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Literature Review: Effects of subsidence on buildings

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Summary

Buildings can deform due to many causes, such as self-weight, changes in temperature, changes in moisture content, or foundation movements. All of the above may lead to a strain in the building which in turn may lead to damage. The aim of this report is to identify the indicators which are relevant to assess building damage and to define lower bound criteria for the initiation of damage when buildings undergo a deformation of the foundation caused by subsidence. This information will then be used to improve the methods to assess building damage related to deep subsidence and heave (“diepe bodemdaling en -stijging”) due to gas extraction in Groningen (the “Groningenveld”) and gas extraction and storage in Norg (the “gasopslag Norg”).

This document presents results of a literature survey of the state-of-the-art for assessing damage on buildings induced by subsidence. First, the main types of damage together with their causes and indicators of damage are analysed. Later, an extensive literature overview is provided on the criteria and threshold values that are used to assess building damage. Finally, a choice has been made regarding the criteria and the threshold values that will be used within the scope of this project.

It is concluded that the approach defined by the study of Boscardin and Cording (1989), which was later refined by Son and Cording (2005), is well accepted internationally for the assessment of damage to buildings. However, within this project, it is proposed to limit the allowable strain to 0.2×10^{-3} instead of 0.5×10^{-3}. This lower allowable strain takes into account buildings with a relatively high percentage of openings which were not considered explicitly in Boscardin and Cording (1989) and Son and Cording (2005). This also leads to a lower allowable curvature at the buildings’ foundation level.
Recommendations are formulated for further analysis of the vulnerability of buildings due to movements of the soil.

Contents

1 Introduction

1.1 Aim and research questions

The extraction of natural gas in the Province of Groningen causes a subsidence bowl over a large area. This subsidence bowl is a possible cause of damage to buildings due to spatially varying settlements over the extent of a building. The aim of this report is to identify the indicators which are relevant to assess the amount of damage in buildings due to subsidence, and to define lower bound criteria for the initiation of damage. This information is used to improve the methods to assess building damage related to deep subsidence due to gas extraction in the "Groningenveld" and the gas extraction and storage in the "gasopslag Norg".

This document presents a literature review of the state-of-the-art for assessing damage in buildings induced by subsidence (Figure 1). The research questions that have been explored in this part of the project are:

- How do buildings behave under subsidence?
- Which damage indicators are relevant?
- Which criteria and threshold values are being used in the assessment of subsidence-induced building damage?

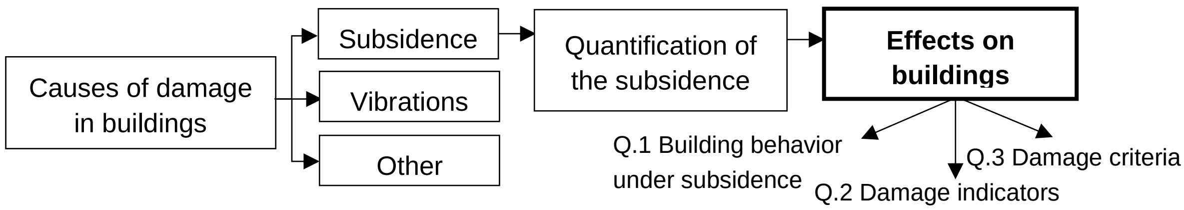

Figure 1 A flow chart visualizing the analysis of damage in buildings. The work reported here focuses on providing a state-of-the-art from the literature for assessing the effects of subsidence on buildings.

1.2 Structure of the report

In Chapter 2, background information on building behaviour under subsidence and relevant damage indicators are provided. Based on the literature survey, main types of damage, causes of damage and damage indicators are summarised. Chapter 3 presents an overview of the criteria for subsidence in relation to building damage and related threshold values are given based on the literature survey. Here, a choice has been made regarding the criteria and the threshold values that will be used in this project. Lastly, Chapter 4 contains the conclusions and follow-up recommendations from this project.

2 Background

2.1 Building behavior under subsidence

Buildings under specific loading conditions can move, deform, tilt, crack and subsequently be damaged depending on their construction type, stiffness, openings and joints Korff (2009). Possible causes of building deformation are self-weight, temperature changes, moisture content changes or subsidence. Building deformation leads to strain in the building which in turn may cause damage to the structure. In addition to deformation, a building may exhibit tilt.

In this study, building deformation due to subsidence is singled out. Subsidence, in particular differences in settlement over the extent of a building, may cause several types of damage. The most likely deformation modes are the ‘hogging’ mode (the sides of the building settle more than the average) and the ‘sagging’ mode (the centre of the building settles most). Figure 2 illustrates the characteristics for the hogging mode and the possible damage mechanisms in brittle, masonry like materials Boscardin & Cording (1989)

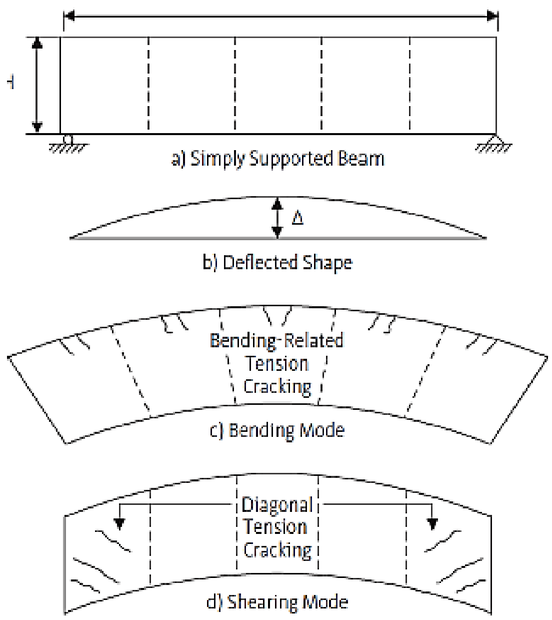

Figure 2 Overview of deformations in buildings and related damage for hogging mode Boscardin & Cording (1989).

Building deformations can be specified in more detail into several modes, such as shear deformation and bending as well as elongations and shortening. Generally, a combination of deformation modes occurs simultaneously. Definitions that are used in this study are described hereafter Korff (2009); Giardina (2013) and visualized in Figure 3 Giardina (2013).

- S: Settlement is the vertical displacement of a point;
- δS or ΔS: Relative settlement or differential settlement is the difference between the settlements of two points;
- Δ: Relative deflection is the maximum vertical displacement relative to the straight line connecting two reference points;
- Δ/L: Deflection ratio is the ratio of the relative deflection between two points to the length, L between them;
- θ : Rotation is the gradient of a straight line (relative to horizontal) connecting two points or slope of a settlement curve;
- ω: Tilt is the rigid body rotation of the entire structure. Rigid body rotation can be assessed in three dimensions and it should be made clear if and in what way tilt is considered (e.g. horizontal, vertical);
- β: Angular distortion (or relative rotation) is the rotation of the straight line connecting two reference points relative to their tilt at the foundation level;
- ε: The change in length (ΔL) of the structure due to the applied horizontal displacements results in a horizontal strain (ε=ΔL/L).

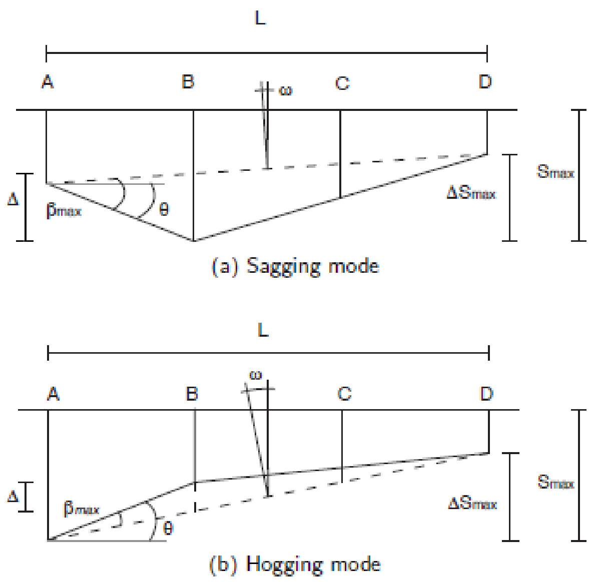

Figure 3 Deformation parameters (Giardina, 2013).

2.2 Building damage

Building damage is defined as the physical harm that impairs the value, usefulness, or normal function of a building. In the following part, main types and causes of damage are defined, and damage indicators are summarised based on a literature survey.

2.2.1 Main types of damage

According to the recent project performed by TU Delft Van Staalduinen et al (2018), the main types of damage in buildings are:

- cracks (indicating permanent loss of cohesion),
- permanent deformation (without loss of cohesion),
- permanent position changes (such as skew or settlement).

The main types of damages in buildings are defined by De Vent (2011) as cracks, deformation and tilt.
With respect to the presence of cracks, the definition of damage considers visible cracks. Cracks which are just visible to the eye have impact on the aesthetical appearance of the building. Cracks with larger size (widths and lengths) can hamper the functional or structural behaviour.

2.2.2 Causes of damage

Damage in normal conditions is expected to occur mostly due to causes related to the building itself and to the environmental changes in and around the building. Typical *building parameters* mentioned in literature are the structure, geometry, load, age, materials, construction principles that were used, foundation, current and historical use, modifications and/or extensions. Furthermore, *environmental conditions* that can cause damage on the buildings are soil characteristics, changes in groundwater level and mining activities (e.g. causing vibrations and deep/shallow subsidence). These can also include the conditions in the surrounding area, such as changes in the neighbouring buildings, vibrations due to traffic, construction of new roads or structures Van Staalduinen et al (2018). For an overview and more detailed description of the causes of cracks, see Sadgrove (2014). An overview of possible causes of building damage is given in Table 1.

The causes of damage in buildings are various and may be interrelated. There is an uncertainty regarding to what extent damage in a building is already present due to normal circumstances and what may be caused by a particular external cause. These external causes can be natural or man induced.

Table 1 Classification of causes of building damage, adopted from Van Staalduinen et al (2018); Borsje & De Richemont (2011)

Group	Description	Cause
Influence of loads on the building	Insufficient resistance	Initial
		Renovation
		Aging
	Overload from use (static)	Normal use
		Altered use
		Renovation/extension
	Overload due to vibration	Road traffic / Rail traffic
		Construction activities
		Industrial activities
		Earthquakes
	Specific reasons for overload	Impact of objects (e.g. collisions, falling objects)
		Explosion
		Weather conditions (e.g. storm, wind, snow)
Deformations	Prevented deformations of the building construction	Initial
		Renovation/extension
		Aging / deterioration
	Imposed deformations	Initial
		Renovation/ extension
		Metal corrosion
		Trees & root growth
Uneven subsidence of subsoil / foundation	Autonomous settlement	Constant loads (self-weight)
		Natural creep in heterogeneous soil
	Change in load	Renovation/extension/change in use
		Nearby buildings
		Heightening
		Excavation
		Construction of roads / railways
	Change in subsoil	Changes in groundwater (GW) level
		Changes in GW level by work activities (e.g. drainage of construction pits)
		Vibrations from the road/rail traffic (liquefaction of the soil)
		Vibrations from work activities
		Earthquakes
		Change in GW level through trees (e.g. extreme drought)
		Deep subsidence effects (elongation, bends, skews)
		Naturally extreme variations in GW level (e.g. extreme drought)

2.2.3 *Damage indicators*

Damage in buildings can be described by combinations of different damage indicators, such as position, orientation, deformation type, crack size, crack width and number of cracks.

Based on over 500 damage cases from masonry buildings selected from literature, De Vent (2011) has introduced 43 possible damage indicators, identified based on their characteristics and each linked to its possible causes. An example of a damage indicator due to settlement is given below Figure 4.

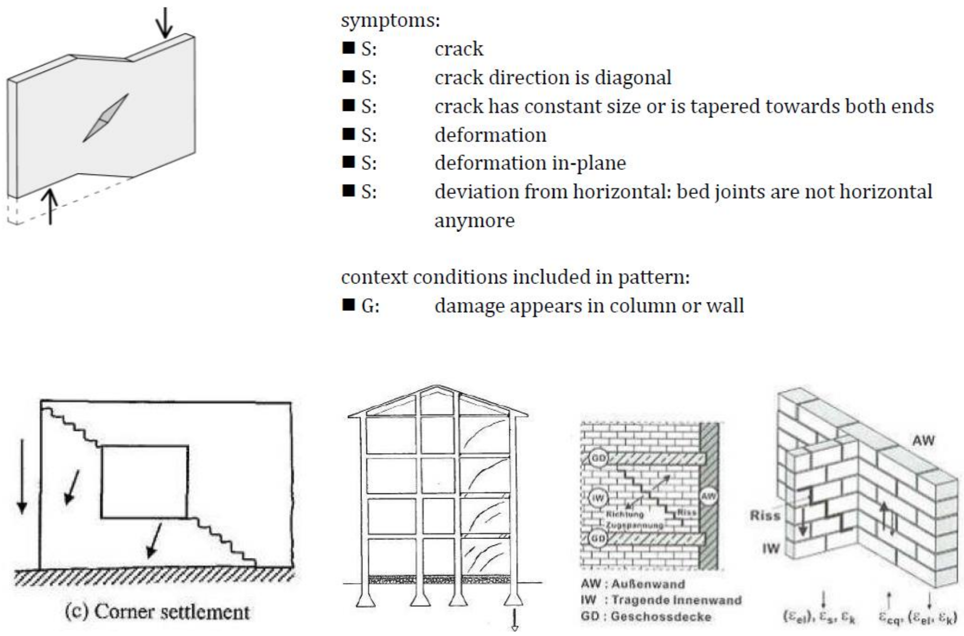

Figure 4 Damage Indicator 21 - due to vertical settlement: Crack → in column or wall / diagonal, in one direction / constant size or tapered towards both ends / in-plane deformation with deviation from horizontal De Vent (2011).

BRE (1995) shows how to identify cracks by their nature and divides between tensile cracks, compressive cracks and shear cracks. Compressive cracks often show small flakes of brick squeezed from the surface or localised crushing. Shear cracks show relative movement of points on opposite side of the crack. When the cracks are produced by foundation movement they tend to be concentrated in areas where maximum structural distortion occurs, or at weak points in the structure.

Korff (2009) lists the damage indicators of the cracks due to settlement as:

- Cracks are usually tapered (small at one end and wider at the other).
- Cracks are often seen both on the inside and the outside of the building.
- Cracks continue below and above ground level.
- The location and the direction of the crack are directly related to the deformation mode (hogging, sagging). Other damage might include broken windows and jamming doors because windows and door openings are distorted, sloping floors and tilting walls.

De Vent (2011) also links each damage indicator caused by vertical settlement to possible hypotheses (causes of damage) which are listed in Figure 5.

B. Hypotheses

☐ 1.1.1	Differential settlement due to change in load, differences in self-weight of the building
☐ 1.1.2	Differential settlement due to change in load, differences in use load
☐ 1.1.3	Differential settlement due to change in load, uneven distribution of loads on the foundations
☐ 1.2.1	Differential settlement due to change in foundation behaviour, differences in foundation type or depth
☐ 1.2.2	Differential settlement due to change in foundation behaviour, differences in basement layout
☐ 1.2.3	Differential settlement due to change in foundation behaviour, local decline due to wood rot
☐ 1.2.4	Differential heave due to change in foundation behaviour, salt attack on the foundations
☐ 1.3.1	Differential settlement due to change in soil behaviour, differences in soil composition
☐ 1.3.2	Differential settlement due to change in soil behaviour, differences in effective stress due to removal of soil
☐ 1.3.3	Differential settlement due to change in soil behaviour, differences in pore (water) pressure
☐ 1.3.4	Differential settlement due to change in soil behaviour, differences in load imposed on the soil (not from damaged building itself)
☐ 1.3.5	Differential heave due to change in soil behaviour, differences in pore (water) pressure
☐ 1.3.6	Differential heave due to change in soil behaviour, local uplift by tree roots
☐ 1.3.7	Differential soil movement due to change in soil behaviour, vibrations in the soil

Figure 5 Hypotheses on the causes of damage defined in De Vent (2011).

3 Criteria and threshold values

3.1 Literature review

Damage to buildings is assessed by several criteria which can be derived either theoretically or from field measurements. This chapter summarizes the results from a literature review to these criteria. In this report, the focus is given on the definition of criteria rather than on the way the assessments are done.

The simplest damage criteria which can be found are using maximum settlement of the structure or differential settlement. Other references describe the maximum or relative rotation (i.e. angular distortion), deflection ratio, or horizontal strain (i.e. tensile strain, elongation) of the building. Angular distortion and deflection ratio are used when analysing the admissibility of the movements in relation to buildings Ricceri & Soranzo (1985). Angular distortion is favoured more in case of shear deformation and deflection ratio more in case of bending deformation. Some authors prefer one of the methods for simplicity of the calculation. According to Korff (2009), the current state-of-the-art for predicting building damage is based on calculating strains from the deformation using deflection ratio, angular distortion or other methods, e.g. fully coupled FEM. Literature on damage to masonry buildings usually relates damage to the combination of curvature and horizontal strain of the soil. More curvature leads to higher strains, and thus, more damage. This means that buildings that only tilt rather than bend usually experience less damage.

Korff (2009) gives an overview of properties which determine what type of buildings are more susceptible to damage due to deformations of the soil than others. The following properties are relevant for our study:

- Buildings with load bearing walls are more vulnerable for damage than buildings with frame structures. For the same vertical displacement, frame structures can accommodate differential displacements by deformation of the beams, whereas load bearing walls need to bend, which leads to cracking more easily. This situation leads to a 20-25% lower tolerable relative rotation and settlement for load bearing walls;
- Buildings subjected to relatively fast deformations (e.g. due to construction activities);
- Buildings with structural discontinuities;
- Buildings subjected to hogging mode rather than sagging mode;

An overview of criteria found for building damage related to subsidence is given in Table 2, which is the result of a literature survey. The criteria used in Table 2 are defined in section 2.1. One should keep in mind that these values should not be considered as rigid rules since the performance of buildings may depend on many factors, such as material properties, environmental conditions, foundation types Ricceri & Soranzo (1985). However, given the scope of this project, a lower bound criterion for buildings is explored to get to a generally applicable conclusion.

Table 2 Overview of the literature review on the criteria and threshold values for subsidence in relation to buildings

Source	Criteria	Explanation	Values	Limit for	Notes
Skempton & McDonald(1956)	β	Angular distortion	$6.66x10^{-3}$	Structural damage in beams or columns	***Empirical method based on field data*** - Data from 98 buildings - Steel or reinforced concrete frame buildings with panel walls of brick or similar construction - Effect of the building geometry (L/H) and horizontal deformations are not taken into account
			$3.33x10^{-3}$	Cracking in wall panels	
	$\Delta S_{T(max)}$	Max. diff. settlement	32 mm	In sand (all types of foundation)	
			45 mm	In clay (all types of foundation)	
	$S_{T(max)}$	Max settlement	51 mm	Isolated foundations in sand soil	
			76 mm	Isolated foundations in clay soil	
			51-76 mm	Raft foundation in sand	
			76-127 mm	Raft foundation in clay	
Polshin & Tokar (1957)	Δ/l per L/H	Deflection ratio per building length/height	$0.3x10^{-3}$	for L/H ≤ 2 Sagging	***Empirical method based on field data*** - Cracking limits - Data from 10 buildings - For brick masonry and unreinforced load bearing walls
			$1x10^{-3}$	for L/H = 8 Sagging	
	β	Angular distortion	$5x10^{-3}$	Cracking to no infill structures	- frame buildings
Wood (1958) Information taken from Son (2003)	β	Angular distortion	$10x10^{-3}$	First visible cracking	***Experiments*** - encased steel frames
			between $2.2x10^{-3}$ and $3.6x10^{-3}$	First visible cracking	- brick infilled panels - brick or block wall
			$1x10^{-3}$	First visible cracking	- brick wall with opening

Source	Criteria	Explanation	Values	Limit for	Notes
Bozuzuk (1962) Information taken from Son (2003)	β	Angular distortion	between 5.8×10^{-3} and 16.6×10^{-3}	Cracking	***Experiments*** - Fiber board or plywood facing on wood frame
			between 3.7×10^{-3} and 6.66×10^{-3}	Cracking	-Gypsum board or fiber board with plaster facing on wood frame
			1×10^{-3}	Cracking	-Structural clay tile Concrete block unit with mortar
			between 1×10^{-3} and 2×10^{-3}	Cracking	-Clay brick unit with mortar
Bjerrum (1963)	β	Angular distortion	2×10^{-3}	Safe limit for no cracking	***Empirical method*** - Addition to Skempton & McDonald (1956), this study includes more limits related to the servicability of buildings (Figure 7). - frame buildings, panel and brick walls
			3.33×10^{-3}	Cracking in panel walls (severe)	
			6.66×10^{-3}	Considerable cracking in panel and brick walls (serious)	
Meyerhof (1953) Information taken from Son (2003)	β	Angular distortion	Ranging between 2.5×10^{-3} and 3.33×10^{-3}	Cracking	- solid brick, clinker and clay block infilling panels in cased steel frames
Meyerhof (1982)	β	Angular distortion	0.5×10^{-3} Hogging zone	Cracking unreinforced load bearing wall	***Empirical method based on limited field data*** - different types of buildings and earth retaining structures (for more detail, see Figure 8) -distinguishing between load-bearing walls and frame structures
			1×10^{-3} Sagging zone		
			2×10^{-3}	Cracking of infilled frames	
			4×10^{-3}	Cracking of frame structures	

Source	Criteria	Explanation	Values	Limit for	Notes
Boscardin and Cording (1989) + used by many more studies	β per ε	Angular distortion versus horizontal strain	β = 1x10^{-3} ε = 0.5x10^{-3}	Negligible damage	***Empirical-analytical method using field data*** - Brick bearing-wall and small frame structures - 18 different types of structures - buildings with 6-40 m length, with L/H=1 and an isotropic beam with E/G = 2.6 (E: flexural stiffness, G: shear stiffness)
			β = 1.5x10^{-3} ε = 0.75x10^{-3}	Very slight	
			β = 3.25x10^{-3} ε = 1.5x10^{-3}	Slight	
			β = 6.5x10^{-3} ε = 3x10^{-3}	Moderate to severe	
			β > 6.5 x10^{-3} ε > 3x10^{-3}	Severe to very severe	
Burland, et al. (1977)	ε	Horizontal strain	0.5x10^{-3}	Visible cracks	***Literature review*** - maximum stretching in a building due to soil deformations - plaster and masonry or brickwork
Base et al. (1966) deduced by Burland and Wroth (1974) Information taken from Son (2003)	ε	Tensile strain	0.5x10^{-3}	the onset of visible cracking	-reinforced concrete beam
Burhouse (1969) deduced by Burland and Wroth (1974) Information taken from Son (2003)	ε	Tensile strain	Ranging between 0.38x10^{-3} and 0.6x10^{-3}	the onset of visible cracking	- brick wall with reinforced concrete supporting beam
Burland and Wroth (1974)	Δ/l per L/H	Deflection ratio per building length/height	0.2x10^{-3} for L/H =1	Damage	***Empirical method*** - unreinforced load-bearing walls - for Hogging - E/G = 2.6
			0.4x10^{-3} for L/H = 5		
	ε	Tensile strain	0.35x10^{-3}	the onset of cracking	Reinforced concrete supporting beam

Source	Criteria	Explanation	Values	Limit for	Notes
Mainstone (1971) Information taken from Son (2003)	ε	Tensile strain	between $0.2x10^{-3}$ and $0.3x10^{-3}$	visible cracking	***Experiments*** -Brick infilled frame
Day (1990) Information taken from Son (2003)	β	Angular distortion	$3.33x10^{-3}$	Cracking in gypsum wall board panels	- 34 residential houses - detached houses with lightly reinforced slab-on-grade foundations and wood-frame construction
			$10x10^{-3}$	Structural damage on the wood columns and beams	
van Sambeek (2000)	β and ε	Angular distortion vs. horizontal strain	$\beta = 0.8x10^{-3}$ $\varepsilon = 0.5x10^{-3}$	Where no damage expected	- Original source text is not available
Kratzsch (1974)	ε	Horizontal strain	$0.5x10^{-3}$	Where no damage expected	- Original source text is not available
Son and Cording (2005)	ε	Tensile strain	$0.5x10^{-3}$	Negligible damage	***Empirical-analytical method*** *based on field data (16 buildings), laboratory data and numerical test data* - masonry bearing wall structures - limiting tensile strains for different damage categories
			$0.75x10^{-3}$	Very slight	
			$1.67x10^{-3}$	Slight	
			$3.33x10^{-3}$	Moderate to severe	
			$> 3.33x10^{-3}$	Severe to very severe	
van Staalduinen, et al. (2018) - TU Delft project	β and ε	Angular distortion versus horizontal strain	$\beta = 4x10^{-4}$ $\varepsilon = 2x10^{-4}$	Cracks	***Literature review (not a new study)*** -deformation criteria due to subsidence in the deep and shallow subsoil
Zhang & Ng (2005)	β	Angular distortion	$2.5x10^{-3}$ to $3x10^{-3}$	Cracks	***Statistical method using field data*** - statistically comparing field data with damage with tensile strains - data from 95 buildings
	S_v	Settlement	100-130 mm		

Source	Criteria	Explanation	Values	Limit for	Notes
					- steel and reinforced concrete frame structures and structures with load-bearing walls on deep and shallow foundations - steel and concrete bridges (not incl. here)
Zhang & Ng (2007)	β	Angular distortion	$2x10^{-3}$ to $6x10^{-3}$	Cracks	***Statistical method using field data*** - original source text is not available - statistically comparing field data with damage with tensile strains - data from 221 buildings - for deep and shallow foundations
	S_v	Settlement	100-220 mm		
Giardina (2013)	Δ/l	Deflection ratio	$0.5x10^{-3}$	Cracks	***Finite element model*** slow deformations of masonry
CEN (2007) (EN 1997-1)	β	Angular distortion	Sagging: $0.5x10^{-3}$ to $3.3x10^{-3}$ Hogging: $0.25x10^{-3}$ to $1.6x10^{-3}$	Damage	***Standards*** - for open or infilled frames and load bearing or continuous brick walls - considers new constructions only
			Sagging: $2x10^{-3}$ Hogging: $1x10^{-3}$	Serviceability limit state	- for many (new) structures
CUR (1996) (Dutch regulations)	θ	Rotation	$\leq 2x10^{-3}$	No damage	***Standards*** - buildings on shallow foundations
			$2x10^{-3}$ to $3,3x10^{-3}$	Aesthetic damage	
			$3.3x10^{-3}$ to $10x10^{-3}$	Structural damage	
			$\geq 10x10^{-3}$	Risk for residents	
SWD (1998)	β	Angular distortion	$20x10^{-3}$		***Standards*** - masonry buildings

Source	Criteria	Explanation	Values	Limit for	Notes
(Amsterdam municipality)	S_{max}	Max. settlement rate	4 mm/y	Demolition of the building (class IV)	
	ΔS_{max}	Max. variation of settlement rate	2 mm/y		
IGWR (2009) Rotterdam municipality	Horiz. ω	Horizontal tilt	< 1/100	Good	***Standards*** - horizontal tilt is for masonry buildings - vertical tilt is for buildings in general - horizontal tilt for concrete buildings also given (not here)
			1/100 – 1/67	Acceptable	
			1/67 – 1/50	Poor	
			> 1/50	Bad	
	Vert. ω	Vertical tilt	< 166	Good	
			1/66 – 1/50	Acceptable	
			1/50 – 1/33	Poor	
			> 1/33	Bad	

In the following part, Table 2 is further elaborated considering the scope of this project in order to find a general criterium to assess building damage.

Several empirical methods for assessing building damage are internationally recognized in engineering practice. They are simple and can therefore be applied to a large number of structures potentially affected by subsidence Giardina (2013). The most relevant studies are discussed below.

In Skempton & McDonald (1956), threshold values are defined for angular distortion. β =3.33x10^{-3} distinctly divides between cracking and non-cracking in wall panels and masonry for mostly industrial buildings. Structural damage in beams or columns can occur from β = 6.66x10^{-3} . However, the effect of the geometry of the building (L/H) and horizontal deformations are not taken into account in this study. In addition to angular distortion, maximum settlement ($S_{T(max)}$) and maximum differential settlement ($\Delta S_{T(max)}$) are given in Table 2. According to this study, building damage due to ground movement is first noticeable on plaster walls, finishes, or claddings.

Polshin & Tokar (1957) defined similar limits for brick walls in terms of deflection ratio, relating them to the building length and height (L/H), given in Figure 6.

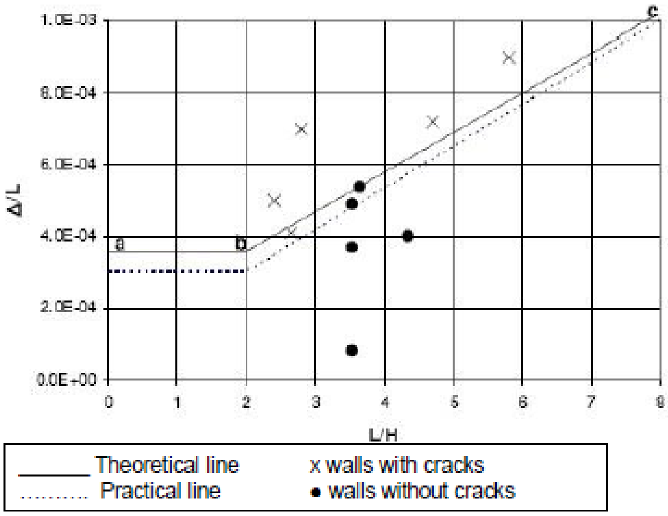

Figure 6 Deflection ratio versus building length/height for 10 brick buildings Polshin and Tokar (1957).

Bjerrum (1963) extended the study of Skempton & McDonald (1956) with more levels of serviceability damage based on the angular distortion of the building, as given in Figure 7.

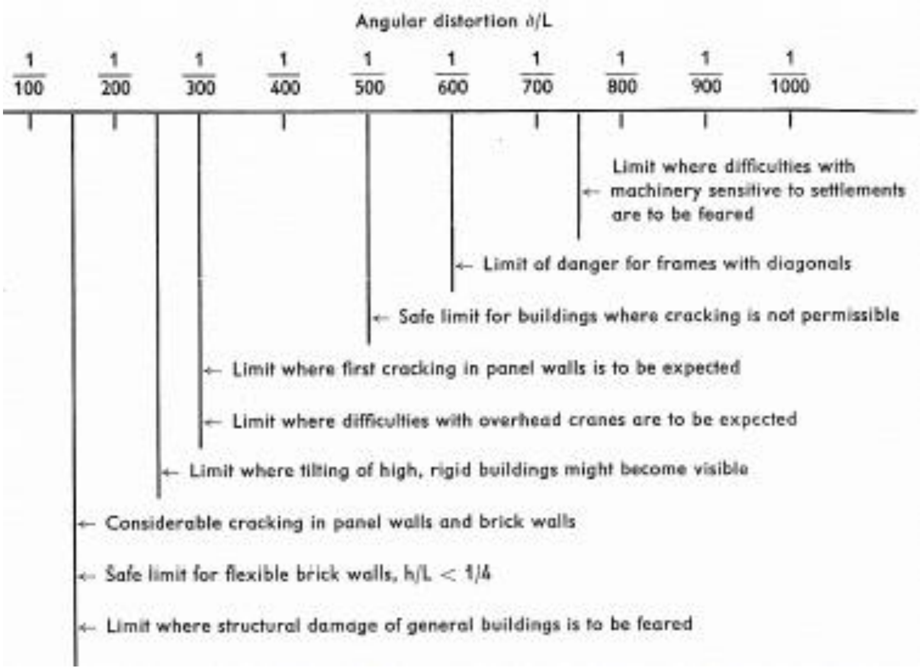

Figure 7 Damage criteria based on angular distortion by (Bjerrum, 1963).

Meyerhof (1982) follows stricter criteria and defines different safe limits for unreinforced bearing walls in hogging and sagging mode and also for open steel and concrete frame buildings, given in Table 2 and Figure 8.

Relative Rotation (δ/l)	Type of limit and structure
1/100	Danger limit for statically determinate structures and retaining walls
1/150	Safe limit for statically determinate structures and retaining walls
1/150	Danger limit for open steel and reinforced concrete frames, steel storage tanks and tilt of high, rigid structures
1/250	Safe limit for open steel and reinforced concrete frames, steel storage tanks and tilt of high, rigid structures
1/250	Danger limit for panel walls of frame buildings and tilt of bridge abutments
1/500	Safe limit for panel walls of frame buildings and tilt of bridge abutments
1/500	Danger limit for sagging of unreinforced load-bearing walls
1/1000	Safe limit for sagging of unreinforced load-bearing walls
1/1000	Danger limit for hogging of unreinforced load-bearing walls
1/2000	Safe limit for hogging of unreinforced load-bearing walls

Figure 8 Relative rotation limits for structures (Meyerhof, 1982)

Meyerhof (1953) also shows that the onset of cracking of solid brick, clinker and clay block infilling panels in cased steel frames occurs with angular distortions ranging between $2.5x10^{-3}$ and $3.33x10^{-3}$ Son (2003).

According to Wood (1958) the first visible crack occurs with angular distortion of (a) $10x10^{-3}$ in an encased steel frame; (b) in the range between $2.2x10^{-3}$ and $3.6x10^{-3}$ in brick infilled panels and brick or block walls; (c) $1x10^{-3}$ in brick walls with openings Son (2003).

The study of Day (1990) focuses on the settlement of detached houses with lightly reinforced slab-on-grade foundations and wood frame constructions. The results show that the threshold value of angular distortion for cracks in gypsum wall panels is $3.33x10^{-3}$ and for structural damage of the wood columns and beams is $10x10^{-3}$ Son (2003).

The results of racking tests as given by Bozozuk (1962) show that the angular distortions for a first crack on (a) fiber board or plywood facing on wood frames occurs in the range of between $5.8x10^{-3}$ to $16.6x10^{-3}$; (b) gypsum board or fiber board with plaster on wood frames occurs between $3.7x10^{-3}$ to $6.66x10^{-3}$; (c) structural clay tiles and concrete block units with cement-lime mortar occurs at $1x10^{-3}$ and (d) clay brick units with cement-lime mortar occurs in the range of $1x10^{-3}$ to $2x10^{-3}$ Son (2003).
According to Son (2003), the study of Base et al (1966) analyses the cracking of reinforced concrete beams and the tensile strain at the onset of visible cracking is deduced to be $0.5x10^{-3}$ by Burland and Wroth (1974). Also, from the work of Burhouse (1969) which focuses on brick walls with reinforced concrete supporting beams, Burland and Wroth (1974) deduce the tensile strain at the onset of visible cracking in range of between $0.38x10^{-3}$ to $0.6x10^{-3}$.

Some other studies focus on the Limiting Tensile Strain Method (LTSM) which is an empirical-analytical method used in engineering practice to predict damage to buildings related to ground deformations, neglecting soil-structure interaction effects Boscardin & Cording (1989); Burland & Wroth (1974); Giardina (2013); Netzel (2009). In LTSM, the building is assumed to be a simple isotropic elastic beam.

The first step is to calculate the ground movements while neglecting the presence of a building. These deformations are then used in a building beam model. In the next step, the settlement-induced deformations and strains of the building are assessed and related to damage levels.

When settlement affects the building, tensile strains occur due to bending deformation and diagonal strains due to shear deformation, generally both at the same time Korff (2009). As one of the first fundamental researches on assessing strains in buildings, Burland & Wroth (1974) relate the deflection ratio to the maximum extreme strain (bending) and the maximum diagonal strain (shear). They refer the maximum allowable deformations to the largest deflection (Δ/L) of a building.
Burland and Wroth (1974) also conclude that the onset of cracking of reinforced concrete supporting beams occurs at a tensile strain of about $0.35x10^{-3}$ Son (2003). Based on an extentive literature survey, Burland et al. (1977) argue that maximum allowed stretching in a building due to soil deformations is in the order of $\varepsilon = 0.5x10^{-3}$, where the visible cracks may occur.

An important development was made by Boscardin and Cording (1989) who added horizontal strains to the bending and shear deformations. They unify the results for angular distortion from Skempton & McDonald (1956); Polshin & Tokar (1957); Bjerrum (1963); Meyerhof (1982) with the tensile strain criterion from Burland & Wroth (1974); Burland et al. (1977). In practice, subsidence criteria from Boscardin & Cording (1989) and later updated by Son & Cording, (2005) (to get a lateral strain independent of L/H, E/G (E: bending stiffness, G: shear stiffness of the building) and the position of the neutral axis) are commonly used for assessing the damage on buildings caused by subsidence. They use a damage criterion for the horizontal strain in combination with the angular distortion of the foundation to describe the effects of this deformation imposed on the building by the subsoil. These criteria are also used in studies related to the effects of mining activities in the Netherlands, such as studies by Pruiksma (2001), Brinkman (2016) and Arcadis (2013).

Boscardin & Cording (1989) define a zone in which 'negligible damage' (see Figure 9) can occur with horizontal stretching of buildings of the order of $0.5x10^{-3}$ or with an angular distortion in the order of $1x10^{-3}$. The study assumes buildings as a simply supported beam (no openings) with 6-40 m length, with L/H=1 and modelled as an isotropic beam with E/G = 2.6. The ratio L/H=1 is conservative and these results are valid for L/H>1 as well. In several studies, such as Burland et al. (1977); Boscardin & Cording (1989); Son & Cording (2005), negligible damage is defined as hairline cracks of less than about 0.1 mm. Van Staalduinen et al. (2018) state in their report that minimum crack width in masonry visible to the naked eye is approximately 0.1 mm.

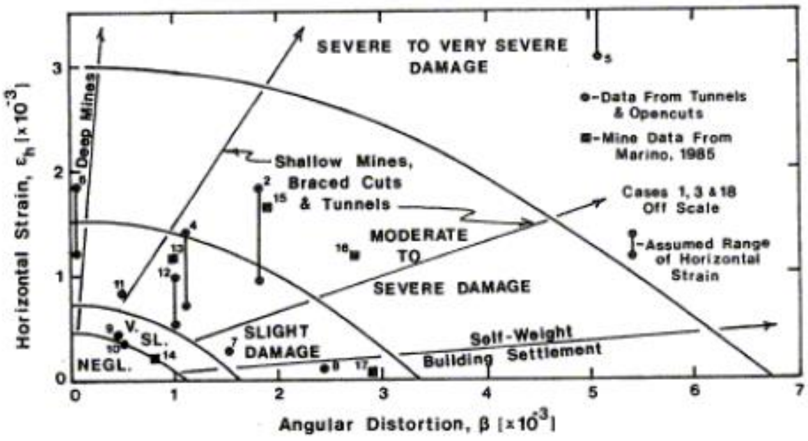

Figure 9 Relationship between angular distortion and horizontal strain Boscardin & Cording (1989)

In Figure 9, both the horizontal strain and the angular distortion as a result of the ground movement must be used together to assess building damage. This can be explained as follows (Figure 10). As an example, the threshold for the horizontal strain inside the building is assumed to be $0.5x10^{-3}$ (given in dashed line). If there is no external relative rotation at foundation level, the allowed external horizontal strain is equal to $0.5x10^{-3}$ (point on vertical axis). As the relative external rotation increases this induces an additional internal strain in the building (indicated with the green arrow in the graph). Then the allowable external horizontal strain becomes less (indicated with the blue arrow). In this manner, Boscardin and Cording (1989) compute the allowable external horizontal strain as a function of external relative rotation, which results in the lowest quarter "circle".

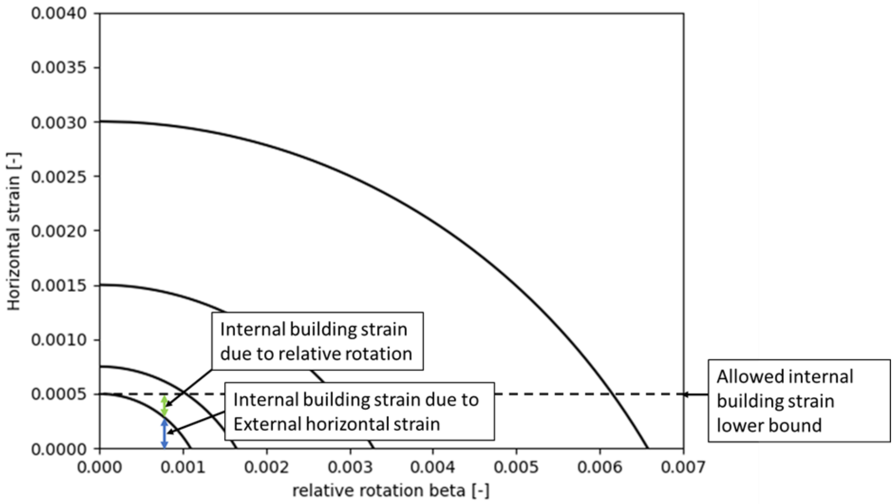

Figure 10 Explanation of the different components related to the horizontal strain and the angular distortion defined by Boscardin and Cording (1989)

The research of Boscardin and Cording (1989) was later updated by Son and Cording (2005) who give limiting tensile strains for different damage categories as in Table 3. In this study, with few changes from Boscardin and Cording (1989), the damage criterion has been described and updated to a generalized state of strain damage criterion. This damage criterion is based on the state of strain at a point, which is not dependent on L/H, E/G, and the position of neutral axis. In Figure 11, the critical tensile strain limits are classified based on field observations, physical model tests, and numerical parametric studies. This study was later extended by Son & Cording (2020) which focuses on estimating building damage and distortion in 3D structural distortion conditions.

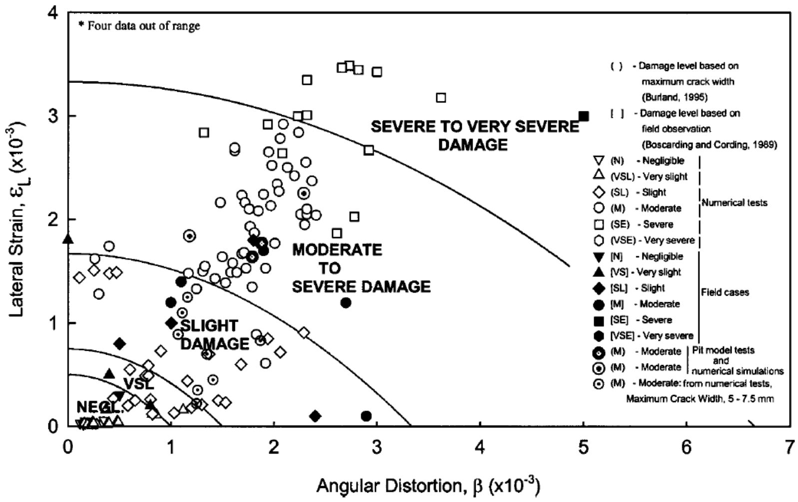

Figure 11 Comparisons between damage estimation criterion and damage levels resulting from field observations, physical model tests, and numerical parametric studies Son and Cording (2005)

Table 3 Summary of limiting tensile strains for damage categories Korff (2009)

Category of damage	Normal degree of severity	Approximate crack widths (mm)	Limiting tensile strain (%)	
		(Burland et al 1974)	(Son + Cording 2005)	(Boscarding+Cording 1989), (Burland 1995)
0	negligible	<0.1	5,00E-04	5,00E-04
1	very slight	0.1 - 1	7,50E-04	7,50E-04
2	slight	1-5	1,67E-03	1,50E-03
3	moderate to severe	5-15 or several cracks ≥3	3,33E-03	3,00E-03
4	severe	15-25, depends on number of cracks	> 3,33E-03	>3,00E-03
5	very severe	> 25, or large number		

According to van Staalduinen et al. (2018), van Sambeek (2000) gives corresponding threshold values for horizontal strain of $0.5\text{x}10^{-3}$ and an angular distortion of $0.8\text{x}10^{-3}$ below which damage is negligible. This value is already found in Kratzsch (1974) who defined the limit for horizontal strain below which damage is negligible in the order of $0.5\text{x}10^{-3}$.

Boone et al. (2001) summarizes the critical strains at the onset of the cracks for different types of structures as given in Table 4 taken from Korff (2009).

Table 4 Summary of critical cracking strain data Boone (2001); Korff (2009)

Test Conditions	**Mode of Deformation**	**Critical tensile strain**
Brick buildings with L/H>3	Tensile from flexure	$0.5x10^{-3}$
Full scale frames with brick in-fill	Diagonal-tensile	$0.81x10^{-3}$ to $1.37x10^{-3}$
	Shear approximation	$1.6x10^{-3}$ to $2.7x10^{-3}$
Hollow tile & clinker block, brickwork	Shear distortions	$2.2x10^{-3}$ to $3.3x10^{-3}$
	Diagonal-tensile	$1.1x10^{-3}$ to $1.6x10^{-3}$
Full scale brick walls with supporting concrete beams, 1.2<L/H<3.0	Tensile from flexure	$0.38x10^{-3}$ to $0.6x10^{-3}$
Concrete beams supporting brick walls	Tensile from flexure	$0.35x10^{-3}$
Fibreboard or plywood on wood frame	Shear strain	$6x10^{-3}$ to $16.6x10^{-3}$
Gypsum/fiberboard/plaster on wood frame	Shear strain	$3.7x10^{-3}$ to $7x10^{-3}$
Structural clay tiles with cement-lime mortar	Shear strain	$1x10^{-3}$
Clay brick with cement-lime mortar	Shear strain	$1x10^{-3}$ to $2x10^{-3}$
Cement-lime mortared concrete blocks	Shear strain	$1x10^{-3}$
Core samples of brick and mortar (*)	Tension	$0.01x10^{-3}$ to $0.1x10^{-3}$
Full scale brick walls in field test	Tension	$0.2x10^{-3}$ to $0.3x10^{-3}$
Re-evaluation of full scale wall panel tests	Principal tensile	$0.2x10^{-3}$ to $0.3x10^{-3}$

(*) Core samples tested under tension give lower values compared to the evaluated full scale test or field observations, see also Table 2. These direct-tension experiments reveal the tensile strain at which cracking begins and, because of the nature of the test, the onset of cracking also corresponds to total failure. This shows that even though microcracks may develop in the masonry material at a lower strain early on, these are not identified as damage in most other studies.

Giardina (2013) and COB (2012) provide an overview of assessment criteria used in practice for subsidence with a focus on damage to buildings as a result of construction work (construction pits, tunnels) and with a focus to foundation restoration in the Netherlands. Giardina (2013) develops an improved damage classification system (based on finite element models), which takes into account the parameters influencing the structural response to settlement, like the non-linear behaviour of masonry and soil-structure interaction. Based on finite element models, Giardina (2013) also demonstrates that with slow deformations of masonry with deflection ratio smaller than the criterion of $0.5x10^{-3}$, cracks with a width smaller than 0.5 mm may occur (Figure 12).

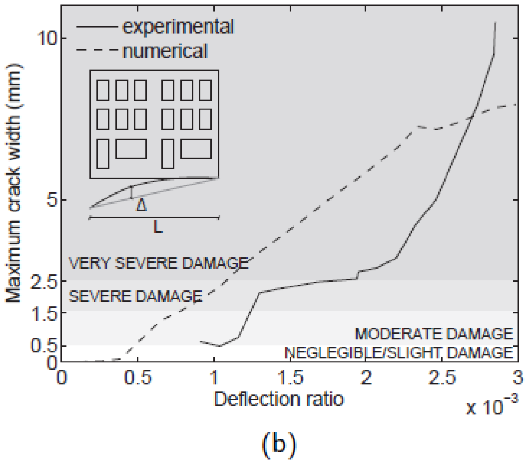

Figure 12 Maximum crack width vs. applied deflection ratio: experimental and numerical results Giardina (2013)

In the project of van Staalduinen et al. (2018), based on literature, deformation criteria due to subsidence in the deep and shallow subsoil are proposed as an elongation (strain) of $2x10^{-4}$ and an angular distortion of $4x10^{-4}$.

According to van Staalduinen et al. (2018), laboratory tests Giardina (2013); Jafari, et al. (2017) show that elongation at which the extremely absorbable bending tensile stress occurs in masonry can be much lower, in the order of $1x10^{-4}$. However, these laboratory results are related to the onset of microcracks, which are usually not noted as damage in practice due to their invisibility. Also the laboratory tests were conditioned to have weaker masonry so damage growth could be studied in the test setup. Compared to these laboratory tests, the criteria mentioned in Boscardin & Cording (1989), van Sambeek (2000), Kratzsch (1974) and Son & Cording (2005) thus imply higher acceptable strains. Thus, the criteria used in practice apparently accept a slight exceedance of the allowable stress in the masonry. At micro level, some form of damage may already have occurred in a building, while it is not yet visible to the naked eye in the form of microcracks van Staalduinen et al. (2018).

Although the studies that have been investigated mostly provide information on masonry, some information was also found on other types of buildings and materials. Several studies provide information on frame buildings (concrete, steel and timber), bridges, earth retaining structures or buildings in general. Meyerhof (1953) focuses on the onset of cracking of solid brick, clinker and clay block infilling panels in cased steel frames. Wood (1958) provides the results of tests on encased steel frames, encased steel frames with brick infilled panels, and brick or block walls without encased steel frame. Burland et al. (1977) apply the set of damage criteria for plaster and brickwork or masonry. Meyerhof (1982) provides limit values of relative rotation for open steel and concrete frame buildings (Figure 8). The study of Day (1990) defines the threshold value of angular distortion for cracks in gypsum wall panels and for structural damage of the wood columns and beams. Bozozuk (1962) reports the results of experiments on walls of various materials (Table 2). Boone et al. (2001) provide critical strains at the onset of the cracks for different types of structures. Burland and Wroth (1974) also focuses on the onset of cracking of the reinforced concrete supporting beams. These limits are higher than given for unreinforced load bearing walls (of e.g. masonry), which are therefore assumed to be the most vulnerable type of construction given. This indicates that when criteria for unreinforced load bearing walls are met, this would also meet the criteria for steel and concrete frame buildings as well as for other materials.

3.2 Chosen criteria and threshold values

Based on more than 25 scientific studies that have been reviewed within the scope of this project, the most common criteria for damage caused by foundation movements which are found are angular distortion (β) and horizontal strain (ε). The approach first defined by Boscardin and Cording (1989), later refined by Son and Cording (2005) is well accepted internationally in order to assess damage to masonry buildings caused by these foundation movements, e.g. by subsidence. Based on our literature review, it is concluded that masonry structures can sustain smaller distortion than frame structures (concrete, steel and timber) before a visible crack occurs. According to the reviewed studies, threshold values for other materials, such as plaster, gypsum, clay tiles or concrete, are greater than the one defined for masonry, as explained in Section 3.1. Therefore, the limits defined by Boscardin and Cording (1989) and Son and Cording (2005) for masonry will be considered for defining a threshold value for negligible damage to buildings in general.

For the purpose of defining a lower bound criterion, and based on all the literature that has been studied, it is proposed to further limit the allowable strain to 0.2×10^{-3} instead of 0.5×10^{-3} which was given by Boscardin and Cording (1989) and Son and Cording (2005). This value of 0.2×10^{-3} is the lowest value found in the literature for the strain below which damage is negligible. This lower allowable strain is chosen by taking into account the buildings with a relatively high percentage of openings which were not considered in Boscardin and Cording (1989). The Groningen building stock contains such buildings with larger opening percentage and therefore this value 0.2×10^{-3} is most appropriate as the threshold. Using the method by Boscardin and Cording (1989) and Son and Cording (2005) this lower strain thresholds leads directly to a lower allowable angular distortion at the buildings' foundation level as explained in Figure 10.

The chosen lower bound is illustrated in Figure 13, where the dotted line represents this lower end criterion. If the combination of horizontal strain and angular distortion is within the lower left area of the graph (underneath the dotted line), damage to buildings caused by these distortion and strain levels can be excluded.

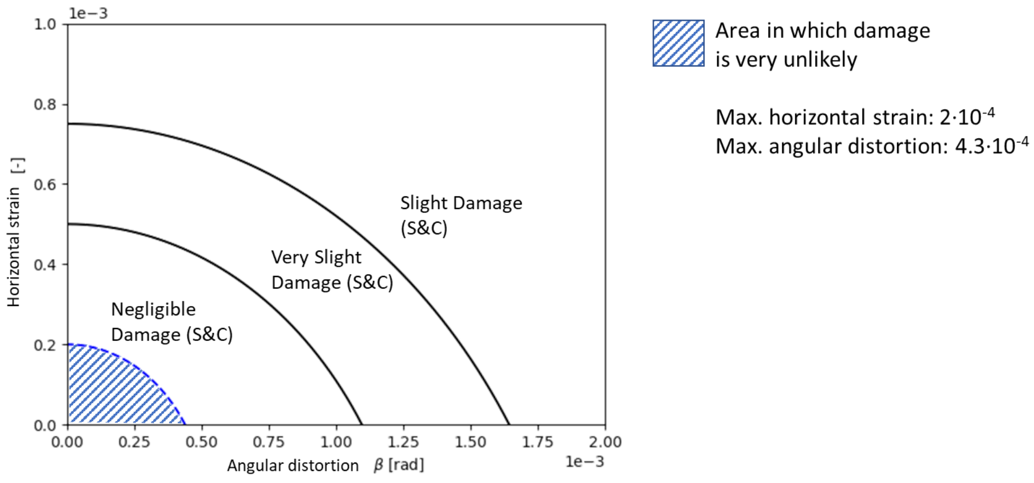

Figure 13 Illustration of area in which damage is very unlikely (represented by dashed area) for the combination of horizontal strain and angular distortion.

4 Conclusions and Recommendations

4.1 Conclusions

In this document, the results of a literature survey are presented of the state-of-the-art for assessing damage in buildings induced by subsidence. The main types of damage, as well as the causes and indicators of damage are analysed. An extensive literature overview is provided on the criteria that are used to assess damage to buildings. Although the majority of the studies focus on masonry, other building materials are also assessed to define a lower bound criterion for building damage. These studies provide information on different building types and materials, such as plaster, gypsum, structural clay tiles, fiber board, plywood, also frame buildings (concrete, steel and timber), bridges, earth retaining structures or (new / old) buildings in general. The results of these studies indicate that the limits for masonry are stricter than for concrete and steel structures as well as for other materials.

Eventually, a choice has been made regarding the criteria and the threshold values for structures that will be used within the scope of this project to assess the possible effects of subsidence.

Based on this overview, the most common criteria are found to be angular distortion (β) and horizontal strain (ε). It is concluded that the approach defined by the study of Boscardin and Cording (1989), which was later refined by Son and Cording (2005), is well accepted for the assessment of damage to buildings. Considering a conservative approach, it has been decided to further limit the allowable strain in buildings. Therefore, the threshold value is defined as 0.2×10^{-3} instead of 0.5×10^{-3}. This lower value of 0.2×10^{-3} is chosen considering buildings with a larger percentage of openings than considered by Boscardin and Cording (1989) and Son and Cording (2005; 2020), which is the critical situation for damage initiation. This lower allowable strain also leads to a lower allowable value for the curvature at the buildings' foundation level.

4.2 Recommendations

Based on the outcomes of this study it is recommended to use figure 13 to define the lower bound criterium for onset of damage caused by subsidence.
If observed values of strains and angular distortion fall outside the indicated area, it is recommended to further study the behaviour of structures with respect to subsidence effects. For observed values within the indicated area, it is very unlikely that damage to buildings will occur.

5 References

Arcadis, 2013. *Samenvattend Onderzoek Hoofdoorzaken Gebouwschade in het bodemdalingsgebied,* sl: Nedmag.

Base, G. D., Read, J. B., Beeby, A. W. .. & Taylor, H. P. J., 1966. An investigation of crack control characteristics o f various types of bar in reinforced concrete beams. *Cement and Concrete Association,* Volume Research Report 18.

Bjerrum, L., 1963. *Allowable settlement of structures.* Wiesbaden, Deutsche Gesellschaft für Erd und Grundbau, Proceedings of the European Conference on Soil Mechanics and Foundation Engineering.

Boone, S. J., 2001. *Assessing construction and settlement-induced building damage: a return to fundamental principles.* London: Underground Construction.

Borsje, H. & De Richemont, S., 2011. *Methodiek voor onderzoek naar oorzaak van gebouwschade - versie 2,* sl: TNO.

Boscardin, M. & Cording, E., 1989. Building response to excavation-induced settlement. *Journal of Geotechnical Engineering,* 115(1), pp. 1-21.

Bozozuk, M., 1962. Soil shrinkage damages shallow foundations at Ottawa, Canada. *The Engineering Journal,* Volume 45 (7), pp. 33-37.

BRE, 1995. *Assessment of damage in low-rise buildings.,* sl: BRE Digest Concise reviews of building technology, BRE.

Brinkman, J., 2016. *Invloed van bodemdaling door zoutwinning Nedmag op bebouwing,,* Delft: Deltares.

Burhouse, P., 1969. Composite action between brick panel walls and their supporting beams. *Proc. Instn. Civ. Eng.,* Volume 43, pp. 175-194.

Burland, J., Broms, B. & de Mello, V., 1977. *Behaviour of foundations and structures.* Tokyo, Proceedings of the IXth Intern. Conf. on Soil Mech. and Found. Eng..

Burland, J. & Wroth, C., 1974. *Settlement of buildings and associated damage.* Cambridge, SOA review, Conference on settlement of structures.

CEN, 2007. *EN 1997-1 Eurocode 7: Geotechnical design - Part 1: General rules,* sl: sn

COB, 2012. *Aanbevelingen voor het ontwerpen van bouwkuipen in stedelijke omgeving,.* sl:sn

CUR, 1996. *Building on soft soil,* sl: Dutch Centre for Civil Engineering Research and Codes.

Day, R., 1990. Differential movement of salb-on-grade structures. *Journal of Performance of constructured Facilities, ASCE,* Volume 4(4), pp. 236-241.

De Vent, I., 2011. *Prototype of a diagnostic decision support tool for structural damage in masonry.* Delft: TU Delft.

Giardina, G., 2013. *Modelling of settlement induced building damage.* Delft : PhD dissertation, TU Delft.

IGWR, 2009. *Richtlijn voor het onderzoeken en beoordelen van bestaande funderingen op houten palen of staal,* sl: Ingenieursbureau Gemeentewerken Rotterdam,.

Jafari, S., Rots, J., Esposito, R. & Messali, F., 2017. Characterizing the material properties of Dutch unreinforced masonry. *Procedia engineering,* Volume 193, pp. 250-257.

Korff, M., 2009. *Deformations and damage to buildings adjacent to deep excavations in soft soils - literature survey,* Delft: Deltares.

Kratzsch, H., 1974. *Bergschadenkunde.* Berlin: Springer.

Mainstone, R. J., 1971. On the stiffness and strengths of infilled frames. *Proc. Instn. Civ. Engrs., Suppl. IV,* pp. 57-90.

Meyerhof, G., 1982. Limit states design in geotechnical engineering. *Structural Safety,* pp. 67-71.

Meyerhof, G. G., 1953. Some recent foundation research and its application to design. *Structural Engineer,* Volume 31, pp. 151-167.

Netzel, H. D., 2009. *Building response due to ground movements.* sl:PhD thesis, TU Delft.

Polshin, D. & Tokar, R., 1957. *Maximum allowable non-uniform settlement of structures.* London, Proceedings 4th Int. Conference On Soil Mechanics and Foundation Engineering.

Pruiksma, J., 2001. *Vervorming van de bovengrond door NEDMAG zoutwinning en schade aan bebouwing,* Delft: GeoDelft.

Ricceri, G. & Soranzo, M., 1985. An analysis on allowable settlement of structures. *Riv. Ital. Geotec.,* Volume 4, pp. 177-188.

Sadgrove, R., 2014. Why do buildings crack?. *BRE,* Volume DG 361.

Shafie, E., 2008. *Effect of building stiffness on excavation induced displacements.* Cambridge: PhD dissertation, University of Cambridge.

Skempton, A. W. & McDonald, D., 1956. *The allowable settlements of buildings.* sl, Proceedings Institution of Civil Engineers part III, volume 5(No. 50): 727-768..

Son, M., 2003. *The response of buildings to excavation-induced ground movements.* PhD thesis: University of Illinois at Urbana-Champaign.

Son, M. & Cording, E., 2005. Estimation of Building Damage due to Excavatioin-Induced Ground Movements. *Journal of Geotech. and Geoenv. Engineering.*

Son, M. & Cording, E., 2020. Estimation of building damage in a 3D distorting structure to tunnel and underground excavation-induced ground movements. *Tunnelling and Underground Space Technology,* Volume 97.

SWD, 1998. *Basisrapport Casco-funderingsonderzoeken Panden in de 19e–eeuwse gordel,* sl: Bureau P/A, Stedelijke Woningdienst Amsterdam (SWD).

van Sambeek, L., 2000. *An introduction to subsidence over salt en potash mining facilities.* Texas, Mining Research Institute, Fall 2000 Meeting.

van Staalduinen, P., Terwel, K. & Rots, J., 2018. *Onderzoek naar de oorzaken van bouwkundige schade in Groningen,* sl: TU Delft.

Wood, R. H., 1958. The stability of tall buildings. *Proc. Insti. Civ. Engrs.,* Volume 11, pp. 69-102.

Zhang, L. & Ng, A., 2005. Probabilistic limiting tolerable displacements for serviceability limit state design of foundations. *Geotechnique,* 55(2), pp. 151-161.

Zhang, L. & Ng, A., 2007. Limiting tolerable settlement and angular distortion for building foundations.. *Probabilistic Applications in Geotechnical Engineering,* pp. 1-11.

6 Signature

Delft, February 2021

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