are likely to be offset by accompanying roof collapse. They also concluded that thermal loading appeared to have a minor influence on surface subsidence owing to the limited extent to which very high temperatures transmit into the sides of the cavity. A further important conclusion reached by these authors is that major roof collapses seem an inevitable consequence of underground coal gasification, particularly in soft strata. They also suggest such effects would appear early in the process.

Concluding remarks

Ground-water withdrawal can give rise to special subsidence effects at the surface, ranging from general subsidence depressions of a fairly uniform nature, through to major fissure occurrence and even sink-hole development. The near-surface rock types and their general geomorphological and hydrogeological conditions substantially influence their behaviour following ground-water withdrawal and the general character of surface subsidence developments. Thorough assessment and investigation of the near-surface ground conditions can greatly assist in indicating the likely response of the surface to ground-water withdrawal.

Subsidence over oil and gas fields has occurred in several countries both on land and over water. The likelihood of subsidence occurring depends upon reservoir depth and size, and the nature of the overlying rocks. In general, subsidence occurrence from oil and gas field operations is not very significant in view of the depth of such reservoirs and their relative thicknesses. Undersea oil and gas production can result in subsidence which may be highly significant to seabed mounted structures.

Surface subsidence resulting from underground coal gasification is likely to be of minor significance unless the depth of operation is shallow.