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Methods for the calculation of settlements due to ground-water lowering

Méthodes de calcul des tassements dûs au rabattement de la nappe

D.PLACZEK, Dr-Ing., Office of Prof. Nendza and Partner, Institute of Soil Mechanics and Foundation Engineering, Essen, FRG

SYNOPSIS: In this contribution, first of all the possible causes for the land subsidences occurring in case of ground-water lowerings are studied phenomenologically. In this, it is differed between the stress-dependent and stress-independent portions of deformation. On basis of theoretical principles, calculation models are developed being applicable for cohesive, non-cohesive and organic soils. Using such calculation models, it is possible to estimate the possible land subsidence and consequently also the possible settlements of structures.

1 INTRODUCTION

The question regarding the causes for land subsidences occurring in case of ground-water lowerings is studied scientifically almost since the beginning of this century and has been dealt with in trade literature. Therefore, the answer to this question is of technical as well as economic significance, the more as the alteration of the ground-water conditions does not only entail ground deformations, but also affects the recovery of ground-water, damages the vegetation and in particular also structures.

Table 1 elucidates the extent of land subsidences by giving some measuring results from literature, according to which the most important lowerings of the ground have been observed in California with an absolute value of approx. 3 m and in Mexico-City featuring an absolute value of approx. 6 m. Also the other territories which partly feature a very dense built-up area, by values up to approx. 1.5 m indicate the danger and risks to which the buildings are subject by such enormous deformations of the ground.

Table 1. Measurements published with regard to land subsidence on account of ground-water lowering

source	location	period	ground-water lowering [m]	type of soil	land subsidence		
					[mm]	[mm/m]	[mm/year]
BERGADO et al. (1987)	Bangkok	1986	6 - 9	clay, sand, gravel	70	10	50
BRAND/PAVEENCHAMA (1971)	Bangkok	1957-1967	15	clay, sand, gravel	900	60	90
CROCE (1975)	Holland	1950-1971	23	sand, clay	100	4	5
CROCE (1975)	Mesola (Po-Delta)	1950-1960	40	sand, silt, clay	1500	38	150
LOFGREN/KLAUSING (1969)	San Joaquin Valley, Kalifornien	1921-1960	34	silty sand, clay	3100	91	80
RICCERI/BUTTERFIELD (1974)	Venedig	1935-1972	10	sand, silt, silty clay	200	20	6
RUDOLF (1967)	Sächsisches Braunkohlenrevier	1950-1962	31	sandy gravel, lignite	715	23	60
VARNHAGEN (1967)	Rheinisches Braunkohlenrevier	1955-1965	300	sand, gravel, clay, lignite	400	1 - 2	40
WILSON/GRACE (1942)	London	1848-1931	40	clay, sand	190	5	2
ZEEVAERT (1953)	Mexiko City	1877-1952		silty clay, sand	6100		80
ZEEVAERT (1953)	Mexiko City	1945-1952	4	silty clay, sand	93	23	30

The movements at the ground surface are defined by the local and temporal progress of the lowering of the ground-water level and by the alterations of the stress level, of the water regime and of other soil-physical and chemical marginal conditions caused hereby. In case of a lowering of the ground-water level soil deformations may generally be caused by:

1. alterations of stress in the soil
2. shrinkage of cohesive soils
3. chemical and/or biological decomposition of organic soils and by
4. alterations in the water regime of the soil on account of vegetation.

Whilst the first cause is defined exclusively by the external state of stress of the soil, the other causes are nearly independent of the external stresses.

To begin with, these causes are studied phenomenologically hereinafter. In order to determine possible land subsidence calculation models are developed on basis of theoretical principles which hereinafter are summarized.

2 LAND SUBSIDENCE ON ACCOUNT OF EXTERNAL STRESS ALTERATIONS

2.1 Calculation models for the stationary condition

For the calculations regarding the stationary condition it is assumed that the lowering of the ground-water level is followed immediately by land subsidence. The lowering of the ground-water level causes an alteration of stress in the soil leading to a compression of the individual soil layers and consequently to settlements at the ground surface.

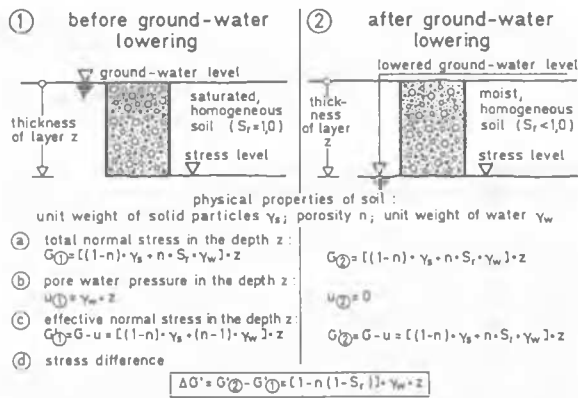


Figure 1. Alteration of stress upon lowering of the ground-water level

The alteration of stress is a reduction of the pore water pressure u by the amount of the lowering so that the effective normal stress σ' is increased (Figure 1). This increase of the effective normal stress by the amount $\Delta \sigma'$ corresponds to an increase of weight of the drained soil.

$$\Delta \sigma' = [1 - n(1 - S_r)] \cdot \gamma_w \cdot z \quad (1)$$

The individual definitions may be taken from Figure 1.

The vertical compression resulting from this additional stress is generally defined by means of the linear-elastic stress-deformation relation. For simplification the soil is assumed to be a homogeneous, isotropic and fully elastic medium. On such basis, the settlement at the ground surface results as

$$s = \frac{1}{E_s} \cdot \int_0^z \Delta \sigma' \cdot dz \quad (2)$$

The modulus of elasticity (or: Young's modulus) in this corresponds to the stiffness modulus E_s (or: oedometric modulus) of the soil, itself being stress-dependent, and which increases under increasing pressure so that the equation (2) represents a pseudo-elastic approach.

In view of the difficulties in differentiating adequate laws of substances (Gudehus 1981) the above approach appears to be acceptable if essential influencing factors like e.g. capillarity, type of subsidence etc. are taken into consideration. The stress-dependence of the oedometric modulus E_s can be integrated in equation (2) via the pressure - void ratio diagram (Figure 2) as follows

$$s = \int_0^z \frac{C_c}{(1 + e_0)} \cdot \log \left(1 + \frac{\sigma'_z}{\sigma'_0} \right) \cdot dz \quad (3)$$

with C_c as compression index corresponding to the inclination of the pressure-void ratio graph, and with the parameters before lowering of the ground-water level e_1 and σ'_1 .

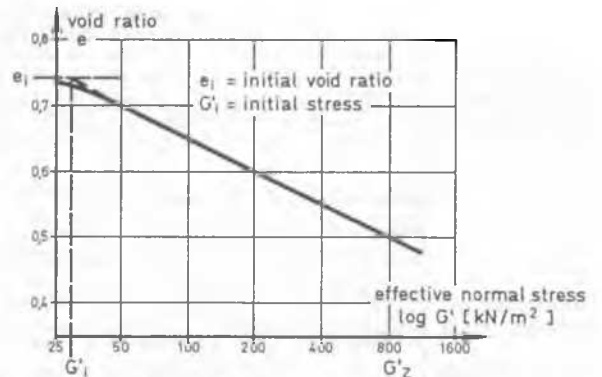


Figure 2. Pressure - void ratio - diagram

The temporal progress of settlement is estimated as a rule according to the one-dimensional theory of consolidation.

2.2 Calculation model for the non-stationary condition

Contrary to the assumption that the lowering of the ground-water level be uniform and stationary, it has been found out by measurements

(e.g. Heydenreich 1969, Lofgren/Klausing 1969 and others) that neither the lowering of the ground-water level nor the possibly following land subsidence are stationary processes. That is why the approaches presented so far have to be considered as rough approximations only.

It is, therefore, absolutely necessary for an appropriate description of the processes to recognize first of all the lowering of the ground-water level in relation to time and space. If the progress of ground-water level lowering and land subsidence are affine to each other (Figure 3), which can be evidenced by measurements, then an alteration of stress $\Delta\sigma'$ can be allocated to each alteration in ground-water level. If $\Delta\sigma'$ is known it will be possible via the usual stress-deformation-relations of the soil to define the value of the land subsidence as well as its temporal progress using the consolidation theory.

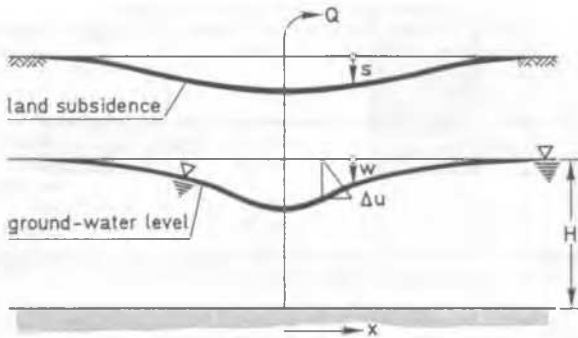


Figure 3. Affine progress of land subsidence s and lowering of ground-water level w

For the local (x) and temporal (t) alteration of the ground-water level in case of a radial-symmetric well flow, Theis (1935) has established basic equations for the perched ground-water table for which Maeckelburg (1965) has given a mathematically strict derivative of the space-time equation as follows

$$w(x, t) = \frac{Q}{4 \pi \cdot k \cdot H} \cdot \ln \left[\frac{2,25 \cdot t \cdot k \cdot H}{x^2 \cdot n'} \right] \quad (4)$$

with the definitions k being the coefficient of water permeability [m/s], H as constant thickness of the aquifer [m], Q as volume of water discharged resp. delivered [m³/s] and n' as drainable porosity. Corresponding approaches exist for the free ground-water table.

Under consideration of equation (1) the alteration of stress causing deformation results as follows

$$\Delta\sigma' = [1 - n(1 - S_r)] \cdot \gamma_w \cdot w(x, t) \quad (5)$$

in which any optional degrees of saturation S_r of the soil are above the lowered ground-water level can be taken into consideration.

Basing on equation (2) the land subsidence may then be defined from the relation

$$s = \frac{1}{E_s} \int_0^z \left\{ [1 - n(1 - S_r)] \cdot \gamma_w \cdot w(x, t) \right\} dz \quad (6)$$

to which the same restrictions apply as mentioned under item 2.1.

2.3 Influence by capillarity

On account of the lowering of the ground-water level, the pore water withdraws into the interior of the soil. At the interface between solid matter, air and water the surface tension of the pore water is produced hereby which means an additional stress on the granular skeleton via the so-called capillary pressure p_k . The capillary pressure p_k can be defined as a function of the capillary elevation h_k .

$$p_k = h_k \cdot \gamma_w \quad (7)$$

To differently saturated soil areas above the lowered ground-water level applies

$$p_{k,i} = n \cdot S_{r,i} \cdot h_{k,i} \cdot \gamma_w \quad (8)$$

According to Figure 4, the capillary pressure may thus be defined if the distribution of the saturation of water $S_{r,i}$ is known. In particular in case of flat lowerings near the surface, the influence of capillarity must not be neglected.

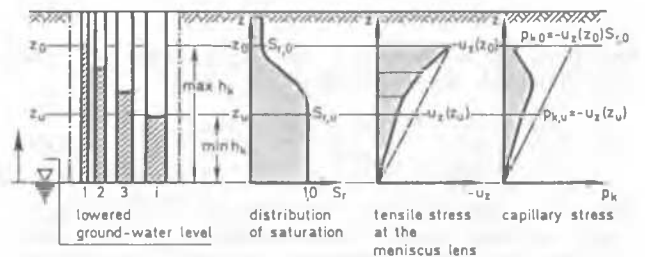


Figure 4. Determination of the capillary pressure as a function of the distribution of water saturation $S_{r,i}$

3 LAND SUBSIDENCE ON ACCOUNT OF SHRINKAGE

3.1 Theoretical principles

A lowering of the ground-water level may cause a drying of cohesive soils leading to a reduction of volume on account of the decrease of water content. This is caused by the capillary forces.

The decrease of water content presupposes an evaporation of the pore water at the stratum end of the cohesive soil. An evaporation of the pore water will be possible only on the condition that there is no steam saturation of the adjacent pore air resp. environmental air.

3.2 Calculation model under consideration of the natural marginal conditions

As shown by studies (Placzek 1982), this essential prerequisite is fulfilled only if

- a. the cohesive, shrinkable stratum is covered by another cohesive stratum, or
- b. if a non-cohesive covering stratum features a water content of less than 5 %, or
- c. if the cohesive, shrinkable stratum occurs directly at the ground surface.

In these cases and knowing the water regime of the soil the deformation by shrinkage can be determined as per Figure 5.

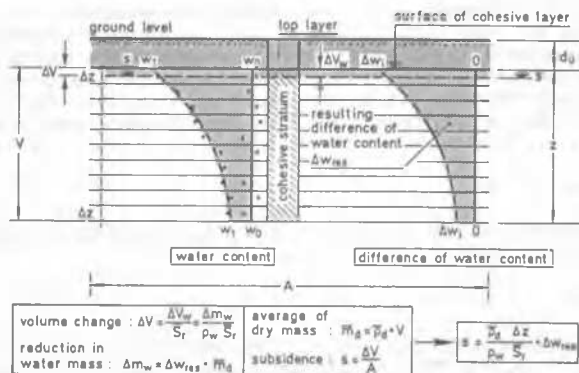


Figure 5. Determination of the deformations by shrinkage by observing and recognizing the water content prevailing in the system of strata

Equation (9) represents an approximation for the uniaxial deformation

$$s = \frac{\bar{\rho}_d}{\bar{S}_r \cdot \rho_w} \cdot \Delta w_{res} \quad (9)$$

with $\bar{\rho}_d$ and \bar{S}_r as mean density of dry soil resp. as mean degree of saturation, ρ_w as density of the water and Δw_{res} as resulting difference of water content.

4 LAND SUBSIDENCE ON ACCOUNT OF CHEMICAL AND BIOLOGICAL DECOMPOSITION

4.1 Theoretical principles

On account of the lowering of the ground-water level, air resp. oxygen will penetrate into the soil which in case of organic soils may lead to alterations of volume and consequently to land subsidences. This is evoked by a biological and/or chemical decomposition of the organic substance and is influenced essentially by the temperature.

For an all-chemical reaction temperatures of more than 85° C are required whilst the biological reaction requires soil temperatures of 0° C to 80° C (McKinney 1962). With the temperatures prevailing in the ground, the biological decomposition will be the main cause for possible additional percentages of ground deformation. It is due to the biological transmu-

tation of the organic substance by microorganisms. Depending on whether oxygen is required for such transmutation it is differentiated between aerobic and anaerobic decomposition.

4.2 Calculation model

The chemical and/or biological decomposition exclusively means transmutation of the organic substance. The mineral portion is not affected hereby.

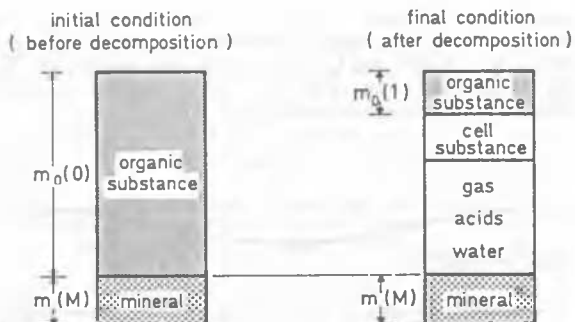


Figure 6. Initial and final state of the decomposition process

Consequently, a possible loss of mass is a loss of mass of the organic substance only. Figure 6 shows how to determine the maximum of a possible land subsidence. Before decomposition, the mass of the organic substance is $m_o(0)$, which on account of the transmutation after decomposition has decreased by the portion of gases, acids and water released to achieve a mass value of $m_o(1)$. The respective rate of decomposition is

$$z = \frac{m_o(0) - m_o(1)}{m_o(0)} \quad (10)$$

and the possible land subsidence is

$$s_o = \frac{z \cdot m_o(0)}{\bar{\rho} \cdot A} \quad (11)$$

with A as cross-sectional area taken into consideration and $\bar{\rho}$ as mean density.

5 LAND SUBSIDENCE ON ACCOUNT OF VEGETATION

5.1 Theoretical principles - Phenomenon

Especially during the vegetation period - i.e. the months from May to September in Middle Europe - a dehydration occurs in the upper strata of the soil via the root system of plants and trees. Such dehydration may lead to land subsidence if the ground-water level has been lowered to such extent that a sufficient moisture can no longer be supplied through the capillary system.

5.2 Possibilities for an estimation of the deformations

Alterations in humidity of soil on account of vegetation are limited to the upper soil areas and to the restricted sphere of influence of plants and trees.

According to recent studies (Biddle 1983), depths and extents of influence for species of trees featuring the highest dehydration capacity can be indicated according to Table 2 from which results that poplars show the largest depth and extent of influence.

Table 2. Mean depths and extents of influence of various species of trees (Biddle 1983)

Species of tree	mean influence depth [m]	mean extent resp. range of influence [m]
poplar	3,50	25
lime	2,00	15
horse chestnut	1,50	12
birch	1,50	10
cypress	1,50	8

Basing on these numerical values, land subsidence may be excluded in case of larger distances between the trees and minor lowerings of the ground-water level than indicated above as influenced depths. On the otherhand, ground deformations by area are limited to the indicate sphere of influence. In case of possible land subsidence in clay soils achieving several decimeters (Biddle 1983) very small radii of curvature of the subsidence curve and consequently a higher stress on structures must be expected.

6 CONCLUSIONS

Causes for the land subsidence occurring in case of a lowering of the ground-water level may be the following:

1. alteration of stress in the soil
2. shrinkage of cohesive soils
3. chemical and/or biological decomposition of organic soils and
4. dehydration of soil by plants and trees.

Although the determination of the individual percentages of land subsidence will be difficult on account of the multitude of factors influencing and affecting each other, as may be seen from the calculation models, the risk of possible land subsidences may well be estimated appropriately considering the prevailing causes and reasons.

The flow diagrams shown in Figure 7, 8, 9 and 10 allow a reliable assessment of the danger potential of a land subsidence caused by lowering of the ground-water level.

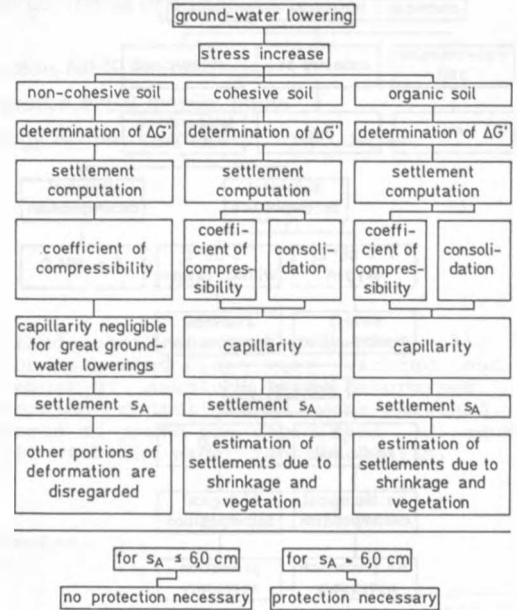


Figure 7. An assessment of the danger and risk of possible land subsidence s_A on account of alterations of stress

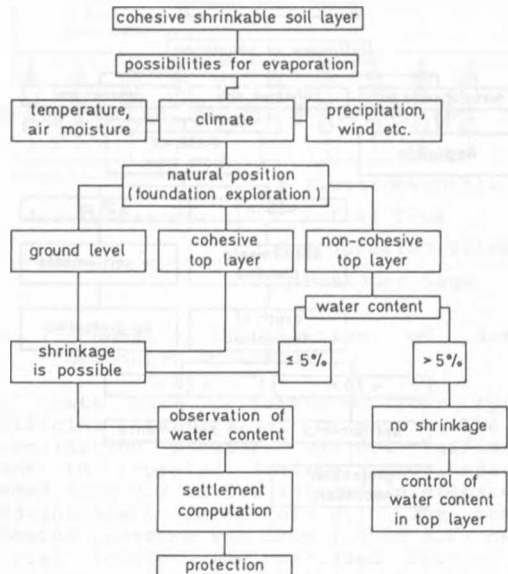


Figure 8. An assessment of the danger and risk of possible land subsidence s_s on account of a shrinkage of cohesive soils

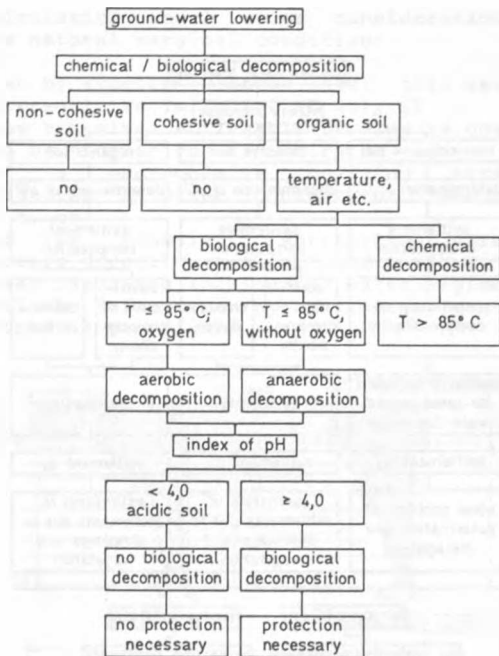


Figure 9. An assessment of the danger and risk of possible land subsidence s_0 on account of a chemical and/or biological decomposition

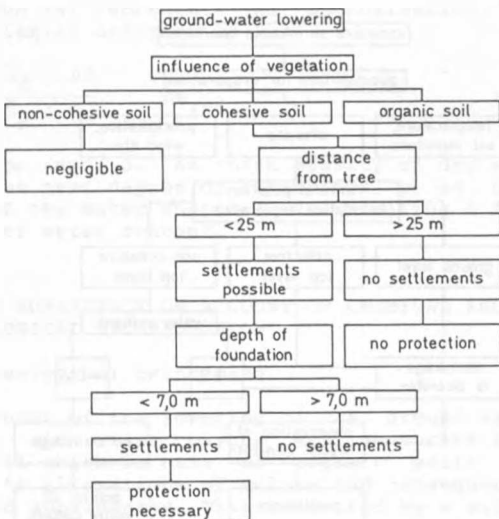


Figure 10. An assessment of the danger and risk of possible land subsidence s_v on account of vegetation

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