Use of the area of main influence to fix a relevant boundary for mining damages in Germany

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**A B S T R A C T**

In 2010, the fracking discussion in Germany caused a number of changes in German law, which came into force in 2016. Especially the production of gas had to be regulated. With the legislation amendment, the Subsidence-Area Mining Regulation has been revised, too. The changes expand the compensation of mining damages, especially to the extraction with drilling from the surface and underground storage. Although the Subsidence-Area Mining Regulation has been revised, the area of main influence (subsidence of 10 cm) remains to determine a relevant boundary for mining damages. The determination and prediction of this boundary above caverns are presented in this paper. In addition, further elements of ground movements and their relevance to mine damages are analyzed. The usage of the area of main influence to fix a relevant boundary for mining damages does not correspond to the relevant elements of ground movements. A limit for differences in subsidence (tilt) or horizontal changes in length should be preferred to describe the relevance of mining damages on buildings. Furthermore, this paper outlines the meaning of using the area of main influence to fix a relevant boundary for mining damages.

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1. Introduction

The Federal Mining Act forms the central legal standard to cover subsidence in Germany. The mining authority refers to the following regulations: the Subsidence-Area Mining Regulation, the Mining Surveyor Mining Regulation, and the Deep-Drilling Regulation [1-2].

Until the law, which generated changes in the Federal Mining Act and the Subsidence-Area Mining Regulation, had passed in 2016, the applicability of the Mining Subsidence Assumption was controversial regarding extraction by drilling from surface and caverns. The Subsidence-Area Mining Regulation did not consider either of them [3].

The Mining Subsidence Assumption contributes to support landowners within the area of main influence, if the landowner wants to claim damages. This support is called reversal of burden of proof. If the affected landowner can prove that: his property is inside the area of main influence, damage may be induced by mining, and damage is caused by ground movements (due to subsidence, extension, compression, soil tear, vibration), it is assumed that the damage is caused by the mining operation. In this particular case, the mining company has to prove that the damages are not mining-induced. Outside the area of main influence and without this regulation, the landowner has to prove that the damage is mining-related [4].

According to the Federal Mining Act, the Subsidence-Area Mining Regulation specifies the way to determine the mining-influenced area.

A statement of why the area of main influence remains to determine a relevant boundary for mining damages in Germany can be taken by the reasoning of the law. It is referred in the original regulation [3]. The area of main influence was chosen for the “reversal of burden of proof” to support the landowner because there are no damages expected outside of this area. In addition, it was proven by measurements that the damage-relevant element tilt does not exceed 2 mm/m outside the area of main influence. For this reason, there was no need to use a further value to determine the relevance to mining damages [5]. This statement and its consequences are considered in this paper.

2. Amended subsidence-area mining regulation

On the one hand, the “Subsidence-Area Mining Regulation” covers an area with regard to the application of the “Mining Subsidence Assumption.” On the other hand, the approval of operating plans are also covered by this regulation [2].
3. Ground movements

The vertical and horizontal convergence of a cavern induces subsidence. The convergence depends on several parameters, such as the height and the geometry of a cavern, the pressure difference between the formation and the medium that is stored, the temperature, as well as the type of rock salt [8]. The subsidence of each cavern superposes to a total subsidence. The subsidence trough is flat and reaches some decimeters after an operating time of 10 to 15 years. After a while, it may reach a few meters [9].

3.1. Two examples for subsidence troughs above caverns

In 2015, the number of gas-stored caverns in Germany amounted to 260 in total [10]. The greatest gas-storage cavern field of the world is located in North Rhine-Westphalia in the north-western part of the Münsterland region [11]. In 2015, 76 caverns were stored with gas. The working gas volume of the caverns amounts to more than 3600 Mio m³. In addition, salt is extracted in more than 25 caverns; oil and helium (since 2016) are stored subordinately [10–12]. Monitoring shows that the highest convergence rates can be expected by the storage of gas (0.8%–1.6%) [11]. In 2013, the maximum subsidence was about 71 cm after an operation time of 41 years (gas storage since 1978). The increase of the subsidence trough amounts to 3 cm per year at the center of the trough [11,13].

In comparison to this, the gas-storage cavern field “Empelde” which is located in Lower Saxony consists of four gas-stored caverns with a working gas volume in amount of 136 Mio m³ [10]. The maximum subsidence amounts to 4.4 cm (2009) after an operation time by approximately 31 years (gas storage since 1981) [14]. As this example shows, subsidence of 10 cm is not reached by every cavern field.

Due to subsidence, other components of ground movements appear. As Table 1 shows, ground movements can be separated into vertical and horizontal components. The corresponding symbols and units are given, as well.

After finishing subsidence, only the point in the center of the subsidence trough is located underneath its original location. All other points of the subsidence trough moved in the direction of the focal point of working. The spatial displacement vector is more or less slanted towards the point of working, depending on the location of the point [9].

The graphical representation of the subsidence underground its original location, without regard to displacement, shows a picture of the subsidence curve. The first derivative gives the tilt curve. The maximum tilt appears at the point of inflection of the subsidence curve. The second derivative gives the curvature curve. The curvature is convex close to the subsidence border and concave above the mining area. The curve has four maxima [9].

Displacement and changes in length are horizontal components. The graphical representation of the displacement can be realized by drawing the determined displacement perpendicular above the center of the point distances. The difference of the displacement of two points yields the changes in length (extension or compression). Above the mining area, changes in length appear as compression, whereas, close to the subsidence border, they appear as extension [9].

Fig. 2 shows the graphical representation of ground movements. Within the German standard for strata and ground movements (DIN 21,917), the ground movements shown are referring to seam mining. On the left hand side, the vertical components are shown, while, on the right hand side, the horizontal components of ground movements are shown.

Table 1

<table>
<thead>
<tr>
<th>Vertical component</th>
<th>Horizontal component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidence $v_z$ (mm)</td>
<td>Displacement $v_x$, $v_y$, $v_z$ (mm)</td>
</tr>
<tr>
<td>Maximum subsidence $v_z$ Max (mm)</td>
<td>Maximum displacement $v_y$ Max (mm)</td>
</tr>
<tr>
<td>Tilt $v_x$ (mm/m)</td>
<td>Changes in length $v_x$ (mm)</td>
</tr>
<tr>
<td>Curvature $v_z$ (1/m)</td>
<td>Extension $v_z$ (mm/m)</td>
</tr>
<tr>
<td>Radius of curvature $v_xvv_z$ (m)</td>
<td>Compression $v_z$ (mm/m)</td>
</tr>
</tbody>
</table>

Note: Further components includes the subsidence factor, mined seam thickness, factor of main influence, and time factor.
4. Subsidence detection and theoretical principles of subsidence modeling above caverns

For extraction by drilling from surface and for the underground storage (caverns), altimetry is required for mining plans. The mining plans have to be updated every year.

Measurement precision is defined by the Mine-Surveyor Mining Regulation depending on the purpose. For the determination of the angle of draw and altimetry, the measurement precision of (Eq. (1)) may not be exceeded. The parameter \( d \) stands for the difference between two independent measurements. \( R \) stands for the simple measurement path in kilometers. For the determination of the angle of main influence, the difference between two independent measurements may not exceed (Eq. (2)).

\[
d = 3 \times \sqrt{R} \\
d = 5 \times \sqrt{R}
\]

Altimetry is required by the “Deep Drilling Regulation” for the storage of fluids and gases, as well (§ 44 BVOT).

Results can be used to determine the total subsidence. The difference between the zero measurement and the altimetry of the last measurement gives the total subsidence. After calculating, isolines of subsidence can be constructed by linear interpolation. This allows a depiction of the total subsidence, as well as the measured area of main influence and the area of mining subsidence graphically.

Subsidence above caverns, which are located in rock salt, is induced by the slow passing convergences instead of fracture mechanisms [14].

For subsidence modeling, different methods were presented in Germany in the past, like Dreyer, Walther and Weber, Sroka and Schober, and Kratzsch [16–19]. In practice, the method of subsidence modeling of Sroka and Schober is used for several cavern fields in Germany [14]. The subsidence modeling of Sroka and Schober contains the Gaussian function as the influence function to predict mining-induced subsidence. In the mathematical sense, this method is similar to the integration method of Knothe [7,20]. This Gaussian function as the influence function has been used for 60 years for subsidence prediction especially for coal mining [8].

Subsidence on surface can be predicted approximately for one cavern by the following Eq. (3) (in comparison to Fig. 3) [8,21]:

\[
s(r,t) = s_{\text{max}}(t) \cdot \exp \left( - \frac{\pi r^2}{R^2} \right)
\]

with \( s_{\text{max}}(t) \) maximum subsidence above the axis of the cavern at time \( t \)

For cylindric caverns (Eq. (4)):

\[
s_{\text{max}}(t) = \frac{a \cdot K(t)}{z_u - z_0} \cdot \tan^2 \beta
\]

where \( r \) is the distance between calculation point and axis of the cavern; the radius of main influence with \( R = \sqrt{z_0 - z_u \cdot \cot \beta} = \sqrt{R_o \cdot R_u} \); \( z_0 \) the depth of the top of the cavern; \( z_u \) the depth of the bottom of the cavern; \( K(t) \) the convergence volume at the time \( t \); \( a \) the propagation factor of the volume; and \( \beta \) the angle of draw by Knothe.

For storage caverns in rock salt, the propagation factor of the volume is \( a = 1 \). It means that the whole convergence volume, which occurs up to the calculation date, induces land subsidence. The angle of draw has to be determined on the basis of location. This angle refers to the geometric mean of the cavern.

The prediction of the other elements of ground movements are not considered, although it is necessary to predict them to calculate their possible impacts on the surface.

Fig. 4 shows a graphical comparison of the measured and modeled (modeling of Sroka and Schober) subsidence for a cavern field in North Rhine-Westphalia (2006). Both with measuring and prediction subsidence, the area of main influence can be determined and presented graphically. In summary, the ground movement can be predicted with a high reliability [8].
5. Ground movements and their relevance for mining damages at the surface

Ground movements have different impacts on objects at the surface. Table 2 gives an overview of the previously presented elements of ground movements and their possible impacts on objects at the surface. Buildings may be damaged because of changes in length (extension and compression), as well as curvature of the ground where the structure is located. Changes in length and curvature affect the building simultaneously. The use of buildings may be influenced by tilt. Subsidence, extension, or compression of the ground may cause damages on transport facilities and sewers. Subsidence may induce water logging and may have an impact on receiving water courses. In hilly mining areas, damages on buildings and transport facilities would be the most frequent. In flat areas, the most frequent damages probably occur because of the impact on receiving water courses [9].

Uniform subsidence does not cause static damages on buildings. However, mining damages can occur in form of flooded basements [22].

The knowledge about permissible stress on buildings is important because not every kind of stress on buildings causes damages. There are different ways in literature to determine the permissible stress [22]. One method is to classify (category 0–4) buildings depending on their characteristic building attributes (for example, length and usage of a building). Depending on their characteristics, permissible values of tilt, radius of curvature, and changes in length are given. Following this classification, urban development belongs to category 2. The limits of the ground movements are as follows: tilt = 5 mm/m, radius of curvature = 12 km, and changes in length (extension and compression) = 3 mm/m [23]. A lower limit for tilt of 2 mm/m has proven effective in practice [22]. It is proven that mining damages can occur outside the area of main influence [24]. The predicted maximum tilt for the cavern field in North Rhine-Westphalia (2069) and Lower Saxony (2060), including the assumptions made, do not exceed this limit [13,14].

### 6. Summary

The amended Subsidence-Area Mining Regulation the detection, and reliable theoretical modeling of subsidence (or the area of main influence) are presented in this paper. Subsidence of 10 cm is not reached by every cavern field. Further ground movements and their possible impact on objects at the surface are presented, as well. Subsidence can affect buildings indirectly. The extent and the rate of ground movements above caverns is significantly lower, compared to ground movements above coal mining. Regarding the prediction of tilt for the presented cavern fields, the tilt does not exceed 2 mm/m.

The aim of the amended Subsidence-Area Mining Regulation is to expand support for landowners in the mining areas with regard to extraction by drilling from surface and underground storage. The “reversal of the burden of proof” covers only the area of main influence. As presented in this paper, mining damages on buildings can occur primarily induced by tilt, curvature, and horizontal changes in length. Subsidence causes mining damages indirectly. In general, mining damages can also appear outside the area of main influence, especially in the case where it is difficult for a landowner to prove that damages are mining-induced. Although the

<table>
<thead>
<tr>
<th>Surface object</th>
<th>Subsidence</th>
<th>Tilt</th>
<th>Curvature</th>
<th>Displacement</th>
<th>Extension (friction/tension)</th>
<th>Compression (friction, earth pressure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential house</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Office block</td>
<td>(x)</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row of house</td>
<td>x</td>
<td>x concave</td>
<td></td>
<td>x</td>
<td>!</td>
<td></td>
</tr>
<tr>
<td>Machine shop</td>
<td>(x)</td>
<td>x</td>
<td></td>
<td>!</td>
<td></td>
<td></td>
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<tr>
<td>Furnace installation</td>
<td>x</td>
<td>!</td>
<td></td>
<td>x</td>
<td></td>
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</tr>
<tr>
<td>Coking plant</td>
<td>!</td>
<td>x</td>
<td></td>
<td>!</td>
<td></td>
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<tr>
<td>Blast furnace</td>
<td>!</td>
<td>x</td>
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<tr>
<td>Machinery</td>
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<td>x</td>
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<tr>
<td>Assembly line</td>
<td>x</td>
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<td></td>
<td>!</td>
<td></td>
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<tr>
<td>Rolling mill</td>
<td>!</td>
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<tr>
<td>Conveyor belt</td>
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<tr>
<td>Chimney</td>
<td>!</td>
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<tr>
<td>Rail line</td>
<td>x</td>
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<td>!</td>
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</tr>
<tr>
<td>Railway station</td>
<td>x</td>
<td>(x)</td>
<td></td>
<td>x</td>
<td>!</td>
<td></td>
</tr>
<tr>
<td>Road</td>
<td>(x)</td>
<td></td>
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<td>!</td>
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<tr>
<td>Canal</td>
<td>!</td>
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<td>!</td>
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</tr>
<tr>
<td>Lock</td>
<td>!</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>!</td>
<td></td>
</tr>
<tr>
<td>Bridge</td>
<td>x</td>
<td>(x)</td>
<td>x</td>
<td>!</td>
<td></td>
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<tr>
<td>Tramway</td>
<td>!</td>
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<tr>
<td>Underground railway</td>
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<td></td>
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<tr>
<td>Tunnel</td>
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<td>Pipeline</td>
<td>!</td>
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<td>!</td>
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<tr>
<td>Water main</td>
<td>!</td>
<td></td>
<td></td>
<td>!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sewer</td>
<td>!</td>
<td></td>
<td></td>
<td>!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas main underground electricity cables</td>
<td>!</td>
<td>Branch-off</td>
<td>x</td>
<td>!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field</td>
<td>!</td>
<td></td>
<td></td>
<td>!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meadow</td>
<td>!</td>
<td></td>
<td></td>
<td>!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>!</td>
<td></td>
<td></td>
<td>!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiving water</td>
<td>!</td>
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</tbody>
</table>

Note: x means the medium; (x) is slight; and ! is high sensitivity.
Subsidence-Area Mining Regulation was revised, the area of main influence (subsidence 10 cm) still defines the relevant boundary for mining damages for an affected landowner. The usage of the area of main influence to fix a relevant boundary for mining damages is not in the interest of the landowner. Because some operational plan procedures include the participation of landowners up to the subsidence border, it is difficult for them to understand why the “reversal of the burden of proof” is only limited to the area of main influence [24].

References