Land subsidence in north-eastern Saxony (Lusatia)/Germany due to Ground Water Withdrawal

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ABSTRACT

In north-eastern Saxony/Germany several large open pit lignite mines are located. To guarantee the production of electric power until the year 2026, a couple of these pits have to be extended. The question to be solved is, whether differences in the vertical surface subsidence caused by mine dewatering might result in vertical stress resulting in building damages.

Most of the open pits are not more than 120…150 meters deep. Nevertheless, a large area is interfered by ground water withdrawal. The area of investigation, near the W. open pit is a 2 km² large building complex that was build in the early 1970s. It will be dewatered by a depth of 70 m below surface, resulting in surface subsidence that has been predicted by both, analytical and empirical methods.

The geological situation is, due to glacial tectonics, relatively complex, nonetheless the beds under the area of investigation are more or less horizontal. Main lithological units are Tertiary clay, sands and gravel as well as 4…6 lignite seams. They are overlain by Quaternary tills in an erosive channel.

From empirical calculations, based on subsidence measurements, a total subsidence of 0.2…0.5 m can be predicted. Analytical calculations, on the other hand, using the principles of Terzaghi's consolidation theory, yield an average possible subsidence of 1.1…1.6 m by the end of 2026.

Several reasons for these differences might be taken into account. First: the sand and gravel lenses in the tertiary clays have not been fully dewatered jet. Second: some of the low permeable units will subsidise very slowly. Third: the sediments have been higher compacted by the Pleistocene glaciers than expected.

Taking into consideration the calculations as well as the known measurements, a subsidence of 0.1…0.2 m is highly likely. Due to the geological situation differences in the amount of the vertical subsidence can not be excluded and might therefore result in damages.

INTRODUCTION

The investigation presented here is the result of an expertise for a large German real estate company. As the case was taken to court neither the name of the open pit nor the name of the residential area will be named here by their full names. To simplify reading of the paper the open pit will be called „W. open pit“ (W.O.P.) and the residential area „B.W.S.“

The first lignite mining in the W.O.P. began in 1973 and until 1993 468 million tons of lignite were produced and 2.2 billion tons of overburden moved. In 1997 the ground water was drained by 650 galleries with a pumping capacity of 200...300 m³/min. As the production of power, according to the Saxonian Regional Plan, has to be guaranteed until 2026, the „Lignite Plan W." was developed. This plan describes the future extension of the open pit as well as drainage and environmental regulations during and after operation. At the end of lignite mining the open pit, including backfilled areas, will extend 14 km by 9 km and will take use of 48 km² of land. At its north-easternmost point it will be as close as 0.8 km to B.W.S.' residential area. As a result of the open pit's extension the ground water table beneath B.W.S. will be lowered as far as 70...80 m NN (Figure 1), which corresponds to a lowering of the water table by 66 m (Table 3, Regionaler Planungsverband Oberlausitz-Niederschlesien 1993, Lausitzer Braunkohle Aktiengesellschaft 1995).

B.W.S. is a residential area whose erection began in 1973. Some of the 4...5 storey buildings are 65 m long and might therefore be damaged by horizontal or vertical differences in surface subsidence. According to the German Mining Law (Bundesberggesetz) the operator of a mine is responsible for any damages that are caused by the mining activities. Until now, in B.W.S., no damages are known to relate to the W.O.P. Nevertheless, the new owners of the B.W.S. residential area wanted to know, if there is a possibility for subsidence induced damages.

GEOLOGICAL AND HYDROGEOLOGICAL SITUATION

In the area of investigation 250 m of Quaternary and Tertiary sediments that were effected by glacial action are occurring. These young sediments are underlain by sand- and mudstones of Upper Cretaceous and Upper Triassic age (Nowel et al. 1994). As these older rocks will not be influenced by the ground water withdrawal, they will not be described here.

Due to glacial and tectonic processes, having caused folding and faulting, the geological situation is very complex. Graben structures (e.g. Graben of Weißwasser), erosive channels (e.g. Nochten-Pechern-Channel), highlands (e.g. Trebendorf Highland), and arc-like glacial folds (terminal moraine loop; e.g. Muskau Arc Fold) are typical structures characterising the geological situation in north-

Table 1: Simplified geological profile of the W.O.P. lignite mine and the B.W.S. residential area Lusatia/Germany. Fm: Formation

Period	member	lithology	thickness
Holocene	–	soil, silt	1...5 m
Pleistocene	–	sand, gravel, silt, clay, till	2...15 m
Miocene	Rauno Fm	sand, gravel, silt	40...60 m
	1st Miocene seam	lignite, sand, silt	10...12 m
	Upper Brieske Fm	sand, silt, lignite	40...50 m
	2nd Miocene seam	lignite, silt	10...12 m
	Lower Brieske Fm	fine sand, silt, lignite	16...24 m
	Spremberg Fm	clay, sand silt (alternating)	70...80 m
	3rd Miocene seam	lignite, silt	4...8 m
	Cottbus Fm	fine to middle sand	15...20 m

eastern Saxony and south-eastern Brandenburg (Lusatia). Furthermore, synsedimentary tectonics during the sedimentation dislocated the lignite (brown coal) seams (Brause & Hahmann 1989, Kupetz et al. 1989).

By extending the W.O.P. into northern and north-eastern direction, the 12 m thick 2nd Miocene coal seam and the 2 m thick (average) Oberbank (upper layer) of the 1st Miocene coal seam will be dewatered and mined (Lotsch 1979, Meier & Rascher 1995). They also extend under B.W.S. and are therefore of special interest if calculating the surface subsidence.

Although the geological surround of B.W.S. is rather complicated, the underground of B.W.S. that will be influenced by the ground water withdrawal is stratified relatively simple (Table 1, Figure 1). The 2nd Miocene lignite seam (Welzow Formation) is approximately 12 m thick and is composed of 3 lignite seams separated by fine sands and silts, from which the lignite will be mined. It is overlain

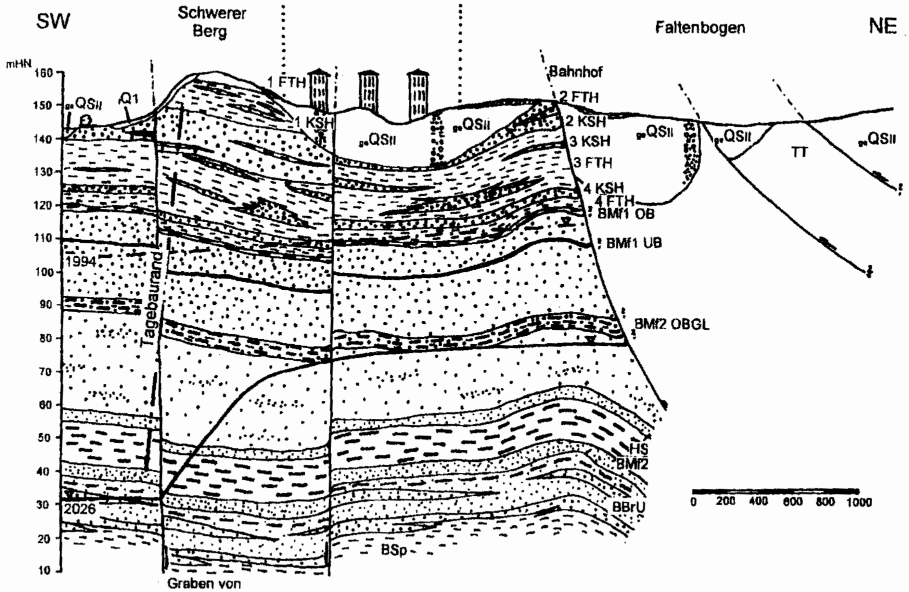

Figure 1: Geological cross section of B.W.S. Bahnhof: train station; Faltenbogen: terminal loop moraine and caused fault system; Graben von: G.B.W.; Tagebaurand: termination of the W.O.P. lignite mine; 1994, 2026: ground water level in 1994 and 2026, respectively (compiled after Meier & Rascher 1995, Lithofazieskarte Quartär Blatt 2470 Weißwasser, Kupetz et al. 1989, Alexowsky et al. 1989, Regionaler Planungsverband Oberlausitz-Niederschlesien 1993, Rascher & Böhnert 1995, Kupetz 1996, Nowel et al. 1994, Eissmann 1987).

by the 40...50 m thick Upper Brieske Formation consisting of a sequence of sands, silts and clays with two thin lignite seams. This sequence is followed by the 1st Miocene lignite seam of the Lower Rauno Formation. Within 10...20 m thick sand and silt two lignite seams, from which the upper one (Oberbank, 2...3 m thick) will be mined, can be found. The covering formation (Upper Rauno Formation) is normally 40...60 m thick and is composed of sands and clays of a deltaic deposit. Due to glacial erosion their thickness is diminished to 20 m in the underground of B.W.S. The youngest sediments building up the underground of B.W.S. are Quaternary sands, gravel, silt, and clay as well as till in a highly disturbed stratification (Alexowsky et al 1989, Brause et al. 1989, Meier & Rascher 1995).

1000 m north of B.W.S. the sediments influenced by the arc-like glacial fold system ends. This fold system was caused by a southwards moving glacier of the 2nd Elster glacial stage who formed the terminal moraine loop, and destroyed the Quaternary and Tertiary sediments as deep as 240 m below surface (Kupetz 1996). Another tectonic structure is a graben structure (G.B.W.) of which the northern fault line, covered under 10...15 m of till, crosses the underground of B.W.S. The fault planes are dipping steep and the displacement underneath B.W.S. is given by 4...10 m (Kupetz et al. 1989, Nowel et al. 1994, Meier & Rascher 1995).

Slight dewatering of the area began as early as 1914 when the first lignite mines started operation. But not until 1960 the dewatering process caused a large scale lowering of the water table by pumping of up to 1.2 billion m³ of water per year. As a result, the water table under B.W.S. was lowered down to 110 mNN (35...40 m below surface) and affected the local aquifer system (Table 2; Meier & Rascher 1995, Rascher & Böhnert 1995, Kaden 1997).

Table 2: Aquifers affected by the dewatering process of the W.O.P. lignite mine between the years 1995 and 2026 (Regionaler Planungsverband Oberlausitz-Niederschlesien 1993).

- Quaternary aquifer (aquifer Nr. 15)
- Tertiary aquifer between Upper and Lower layer of the 1st Miocene lignite seam (aquifer Nr. 253)
- Tertiary aquifer overlaying the 2nd Miocene lignite seam (aquifer Nr. 44)
- Tertiary aquifer underlaying 2nd Miocene lignite seam (aquifer Nr. 50)

GROUND WATER WITHDRAWAL AND SURFACE SUBSIDENCE

Basic works on surface subsidence

Since the 1950s numerous studies about ground water withdrawal and surface subsidence were conducted and papers published. As this paper deals with surface subsidence caused by ground water withdrawal for mine dewatering (mine drainage), no attention will be given to surface subsidence by longwall mining (a list of papers is given in Whittaker & Reddish 1989 and can be found in former IMWA Journals, or IMWA Proceedings: e.g. Whittaker et al. 1991).

First investigations of surface subsidence and the time dependence (Figure 2) were carried out in Europe by Kögler & Leussink (1938), Terzaghi & Jelinek (1954) or Rudolf (1969). Considerable

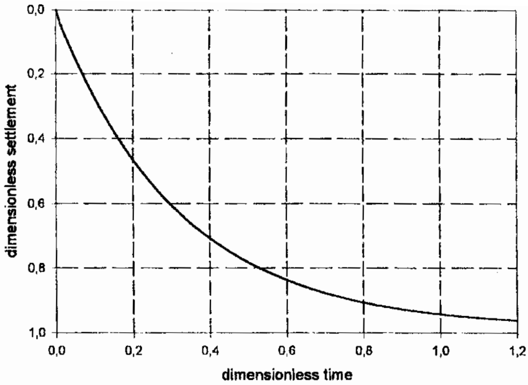

Figure 2: Time dependence of soil settlement (after Terzaghi 1925).

work about surface subsidence by ground water withdrawal has been conducted by Poland (1984). Due to huge problems many studies deal with surface subsidence in Venice, Japan or Mexico City (summarised in Poland 1984, Johnson et al. 1986 or Waltham 1989).

Since most of these surface subsidences result in vertical stress, only little attention has been given to horizontal stress and cracks resulting thereby. Rudolf (1974) stated that ground water withdrawal does not cause noticeable horizontal movements. Therefore, the theoretical background of vertical surface movements is well understood, whilst the background of horizontal movements is purely investigated (Holzer 1984, Waltham 1989; in the case of longwall mining horizontal stress situations can be fairly well predicted as described by Whittaker & Reddish 1989). Helm (1984) summarises: „The state of the science of predicting horizontal movement today is similar to the state of the science in the 1950s for predicting vertical subsidence".

Damages and amounts of subsidence

Because of ground water withdrawal the buoyancy forces of the soils above the ground water table are lost and result in an increase of the soils weight. This situation is similar to the settlement under engineering constructions and can therefore be calculated by using Terzaghi's (1925, 1954) consolidation theory. As in engineering construction, only differences in subsidence as they occur in a geologically complex environment will result in horizontal or vertical stress followed by damages (Helm 1984, Waltham 1989, Herth & Arndts 1994). These damages can be small cracks or leaning in engineering constructions as well as a total lost of the building (Rudolf 1974, Rasche & Fenk 1984).

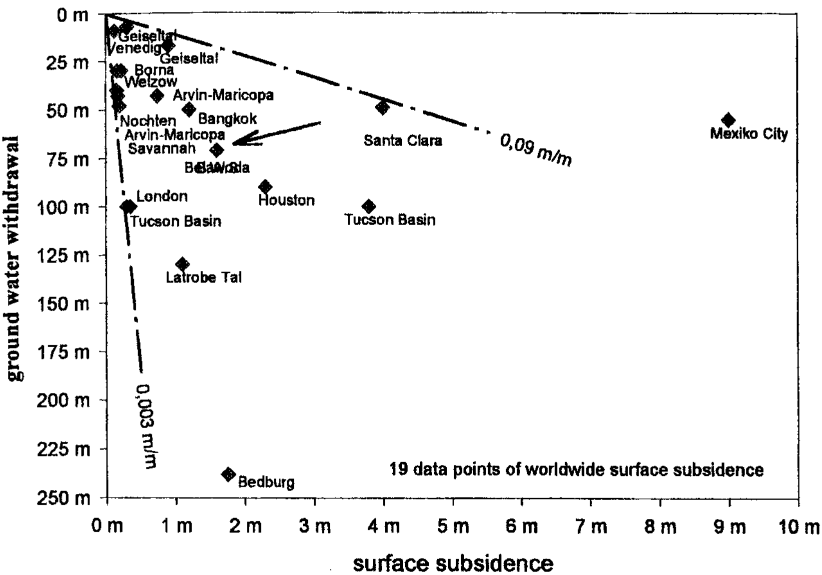

Figure 3: Comparison of ground water withdrawal and surface subsidence of different areas having a geological environment similar to this of the W.O.P. lignite mine (Gloe 1979, Heydenreich 1969, Holzer 1984, Lofgren 1975, Rasche & Fenk 1987, Rathsmann 1986, Routschek 1968, Rudolf 1969, Rudolf 1974, Waltham 1989, Wilkening 1975).

By comparing situations that are geologically similar to the W.O.P. lignite mine and B.W.S. residential area, the specific subsidence is found to be 0.003...0.09 m/m (surface subsidence in m per m of ground water withdrawal), as can be seen in Figure 3. These results confirm with Routschek's study conducted at the W.O.P., who reports 0.002...0.009 m/m specific subsidence (Routschek 1968, arrow pointing at B.W.S. in Figure 3).

Calculation methods and problems

Apart the theoretical model used to describe surface subsidence, three calculation methods can be applied to predict surface subsidence: analytical, numerical and empirical methods (Fenk 1976, Helm 1984, Gudgeon et al. 1988, Dassargues 1995). Although good computer codes can serve to predict surface subsidence (Acosta-Gonzales et al. 1988, Leak & Prudie 1988, Hanson et al. 1990, Oostindie & Bronswijk 1992 or Donaldson 1995), none of these models were used for B.W.S. due to a lack of qualitatively high input data and the complex geological setting. As Förster et al. (1992, and pers. comm. 1997) reported the results of numerical simulations of the Zittau open pit lignite mine

(Saxony, Germany) were close to analytical calculations calibrated by empirical observations. Therefore, the authors of this paper decided to estimate the surface subsidence of the B.W.S. residential area by an empirical and analytical method. The analytical method is based on the model of Kögler & Leussink (1938) and Rudolf (1969) and will therefore not be described in detail here.

Most of the models cannot handle varying soil parameters during time or within the sediments itself. Due to compaction the porosity, the compressibility, or the conductivity, to name the significant parameters, of unconsolidated sediments will change. Furthermore, parts of the sediments will be more or less dewatered than other parts. As these changes are not known accurately enough, the results of computations – be it numerically or analytically – may sometimes differ from the observed amount of subsidence.

To predict the surface subsidence beneath B.W.S. a simplified geological model was used and neither varying soil parameters during time nor partial dewatering of the sedimentary beds were taken into account. Both, an analytical calculation and estimations based on empirical observations were carried out and were compared with up to date subsidence measurements.

PREDICTION OF B.W.S.'S SURFACE SUBSIDENCE

Used data and methods

Based on a simplified geological and hydrogeological model of B.W.S.'s underground, the soil's properties, and the known degree of ground water withdrawal the authors calculated the surface subsidence. Two phases of ground water withdrawal were taken into account (see Figure 1 for details): from the beginning of the mining activities until 1994 (phase I) and from 1994 until the end of lignite mining in 2026 (phase II). Both, analytical and empirical methods were used for the estimation.

On the basis of Routschek's (1968) observations at the beginning of the mining operations the maximum and the minimum of the surface subsidence were found to be 0.009 m/m and 0.002 m/m, respectively. The ground water table for phase I was lowered by 29 m and will be lowered by 66 m for phase II. These values were used to estimate the surface subsidence by an empirical formula.

For the analytical estimation a 22 -bed-model with average values for thickness, compressibility and porosity was applied (Table 4). This 22-bed-model bases on the geological situation in the underground between the two right buildings as shown in Figure 1.

The settlement s_i of each bed i is calculated by using the known degree of ground water withdrawal h_i, the difference in pressure Δp_i and the modulus of compression (compressibility) E_{vi}:

$$s_i = \frac{h_i}{E_{v_i}} \cdot \Delta p_i \qquad (1)$$

Therein the difference in pressure Δp_i is the total of the average loss of buoyancy Δp_a in bed i (if dewatered) and the pressure increase due to the loss of buoyancy in the dewatered beds above bed i Δp_e (if existing). These pressures depend on the fluids density γ_w, the porosity n, the loss of buoyancy $\Delta\gamma$ and the thickness of the dewatered bed h_i:

$$\Delta p_i = \Delta p_a + \sum_1^{i-1} \Delta p_e = \frac{\Delta\gamma_i \cdot h_i}{2} + \sum_1^{i-1} \Delta\gamma_i \cdot h_i \qquad (2)$$

with

$$\Delta\gamma = (1-n)\cdot\gamma_w \cdot h \qquad (3)$$

The total of the surface subsidence s_g will be calculated by adding the settlements s_i of all n beds above the aquifer's basis:

$$s_g = \sum_1^n s_i = \sum_1^n \frac{h_i}{E_{v_i}} \cdot \Delta p_i \qquad (4)$$

In varying the soils properties within the natural possible values, the surface subsidence's maximum and minimum can be estimated.

Results

The empirical estimations resulted in an average surface subsidence of 0.16 m for phase I and 0.36 m in phase II (Table 3). Differences in the surface subsidence which would result in damages of buildings could not be predicted by this method, as the data base is very low.

On the basis of formula 4 the analytical estimation of the surface subsidence yielded an average surface subsidence of 1.1 m for phase I and 1.6 m for phase II at the end of lignite mining and mine dewatering (Table 4). It can therefore be estimated that during the next 30 years the surface of B.W.S. will subside by another 0.2 to 0.5 m.

CONCLUSIONS

As can be seen the differences between the predicted average surface subsidences by empirical and analytical methods vary between a large scale (0.2...1.1 m for phase I; 0.5...1.6 m for phase II). Three main reason for explaining these differences may be taken into account: specific subsidences chosen are too low; the varying of soil parameters within time is of importance; the sediments have been higher compacted by the Pleistocene glaciers than expected.

The data for calculating the specific subsidence is from the beginning of the mining operation in the late 1960s. It must therefore be assumed, that the soils were at the beginning of their settlement,

Table 3: Minimum and maximum of surface subsidence based on empirical calculations for phases I and II. Minimum of specific subsidence: 0.002 m/m; maximum of specific subsidence: 0.009 m/m.

phase	lowering of ground water table h	minimum of surface subsidence	maximum of surface subsidence	average
I (1994)	29 m	0.06 m	0.26 m	0.16 m
II (2026)	66 m	0.13 m	0.59 m	0.36 m

as can be seen in Terzaghi's dimensionless settlement diagram (Figure 2). The aquifers between low permeable silts or clays had not been fully dewatered at that time and the loss of buoyancy forces was less than predicted by theory. Therefore the specific subsidences used might be too low for calculations into the future.

On the other hand, the analytical results might be inaccurate. In that case the varying of the soil parameters is of more importance than assumed. For the analytical solution it is supposed, that sediments above the water table are fully dewatered. In fact this would never be the case as there will always be some water in the sediments.

A third possibility is, that the Miocene sediments had already been compacted by the glaciers of pre-Elster-2 glacial stages. In that case the sediments are pre compacted and will not settle as much as analytically calculated, thus resulting in less surface subsidence.

By using all available data, including unofficial up to date measurements of observed surface subsidences at B.W.S., it can be stated, that the surface subsidence in B.W.S. will range between 0.2 m and 0.5 m at the end of 2026. As the geological situation, fortunately, does not show significant horizontal changes, surface subsidence will not necessarily result in a stress field causing damages of engineering constructions as long as they are built according to the German standards. Nevertheless,

Table 4: Geological model, soil mechanical parameters used, and results of the analytical estimations for surface subsidence at the end of phases I and II.

bed	lithology	thickness M m	compressibility E_v MN/m	porosity n 1	average subsidence (phase I: 1994) cm	average subsidence (phase II: 2026) cm
1	sand/gravel	15	80...200	0.32	0.7	0.7
2	sand/gravel	1	80...200	0.32	0.1	0.1
3	clay	5	4...10	0.53	10.5	10.5
4	sand/gravel	2	80...200	0.32	0.2	0.2
5	clay	6	4...10	0.53	16.8	16.8
6	sand/gravel	1	80...200	0.32	0.2	0.2
7	clay	2	4...10	0.53	6.5	6.5
8	sand/gravel	2	80...200	0.32	0.3	0.3
9	clay	3	4...10	0.53	11.1	11.1
10	lignite	2	20...20	0.6	1.9	1.9
11	sand	9	60...150	0.35	2.4	2.7
12	lignite	1	20...30	0.6	0.9	1.2
13	sand, silt	16	40...100	0.35	6.3	9.5
14	lignite	4	20...30	0.6	3.8	6.7
15	sand, silt	22	40...100	0.35	8.7	15.7
16	silt	3	5...15	0.4	9.0	16.3
17	lignite	11	20...30	0.6	10.4	18.7
18	fine sand	4	40...80	0.35	1.7	3.1
19	lignite	3	20...30	0.6	2.8	5.1
20	fine sand	4	40...80	0.35	1.7	3.1
21	silt	5	5...15	0.4	15.1	27.2
22	fine sand	4	40...80	0.35	1.7	3.1
sum	–	125	–	–	113	161

the fault line of the G.B.W. runs through B.W.S. For constructions crossing this fault line of the graben or being close to the line damages, caused by vertical differences in surface subsidence, can not be excluded.

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REFERENCES

Acosta-Gonzales, G. & Reddell, D. L. (1980): Optimal use of Groundwater and Surface Water to reduce Land Subsidence. – Texas Water Resources Institute Texas A & M University Technical Report, **103**: 228, num. fig., num. tab.; Texas.

Alexowsky, W., Standke, G. & Suhr, P. (1989): Beitrag zur weiteren lithostratigraphischen Untergliederung des Tertiärprofils in der Niederlausitz. – Geoprofil, **1**: 57—62, 3 fig.; Freiberg.

Brause, H. (1990): Beiträge zur Geodynamik des Saxothuringikums. – Geoprofil, **2**: 1—88, 104 fig., 5 tab; Freiberg.

Brause, H. & Hahmann, H.-G. (1989): Kipp-Gleit-Tektonik Typ Nochten. – Geoprofil, **1**: 63—64, 4 fig.; Freiberg.

Brause, H., Rascher, J. & Seifert, A. (1989): Transgressionsgeschichte und Kohlenqualität im Miozän der Lausitz. – Geoprofil, **1**: 18—30, 25 fig., Freiberg.

Dassargues, A. (1995): On the necessity to consider varying parameters in land subsidence computations. – In: Barends, F. B., Brouwer, F. J. J. & Schröder, F. H.: Land subsidence – by fluid withdrawal, by solid extraction, theory and modelling, environmental effects and remedial measures; proceedings of the fifth International Symposium on Land Subsidence, held at The Hague, The Netherlands, 16—20 October 1995 – IAHS publication. – p. 258—269, 6 fig.; Wallingford (IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire).

Donaldson, E. C. (1995): Simulation of compaction due to fluid withdrawal. – In: Chilingorian, G. H., Donaldson, E. C. & Yen, T. F.: Subsidence due to fluid withdrawal – Developments in Petroleum Science 41. – p. 425—439, 5 fig.; Amsterdam u.a. (Elsevier).

Eissmann, L. (1987): Lagerungsstörungen im Lockergebirge. – Geophys. u. Geol., **III**: 7—77, 35 fig.; Leipzig.

Fenk, J. (1976): Senkungen der Tagesoberfläche als Folge von Grundwasserentzug. – Neue Bergbautechnik, **6**: 198—200, 3 fig.

Förster, W., Ulbricht, K. & Wittig, M. (1992): Senkungsprognose Zittau. – Neue Bergbautechnik, **22**: 62—66, 4 fig., 1 tab.

Gloe, C. P. (1979): Bodensetzung infolge Grundwasserentzugs, erläutert am Beispiel des Latrobe-Tals, Viktoria, Australien. – Braunkohle, **1979**: 261—267, 8 fig.

Gudgeon, D. L., Warner, M. F. & Stowell, J. (1988): Prediction of settlement due to dewatering for deep excavation. – In: Bell, F. G., Culshaw, M. G., Cripps, J. C. & Lovell, M. A.: Engineering Geology of underground Moments. – p. 377—386, 8 tab., 6 fig.; London (Geological Society London).

Hanson, R. T., Anderson, P. R. & Pool, D. R. (1990): Simulation of Ground-Water Flow and potential Land Subsidence, Aura Valley, Arizona. – Water-Resources Investigations Report, **WRI 90—4178**: 41, 20 fig., 2 tab.; Reston, VA (United States).

Helm, D. C. (1984): Field-based computational techniques for predicting subsidence due to fluid withdrawal. – In: Holzer, T.: Reviews in Engineering Geology – Man induced land subsidence. – p. 1—22, 22 fig., 4 tab.; Boulder, Colo. (Geological Society of America).

Herth, W. & Arndts, E. (1994): Theorie und Praxis der Grundwasserabsenkung. – 3. ed., 357 p., 152 fig., 13 tab.; Berlin (Ernst & Sohn).

Heydenreich, H. (1969): Der zeitliche Ablauf der vertikalen Bodenbewegungen bei örtlich stationären und veränderlichen Grundwasserstandsänderungen und bei Überlagerungen nach Messungen in situ. – Bergbautechnik, **19**: 627—631, 13 fig.

Holzer, T. L. (1984): Ground failure induced by ground-water withdrawal from unconsolidated sediment. – Geological Society of Amerika: 67—105, 36 fig., 1 tab.

Johnson, A. I. (1986): Land subsidence – Proceedings of the 3rd Internat. Symposium on Land Subsidence held in Venice, Italy, 19—25, March 1984. – In: International Association of Hydrological Sciences: IAHS-AISH publication. – 939 p., num. fig., num. tab.; Wallingford.

Kaden, S. (1997): Water Resources Modeling for Decision Support in Open-pit Lignite Mining Areas. – p. 385-395, 6 fig., 2 tab.; Ljubljana (Proceedings, 6th International Mine Water Congress, Bled, Slovenia).

Kögler, F. & Leussink, H. (1938): Setzungen durch Grundwasserabsenkung. – Die Bautechnik, **15**: 409—413; Berlin.

Kupetz, M. (1996): Der Muskauer Faltenbogen – ein Geotop von europäischer Bedeutung. – Brandenburgische Geowissenschaftliche Beiträge, **3**: 125—136, 4 fig.; Kleinmachnow.

Kupetz, M., Schubert, G., Seifert, A. & Wolf, L. (1989): Quartärbasis, pleistozäne Rinnen und Beispiele glazitektonischer Lagerungsstörungen im Niederlausitzer Braunkohlengebiet. – Geoprofil, **1**: 2—17, 18 fig., 1 tab.; Freiberg.

Lausitzer Braunkohle Aktiengesellschaft (1995): Das schwarze Gold der Lausitz. – 3. ed., 28 p., 20 fig., 1 tab.; Senftenberg (Eigenverlag).

Leake, P. A. & Prudie, D. E. (1988): Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model. – U.S. Geological Survey Open-File Report, **88—482**: 80; Menlo Park, Cal.

Lofgren, B. E. (1975): Land subsidence due to ground-water withdrawal, Arvin-Maricopa area, California. – Geological Survey Professional Paper, **437-D**: 55, 9 tab., 43 fig.; Washington, D.C.

Lotsch, D. (1979): Entwicklungsbericht zur Standardisierungaufgabe TGL 25234/08. – Berlin (Zentrales Geologisches Institut).

Meier, J. & Rascher, J. (1995): Exkursion: Bergbau und Bergbaufolgelandschaft im Bereich der Kohlenfelder Nochten und Lohsa. – Exkursionsführer und Veröffentlichungen der Gesellschaft für Geowissenschaften, **196**: 47—59, 6 fig., 2 tab.; Berlin.

Nowel, W., Bönisch, R., Schneider, W. & Schulze, H. (1994): Geologie des Lausitzer Braunkohlenreviers. – 102 p., 77 fig., 4 tab.; Senftenberg (Lausitzer Braunkohle Aktiengesellschaft).

Oostindie, K. & Bronswijk, J. J. B. (1992): FLOCR - A simulation model for the calculation of water balance, cracking and surface subsidence of clay soils. – Winand Staring Centre for Integrated Land, Soil and Water Research, **47**: 53, 6 fig.; Wageningen.

Poland, J. F. (1984): Guidebook to studies of land subsidence due to ground-water withdrawal. – In: Studies and reports in hydrology. – 305 p., num. fig., num. tab.; Paris (Unesco).

Rasche, H. & Fenk, J. (1987): Senkungen der Tagesoberfläche durch Grundwasserentzug im Braunkohlenbergbau der Deutschen Demokratischen Republik. – Neue Bergbautechnik, 17: 128—131, 5 tab., 4 fig.

Rascher, J. & Böhnert, W. (1995): Ergebnisse von geologischen Untersuchungen und Biotopkartierungen im Raum Nochten/Reichwalde als Grundlage zur weiteren Ausgestaltung der Bergbaufolgelandschaft. – Exkursionsführer und Veröffentlichungen der Gesellschaft für Geowissenschaften, 196: 33—42, 8 fig., 1 tab.; Berlin.

Rathsmann, W. (1986): Bodenbewegung als Folge von Grundwasserentzug im rheinischen Braunkohlerevier. – Braunkohle, 1986: 82—86, 6 fig.

Regionaler Planungsverband Oberlausitz-Niederschlesien (1993): Braunkohlenplan Tagebau Nochten für das Vorhaben Weiterführung des Tagebaues Nochten 1994 bis Auslauf. – In: Regionale Planungsstelle Oberlausitz-Niederschlesien: Braunkohlenplan Tagebau Nochten. – p. 1—57, 3 fig., 8 tab.; Bautzen.

Routschek, H. (1968): Einiges zur Bodensetzung infolge Grundwasserentzuges. – Bergbautechnik, 18: 630—634, 9 fig., 5 tab.

Rudolf, H. (1969): Senkungen im Bereich von Braunkohletagebauen als Folge von Grundwasserentzug. – Bergbautechnik, 19: 16—22, 4 fig., 3 tab.

Rudolf, H. (1974): Ursachen von Bodenbewegungen im Geiseltal und Auftreten von Bergschäden. – Neue Bergbautechnik, 4: 567—573, 2 fig.

Terzaghi, K. (1925): Erdbaumechanik und bodenphysikalische Grundlage. – 399 p., 65 fig., 63 tab.; Leipzig Wien (Deutike).

Terzaghi, K. & Jelinek, R. (1954): Theoretische Bodenmechanik. – Berlin (Springer).

Waltham, A. C. (1989): Ground subsidence. – p. 116—140, num. fig., num. tab.; Glasgow u.a. (Blackie).

Whittaker, B. N. & Reddish, D. J. (1989): Subsidence – Occurence, Prediction and Control. – In: Developments in Geotechnical Engineering. – 528 p., 35 tab., 259 fig.; Amsterdam (Elsevier).

Whittaker, B. N., Reddish, D. J. & Sun, G. (1991): Mine Design and Planning Aspects: Undermining Aquifers and Surface Water Bodies. – Proceedings, 4th International Mine Water Congress, Ljubljana (Slovenia)-Pörtschach (Austria), 2: 199-210, 11 fig.; Ljubljana.

Wilkening, W. (1975): Setzungsbeobachtungen am Nordrand des Tagebaus Alversdorf. – Braunkohle, 1975: 183—189, 12 fig., 1 tab.