GROUND WATER WITHDRAWAL AND LAND SUBSIDENCE IN NORTHEASTERN SAXONY (GERMANY)

Technical Contribution by:
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ABSTRACT

Several large open pit lignite mines are located in northeastern Saxony, Germany. To guarantee the production of electric power until the year 2026, a couple of these pits have to be extended. Most of the open pits are, at most, 120-150 meters deep. Nevertheless, a large area is affected by ground water withdrawal. There is a concern that differential subsidence due to mine dewatering might cause vertical stress and building damage. The area of investigation is a 2 km^2 large building complex built in the early 1970's. It will be dewatered to a depth of 70 m below the surface, resulting in subsidence that has been predicted by both analytical and empirical methods.

From empirical calculations, based on subsidence measurements, a total subsidence of 0.2-0.5 m was predicted. Analytical calculations, on the other hand, using the principles of Terzaghi's consolidation theory, yielded an average possible subsidence of 1.1-1.6 m by the end of 2026. These differences might be due to the fact that sand and gravel lenses in the tertiary clays have not been fully dewatered, or that some of the less permeable units will subside very slowly, or that the sediments were compacted more by the Pleistocene glaciers than expected. Taking into consideration the calculations as well as the known measurements, a subsidence of at least 0.2 m is highly likely. Due to the geological situation, differential subsidence and the associated damage is possible for part of the area.

INTRODUCTION

The investigation presented here was conducted 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. Instead, the open pit will be called "W. open pit" (W.O.P.) and the residential area, "B.W.S.". Lignite mining began in the W.O.P. in 1973, and by 1993, 468 million tons of lignite had been extracted 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 m^3/min. As the production of power has to be guaranteed until 2026, according to the Saxonian Regional Plan, the "Lignite Plan W" was developed. This plan describes the future extension of the pit as well as drainage and environmental regulations during and after operation. At the end of mining, the pit, including backfilled areas, will extend 14 km by 9 km and will encompass 48 km^2 of land. At its northeastern-most point, it will be as close as 0.8 km to the B.W.S. As a result of the pit's extension, the ground water table beneath B.W.S. will be lowered by as much as 66 m (Figure 1, based on data from Table 3; Regionaler Planungsverband Oberlausitz-Niederschlesien, 1993; Lausitzer Braunkohle Aktiengesellschaft, 1995).

B.W.S. is a residential area initially constructed in 1973. Some of the 4-5 story 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, the W.O.P. has caused no known damage to B.W.S. Nevertheless, the new owners of the B.W.S. residential area wanted to know if there was a possibility for subsidence-induced damages.

GEOLOGICAL AND HYDROGEOLOGICAL SITUATION

In the area of investigation, 250 m thick Quaternary and Tertiary glacial sediments occur above sand - and mudstones of Upper Cretaceous and Upper Triassic age (Nowel et al., 1994). As the older rocks will not be influenced by the ground water withdrawal, they will not be described here.

The geological situation is very complex due to folding and faulting caused by glacial and tectonic processes. 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 geological structures in northeastern Saxony and southeastern Brandenburg (Lusatia). Furthermore, synsedimentary tectonics during the sedimentation dislocated the lignite (brown coal) seams (Brause and Hahmann, 1989; Kupetz et al., 1989).

By extending the W.O.P. in the northern and northeastern 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 and Rascher, 1995). These seams extend under B.W.S. and are therefore of special interest in calculating the surface subsidence.

Although the geological surroundings of B.W.S. are rather complicated, the area beneath B.W.S. that will be influenced by the ground water withdrawal is relatively simply stratified (Table 1, Figure 1). The 2nd Miocene lignite seam (Welzow Formation), which will be mined, is approximately 12 m thick and actually contains 3 lignite seams separated by fine sands and silts. It is overlain 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, which contains 10-20 m of sand and silt and two lignite seams. The upper seam (Oberbank, 2-3 m thick) will also be mined. The covering formation (Upper Rauno Formation) is normally 40-60 m thick and is composed of sands and clays of a deltaic deposit.

Table 1. Simplified geological profile of the W.O.P. lignite mine and the B.W.S. area.

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

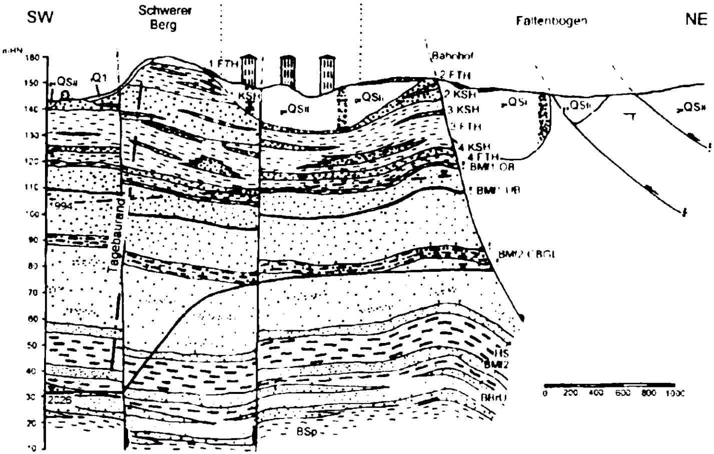

Figure 1. Geological cross section of the B.W.S. Bahnhof train station, Faltenbogen: terminal loop moraine and fault system; Graben von G.B.W.; Tagebaurand termination of the W.O.P. lignite mine; 1994, 2026: ground water level in 1994 and 2026, respectively (compiled after Meier and Rascher, 1995; Lithofazieskarte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

Due to glacial erosion, their thickness is diminished to 20 m beneath B.W.S. The youngest sediments beneath 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 and Rascher, 1995).

About 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 glacier of the 2nd Elster glacial stage, which formed the terminal moraine loop and eroded the Quaternary and Tertiary sediments as deep as 240 m (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 beneath B.W.S. The fault planes are steeply dipping and the displacement beneath B.W.S. is 4-10 m (Kupetz et al., 1989; Nowel et al., 1994; Meier and Rascher, 1995).

Slight dewatering of the area began as early as 1914 when the first lignite mines started operating. In 1960, the dewatering began to cause a large scale lowering of the water table by pumping up to 1.2 billion m^3 of water per year. As a result, the water table under B.W.S. was lowered to 110 mNN (35-40 m below surface), which affected the local aquifer system (Table 2; Meier and Rascher, 1995; Rascher and Böhnert, 1995; Kaden, 1997).

GROUND WATER WITHDRAWAL AND SURFACE SUBSIDENCE

Basic Works on Surface Subsidence

Since the 1950's, numerous papers have been published on ground water withdrawal and surface subsidence. As this paper deals with surface subsidence caused by ground water withdrawal for mine dewatering (drainage), no attention will be given to surface subsidence by longwall mining (instead, see Whittaker and Reddish, 1989 and previous IMWA publications: *e.g.*, Whittaker et al., 1991).

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 overlying the 2nd Miocene lignite seam (aquifer Nr. 44)
- Tertiary aquifer underlying 2nd Miocene lignite seam (aquifer Nr. 50)

Early investigations on the time dependence of surface subsidence (Figure 2) were carried out in Europe by Kögler and Leussink (1938), Terzaghi and Jelinek (1954) and Rudolf (1969). Considerable work on surface subsidence caused by ground water withdrawal was conducted by Poland (1984). Many studies deal with surface subsidence in Venice, Japan or Mexico City (summarized in Poland, 1984; Johnson et al., 1986; Waltham, 1989). Due, in part to Rudolf (1974), who stated that ground water withdrawal does not cause noticeable horizontal movements, the theoretical background of vertical surface movements is well understood, while the nature of horizontal movements is less well investigated (Helm, 1984; Holzer, 1984; Waltham, 1989).

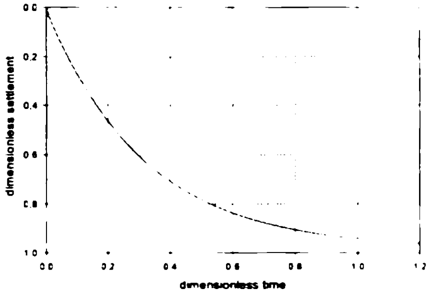

Figure 2. Time dependence of soil settlement (after Terzaghi, 1925).

Damages and Amounts of Subsidence

Because of ground water withdrawal, the buoyancy forces of the soils above the ground water table are lost, resulting in an increase in effective soil weight. This situation is similar to settlement under engineering constructions and can therefore be calculated using Terzaghi's (1925, 1954) consolidation theory. As in engineering construction, only differences in subsidence that occur in a geologically complex environment will result in horizontal or vertical stress (Helm, 1984; Waltham, 1989; Herth and Arndts, 1994). Such stress can cause small cracks, out-of-plumb engineering constructions or a completely unsafe building (Rudolf, 1974; Rasche and Fenk, 1984). By comparing situations that are geologically similar to the W.O.P. lignite mine and B.W.S. residential area, the specific subsidence is predicted 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. This is in accordance with measurements of 0.002-0.009 m/m specific subsidence taken at the W.O.P. (see arrow in Figure 3; Routschek, 1968).

Calculation Methods and Problems

In addition to the theoretical model, analytical, numerical and empirical methods can be applied to predict subsidence (Fenk, 1976; Helm, 1984; Gudgeon et al., 1988; Dassargues, 1995). Although good computer codes exist to predict surface subsidence (Acosta-Gonzales et al., 1988; Leak and Prudie, 1988; Hanson et al., 1990; Oostindie and Bronswijk, 1992; 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 and Leussink (1938) and Rudolf (1969), and will therefore not be described in detail here.

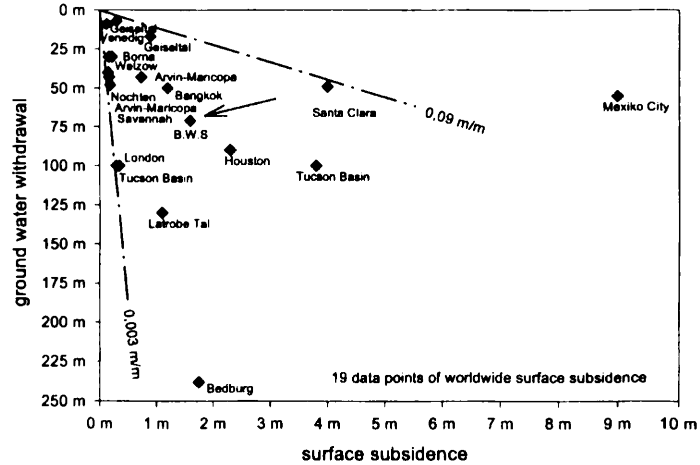

Figure 3. Comparison of ground water withdrawal and surface subsidence of different areas having a geological environment similar to this of the W.O.P. lignite mine (Gloe, 1979; Heydenreich, 1969; Holzer, 1984; Lofgren, 1975; Rasche and Fenk, 1987; Rathsmann, 1986; Routschek, 1968; Rudolf, 1969; Rudolf,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

Most models cannot handle soil parameters varying over time or within the sediments. Due to compaction, the porosity, the compressibility, or the conductivity, to name the significant parameters, of unconsolidated sediments do 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 numerical or analytical computations may sometimes differ from the amount of subsidence observed.

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

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

Data and Methods Used

Based on a simplified geological and hydrogeological model of B.W.S., the soil 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.

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 estimate, a 22-bed model with average values for thickness, compressibility and porosity was applied (Table 4). This 22-bed model was applied to the geological situation beneath the two buildings on the right side of Figure 1. The settlement s_i of each bed i was 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}:

$$s_i = \frac{h_i}{E_{v_i}} \cdot \Delta p_i \tag{1}$$

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 fluid's density γ_w, the porosity n, the loss of buoyancy $\Delta\gamma$ and the thickness of the dewatered bed h_i .

$$\Delta p_i = \Delta p_a + \sum_1^{i-1} \Delta p_e = \frac{\Delta\gamma_i \cdot h_i}{2} + \sum_1^{i-1} \Delta\gamma_j \cdot h_j \tag{2}$$

with:

$$\Delta\gamma = (1-n) \cdot \gamma_w \cdot h \tag{3}$$

The total of the surface subsidence s_g can then be calculated by adding the settlement s_i of all n beds above the aquifer's base:

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

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

RESULTS

The empirical estimates resulted in an average surface subsidence of 0.16 m for phase I and 0.36 m in phase II (Table 3). Differences in surface subsidence, which could cause damage to buildings, could not be predicted by this method due to the lack of data.

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.

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

Table 4: Geological model, soil mechanical parameters used, and results of the analytical estimates 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	20-30	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
Σ	–	125	–	–	113	161

CONCLUSIONS

The differences between the predicted average surface subsidence by empirical and analytical methods vary significantly (0.2-1.1 m for phase I; 0.5-1.6 m for phase II). The most likely reasons for these differences are: specific subsidence rates chosen are too low; the varying of soil parameters with time is important; or the sediments have been more highly compacted by glaciation than expected.

The data for calculating the specific subsidence begins in the late 1960's, and it can be assumed that the soils were at the beginning of their settlement at that time. The aquifers between the less permeable silts or clays would not have been fully dewatered then and the loss of buoyancy forces would be less than predicted by theory. Therefore, the specific subsidence rates used might be too low for extrapolations into the future.

On the other hand, the analytical results might be inaccurate. In that case, the varying of the soil parameters is more important 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 will not settle as much as analytically calculated, thus resulting in less surface subsidence.

By using all available data, including unofficial recent measurements of observed surface subsidence at B.W.S. (Wagenknecht, 1988, pers. comm.), 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 damage to engineering constructions, as long as they are built according to the German standards. Nevertheless, the fault line of the G.B.W. runs through B.W.S. For constructions that are close to or that cross this fault line of the graben, damages caused by vertical differences in surface subsidence cannot be excluded.

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