

Land subsidence – The last five years: Report by Technical Committee TC 12

Affaissements de terrains – Les cinq dernières années: Rapport du Comité Technique CT 12

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SYNOPSIS

The last five years have witnessed further examples of land subsidence and an increased appreciation of the problem as shown by the numerous conferences and publications on the subject. This report starts with a brief overview of the topic, and contains nine short national reports prepared by TC 12 committee members.

INTRODUCTION

Land subsidence is a major geotechnical process that is having damaging economic effects on some of the world's major cities and development areas. This subsidence is caused by two main factors:

- special geological conditions
- extraction of resources

In the case of special geological conditions the subsidence effects are often accelerated by man's activities, in the case of resource extraction the subsidence is directly caused by man's activities. Subsidence is therefore a major problem that is predominantly man-made, and therefore in principle preventable by man. However a balance has to be struck between the benefits of the activities causing the subsidence, and the cost of the subsidence. In many cases the benefits outweigh the costs, and it falls to the geotechnical engineer to provide the most economic and effective solutions to the subsidence problems created by others. In this report we give an overview of the international 'state of play' regarding land subsidence, principally over the last five years. This report has been prepared on the basis of national reports submitted by TC 12 members (TC 12), on the papers related to subsidence submitted to this conference (Rio), and on recent publications.

SPECIAL GEOLOGICAL CONDITIONS

There are many special geological conditions that can lead to subsidence but for simplicity we have categorised them as follows:

- soluble rocks
- sensitive soils
- tectonic and sea level changes

Soluble Rocks

Soluble rocks include carbonates such as limestone and dolomite, and evaporites such as gypsum and common salt. The carbonates are the most common cause of land subsidence.

Most of the countries in the world have some limestone and many have karst development. Karst is the term given to natural cave and gorge formation by solution in carbonate rocks. Large areas of southern China and south-west USA are underlain by karst, together with large areas of south-east Asia and southern Africa in particular. National solution rates are very low, around 5000 years being required to form a limestone cave 1 m in diameter. Current solution is not therefore the cause of current subsidence problems. However vast cave systems have developed over periods of many tens of thousands of years. For example the largest known cavern exists in Sarawak and is 700 m long and 400 m wide. These large cave systems can cause land subsidence, particularly when environmental conditions are changed by man's activities.

The paper by Wagener et al (Rio) describes current problems in South Africa where dewatering for mining operations is causing serious subsidence over karstic dolomite. The subsidences are in the form of small and steep sided sink holes, and larger shallower sided dolines. According to Wagener (TC 12) a 90 square kilometre area 60 km west of Johannesburg is being dewatered at present. The owners of the mine had to do exhaustive geophysical and geotechnical tests before dewatering was allowed. Based on the tests safe and unsafe areas were demarcated. Unsafe areas were purchased by the mining company and evacuated. A major road cut was stabilised by compaction grouting and a water supply dam was relocated out of the area. This example well illustrates the need for thorough geotechnical investigations and the expense of dealing with environmental effects in karst areas.

Sensitive Soils

Sensitive soils include loose silts prone to hydrocompaction, peats which are subject to oxidation and dewatering, and highly compressible and unstable clays.

Hydrocompaction is a particular hazard in the loess soils which cover extensive areas of the Missouri basin in the USA, the Danube basin of Europe, the Steppes of Russia and the Yellow River area of China. These high porosity silts are liable to collapse on wetting, and for example have caused major irrigation canal damage in the Soviet Union.

An example of hydrocompaction is given by Boncompain et al (Rio). In this case an artificial soil is the problem, rather than a natural soil. The soil in question is poorly compacted unsaturated fill material placed around instrument riser pipes in an earth dam. During filling of the reservoir a number of major sinkholes appeared in the dam crest, surrounding the riser pipes. The sinkholes formed major craters up to 4 or 5 m across, which must have given the dam builders pause for thought. As well as being a useful example of hydrocompaction this example does give a rather ironic example of how measures to increase dam safety can sometimes appear to be counterproductive.

Another example of sensitive soils is given by Abrahao et al (Rio). In this case a township near Brasilia was threatened by a deep gully and advancing line of sinkholes that developed after a heavy rainstorm. In this case the problem soil proved to be a thick lateritic soil of colluvial origin, with high porosity and tendency to collapse. Concentration of surface drainage into the collapsible soils led to the gully and sinkhole formation, leading to demolition of buildings and conversion of the area to public open space.

Tectonic and Sea Level Changes

Tectonic events are characteristically very fast or very slow. The very fast events are earthquakes which can cause rapid subsidence of large areas of land and liquifaction of sensitive soils. The very slow events are the almost imperceptible crustal deformations that invariably involve large land masses. Sea level rising may not be subsidence as such, but has the same effect with regard to adjacent land.

Riccerri (TC 12) reports that natural land subsidence is a contributor to the overall subsidence problem in the Po Valley, as revealed by periodic levelling since the beginning of this century. This subsidence originates from the tectonic deformations of the bedrock and from the continuous consolidation of geologically more recent deposits. Carter (TC 12) reports that the very slow subsidence of the North Sea basin at about 2 mm/year is one of the factors which led to the multi-million pound construction of the River Thames barrier.

Rising sea levels are referred to by Barends (Rio) who indicates the coastal areas of the world endangered by sea level rise. Many of these are also areas of subsidence due to groundwater lowering and the combined effect is placing parts of several major cities, such as Bangkok, below sea level. According to Barends, a rise in the order of 2 m may be expected by the end of the next century, accelerating due to the "greenhouse effect" and other man induced environmental changes.

EXTRACTION OF RESOURCES

Resource extraction leads to major land subsidence problems around the world. The three main culprits are:

- hard rock mining
- groundwater abstraction
- oil and gas abstraction

Hard Rock Mining

Hard rock mining has long been a major cause of land subsidence. Present day urban renewal is often held back by the threat of subsidence from the very mining that created the urban areas in the first place. A large number of materials have been extracted by underground mining, including coal in particular, limestone, iron ore, fireclay, building stone, gypsum, rock salt and many more. Underground mining has a long history of many centuries in the older industrial areas. Subsidence due to hard rock mining can be categorised as subsidence due to old abandoned mineworkings, and subsidence due to current mineworkings.

a) Abandoned Mineworkings

Old abandoned mineworkings were most usually created using partial extraction techniques by the "room and pillar" method. Mineral was worked from the rooms whilst pillars were left in place to support the roof. Subsidence from such workings occurs in two main forms; crown holes due to room collapse and subsidence depressions due to pillar failure. Old shafts also pose a major hazard. Vein minerals were generally worked by stoping methods which can cause major fissures at ground surface.

Akagi (TC 12) reports subsidence due to mining of volcanic tuff as a building material. On February 10th 1989 a large sinkhole developed suddenly in the suburbs of Utsunomiza, about 100 Km North of Tokyo. The sinkhole covered an area 100 m by 50 m and showed a maximum subsidence of 30 m. At least 20 sinkholes have occurred in the same area for the last 35 years or so, this being one of the largest. Carter (TC 12) reports subsidence in the West Midlands due to room and pillar workings in limestone up to 150 m deep and up to 10 m in thickness. It was found that at depths of up to 100 m the most common subsidence was crown hole formation due to roof collapse whereas at greater depths than 100 m the form of subsidence was saucer shaped depressions caused by failure of the pillars, or of the weak strata overlying the pillars.

b) Modern Mineworkings

Modern mining is by longwall workings or large scale room and pillar workings, with stoping for vein minerals. Subsidence from longwall workings takes the form of general subsidence depressions, subsidence from room and pillar workings can create general subsidence or localised crane holes. A great deal of observation and research into modern mining subsidence effects has taken place in the last twenty years.

Wagener et al (Rio) report on subsidence effects from the modern mining of many different minerals in South Africa. Coal mining is the largest cause of subsidence. problems in South Africa and Wagener classifies subsidence into unplanned and planned subsidence. An analysis of seventeen cases of unplanned subsidence caused by room and pillar workings shows that the vertical subsidence exceeds the amount caused by total extraction methods. Planned subsidence due to longwall workings is greatly affected by the very strong rocks overlying the coal measures. As a result the subsidence trough is generally smaller than the mined area and the magnitude of subsidence is generally half the extracted height. These subsidence effects are much smaller in magnitude than is the case for equivalent mining in the U.K. coal measures which have much weaker roof strata.

Saxena (TC 12) reports that most Indian subsidence relates to coal mining, with an average seam depth of 250 m. Room and pillar mining constitutes about 90% of all mining but longwall methods are becoming more accepted. The Central Mining Research Establishment has been conducting subsidence studies for 25 years. Mining subsidence effects include wide cracks and steps in the ground surface, serious depletion of the water table, underground fires, retarded vegetation and waterlogging. The maximum subsidence over caved workings is not more than 60% of extracted thickness, and this decreased to only 6% for hydraulic sand stowed workings. The surface area is always greater than the extracted area in India, with a limit angle of up to 42°.

Carrillo et al (Rio) describe subsidence caused by vein working in Peru of a polymetallic ore deposit including lead silver copper and gold. Poor hydraulic stowage and the influence of groundwater have led to the failure of deep workings on the steeply dipping ore bodies, leading to severe ground subsidence. The subsidence control programme temporarily suspended mining operations, established good backfilling methods and implemented an underground drainage system to relieve groundwater pressures, together with grouting of selected areas. Above ground and below ground monitoring stations have also been established.

Groundwater Abstraction

Groundwater abstraction from non-indurated sediments has been responsible for excessive land subsidence in many areas of the world, particularly in the last twenty to thirty years. Large areas are usually involved and

depths of recorded subsidence range up to 10 m. Urban areas are usually involved since it is abstraction for urban needs that has caused the problem. Subsidence often occurs in low lying alluvial planes close to sea level and some important cities are now subsiding below sea level. The case of Venice has assumed international importance due to the potential loss of a major site of historical and architectural heritage. A more recent example is Bangkok where four million people live only 1 to 2 m above sea level, and future subsidence is expected to exceed 2 m. Not surprisingly several of the papers to this conference, and reports by TC 12 committee members, deal with this problem.

Belfiore et al (Rio) report on the subsidence of Bologna where a decrease in groundwater level of more than 20 m has occurred in the last 20 years, with resulting surface settlements of more than 2 m. Water is abstracted from sand and gravel aquifers which are interbedded with clay aquitards of medium to high compressibility. The subsidence distribution was found to depend more on the mechanical properties of the compressible layers than on the location of abstraction wells. A 300 m deep geotechnical borehole was sunk with comprehensive sampling testing and monitoring, which indicates that layers even deeper than 300 m are contributory to the surface settlement.

Three papers to the Rio conference deal with theoretical aspects of subsidence due to groundwater withdrawal. Rodriguez et al deal with the load mechanism on friction piles supported on a subsoil undergoing subsidence. The results of subsidence at the Centro Nacional SCT in the valley of Mexico are presented, together with a worked example. Placzek describes methods for the calculation of settlements due to groundwater lowering. On the basis of theoretical principles calculation models are developed for cohesive, non-cohesive and organic soils. Janbu takes a number of case records to back-calculate creep rates. The settlement observations range from 5 to 60 years duration and it was found that the primary consolidation was shorter than classical one-dimensional theory would indicate whereas apparent creep dominated from an early stage.

Ricceri (TC 12) deals particularly with the subsidence of Ravenna in the Po Valley. Ravenna is of great historical interest, having been the capital of the Western Roman Empire 1500 years ago, and contains many historically important buildings such as the Saint Vitale Basilica. Strata up to 500 m in depth have consolidated due to groundwater withdrawal, giving a maximum 1.2 m subsidence caused by a maximum 41 m piezometric decline. A continually sampled 500 m deep borehole has been sunk to establish the geotechnical situation and the national oil company carried out additional sampling at greater depths. Flooding of the harbour area and danger to historic monuments has been caused by the subsidence. Subsidence rates have now diminished from 10 - 15 mm/year to 5 mm/year.

Akagi (TC 12) reports that Japan currently uses 11.4 billion cubic metres of groundwater annually. Much of this is abstracted from coastal alluvium, resulting in large scale subsidence of many important coastal cities. Control of groundwater abstraction since about 1970 has markedly decreased subsidence. For example the areas settling at a rate of more than 4 cm/year was only 7 km² in 1986 as compared with 404 km² in 1978.

Carter (TC 12) reports that in the U.K. subsidence in reverse is starting to occur as groundwater abstraction beneath the cities diminishes and groundwater tables rebound towards their original level. For example in London abstraction from the deep aquifer beneath the London Clay has diminished from 227 M/litres/day to 121 M litres/day and the groundwater table is now rising at 1.5 m/year. It is considered that some £150 M worth of damage will be caused to deep structure by this process, unless prevented by a regional groundwater lowering scheme.

Oil and Gas Abstraction

Oil and gas abstraction have caused widespread subsidence in areas of shallow non-indurated reservoirs. Subsidence values of up to 5 m have been encountered around Lake Maracaibo, and up to 9 m in California. In California a massive programme of water injection was used to halt subsidence and in Italy the pumping of the Po Valley gasfield was stopped by legal action.

Barends (Rio) gives a theoretical approach to estimation of subsidence effects due to fluid removal, including the release and re-dissolving of free gas during reservoir depletion and cessation. The incorporation of leaking layers in the aquifer performance has been used to evaluate land subsidence at Lake Maracaibo.

Murria (TC 12) reports on a global positioning system together with conventional levelling programme implemented in 1988 to monitor subsidence in the Lake Maracaibo area. Oil is drawn from relatively shallow (330-1000 m) reservoirs and the resulting subsidence has now reached a maximum of about 5 m. Murria considers that the new system has accuracies in the order of ± 5 cm and that this accuracy will be greatly improved once the number and geometry of satellites is improved in 1991-2.

Carter (TC 12) reports on the major subsidence of the Ekofisk field in the North Sea where subsidences of up to 1.6 m had occurred by 1985, with a maximum of 6 m being forecast. This subsidence is exceptional in that the reservoir is 3000 m down in an indurated Chalk rock reservoir. Subsidence was not anticipated. Ekofisk contains several steel jacket platforms, a major concrete gravity storage tank, and is a major distribution centre with pipelines to the U.K. and Germany. Seabed is at a depth of 70 m and the resulting settlement brought the structures within range of storm wave conditions. As a result the steel jackets were heightened by 6 m at a cost of £200 million and in June 1989 a concrete

gravity circular wave barrier was established to protect the tank at a cost of £130 million.

CONFERENCES AND PUBLICATIONS

The following list gives an indication of the importance of subsidence in the last five years, but is most certainly not an exhaustive list. Many local and regional conferences have been held which do not appear on this list, which has been compiled on the basis of the authors personal knowledge.

- 1984 Third International Symposium on Land Subsidence held in Venice, Italy, March 1984. Sponsored by IAHS, UNESCO and CNR. Proceedings edited by Johnson et al and published by IAHS as Publication No. 151. ISBN 0 - 947571 - 40 - X.
- 1984 Man Induced Land Subsidence. Edited by T.L. Holzer. Rev.Eng. Geology VI. The Geol.Soc. of America
- 1984 Guidebook to studies of land subsidence due to groundwater withdrawal. Edited by J F Poland. Prepared for the International Hydrological Programme, Working Group 8.4 UNESCO USA ISBN 92 - 3 - 102213 - X.
- 1984 International Symposium on Geotechnical Aspects of Mass and Material Transportation. Bangkok December 1984. Proceedings edited by A.S. Balasubramaniam et al. Balkema.
- 1984 Third international conference on ground movements and structures. Cardiff 1984. Proceedings edited by Geddes J.D., Pentech Press. ISBN 0 - 7273 - 0701 - 0.
- 1984 Mining 84. International Conference on Construction in areas of abandoned mineworkings, Edinburgh March 1984 Proceedings edited by M.C. Forde et al. Engineering Technics Press pp. ISBN 0 - 947644 - 02 - 4.
- 1985 ICSMFE San Francisco.
- 1987 The role of Geology in Urban Development Hong Kong, December 1986. Proceedings edited by Peter Whiteside, Geol.Soc. H.K. Bulletin No.3 ISSN 1010 - 3341.
- 1987 Engineering Geology of Underground Movements. Nottingham September 1987. Proceedings of the 23rd annual conference of the Engineering Group of the Geological Society edited by F.G. Bell et al. Published by the Geology Society. ISBN 0 - 903317 - 41 - 9.
- 1987 Groundwater effects in geotechnical engineering. ECSMFE. Dublin August 1987. Proceedings edited by E.T. Hanrahan et al. Balkema ISBN 90 6191 720 4.
- 1988 Mining 88. Second international conference on construction in areas of abandoned mineworkings. Edinburgh June

1988. Proceedings edited by M.C. Forde et al. Engineering Technics Press
ISBN 0 - 947644 - 08 - 10

- 1989 Subsidence, Occurrence Prediction and Control. Whittaker B.N. & Reddish D.J. Elseveir. 528 pp. ISBN 0 -444 - 87274 - 4
- 1989 Ground Subsidence. A.C. Waltham. Blackie. 202 pp. ISBN 0 - 216 - 92500 - 2.
- 1989 International Symposium on Land Subsidence. Central Mining Research Station, Dhanbad, India. December.
- 1990 Inventory of Land Subsidence. IAHS publication No. 127. By A.I. Johnson.
- 1991 IAHS Fourth International Symposium on Land Subsidence, Houston, Texas. Spring.

CONCLUSION

This brief review of the last five years shows an increasing awareness of land subsidence and a greater appreciation of how to deal with problems caused by subsidence. More work is still required and building up a data bank of well observed and researched case histories is of the greatest importance.

**NATIONAL CONTRIBUTIONS BY TC12
LAND SUBSIDENCE COMMITTEE MEMBERS**

National contributions on the subsidence situation have been prepared by the following TC 12 committee members:

<u>Member</u>	<u>Country</u>
Toshinobu Akagi	Japan
Frans Barends	The Netherlands
Paul Carter	United Kingdom
Sven Hansbo	Sweden
A.I. Johnson	U.S.A.
Juan Murria	Venezuela
Giuseppe Ricceri	Italy
N.C. Saxena	India
Fritz Wagener	South Africa

JAPAN

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INTRODUCTION

Land subsidence in Japan has a long history and has been noted since around 1910. Some of the typical subsidence records in several cities in Japan are shown in Fig.1. Presently the areas where land subsidence is observed amount to 60

areas in 36 prefectures (Japan consists of 47 prefectures), but have in recent years shown a definite tendency to diminish the rate of subsidence quite dramatically except at some limited localities.

Groundwater

It is well recognised here that land subsidence is caused principally by excessive pumping of groundwater. Groundwater is still used extensively for industrial plants, buildings, water supply, agriculture, fish farming, snow melting, etc.

It is estimated that Japan currently uses 11.4 billion cubic metres of groundwater annually consisting of 3.8 billion for agriculture, 3.3 billion for water supply, 3.2 billion for industries and 1.1 billion for buildings and others. Approximately 30% of the water used by industries, 22% of the water for water supply and 7% of the water for agriculture are derived from groundwater resources.

The recent characteristics of land subsidence in Japan may be summarised as follows:

1) Extensive observation networks have long been established in land subsidence afflicted areas monitoring subsidence and groundwater levels at numerous locations. Although in many areas the rate of subsidence has generally decreased to a nominal level, several areas indicated progress of significant land subsidence with the maximum of 6.7 cm measured in Suwa, Nagano in 1987. In the entire Japan the area which subsided more than 2 cm a year amounted to 396 km² in 1986, whereas it was as much as 616 km² in 1982 and 1946 km² in 1978. The area which subsided more than 4 cm a year was only 7 km² in 1986, while it was 45 km² in 1982 and 404 km² in 1978.

2) The cities which once experienced severe land subsidence (at rates exceeding 20 cm a year) including Tokyo, Osaka, Nagoya, etc., show insignificant subsidence or even small heaves in places on account of dramatic recovery of groundwater levels. In most areas of Japan, a trend of remarkable improvement is noted, but there are still some localities where land subsidence takes place at alarming rates.

3) Land subsidence which continued for prolonged periods of time in the past caused damage to various structures and facilities related to rivers, harbors, agriculture, etc. "Zero-meter areas" which have resulted from serious subsidence are always threatened by possible damage due to floods, high tides and tidal waves due to earthquakes.

Land subsidence here is not quite a thing in the past yet, but has in recent years been arrested in most areas quite successfully by effective control of groundwater pumping and provision of adequate water supply from sources other than wells. Two laws enacted in 1956 and 1962 were enforced to control groundwater pumping and subsidence quite dramatically in Japanese cities. The two laws as well as

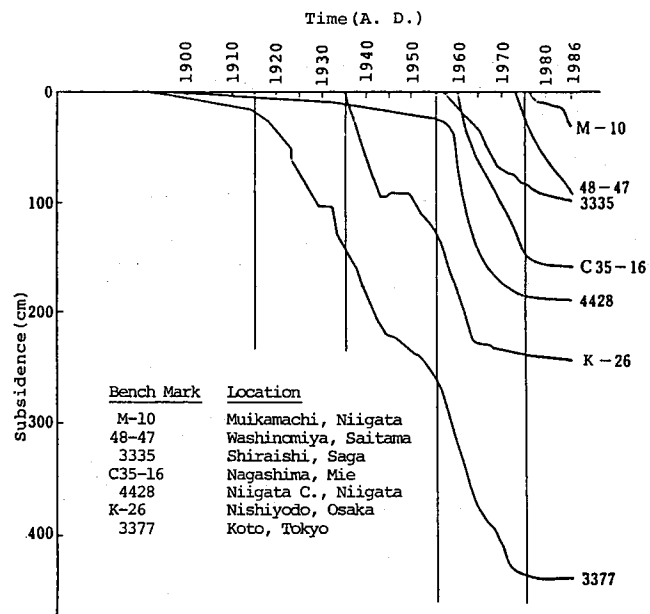


Fig. 1 Settlements of Principal Bench Marks

ordinances set forth by local governments still function successfully, protecting many areas where serious land subsidence was once in progress.

Mining

One topic related to mining is a large sinkhole which developed suddenly in the suburbs of Utsunomiya, about 100 Km north of Tokyo, on February 10, 1989. The sinkhole is roughly 100 m by 50 m and 30 m deep, located in an area, about 6 Km by 3 Km, where the underlying tuff has long been extensively mined as building material. At least 20 sinkholes have resulted in the area for the last 35 years or so, this being one of the largest.

Japan has ten underground coal mines in operation and appreciably one thousand mines inactive or abandoned. All active mines are operating under the sea, forests or waste land. The reasons for this is not so much coal shortage but rather to prevent damage to land. Remnant damages due to old workings are estimated at about 600 billion yen (5 billion dollars).

A particularly interesting example is subsidence in an area of thick alluvium overlying coal seams in the Miike coalfield. A colliery is working beneath the shallow Ariake sea producing 5 million tonnes of coal annually with mechanised longwall faces. Quaternary and Tertiary deposits overlie the coal seams, which dip seawards from near ground level to 600 m. The Quaternary alluvium consists of 100 to 150 m of soft clay and loose sand. The Tertiary consists of sandstones interbedded with shale, conglomerate and coal seams. The subsidence profile is remarkable, the angle of draw from the horizontal being only 46 - 50° in

the Tertiary but as steep as 72 - 79° in the Quaternary. Full subsidence of 185 cm occurred due to extraction of 270 m of coal. After extraction had been completed a 50 cm rebound was recorded.

Cave-ins due to collapse of old workings is of concern, particularly in such areas as the Chikuho district where 50 to 60 cave-ins occurred every year between 1974 and 1987. The main triggering factor appears to be rainfall, as the frequency increased during the rainy season. In the Tohoku district many shallow pillar and stall lignite mines occur and earthquakes cause a large increase in cave-ins. For example the normal 15 to 20 annual levels of cave-ins increased to 219 in 1978 due to an earthquake.

THE NETHERLANDS

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INTRODUCTION

Land subsidence problems in the Netherlands have been mainly due to gas extraction beneath low lying land and due to reclamation of land in a delta area.

PREDICTION OF ULTIMATE SUBSIDENCE OF A GAS RESERVOIR IN GRONINGEN

In the north of the Netherlands in the province Groningen, a large gas-reservoir was found in 1953. Ten years later exploitation started. Up to 40% of the recoverable gas has been produced since, and production is likely to continue into the 21st century.

The province of Groningen is a low-land, for the major part consisting of polders in which the water level is controlled precisely. The top stratification consists of soft and compressible soils. Land subsidence of several decimeters will have serious environmental implications.

Since an early stage of the depletion the Dutch National Gas Company has devoted great attention to expected subsidence. The first prediction based on analytical methods showed an ultimate subsidence of 1.0 m and a subsidence bowl with a diameter of 60 Km. Extensive field measurements during the following decades justified a reduction of this subsidence to 30 cm.

Recently this prediction has been adjusted to about 50 cm, because of new insight into the so-called rate effect (Waal, 1986). The latest aspect considered is the disconnectivity of the reservoir which prohibits deeper water from replacing the pore space evacuated by the produced gas in some places. To deal with damage claims the gas company has reserved 300 million US\$. A committee of advisors has been

founded to evaluate the progress of insight into the subsidence phenomenon and to handle claims.

This committee requested two additional studies. One was to study the possibility of reactivation of existing faults in the geological profile triggered by the compacting reservoir (at depth of 3 Km). And one dealing with the effect of water level adjustments in the subsiding polders, which may give rise to differential settlements and cause damage to existing buildings. Both studies have been completed. The first claim was forwarded by one of the coastal polder authorities last May, a claim of 50 million US\$.

It is worthwhile to mention that probabilistic methods have been applied for the assessment of possible damage to buildings (Barends e.a., 1989a).

AN EXTENDED WELL-FUNCTION

When exploiting a reservoir at great depth a significant pressure drop is applied. The corresponding increase in effective stresses will give rise to compaction. This compaction causes a change in porosity. Consequently, the permeability will alter, and it will change even more dramatically, because it is related to the porosity at a power in between two and three. For long term production this aspect cannot be disregarded, particularly not for the estimation of the ultimate compaction, as the less the permeability becomes the higher the pressure drop to keep up production. Another aspect is the increase of stiffness of the reservoir with compaction, which is pronounced for long term production, but less significant than the permeability change. These aspects considered in a common reservoir model render it non-linear and difficult for practical applications. Delft Geotechnics has developed a new comprehensive well-function suitable for the simulation of the time-dependent behaviour of a multi-well system taking into account nonlinear aspects to the reduction of permeability and the increase of rigidity during compaction.

The method is based on a special transformation technique (Barends, 1980, 1989b). A computer model for this method is available (PC-model). It has been tested on a real case, the Lake Maracaibo oil field, and proved suitable.

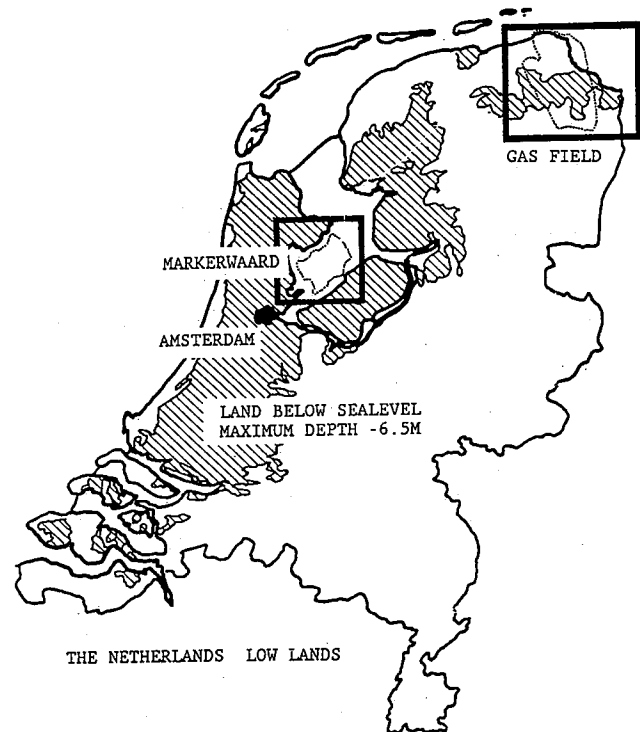
LAND SUBSIDENCE DUE TO RECLAMATION OF NEW LAND IN A DELTA AREA

The Netherlands is a small and crowded country. Need for new land to cope with increasing demand for space inspired the idea to reclaim a large (3000 Km²) new polder in the lake IJsselmeer, called Markerwaard, in the neighbourhood of the famous island Marken. The lake is several meters deep. The construction of the polder will involve a roundabout of dykes and dewatering of the inter area. Natural shrinkage of the lake bottom soil and

consolidation of the top alluvial soft soil layers of about 8 m thick will cause a lowering of the new land surface. Under the alluvial top layers a thick sandy aquifer is present extending under existing land, the province of North Holland (Amsterdam). The lowering of the watertable in the large polder will cause a drastic pore pressure reduction in the sand aquifer under North-Holland. Additional subsidence and negative skin friction on the traditional wooden pile foundation of thousands of houses, famous monuments, bridges and keywalls will cause a large environmental impact. It has been a serious reason to delay the project so far (see Venice Conference on Land Subsidence 1984).

Recently a large size investigation has been completed to study one of the counter measures: permanent infiltration by a well-system along the border of the newly planned polder facing the province of North-Holland.

Problems of filter clogging by chemical reaction and temperature effects have been solved. The conclusion is that the method can work on this large scale. About 500 infiltration wells will be required involving 130 million US\$. At present the issue of the new polder has been reopened in parliamentary discussion. Beside the possibility of infiltration wells a smaller polder is suggested. The construction of the polder is offered by a group of land reclaiming companies and for 100% supported by private investors.



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UNITED KINGDOM

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INTRODUCTION

This brief review will deal with some of the more important subsidence experience in the UK area over the last five years in terms of:

- Oil and Gas
- Mining
- Groundwater
- Natural Processes
- Conferences
- Books

OIL AND GAS

One of the most startling subsidence cases in the UK area has been the discovery of large scale subsidence in the Ekofisk oil field in the North Sea. Subsidence had not been expected in the North Sea due to the great depth of the oil reservoirs and the indurated nature of the strata.

The Ekofisk reservoir lies at a depth of 3000 m in a chalk reservoir rock overlain by shales and clays. In 1984/5 the sea bed was found to have subsided by 2.6 m since 1979. The depression was about 6 Km long and 4 Km wide. Predictions suggested that settlement could increase to about 7 m finally, although this settlement could be reduced to about 5 m by fluid injection.

The Ekofisk field is of major importance and includes several steel jacket platforms and a concrete gravity holding tank, all situated in about 70 m of water. The installation gathers gas and oil from wells in the Norwegian sector with pipelines to Teeside in the UK and Emden in West Germany.

In a costly exercise the steel jacket platforms

were all raised by 6 m in 1987, with new sections added during a complex jacking operation, at a cost of about £200 million. However the concrete tank could not be raised in a similar fashion and it was decided to construct a massive concrete wave barrier. This consists of a 140 m diameter 108 m deep slip-formed cellular concrete barrier built in two halves in Norway. At the time of writing (June 1989) the 192,000 tonne barrier structures were due to be towed into place by eight tugs. Total cost of the concrete barrier is about £135 million.

MINING

Britain suffers a fairly large amount of subsidence due to old mine workings and current mine workings.

Coal workings are the major cause of subsidence and these are widespread in the main industrial areas of Wales, the Midlands, Northern England and Central Scotland. However many other materials have been mined and in recent years much attention has been focused on old limestone mines in the Midlands of England. These have caused particular problems for urban regeneration of old industrial areas. In the past the depth of these workings has been such that subsidence was not suspected, but recently workings up to 150 m deep have caused extensive subsidence bowls more than 1 m deep due to failure of weak roof strata over the old limestone pillars.

Subsidence due to modern longwall coal mining has long been estimated in the UK on the basis of the Subsidence Engineers Handbook, the most recent edition being produced in 1975 by the NCB, now British Coal. It has been found that the SHE methods often overestimate subsidence and strains by up to about 15% and present day practice is to be more site specific and calibrate SHE forecasts against local experience. The area zoning method has come to prominence, based on SHE predictions, and this is now operated by computer using MURPLAN. Present research is based on three dimensional recording of field information from a remote stable viewing line 1 Km in length using high precision survey techniques.

GROUNDWATER

Subsidence due to groundwater abstraction has not been a major problem in the UK as groundwater has mainly been drawn from indurated rocks such as chalk, limestone and sandstone. However it is considered that over-abstraction from the Chalk aquifer beneath London may have led to consolidation by about 0.3 m of the overlying London Clay during the last one hundred years.

Ironically the main problem now with groundwater in the UK is rising groundwater levels due to cessation of abstraction in the older urban areas. This is affecting many areas including Merseyside, the Midlands and

London in particular. The Construction Industry Research & Information Association (CIRIA) has just produced a major study of this problem entitled "The Engineering Implications of rising groundwater levels in the deep aquifer beneath London". Abstraction in the London basin has fallen from a peak of 227 million litres/day in 1940 to 121 million litres/day in 1984. London's groundwater as a result is now rising at rates of up to 1.5 m/year and deep buildings and tunnels will be at risk in about 20 years, shallow construction within 40 years.

It is considered that £150 million of damage could be caused by the rising groundwater level and several new structures with deep basements, such as the British Library, have been fitted with costly relief wells. CIRIA point out that major savings could result by having a London wide groundwater pumping scheme, which could cost as little as £6 million if the water could be utilised. Pumping rates of up to about 25 million litres/day would be required to achieve this.

NATURAL PROCESSES

Britain suffers a certain amount of subsidence due to natural processes, such as limestone caves, salt solution, peat subsidence etc. but there have been few problems in this field in the last five years. It is believed that the south east of England is subsiding at a slow rate due to subsidence of the North Sea basin of about 2 mm year. This has been a contributory factor to the construction of the Thames flood surge barrier, one of the UK's most prestigious recent civil engineering projects.

CONFERENCES

Over the past five years a number of conferences in Britain and Ireland have concentrated, in whole or in part, with subsidence problems. These are:

- 1984 Second Conference on Large Ground Movements and Structures. Cardiff 1984 Proceedings.
- 1984 Mineworkings 84. International Conference on Construction in Areas of Abandoned Mineworkings. Edinburgh June 1988. Proceedings Edited by Forde et al. Engineering Technics Press. ISBN 0 947644 - 02 - 4
- 1987 Groundwater Effects in Geotechnical Engineering IX ECSMFE Dublin, August 1987. Proceedings edited by Hanrahan et al. Balkema. ISBN 90 6191 720 4
- 1987 Engineering Geology of Underground Movements. Nottingham, September 1987. Proceeding edited by Bell et al and published by the Geological Society as Engineering Geology Special Publication No.5.

- 1988 Mineworkings 88. Second International Conference on Construction in Areas of Abandoned Mineworkings. Edinburgh June 1988. Proceedings edited by Forde et al, Engineering Technics Press. ISBN 0 - 947644 - 08 10.

BOOKS

Subsidence related books in the last five years include:

- 1984 Ground movements and their effects on structures. Edited by Attewell and Taylor. Surrey University Press. 441 pp. ISBN 0-903384-36-1. This book contains contributions from twenty leading British authorities in the field.
- 1984 Construction over abandoned mine workings. Healy and Head. CIRIA special publication No. 32.
- 1988 Treatment of Disused Mine Openings. Freeman Fox Ltd. Department of the Environment Planning Research Programme. Contract PECD 7/1/223.
- 1989 Ground Subsidence. AC Waltham. Blackie. 202 pp. ISBN 0 - 216 - 92500 - 2. This is a very readable book that covers the whole subject on a worldwide basis, whilst concentrating on U.K. examples. The emphasis is on natural subsidence but man induced subsidence is also covered.
- 1989 Subsidence, Occurrence Prediction & control. Whittaker & Reddish. Elsevier. 528 pp. ISBN 0 - 444 - 87274 - 4 (Vol. 56). This is a weighty volume that concentrates heavily on mining subsidence, with some coverage of natural subsidence and fluid withdrawal.

SWEDEN

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INTRODUCTION

The land subsidence problems encountered in Sweden have their background in the special geological conditions created by the latest glaciation period. Large areas are covered by normally consolidated glacial and postglacial clay soils underlain by coarser, pervious material. The post-glacial clays are often organic and therefore highly compressible. The bed-rock usually consists of granite or gneiss characterised by frequent joint systems and fractured zones.

Obviously, withdrawal of groundwater from pervious strata underneath the clay or from fractured zones in the bed-rock (often in

direct connection with the aforementioned pervious strata) will reduce the hydraulic head of the groundwater in the aquifer. A consolidation process will be started up in the overlying clay, followed by settlement, the magnitude of which will depend on the relative drop in hydraulic head. Withdrawal of groundwater from pervious strata underneath a clay layer is the foremost reason for the occurrence of land subsidence in Sweden.

Occasionally, superficial drainage also brings about subsidence problems. Other causes, for example placing of fill, are very common in connection with urbanisation.

ANALYTICAL APPROACH EFFECT OF GROUNDWATER LOWERING ON PORE PRESSURE DISTRIBUTION

In the analysis of the settlement caused by groundwater lowering, the most important problem is how to predict the final equilibrated pore pressure distribution in the clay layer. Fortunately, some very interesting case records have been publicised, which can serve as a template for our judgement. From the results of a large number of pore pressure observations, some representing cases where groundwater lowering took place more than a thousand years ago, we can infer that a lowering - or a rise - of the groundwater level in a pervious aquifer beneath a clay layer will lead to a state of equilibrium, with hydrostatic pressure in the upper part of the layer, in the fissured zone (or the zone affected by root systems), and below this a hydrodynamic, more or less linear, pore pressure distribution governed by the pore pressure in the upper part and the pervious aquifer below. This inference can be drawn also in cases of superficial drainage, or cases where surface infiltration of rainwater is prevented, leading to a lowering of the groundwater level in the upper part of the clay layer.

If infiltration of rainwater is completely prevented by for example paving, or some other tight material covering large areas, we might end up with a hydrostatic pore pressure distribution throughout the entire clay layer. Normally, however, flow of superficial water in the horizontal direction from the surrounding area would prevent this situation from occurring.

CASE RECORDS WITHDRAWAL OF GROUNDWATER BY PUMPING

A case record of subsidence caused by groundwater abstraction from some wells in the block "Slakthuset 6" in the city of Norrköping was presented by Bjurström (1977). The subsoil at the site consists of around 12 - 14 m of soft organic clay underlain by sand and gravel on till. Pumping took place in the sand/gravel layer which had a thickness of more than one metre. The out-take of groundwater was concentrated to three wells, of which one, installed in 1913, gave 5 m³/h and the others,

installed in 1943, 3 and 11 m³/h, respectively.

The withdrawal of water from these three wells entailed a drop of the hydraulic head in the sand/gravel layer of between 8 and 9 m. As a result, about 1 m of subsidence occurred within a large area up to the middle of the 1970s (i.e. during a pumping period of around 30 years). The houses in the block, resting on piled foundations were severely damaged.

Water Leakage into Rock Tunnels

This is a very common cause of groundwater lowering. A typical case record from the centre of Stockholm was presented by Knutsson & Morfeldt (1973). Here, the underground railway is placed at considerable depth in the bedrock.

In its passage below Karlaplan, for example, it runs across a crushed zone. During construction, in connection with the crossing of this zone, a heavy leakage took place, but after some while the leakage was reduced and changed into dripping.

As a result of the leakage, the hydraulic head in the sand and gravel underneath the clay sank around 6 m. The buildings in the area were severely damaged, and connecting pipes broken.

Attempts have been made to establish theoretical models for the prediction of which area will be affected by leakage into tunnels and caverns in bedrock. However, the extent and distribution of groundwater lowering in such a case depends on the range of fissure planes and crushed zones and the soil conditions nearest to the bedrock. It is therefore extremely difficult to predict where the groundwater pressure will be mostly affected. For example, in a case where leakage took place into a rock tunnel, the groundwater pressure in a sand aquifer underneath the clay dropped more than 100 kPa within a fairly limited area with its centre about 300 m away from the tunnel line. A large number of dwelling houses some kilometers away were damaged by excessive settlement (Hansbo, 1973).

Land Uplift

Because of the isostatic uplift taking place after the glaciation period, a groundwater lowering will have to be expected in the long run. The annual uplift in Sweden varies from about zero in the south of Sweden to a maximum of 10 mm in the north. In the Stockholm area it is around 5 mm/year. The effect of land uplift is mostly restricted to coastal regions.

REMEDIAL MEASURES PREVENTION OF GROUNDWATER DISTURBANCE DUE TO LEAKAGE

Before tunnelling is carried out, the existence of possible fissured and/or crushed zones has to be carefully investigated by drilling and sampling operations. In case the tunnel will be passing such zones, injection with cement, or with other types of injection material, is generally carried out to ensure that leakage is reduced to a minimum.

All the same, cases will occur where leakage will affect the groundwater balance in a destructive way. Then reinfiltration of water into the soil may be a useful means of restoring the groundwater situation. However, the problem of creating a successful reinfiltration is not easy. The main difficulties arise in finding proper infiltration points where the hydraulic connection with the total area under consideration can be guaranteed. Some new infiltration techniques have been tested which have turned out very satisfactorily. Most interesting are two infiltration plants, one of which is in Kista, Stockholm, and the other in Solna, a suburb of Stockholm (see Hansbo, 1987).

In Kista, an infiltration tunnel, 250 m in length, was blasted in the bedrock. Boreholes in all directions were made in order to ascertain that the tunnel had contact with crushed zones in the bedrock. The tunnel was then sealed and filled with water. By means of a simple charging device, the hydraulic head of the filled-in water was kept at the original groundwater level. In this way the original groundwater level could be re-established within an area of 30 ha.

In the other case, in Solna, a borehole was made above and parallel to the planned tunnel, and put under water pressure before tunnelling. Thereby, possible leakage into the tunnel, affecting the groundwater pressure in the soil and rock above the tunnel line, could be avoided.

LEGAL ASPECTS

Land subsidence resulting from groundwater lowering has brought about a large number of cases in which structural damage to buildings and the breakage of connecting sewers and water-pipes have occurred. As the groundwater situation is generally affected by local council decisions and activities, the legal responsibility for possible detrimental effects on private property falls upon the Council. A number of test cases form a precedent.

The cost of repairs and environmental restoration is usually quite significant. As an example, in the 1970s the Stockholm Council was ordered by the district court to pay 4.5 million SEK (about 700 000 USD) for the underpinning of 3 buildings which had been damaged due to groundwater lowering caused by tunnelling, and about 400 000 SEK (over 60 000 USD) in legal costs. The judgement was appealed against but the Council lost the case even in the Court of Appeal.

As a result of another trial, a Council in south-eastern Sweden was ordered to pay for the restoration of 34 dwelling houses which had been damaged due to groundwater lowering. The estimated cost of restoration is between 5 and 10 million SEK.

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USA

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INTRODUCTION

Most of the major subsidence areas in the United States of America have developed in the past few decades, mainly starting during World War II and continuing at accelerated rates since, in order to satisfy the rapidly increasing needs for groundwater and for oil and gas. Most area of known subsidence are along coasts where the phenomenon becomes quite obvious when the ocean or lake waters start coming further up on the shore. In some such areas, the usual heavy population and intensive industrial development are protected from being covered by several metres of water only by construction of an extensive and very expensive system of dykes, flood walls, and pumping stations. The most common subsidence, due to pumping of groundwater or oil, is such a subtle phenomenon often of large aerial extent and at a slow rate - that the problem is not evident in inland areas until new precise levelling takes place or underground pipelines crack, well casings fail or stand above groundlevel, or canals no longer carry original design flows.

Subsidence in the United States ranges from something less than one metre (m) in Baton Rouge, Louisiana to as much as 9 m in the San Joaquin Valley, California. The aerial extent of subsidence ranges from slightly more than ten sq km. (Km²) in the San Jacinto Valley to nearly 14,000 sq. km. in the San Joaquin Valley, both in California. Because the detailed study of subsidence levelled off

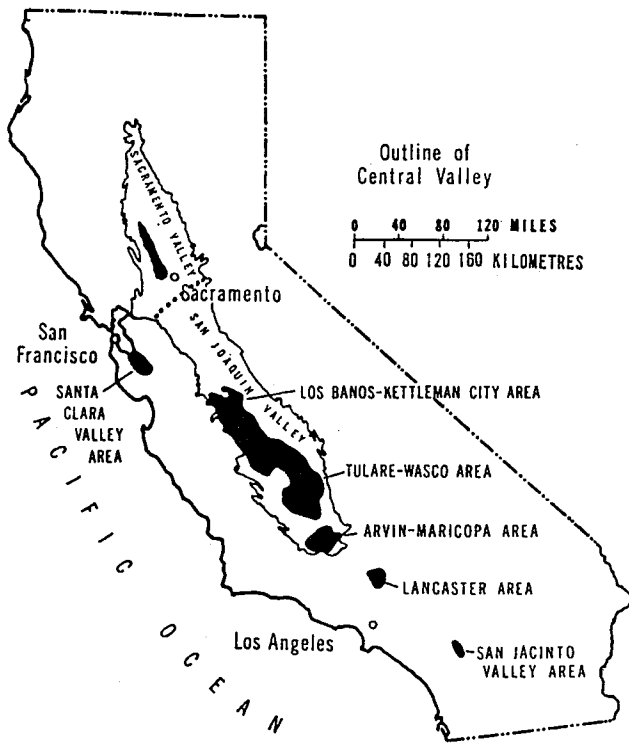


Fig.1. Areas of Land subsidence in California due to groundwater withdrawal (after Poland 1981)

somewhat in the 1980's, most data readily available on USA subsidence are for periods prior to the 80's.

In addition, there is extensive carbonate sinkhole type subsidence in the south-eastern states and some more recent evidence of relatively small subsidence of the sediments in Denver, Colorado and along the Atlantic coastal plain as far north as the Chesapeake Bay (New Jersey and Delaware area, for example).

CALIFORNIA

Because the major subsidence in the USA is in California, a more detailed look is taken of that area first. California pumps for irrigation of its very extensive agricultural development around one-fourth of all the groundwater used for irrigation in the whole United States. Fig.1 shows for California the major subsidence areas due to pumpage of groundwater. Huge pumps have drawdown the water levels more than 30 m in most basins, with drawdowns of as much as 130 m on the west side and southern end of the San Joaquin Valley. The decrease in the head in the confined aquifers resulted in extensive subsidence. In the San Joaquin Valley, there are three main centres of subsidence. The most subsidence, about 9 m occurred in the Los Banos to Kettleman City area, just west of Fresno. The second major area to the south is between Tulare and Wasco with around 4 m maximum

subsidence, and the third area is the Arv-Maricopa area just south of Bakersfield, with around 2.5 m of substance.

At a site about 16 Km south-west of Mendota, subsidence of nearly 9 m occurred between 1943 and 1969 in response to a water-level decline of over 100 m. Large surface water imports from northern California to overdrawn areas in the west side and south end of the valley began in 1967 with completion of the California Aqueduct. As a result of these large surface water imports, the rate of groundwater pumpage decreased sharply and by the 1970's hundreds of the irrigation wells were unused. Thus, water levels recovered and land subsidence stopped completely by 1975. Then, during 1976 and 1977, a severe drought hit the area and surface water imports had to be cut to about 20% of the 1976 level. As a result, large increases in use of groundwater caused the water level to fall about 50 m in 8 months and subsidence began once again.

Subsidence in the Santa Clara Valley at the south end of San Francisco Bay was first reported in 1933. During the 33-year period 1934 to 1967, subsidence in the San Jose area was as great as 2.5 m. Total damage resulting from subsidence in the Valley is estimated at \$100 million. By importation of water, artificial recharge to facilities in stream beds where the aquifer system is unconfined, and good management of local water supplies, land subsidence was brought under control by 1975, all accomplished by bond issues, revenue from taxes, and water charges.

There are several other types of interesting subsidence represented in California. One is what has been called hydrocompaction - the collapse of soil structure in dry, low-density, fine-grained sediments when those sediments are wetted. Major impacts from this subsidence have been on revised design, construction, and operation of structures such as canals and dams. Differential subsidence caused by irrigation frequently required releveling of fields. Construction of the huge California Aqueduct along the west wide of the San Joaquin Valley required pre-soaking of excavated sections in hydrocompaction susceptible areas prior to construction of concrete linings. The second type of subsidence of major significance in California is that due to pumping of petroleum. Such withdrawal in Long Beach, California resulted in parts of the city's harbour facility subsiding about 9 m from 1937 to 1966.

Starting in 1954, repressuring by injection of water slowed the subsidence and finally arrested it throughout most of the Long Beach area. California law now requires repressuring of subsurface formations in order to ameliorate subsidence that might be caused by petroleum withdrawal.

TEXAS

Another interesting and major area of subsidence is the Houston-Galveston area of

Texas. The centre of maximum subsidence is near Pasadena, with as much as about 2.5 m occurring between 1943 and 1973. Pumping of groundwater for municipal, industrial and irrigation purposes was over 2 million m³ per day by 1972. An area of about 8 Km² containing over 400 high-quality homes has been submerged due to subsidence in excess of 2.5 m along tidal reaches of Galveston Bay. In addition, high tides of more than 3 m resulted from Hurricane Alicia in 1983 and caused wide spread flooding and damage in the highly developed area around the Bay where subsidence had caused the land to be near sea level. The subdivision problems led to a lawsuit that resulted in a historical decision limiting the common-law rule of absolute ownership of groundwater. The court held that groundwater users were not responsible for damages caused by past actions, but could be held responsible for damages due to future pumpage if such were conducted in a negligent or malicious manner.

The Harris-Galveston Coastal Subsidence District was created by the Texas state government to regulate the withdrawal of groundwater in Harris and Galveston Counties in order to end subsidence (Neighbors, 1981). Through the District's well permitting system, control of total groundwater withdrawals was achieved. In addition to control of new groundwater development, pumpage from earlier wells was reduced by importing surface water through an extensive pumping and distribution system bringing water from Lake Livingston west of Houston to industries in the Harris-Galveston County area. Although alleviation of much of the subsidence was achieved, the surface water importation (maximum capacity of nearly 52 m³/s) will not be able to maintain adequate supply for the rapid rate of growth of both population and industry in the Houston area.

KARST

Another type of major subsidence in the USA occurs in karstic areas, primarily in Alabama, Florida, Georgia, Missouri, Pennsylvania, and Tennessee. Induced sinkholes, appearing in a matter of seconds, result from a decline in water table due to groundwater withdrawal. The water table decline results in a loss of buoyant support and the downward migration of sediments filling former cavities in the limestone suddenly collapse and sinkholes ranging in diameter from a metre to over a hundred metres suddenly occur. An example is one known as the Winter Park Sinkhole, which occurred suddenly in 1981 with lots of damage but fortunately no loss of life, at Winter Park, Florida. This sinkhole was over 100 m in diameter and around 30 m deep and swallowed a house, streets, parts of several businesses, trees, and six vehicles. As another example, there have been over 4,000 induced sinkholes occur in Alabama since 1900 and many millions of dollars of damage to highways, railroads, buildings, and other construction has resulted.

It seems logical to predict that new subsidence will multiply many fold in the next few decades as a result of accelerated exploitation of

natural resources, especially groundwater and petroleum, in order to meet the water supply and energy demands of an increasing population and industrial development, not only in the United States but throughout the world. Unfortunately, many planners and managers of industrial complexes, urban developments, and water resources systems are inadequately informed about the potential hazards, problems, and costs that can result from land subsidence.

Additional information on subsidence in the United States, as well as the rest of the world, is available in the Unesco "Guidebook to Studies of Land Subsidence due to Groundwater Withdrawal (Poland, 1984), the proceedings of the American Society of Civil Engineers' Session on Legal, Socio-Economic, and Environmental Significance of Land Subsidence in the United States (Johnson, 1981), and the International Association of Hydrological Sciences (IAHS) series of proceedings on their three previous International Symposia on Land Subsidence (IAHS Publications No. 88 - 89, Tokyo, Japan, 1969; No. 121, Anaheim, California, 1976; and No. 151, Venice, Italy, 1984). More up to date information will become available after IAHS has held its Fourth International Symposium on Land Subsidence, Scheduled for Houston, Texas during the spring of 1991. ISSMFE has been a co-operating society for all of the IAHS international symposia on land subsidence.

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VENEZUELA

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INTRODUCTION

One of the more interesting developments in subsidence monitoring in recent years has been the development of the Integration of Global Positioning System (GPS) and Conventional Levelling for Ground Subsidence Measurements.

Oil production from relatively shallow (300 - 1000 meter) reservoirs in the Eastern Coast of Lake Maracaibo, Venezuela, began in 1926 in Lagunillas. Due to reservoir characteristics (relatively shallow, unconsolidated, highly compressible, highly porous), ground subsidence has been taking place in an area of some 500 Km², resulting in three separate subsidence basins, corresponding to the oilfields of Tia Juana, Lagunillas and Bachaquero, known collectively as the Costa Oriental Oilfields. Subsidence was first detected in 1929 and has reached as much as 5.00 m in some points.

The combination of geomorphology (low laying, swampy, coastal land) and subsidence, prompted the continual construction of three coastal dykes (Tia Juana, Lagunillas and Bachaquero) for protection against flooding from Lake Maracaibo waters.

MONITORING SYSTEM

A levelling network was established in 1929 in Lagunillas and later extended to cover the Cabimas, Tia Juana, Bachaquero, and Mene Grande, as well as nearshore lake oilfields. To date, the network covers an area of about 800 Km² and comprises over 1,600 bench marks which are measured biennially by conventional levelling with a resulting accuracy of ± 3 cm for any given bench mark.

A joint Maraven-University of New Brunswick project was launched in 1985 to determine the feasibility of implementing global positioning system (GPS) techniques for the biennial subsidence levelling. A GPS together with conventional levelling program was implemented in 1988. Preliminary results are encouraging, as punctual accuracies in the order of ± 5 cm have been obtained. It is expected that this accuracy will be greatly improved once the number and geometry of satellites is improved (1991 - 92).

It is expected that benefit from the new system will include reduction from 4 to 1 month, mainly in field work, for each levelling campaign, since about 550 Km of levelling lines

will be replaced by GPS lines and lower order levelling lines with estimated savings of about US \$100,000.

ITALY

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INTRODUCTION

The cases of subsidence in Italy are mostly concentrated in the northern region, the Po Valley, where the longest Italian river flows. The subsidence phenomena started to interest Italian researchers after 1950, when the rapid industrialization of the country and the increasing demand for water and energy for industrial, civil and agricultural aims caused a series of local problems. These were extremely dangerous for the protection and the working order of the cities affected. This happened where the nature of the subsoil was particularly sensitive.

Periodic levellings, carried out in Northern Italy from the beginning of the century till now, have shown the actions of three phenomena, independent of each other, but causing summing effects on the land: natural and anthropic subsidence and eustatism.

Natural subsidence concerns the whole Po Valley and originates from the tectonic deformations of bedrock and from the continuous consolidation of geologically more recent deposits. The extent of the phenomenon increases moving towards the Eastern part of Italy, particularly along the coastal lands from Venice to Ravenna. Until now the researchers could not differentiate the effect due to the tectonic deformations of bedrock from that due to the natural consolidation of recent sediments.

Eustatism is connected to sea-level variations due to the earth's climatic fluctuations. Although it is completely independent of subsidence, eustatism can also contribute to make the limit of dry land withdraw during the raising of the sea-level.

Finally, in Italy the anthropic subsidence depends mostly on the unchecked withdrawal of water and sometimes gas from subsoil deposits. The most important cases of subsidence which took place in Italy are summarised in Table I.

The cases of Venezia, Ravenna and Po River Delta have been widely dealt with in the technical literature: however many other interesting phenomena of subsidence have happened in Italy, in particular at Modena and Bologna.

Modena, situated at the southern part of the Po Valley, sunk down nearly 1 m from 1962 to 1981,

because of a decline of the piezometric surface of 10 m. The last measurements point out that at the moment the subsidence rate is nearly equal to 25 mm/year.

The subsidence at Bologna started in the 1950's and caused a maximum settlement of 1.20 m in the period 1950 - 73. At the moment the estimated subsidence rate is 115 mm/year.

The Po River Delta area sunk down more than 3 m in the period 1951 - 65 because of an unchecked gas withdrawal: after closing the wells the phenomenon stopped.

The sinking of Venice is due to the combined effects of the natural and anthropic subsidence and the eustatism. The anthropic effect at the moment is practically negligible, after having closed the wells. The natural subsidence is estimated equal to 0.4 mm/year. Raising of sea level is estimated equal to 1.3 mm/year.

In the following headings the case of Ravenna is considered: the most recent measurements and analysis of the subsidence phenomenon are summarised.

THE SUBSIDENCE OF RAVENNA

Ravenna is a small town located on the south-east part of the Po Valley. It became a political and artistic centre when it was designated capital of the Western Roman Empire (V century A.D.). In that period several important monuments were built, such as S. Vitale Basilica (VI century A.D.) which have made Ravenna famous all over the world.

After the Second World War, the Ravenna area was subjected to generalised subsidence, which increased progressively until the 1970's. The phenomenon was more evident in the industrial zone, but it also caused serious problems in the historical centre, in the harbour and along the coastal lands.

The analysis of such a complex phenomenon consisted of the estimation of the effects on land caused by both the unchecked withdrawal of water from the shallowest aquifers and the deep gas reservoirs. The study involving a wide area (hundreds of square kilometers) and extending to a considerable depth, would have required a large series of experimental data extending over the whole territory. This is because of the natural heterogeneity of the physical medium, of the different possible causes of subsidence, and of the problems involved. However this was not possible for economic reasons. Therefore, only a few representative areas were accurately investigated. Afterwards, the results obtained were extrapolated to include the remaining territory.

The analysis of the effects caused by withdrawal of water was taken to a depth of 500 m, while it was taken as deep as 4000 m in depth in order to estimate the effects caused by the withdrawal of gas. The first ones involve a wide area of land, while the others are restricted to a limited area.

The Ravenna area has been subjected to a generalised phenomenon of subsidence. In the 70's and 80's several precise levellings were carried out to check the evolution of the subsidence and to verify some hypotheses on the relations between causes and effects induced. These levellings were carried out in the years '72 - '73, '77 - '78, '82 and '86. The results obtained were compared with those of the 1949 levelling carried out in a period when anthropic subsidence had not begun.

The peak values of the subsidence rates were registered in the years '72 - '77 in the industrial zone. The maximum settlement, which took place in the period 1949 - 1986 was about 1.15 m; the peak, subsidence rate increased from 30 - 40 mm/year in the period '49 - '72 to 60 - 70 mm/year in the period '72 - '77.

Until 1972 the phenomenon seemed to be limited only to the industrial zone, later it began to extend. In order to give evidence to this, it is sufficient to notice that the highly subsiding area was about 4 sq km until '72, whereas it was of 80 sq km in '77. The deleterious effects on the land became progressively more frequent causing the withdrawal of the coastal land (intensely exploited from a touristic point of view), frequent floods of the monumental, industrial and harbour zones and hydraulic problems of sewers, drainage system and reclaim channels.

Comparisons between the average piezometric declines, registered in five main aquifers from '50 to '86, and the average settlement, registered in the same period in the monumental and industrial zones, have been made (Fig.1). The peak subsidence rate decreased from 10 - 14 mm/year (period '77 - '82) to 5 mm/year (period '82 - '86). Rates of 10 - 15 mm/year still occur in some centres in the coastal lands (Fig.2). This is due to the consolidation induced by materials, transported by the rivers flowing into the sea, on the shallowest sediments.

The reconstruction of Ravenna's soil profile was difficult initially because of the very small amount of historical data and the scant reliability of the few data available. At the beginning of the '80's, in order to fill this gap, it was decided to carry out a continuous sampling borehole down to -500 m. At the same time Agip (National Italian Oil Company) was commissioned to take a hundred representative soil samples during an oil drilling at more than 1000 m in depth. Both boreholes were carried out inside the industrial zone that is in the area which suffered the most from the effects of subsidence.

Either in the deep boreholes, or in other water wells, already existing for civil and industrial aims, several electric and thermal logs were carried out. So it was possible to calibrate the results obtained by logs with the exact stratigraphic profile derived from the deep boreholes.

By means of the geotechnical information obtained from the undisturbed samples of soil a mathematical model for the simulation of subsidence due to the withdrawal of water was developed.

TABLE I
SUBSIDENCE IN ITALY

(A)	(B)	(C)	(D)	(E)	(F)
Location	Time of principal occurrence	Depth range for compaction beds (m)	maximum piezometric decline (m)	maximum subsidence (m)	(D)/(E) Ratio
Venezia	1952 - 1970	70 - 350	12	0.15	80.0
Ravenna	1950 - 1977	80 - 500	41	1.20	34.2
Po Delta	1951 - 1966	100 - 600	50	3.20	15.6
Modena	1962 - 1981	35 - 300	10	0.85	11.8
Bologna	1950 - 1983	50 - 250	35	1.20	29.2

The phenomenon of subsidence at Ravenna has now greatly decreased and has settled around a rate of 5 mm/year.

INDIA

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SUMMARY

Subsidence studies in India have been mainly confined to coal mining areas only and in this field remarkable advances have been made, which have proved useful for designing underground extractions underneath and in the vicinity of surface properties. Some instances of subsidences due to other activities, both natural and manmade have taken place. An urgent need is felt to initiate subsidence studies in areas having pumping of water and petroleum, possibilities of shrinkage and drifting of sub-soil, land slides, non-coal mining, and possibilities of underground cavities.

A main railway line at Sudamdih in Jharia coalfield has been made to subside by a maximum of 630 mm in a span of over 18 years without any disturbance in its operation. Further intensive subsidence studies in coal mining areas are also felt necessary.

INTRODUCTION

It is a well known fact that subsidence can take place anywhere due to various natural and manmade activities and can have an impact on day to day life depending on the nature magnitude and extent of subsidence and its impacts on surface, sub-surface and underground properties.

Through the importance of subsidence world over was realised long ago, very little thought went for subsidence in India before independence in 1947. Even today subsidence research is mainly confined to coal mining areas. Very little attention has been paid to other subsidence prone areas and activities. The main agency engaged in subsidence studies is the Central Mining Research Station (CMRS), Dhanbad. Some other organisations associated with coal mining have also contributed.

Although instances of subsidence have been reported in areas other than coal mining, some examples are given later, practically no subsidence data is available from areas having non-coal mining, pumping of water and petroleum from below ground, natural cavities, sub-soil drainage etc.

SUBSIDENCE DUE TO NATURAL CAUSES

Practically no study of subsidence due to natural causes is available in India. But, some of these activities and their impacts as observed are as given below.

1. Rising of Himalayan mountains due to plate movements.
2. Damage to surface properties and development of cracks on the surface due to earthquakes in Bihar and Assam in 1988 and also impacts of earlier earthquakes.
3. Land slides in hilly regions, leading to damage to roads and other properties, due to frosting and de-frosting, sliding of rocks and drifting of sub-soils.
4. Small subsidences over underground cavities formed by rodents have been reported from an area in Jharia coalfield. In one instance due to such a subsidence a main railway line had to suspend its operation for a few hours at Sudamdih.

There is practically no report of any subsidence due to underground cavities formed due to natural causes and if some instances have taken place they have gone either unnoticed or have not been investigated.

Some unconfirmed cases of subsidence due to drainage of sub-soil have been heard but no studies are available in respect of such subsidences.

SUBSIDENCE DUE TO MAN-MADE CAUSES

Pumping of water and petroleum from below ground.

Pumping of water for industrial and domestic use is being done in many areas in India. Some of them are the major cities, e.g., Calcutta, Bombay, Madras and Delhi. Practically no study of subsidence is available from these cities and other areas although some instances of subsidence have come to notice. In Calcutta city some areas have been reported to be subsiding due to pumping of water from an aquifer lying at 30 - 50 m depth below a clay bed. It is being proposed to study subsidence in Calcutta. An instance of damage to a large number of buildings in Meerut district was reported. This was probably due to subsidence as a result of large scale pumping of underground water. There may be many more instances of subsidence in India due to pumping of water from underground which have either not been noticed or reported.

Pumping of petroleum from underground in India is going on since about 20 years and more in Assam and Gujrat. No study of subsidence is available from any on-shore oil field.

Open excavations for metro rail in Calcutta caused flow of clayey sub-soil resulting in damage to nearby buildings. As a result precautionary measures were taken to minimise flow of clay into the excavations. The author's parental house at Bareilly in U.P. was severely damaged due to flow of sub-soil when a trench was cut by the side of the foundation for laying an underground sewer. Some other buildings in the locality were also damaged. No detailed study was made.

Non-coal mining.

Although marked subsidences, causing severe impacts, have taken place in non-coal underground mining areas practically no study is available. Two examples of such marked subsidences are one each at Zawar (Zinc mining complex) and Khetri (Copper mining complex) both in Rajasthan. In both the cases mining was being done in steep ore bodies. The subsidences resulted in making scars on hilly surfaces.

Underground coal mining.

As stated almost all the subsidence studies in India are confined to underground coal mining areas. The studies were being conducted with a view to developing an understanding of

subsidence behaviour of India coal measures for planning extraction of coal seams underneath and in the vicinity of surface, sub-surface and underground properties. From the point of view of subsidence the conditions in coal mining areas in India can be summarised as below.

1. Depth - the depth of underground workings varies from about 15 to 800 m. The average depth may be about 250 m. Only a few coal mines have depth more than 400 m.
2. Thickness - the extraction thickness of coal seams generally ranges between 2 and 3 m. Seams thinner than 0.9 m in thickness are considered unworkable. The maximum thickness of a slice may be up to 4.8 m.
3. Method of exploitation - Bord and pillar method with its various forms has been contributing to the extent of 90% to production from underground mines. Longwall mining is gradually picking up. Hydraulic sand stowing and partial extraction methods with and without stowing are being adapted in situations needing subsidence controls.
4. Coal measures - the India coalfields belong to Gondwana and Tertiary periods. The coal measures consist of sandstones, shales, coal seams and clays. The sandstones, fine to coarse grained, are bedded as well as massive and their percentage varies from about 60 to 95. In Pench coalfield the thickness of motur clays is up to 250 mm.

All the Indian coalfields have multiple number of seams in close proximity. The maximum number of coal seams available in a coalfield is 40. In most of the coal mines multi-seam mining is being done.

The coal seams in most coalfields are flat. Some areas in the outskirts of Jharia coalfield and in Assam have semi-steep to steeply dipping seams.

MINING SUBSIDENCE STUDIES

The CMRS has been conducting subsidence studies since 1964. They include field studies and laboratory two and three dimensional modelling.

The field studies over 150 mine workings have revealed the following noticeable aspects of subsidence.

1. Environmental impacts - there was practically no visual impact of underground extractions with hydraulic sand stowing on surface topography because under such conditions subsidence was far less than caving, slow and gradual. However, Underground extractions with caving caused severe damage to surface topography in the form of wide cracks, formation of steps, depressions and distinct modification in surface topography.

2. Impacts on water bodies - serious depletion of the water table was observed over both caved and stowed underground workings resulting in poorer availability of water in almost all the Indian coalfields.
3. Underground fires - more than half of the fires in Jharia and Ranigunj coalfields have taken place due to heating of coal left in goafs, on getting air through cracks developed due to subsidence. There are more than 80 fires in the two coalfields covering an area of about 20 sq. km.
4. Vegetation - growth of vegetation over subsided areas, specially those over caved workings, is retarded due to loss in water retaining capacity of sub-soil. In many areas surface land is not being put to any use after subsidence.
5. Waterlogging - waterlogging of subsided areas over caved workings was frequently observed.
6. Non-effective width - underground excavations with widths ranging from 0.3 to 1.17 times the depth have not caused practically any subsidence. The details of these observations are discussed elsewhere (Saxena, et al, 1989), which were used to plan underground extractions in situations where practically no subsidence was desired on the surface.
7. Subsidence profiles - subsidence profiles over stowed workings were generally smooth and without any discontinuity in the form of cracks. Over caved workings subsidence profiles were continuous as well as discontinuous and at some locations sinkholes also developed.
8. Maximum subsidence - the maximum subsidence over hydraulically sand stowed workings was not more than 6.5% of the thickness extracted underground. Over caved workings in undisturbed rock mass the maximum subsidence was not more than 60% of the thickness extracted underground.
9. Maximum slope and strains - the damage to surface environment as well as properties due to subsidence over underground coal mining takes place due to slope and strains developed in subsidence trough. The general relationships between various subsidence parameters are as given below.

$$G = K_1 \frac{S}{h} ; E_{(-)} = K_2 \frac{S}{h} ; E_{(+)} = K_3 \frac{S}{h} ;$$

$$E_{(-)} = K_4 G ; \text{ and } E_{(+)} = K_5 G \quad \dots (1)$$

where S is maximum subsidence, h is depth of workings, G is maximum slope, E is maximum strain (-) being compressive and (+) being tensile, and K1 to K5 are constants. Relationships and norms have

been established for anticipation of maximum slope and strains.

10. Area and volume of subsidence trough - the area influenced on the surface due to underground extraction of coal seams was always more than that extracted underground. In some cases the extent of influence was up to 42° from the edge of underground extraction. The maximum volume of subsidence trough over hydraulically sand stowed workings was about 2% of that extracted underground while over caved faces this value was 40%.
11. Limits - safe limits of subsidence movements have been defined for jointed construction railway lines, water bodies, buildings, aerial ropeway trestles and high tension pylons.

The above findings of subsidence studies in Indian coalfields have been used to study the possibilities of extraction of coal seams underneath and in the vicinity of surface, sub-surface and underground properties at more than 100 locations. As a result it has been possible to help the coal mining industry to extract more than 10 million tonne of coal under such conditions and many more million tonne may be extracted in the near future. A main railway line has been gradually made to subside by a maximum of 630 mm in a span of over 18 years without any disturbance in its operations at Sudamdih in Jharia coalfield. In fact the findings are now being used for designing almost all the underground coal mining underneath and in the vicinity of surface properties.

CONCLUDING REMARKS

Although remarkable advancements have been made in the field of subsidence in coal mining areas in Indian coalfields there is an urgent need to further intensify the studies in coal mining areas and to start subsidence and related studies in the areas:

- having pumping of water and petroleum from below ground,
- having possibilities of shrinkage and drifting of sub-soil,
- with possibilities of land slides due to action of water and frosting and defrosting.
- of non-coal mining, and
- suspect for having underground cavities.

ACKNOWLEDGEMENT

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SOUTH AFRICA

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INTRODUCTION

Major surface subsidence problems in southern Africa are restricted to development in dolomitic rocks and shallow coal mining in sedimentary rockmasses. Minor subsidence problems occur in other areas and are all mining related.

THEORY AND MODELLING

Dolomite

The theory of subsidence and modelling of sinkhole (sudden subsidence) and doline (slow subsidence) formation is well established. The problem is restricted to carbonate rocks (e.g. dolomite) susceptible to acid attack by percolating groundwater in the phreatic zone. Subsequent internal erosion, or a lowering of the water table, can lead to the formation of sinkholes and dolines.

The mechanisms are described in greater detail by Wagener et al (Ref. 1).

Mining

Coal is generally mined at depths of 60 m to 200 m below surface in horizontally bedded sedimentary rockmasses. The mining environment is strong when compared with conditions in Europe and Britain. (Unconfined compressive strength usually in excess of 50 MPa). Coal mining methods range from the conventional bord and pillar to the increasingly popular high extraction mining methods. Where high extraction methods are employed surface subsidence invariably results.

The magnitude of subsidence is generally half the extracted heights with the subsidence trough normally well contained within the perimeter of the underground panel (Ref. 1). A deviation from the above magnitude has been encountered where double seam extraction was done (subsidence 87% of extracted height). Smaller subsidence is encountered when high extraction mining occurs below a dolerite sill. (Subsidence generally 20% of extracted height). In the latter case substantial secondary subsidence may occur.

The theory of subsidence due to total extraction of coal is relatively new and is being verified by field measurements. Research is being conducted by the Chamber of Mines and the large coal companies to establish the subsidence criteria.

INSTRUMENTATION AND MEASUREMENT

Dolomite

Sinkholes are difficult to instrument as they occur randomly, however, dolines occur over larger areas and can be instrumented by surface levelling.

Monitoring of a suspect area usually consists of daily inspections on foot to look for signs of surface cracking, cracking of structures and an analysis of levelling observations.

Mining

Surface levelling is done before and after total extraction and for some time thereafter to establish time settlement curves.

GROUNDWATER WITHDRAWAL

"Active" dewatering in dolomitic areas has been the main cause of severe subsidence problems in this country (Ref. 1).

Large scale dewatering of dolomitic areas has been allowed where the dolomitic rocks are underlain by gold bearing reefs.

A 90 sq. km. area 60 Km west of Johannesburg is being dewatered at the moment. The owners of the mine had to do exhaustive geophysical and geotechnical tests before dewatering was allowed. Safe and unsafe areas were demarcated. Unsafe areas were purchased by the mining company and evacuated. A major road was stabilised by compaction grouting and a water dam was relocated out of the area. To date a number of relatively small sinkholes have occurred in the area being dewatered and additional houses had to be evacuated due to distress.

Monitoring mainly consists of measures as mentioned above.

REMEDIAL MEASURES

Dolomite

When a structure is engulfed by a sinkhole or breaks up because it is located on the perimeter of a doline not much can be done. Where structures crack due to subsidence which can be halted they can be repaired. The first step would be to determine the cause of the subsidence. If the subsidence is being caused by subsurface erosion due to water ingress this can be stopped, the subsurface damage repaired by grouting and the structure repaired conventionally.

Mining

During total extraction of coal, structures are influenced as the wave of subsidence passes below them. If damaged the structures can be repaired if the damage has not been too severe.

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ECONOMIC, ENVIRONMENTAL AND LEGAL ISSUES

The value of the minerals underlying the surface are usually many orders of magnitude more than the value of the surface development in sparsely populated areas. However, in densely populated areas the costs would escalate and it will not be possible to relocate scores of people due to economic and political reasons.

Legally the owner of mineral rights is allowed to mine the minerals even if the surface rights belong to another party. However, he may not dewater the area without a permit from the Department of Water Affairs. He also has to compensate the surface owner for damage to the land or to improvements.

Environmentally dewatering of for instance a dolomite aquifer causes many problems. Areas are depopulated and sinkholes and dolines make farming impossible in high risk areas. In addition depletion of the groundwater reserves causes problems to farmers staying in the area.

THOUGHTS FOR THE FUTURE

High extraction methods of coal mining is becoming increasingly popular and large areas will be subjected to subsidence of 1 to 2 m in the near future. Research has been done and it has been shown that gravel roads, pipelines and electric pylons can be undermined without having to close down the facility. Where roads are undermined the authorities still require a temporary deviation. Buildings have to be evacuated but could be repaired.

There is concern about the effect on farming. Extraction is not complete and ridges and mounds result which affect the surface drainage of the land. Dewatering during mining and the cracking of the subsurface strata upsets the groundwater regime and is cause for concern.

At present mining is restricted mainly to sparsely populated farming areas and farming continues after mining. However, it may soon become necessary to develop towns and industries on subsided areas. Further research is required so that the extent, magnitude and rate of subsidence can be determined to be able to develop the subsided areas fully.

GENERAL

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