# Explanatory note on the link chain between surface-water level change and building damage risk

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# Preamble

This document presents a concise overview of the cause-effect link chain between surface water level (SWL) change and building damage risk. The document is prepared in the framework of the ‘Kennisprogramma Effecten Mijnbouw’, project KEM16b, at the request of the ministry of economic affairs and climate (Dutch: EZK).

Surface water levels in the Netherlands are managed in a system of fixed water level areas, water courses, locks, weirs, and pumping stations. Occasionally, surface water levels are lowered or raised for construction purposes or to meet changing water management requirements. If conditions are unfavorable and insufficiently controlled, these SWL changes may cause groundwater level changes, which can contribute to damage of houses and other buildings. In the province of Groningen and elsewhere in the Netherlands, mining activities such as gas or salt production from deep subsurface layers, have also caused or still cause SWL changes. The SWL can rise or fall slowly relative to the land due to land subsidence caused by the mining, posing a potential damage risk. To mitigate these risks, SWL’s often are periodically adjusted. However, SWL change due to mining subsidence cannot be totally prevented. Building damage (risk) due to SWL change, therefore, requires attention in many circumstances and due to various activities, including (deep) mining (Deltares, 2021)[1].

With increasing concern for and interest in building damage in The Netherlands, there is a growing need for accessible information on all aspects of building damage among a wide range of stakeholders. The role of SWL change is one of them. This document aims to provide both a comprehensive and comprehensible overview of knowledge of the topic. To convey the information, technical jargon cannot be totally avoided. However, an attempt has been made to keep it minimal, to include explanatory graphics, and to explain terminology. For more extensive descriptions of cause-effect relationships bearing on building damage in The Netherlands, the reader is referred to chapter 3 in part 2 of Rli (2024; in Dutch).

[1] This effect of mining is referred to as an indirect effect of deep subsidence (IEDS; Dutch: IEDB; Deltares (2021) report 11207096). In the Groningen area the role of SWL change is being addressed by the Institute Mijnbouwschade Groningen in addition to damage by earthquakes due to gas production.

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# 1 Link chain SWL lowering – building damage

## 1.1 Overview link chain

This chapter elucidates the ways in which surface water level (SWL) lowering can contribute to building damage. Figure 1 depicts the link chain components and the links. Figure 2 elucidates the hazards listed in component 3 of the link chain.

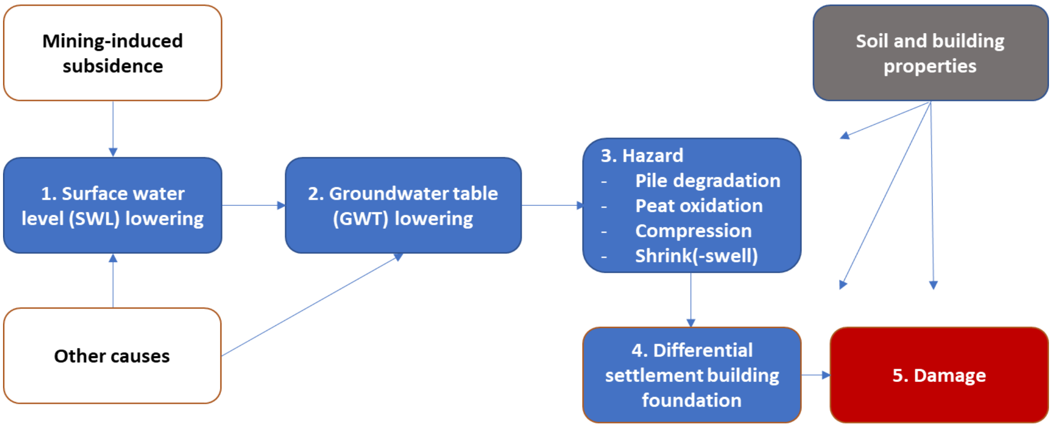



*Figure 1 Components (numbered) and links (arrows) of the link chain between surface water level lowering (component 1) and building damage (component 5). Various activities (white) can cause SWL lowering.*

SWL lowering has the potential to cause groundwater table (GWT) lowering (e.g., Deltares (2021), paragraph 2.4). The link between them is not detailed in this note. GWT lowering may cause various hazards, that are described in the next paragraph. The hazards may cause differential settlement of the building foundation, thereby contributing to potential damage. The risk of damage does not only depend on the magnitude of GWT lowering at the building, but also on soil conditions and building properties. Chapter 3 elaborates further on 'damage'.

## 1.2 Hazards related to SWL lowering

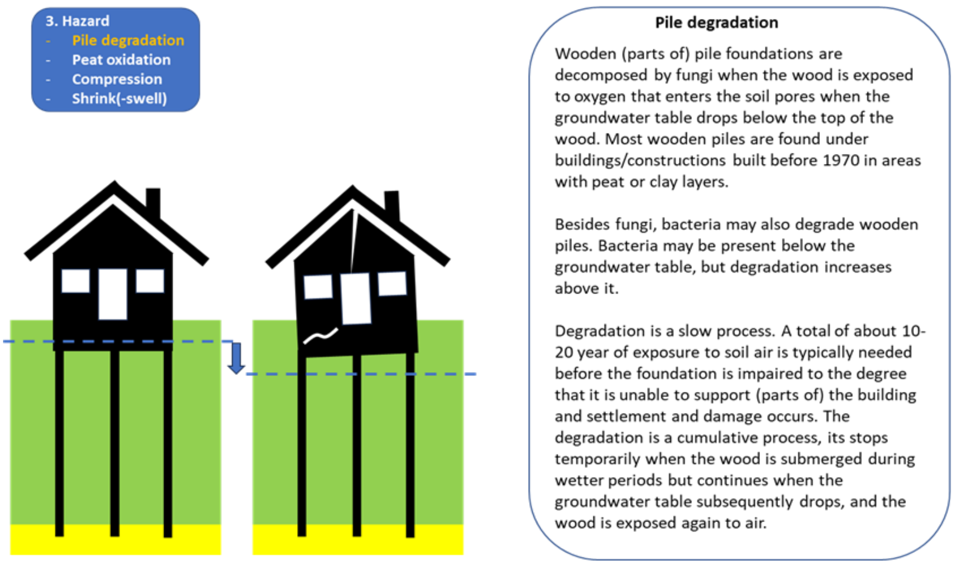
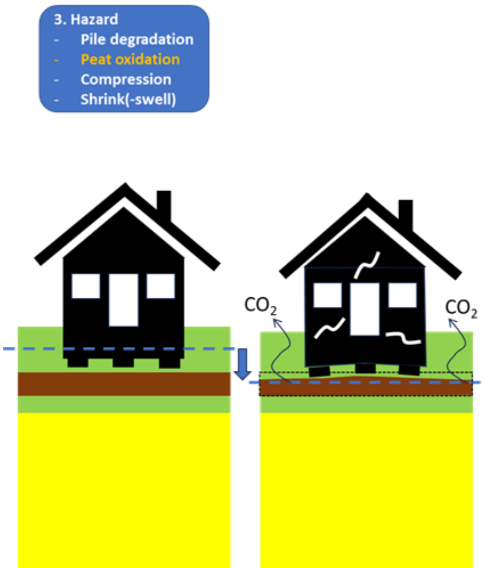



*Figure 2 Clarification of the hazards listed in component 3 of the link chain for SWL lowering (Figure 1).*

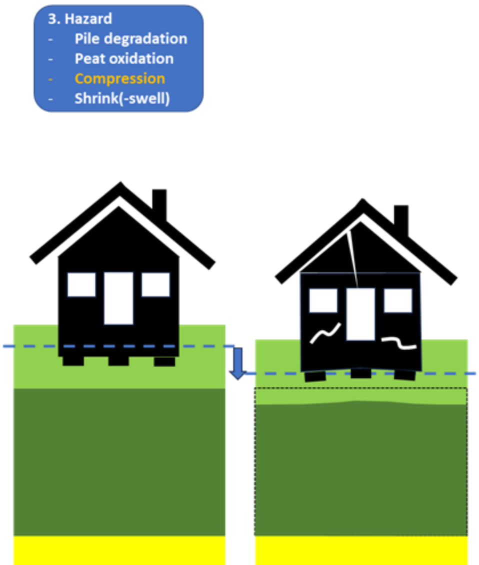



**Peat oxidation**

Peat layers contain abundant dead organic (plant) material. When the groundwater table drops so that oxygen can enter the peat, the plant material oxidizes (is consumed by fungi and bacteria). The thickness of the peat layer decreases as the organic material is largely converted to water and $CO_2$ (gas).
When peat oxidizes underneath a building with a shallow foundation, the building will settle. Differential settlement may lead to structural damage of the foundation and superstructure (above ground parts of the building).

Most of the peat loss and settlement may take many years to complete. The process may also be slow when the groundwater lowering develops slowly.

Buildings founded above shallow peat layers are rare. The peat is usually excavated, and the building founded on deeper, less soft soil. However, shallow peat occasionally occurs underneath older buildings, notably on dikes, and underneath building extensions, stables, barns and sheds.

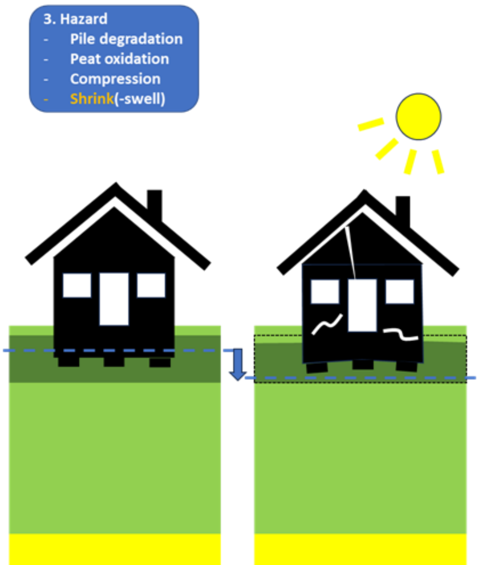



**Compression**

Clay and/or peat layers (dark green) that are present below the groundwater table can compress when the groundwater table is lowered. Part of the groundwater is squeezed from the layers and the solid parts are pushed closer together. The thickness of the layers decreases (compacts).
When this occurs underneath a building with a shallow foundation, the building will settle. Differential settlement may lead to structural damage of the foundation and superstructure (above ground parts of the building).

Part of the compression and settlement in response to groundwater table lowering can be smeared out over decades and therefore develops very slowly. The process may also be slow when the groundwater lowering develops slowly. The construction of the building itself initially also caused settlement.

In case of pile foundations, the soil compression causes the soil to slide down along the pile. This reduces the friction support of the pile (development of negative skin friction) and may cause additional pile and thus building settlement.




**Shrink(-swell)**

When the groundwater table is lowered, the soil above the groundwater table becomes drier. Clay usually responds to drying by shrinkage (volume reduction due to water loss above the groundwater table).
When this occurs underneath a building with a shallow foundation, the building will settle. Differential settlement may lead to structural damage of the foundation and the superstructure (above ground parts of the building).

Shrinkage of clay is mostly reversible: when the clay is subsequently wetted, it typically swells back to the original volume. This causes uplift of the building. Some shrink and swell and associated settlement and uplift of buildings with the seasons and weather conditions is normal (the groundwater table also varies with seasons and weather conditions). Buildings on shallow foundations can usually withstand 'normal' shrink-swell movements. SWL lowering may contribute to damage development when it causes the drying and shrinkage movement to exceed 'normal' values.

*Figure 2 (continued from previous page).*

# 2 Link chain SWL rise – building damage

## 2.1 Overview link chain SWL rise

This chapter elucidates the ways in which surface water level (SWL) rise can contribute to building damage. Figure 1 depicts the link chain components and the links. Figure 4 elucidates the hazards listed in component 3 of the link chain.

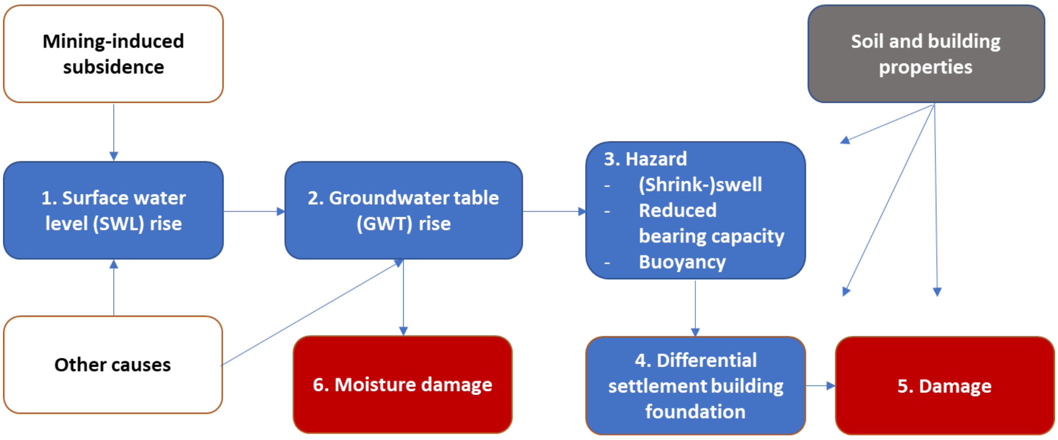



*Figure 3 Components (numbered) and links (arrows) of the link chain between surface water level rise (component 1) and building damage (component 5) as well as moisture damage (component 6).*

SWL rise has the potential to cause groundwater table (GWT) rise (e.g., Deltares (2021), paragraph 2.4). The link between them is not detailed in this note. GWT rise may cause various hazards, as described in the next paragraph. The hazards may lead to differential settlement of the building foundation, thereby contributing to damage. The risk of damage does not only depend on the magnitude of GWT rise at the building, but also on various soil conditions and building properties. In addition to structural damage (e.g., cracks or tilting of the building) by differential settlement, GWT rise can also cause moisture damage. Chapter 3 elaborates further on moisture and settlement damage.

## 2.2 Hazards SWL rise

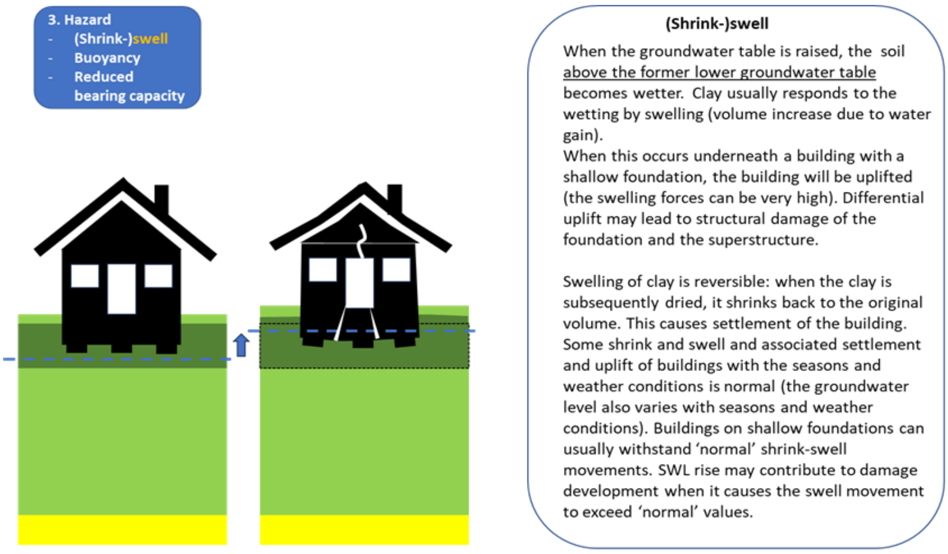
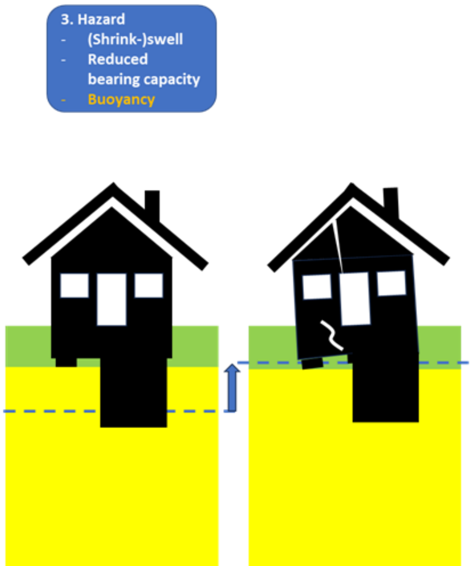



*Figure 4 Clarification of the hazards listed in component 3 of the link chain for SWL rise (Figure 3).*


**Reduced bearing capacity**

When the groundwater table is raised, the saturated soil can lose strength. This means that the bearing capacity of the soil is reduced. When this occurs underneath a building with a shallow foundation, and the soil was close to its bearing capacity, the building may settle ('sink into the soil'). Differential settlement may lead to structural damage of the foundation and the superstructure of the building.




**Buoyancy**

An 'empty' (and watertight) subsurface space such as a basement, experiences an upward force due to the groundwater pressure at its base. When the groundwater table is raised, this upward force is increased. The basement then has the tendency to 'float up' (Archimedes' principle). When the basement supports part of the building, it may lift the building unevenly, thereby potentially causing structural damage of the foundation and the superstructure of the building.
Empty outdoor swimming pools also are susceptible to damage by a raised groundwater table.

*Figure 4 (continued from previous page).*

# 3 Settlement damage and moisture damage

## 3.1 Damage due to differential settlement of the building foundation

Damage to buildings due to deformations of the foundation manifests itself in the form of rotation or the appearance of cracks. The superstructure (the part of the building above the foundation) will adjust to deformations of the foundation and will therefore also deform. This causes tension in the material of the building structure. If these stresses exceed the strength of the building material, the material will begin to crack. Damages manifest over time and usually develop gradually. The damage is usually noticed when there are visible cracks. This often means that the underlying cause has been present for some time and the process that causes the damage has been active for some time.

The extent to which the imposed deformation is uneven determines the severity of damage to the superstructure. If a foundation settles evenly and does not deform further, no tensions will arise in the structure above and therefore no damage. The extent to which a building is vulnerable to foundation damage is determined by both the properties of the foundation and the superstructure.

## 3.2 Moisture damage

Besides cracks, damage may also present itself in the form of moisture related problems, when the groundwater table rises relative to the building. Buildings closer to the groundwater may result in flooded cellars, rising damp (damage to wooden floors and walls) and mold. Low-lying buildings are also extra sensitive to flooding from the street if surface water (for example due to heavy rain showers) cannot drain away properly.

Rising damp means that groundwater is absorbed by the walls (through cracks and crevices). This can penetrate directly from the groundwater into the walls, or indirectly via a damp basement or crawl space. A flooded crawl space can occur if it is not properly moisture-proof and is permanently or temporarily (partly) below the groundwater table. In addition to physical damage to plasterwork and wooden floors, rising damp can lead to excessive humidity in the home: this is bad for the respiratory tract and, in the worst case, can lead to harmful mold.

# 4 Guidelines for quantitative assessment of the chain links

## 4.1 SWL change and settlement-induced damage

Attribution of settlement-induced damage to SWL change or assessment of damage risk due to SWL change requires quantitative assessment of chain links (Figure 1 and Figure 3):

Chain link 1: GWT change (at the building location) due to SWL change (components 1→2)
Chain link 2: The hazards associated with the GWT change; which ones apply, and which ones can be ignored? (components 2→3)
Chain link 3: Differential settlement (or uplift) due to the GWT change for each distinguished hazard (components 3→4)
Chain link 4: Damage due to differential settlement (components 4→5)

<u>Chain link 1</u>
For chain link 1, GWT change due to SWL change, no formal guidelines exist. In 1987, the Commission Subsidence due to Gas extraction (CBA,1987) introduced Table 1 that served/serves as a rough-and-ready rule. The table pertains to SWL lowering and resulting GWT lowering only. Within the *Kennisprogramma Effecten Mijnbouw* (KEM 16b), efforts are underway to generate updated tables. Various approaches may be applied to try to infer GWT change due to a known or estimated SWL change from GWT measurements. However, usable measurements are rare, and uncertainty is generally high.

*Table 1 Relationship between ditch level lowering and groundwater table lowering from CBA (1987). The entries are based on model calculations. The meaning of the second 'clay' entry is unclear. The ratio of groundwater table and ditch level lowering is presumed to apply to other magnitudes of SWL lowering as well.*

| Soil type | Ditch level lowering (m) | Groundwater table lowering (m) |
|---|---|---|
| **Clay** | 0.20 | 0.05-0.10 |
| **Peat** | 0.20 | 0.10 |
| **Sand** | 0.20 | 0.10-0.15 |
| **Clay (?)** | 0.20 | 0.20 |

<u>Chain link 2</u>
For chain link 2, hazards associated with GWT change, also, no formal guidelines exist. Judgement largely depends on 'common sense'. Evidently, pile degradation can be ruled out in case of shallow foundations or concrete piles. Similarly, buoyancy need not be considered in the absence of basements. Peat oxidation can be ruled out if peat does not occur underneath the building, or only at levels deeper than the deepest GWT. And shrink-swell can be ignored if the soil between the deepest GWT and the foundation of the building are void of clay. Table 2 was introduced in the 1980's (CBA, 1987) to serve as a rough-and-ready rule to decide that a damage contribution from GWT lowering is negligible. It should be emphasized that the tabulated values were based on model calculations involving the hazard 'compression' only.

*Table 2 Rough-and-ready rule to rule out a damage contribution from GWT lowering (CBA, 1987). The entries are based on model calculations considering the hazard 'compression' only. GLG is the multi-annual mean lowest GWT.*

| Soil predominantly consisting of | Allowable 'GLG' lowering |
|---|---|
| Sand | 0.24 |
| Clay | 0.10 |
| Peat with clay cover | 0.07 |

<u>Chain link 3</u>

For chain link 3, calculation of (differential) settlement due to GWT change for specific hazards, information on formal and less formal guidelines is summarized in Table 3. The most comprehensive guideline pertains to compression-induced settlement due to GWT lowering. However, this guideline still leaves room for various choices. Differences in outcome or judgement by different experts, therefore, cannot be avoided.

*Table 3 Overview of formal guidelines and less formal guidance for calculation of (differential) settlement due to GWT change.*

| Hazard | Foundation type | Formal guideline |
|---|---|---|
| **SWL/GWT lowering** | | |
| Degradation wooden pile foundation | wooden pile | None. Guidelines do exist to judge the quality of the foundation and if the 'current' groundwater level provides sufficient safety to prevent/limit wood degradation (NEN8707; F3O). |
| Peat oxidation | shallow | None. |
| Compression | shallow | NEN9997 (Geotechnical design of structures; general rules). The guidelines for calculation of settlement due to the load of the construction provide a logical basis for calculating settlement caused by GWL lowering, where the equivalent load of the latter is applied. |
| Shrink(-swell) | shallow | None. At present shrinkage due to GWL lowering is not quantified separate from compression. In NEN9997 paragraph 6.5.5 it is stated "In expansive soils (= shrink-swell prone), the potential of uneven swelling should be judged and the foundation of (a new) construction should be designed to be able to withstand the deformations". |
| **SWL/GWT rise** | | |
| (Shrink-)swell | shallow | See Shrink(-swell) |
| Reduced bearing capacity | shallow | None. |
| Buoyancy | Shallow + basement | None. However, the (excessive) force on the building caused by a raised GWL (relative to a reference high GWL the building was designed for) can be readily calculated (NEN9997 paragraph 10.2) |

<u>Chain link 4</u>

For chain link 4, the assessment of damage caused by differential settlement of the foundation of a building, no formal guidelines (e.g. via the Royal Netherlands Standardization Institute, NEN) exist. However, in practice, the British approaches are generally applied (Burland, 1977; Boscardin and Cording, 1989). In these approaches, damage is classified, based on the number and size of cracks (Table 4). Measures of the differential settlement (deformation of the foundation) are linked to the damage classes. The system is set up for masonry buildings. In The Netherlands the system is used to quantify effects of settlement damage related to the construction of excavations F530 guideline (COB, 2012). Older guidelines specifically for the effects of groundwater changes (SBR, 1992) are also still used in practice.

*Table 4 Classification of visible damage (Burland et al., 1977, slightly modified by BRE, 1995)*

| Category of damage | Normal degree of severity | Description of typical damage<br>Ease of repair in italic type |
|---|---|---|
| **0** | Negligible | Hairline cracks of less than about 0.1 mm |
| **1** | Very slight | Fine cracks which can be treated easily using normal decoration. Damage generally restricted to internal wall finishes; Close inspection may reveal some cracks in external brickwork or masonry.<br>Typical crack widths up to 1 mm. |
| **2** | Slight | Cracks easily filled. Redecoration probably required. Recurrent cracks can be masked by suitable linings. Cracks may be visible externally and some repointing may be required to ensure weather-tightness. Doors and windows may stick slightly.<br>Typical crack widths up to 5 mm. |
| **3** | Moderate | Cracks which require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Weather-tightness often impaired.<br>Typical crack widths 5 -15 mm, or several > 3 mm. |
| **4** | Severe | Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably*. Walls leaning or bulging noticeably*, some loss of bearing in beams. Service pipes disrupted.<br>Typical crack widths 15 - 25 mm, but also depending on the number of cracks. |
| **5** | Very severe | Structural damage which requires a major repair job, involving partial or complete rebuilding. Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability.<br>Typical crack widths are greater than 25 mm but depends on number of cracks. |

* Local deviation of slope, from the horizontal or vertical, of more than 1/100 will normally be clearly visible. Overall deviations more than 1/150 are undesirable.

## 4.2 SWL rise and moisture damage

Attribution of moisture damage to SWL rise or assessment of moisture damage risk due to SWL rise requires quantitative assessment of two chain links (Figure 3):

1. GWT rise (at the building location) due to SWL rise (components 1→2)
2. Damage due to the GWT rise (components 2→6)

<u>Chain link 1</u>
For chain link 1, GWT rise due to SWL rise, no formal guidelines exist. Because the GWT normally fluctuates with the seasons, the wet season GWT rise evidently is most relevant. And since high GWT's often are controlled by artificial drainage systems such as pipe drains, a rise of the high GWT will usually require deteriorated efficiency of these systems.

The causes behind the GWT rise of course differ: settlement of the building with constant GWT, increasingly wet conditions, deteriorating pipe drains. Also, replacement of leaky sewage systems is a notorious cause of GWT rise.

Chain link 2

For chain link 2, moisture damage due to the GWT rise, no formal guidelines have been found. However, as a rule of thumb, damage needs to be considered if the GWT reaches < 60 cm from the floor level.  Whether and to what extent moisture damage actually occurs depends on the quality of the building.

If the GWT exceeds the floor level, this is referred to as groundwater flooding.

Especially in older houses with a non-damp-tight floor or rising damp through the walls, groundwater flooding almost certainly leads to moisture in the home and therefore to a greater risk of health problems. In 2001, 260,000 homes in the Netherlands suffered from incidental or regular groundwater flooding.

No guidelines are known for SWL/GWT rise.

# 5 Knowledge gaps

The following three knowledge gaps contribute most to uncertainty in the assessment of building damage (risk) due to SWL change:

1. *GWT change due to SWL change.*

According to current understanding (Deltares, 2023a), the groundwater response to SWL depends on many factors other than the simple soil types (clay, sand, peat) in the CBA (1987) table. The relationships need to be elaborated and transferred into practicable tools that can be incorporated in formal guidelines or improved rough-and-ready rules.

2. *Shrink-swell change due to GWT change.*

There is increasing evidence (Stuurman et al., 2021; Blom et al., 2023) that enhanced shrink-swell movements – presumably mostly due to climate change effects – are an important cause of building damage in areas with clay soils in the Netherlands. To what extent GWT change due to SWL change plays a role as well is still largely unknown, and approaches to quantify the impact of SWL change are currently lacking.

3. *Characteristics of peat oxidation.*

The following aspects of peat oxidation are still rather uncertain (e.g., Deltares, 2023b):

- To what depth aerobic peat oxidation (by oxygen) occurs with respect to the GWT. There are observations that indicate that oxidation penetration in the soil is less deep than the depth of the mean lowest GWT, but by how much, and if this is variable, depending on local conditions, in insufficiently known.
- The rate of oxidation and settlement. This may be different for peat that is strongly compressed by the weight of the building than for peat at the same depth in the surroundings.
- To what extent anaerobic oxidation (without oxygen) below the GWT also contributes to settlement of buildings on shallow foundations.

*Additional considerations regarding development of guidelines*

If guidelines for damage risk assessment are to be developed, it is desirable to also address the following:

- Ensuring that all potential hazards always need to be addressed.
- Differentiating between rapid and slow SWL and GWT change. Conventional approaches to calculate the impact of GWT change commonly assume rapid (instantaneous) change. SWL change due to mining-induced subsidence can develop slowly in the course of decades. Common approaches are needed to account for the slowness of development in calculation of (differential) settlement for several hazards (oxidation, compression).

# 6 Damage causes other than mining

The note so far described the link chain between SWL change and building damage, where mining-induced subsidence can be one of the drivers of SWL change. There are many other activities that have an influence on one of the components of the chain. SWL change also occurs due to other activities than mining (Figure 1 and Figure 3), and SWL change is not the only cause of GWT change. Furthermore, differential settlement of buildings can be caused by other factors than GWT change and building damage also occurs without soil and foundation deformations.
This chapter aims to give clarity about the position of the link chain described in this note in the wider context of other potential causes also relevant to building damage. For that reason, three diagrams are presented that aim to clarify the pathways that lead to damage by differential settlement that do not include mining.

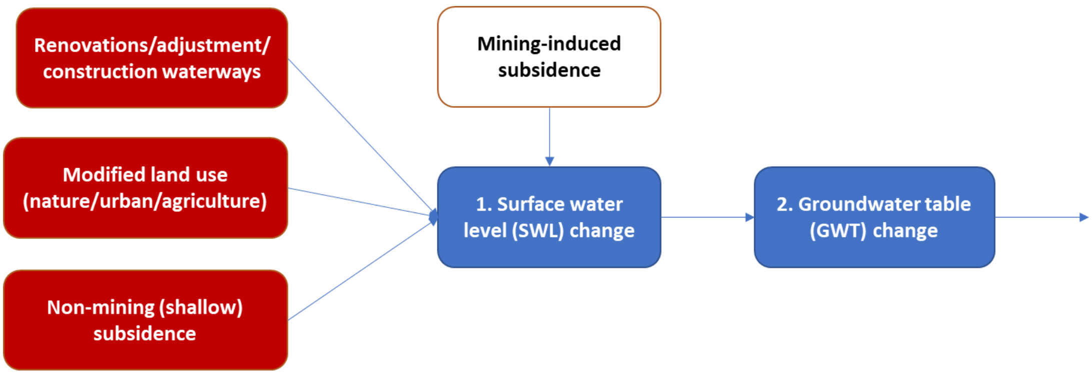



*Figure 5 Other causes of SWL change than mining (red) that can cause building damage by (differential) settlement.*

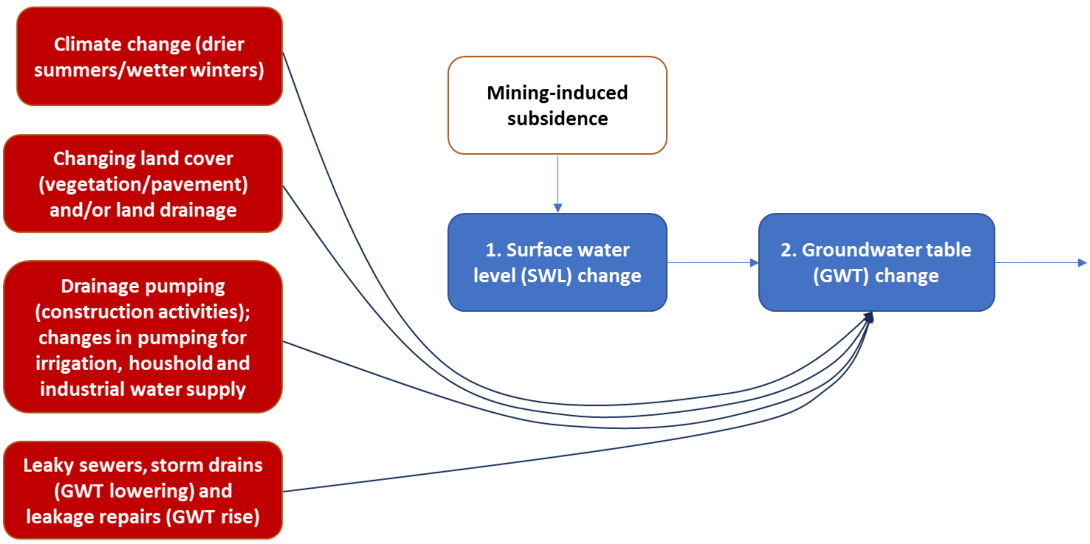



*Figure 6 Other causes of GWT change than mining (red) that can cause building damage by (differential) settlement.*

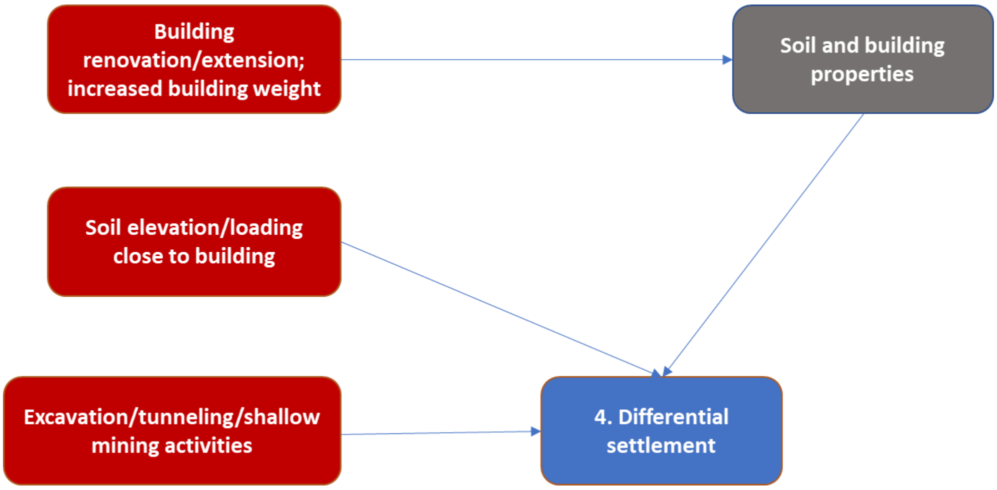



*Figure 7 Other causes of differential settlement-related building damage than through GWT change.*

Other causes of building damage not related to differential settlements also exist, as described by Commissie Mijnbouwschade (2021). They mention for example:

- Insufficient strength (from design, execution or ageing)
- Higher loads, incidental loads (impact)
- Restricted deformations (temperature, moisture related)
- Vibrations (traffic, earthquakes, construction works or otherwise)

# 7 Relationship of the discussed link chain with ‘shallow subsidence’

This note aimed to shed light on the link chain between SWL change and building damage risk. However, many readers may still be left with the question how this relates to another linkage that is often encountered in the context of building damage: the link between shallow subsidence and building damage. In closing, this chapter dedicates a few words and graphics to this relationship.

*Shallow subsidence*

Subsidence refers to the lowering of the land surface over fairly extensive areas and therefore includes, or specifically concerns, the broader surroundings of individual buildings. *Shallow* subsidence is a term that is used to indicate subsidence caused by processes in shallow soft soil layers that are typically present at depths of several meters to about twenty meters: compression, oxidation, irreversible shrinkage. These processes also are involved in several of the hazards that are responsible for building damage due to SWL and GWT lowering.

In western and northern parts of the Netherlands that are underlain by (Holocene) soft soils, shallow subsidence due to compression, oxidation and shrinkage started centuries ago when the land started to be drained (SWL lowering and GWT lowering) to improve the bearing capacity and production capacity of the soil for agriculture and building (Figure 8A). However, a subsiding land surface reduces the effectiveness of drainage, and causes the bearing capacity to deteriorate (Figure 8B). The SWL, therefore, needed to be lowered again, inducing a new cycle of subsidence (Figure 8C). This cycle of subsidence and SWL lowering often perpetuates to the present day and in some areas several meters of subsidence have been incurred over the centuries.

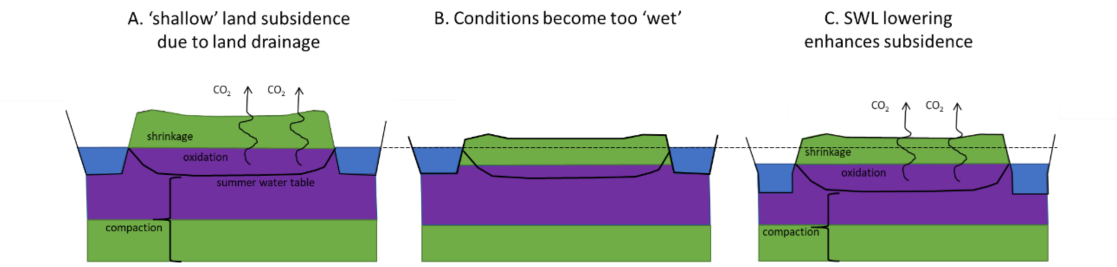



*Figure 8 Schematic illustration of the shallow subsidence cycle, perpetuated by periodic SWL lowering.*

In built-up areas, shallow subsidence of private and public space such as roads and gardens, often occurs as a compression (also: compaction) response to applied loads (sand layers applied before building started and at later stages to compensate for subsidence).

*Shallow subsidence and building damage*

Shallow subsidence can lead to building damage in the following two ways.

1. Shallow subsidence often is the main reason for SWL lowering, which may then cause GWT lowering and building damage risk, as explained in the main part of this note. This perspective is represented by the third red box in Figure 5.

2. Shallow subsidence due to applied surface loads close to a building may cause damage risk by stresses on pile foundations or differential compaction of the soil underneath shallow foundations. This perspective is represented by the second red box in Figure 7. This link with shallow subsidence is detached from the cause-effect link chain between surface water level (SWL) change and building damage risk that is the focus of this document.

It may be tempting to presume that the compression, oxidation, and irreversible shrinkage that occurs in the surroundings of buildings extends underneath buildings and, therefore, can cause differential settlement of buildings on shallow foundations. Although this may sometimes approximate the situation, soil conditions, the processes, and the subsidence of the soil underneath a building can differ markedly from that in the surroundings. Settlement differences between the green field (next to) and the soil underneath buildings should, therefore, be anticipated. Absence of shallow subsidence does not necessarily indicate a reduced risk of damage due to reversible shrinkage (shrink-swell). In particular stiff clays that do not contribute to subsidence can pose a large damage risk.

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