Monitoring the Combined Effects of Induced Earthquakes and Climate Change on a Heritage Building in Groningen

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Abstract. Heritage buildings are often subjected to loading conditions that they were not exposed to in their earlier life span. Induced earthquakes in non-seismic regions caused by energy exploitation activities, or strains in the ground that are caused by the climate changes, are new phenomena that alter the usual loading situations for historical buildings.

In this paper, monitoring results of a historical building in Groningen (Netherlands) in case of induced seismicity as well as climate change effects has been presented. Long-term monitoring results, detected cracks and relevance of the monitoring data are discussed. In the special case of Groningen, weak and agricultural soil properties dominate the structural response in the region. The gas extraction activities caused a soil subsidence in the giant Groningen Gas Field, resulting decameters of settlement in the entire area, thus an increase of the ground water level in respect to the ground surface. This is the reason why the heritage structures in the region are more vulnerable to soil-water-foundation interactions caused by climate change as compared to the time these heritage structures were constructed. The ground water monitoring as well as the interaction of soil movements with the structural response become important. The study presented here suggests ways on how to effectively monitor historical structures subjected to induced seismicity as well as harsh climate effects at the same time.

It was shown here that the newly developed cracks on the structure were detected in a very narrow time window, coinciding with extreme drought and a small induced earthquake at the same time. One explanation provided here is that the soil parameters, such as shrinking of water-sensitive soil layers, in combination with small earthquakes, may cause settlements. The soil effects may superimpose with the earthquake effects eventually causing small cracks and damage. The effects of the climate change on historical buildings is rather serious, and structures on similar soil conditions around the world would need detailed monitoring of not only the structure itself but also the soil-foundation and ground water conditions.

Keywords: Heritage Buildings · Induced Earthquakes · Monitoring · Climate Change

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1 Introduction

Heritage structures are subject to various structural threats. In the case of Groningen in North Netherlands, for example, induced earthquakes impose threat to the heritage structures in addition to the environmental and climate-related issues.

Groningen is a large gas field and is being exploited since 1963. In the recent years, there have been more than 1,300 registered small-magnitude earthquakes, the largest of which was ML 3.6 in 2012 [1]. Groningen has turned into the spearhead of the research related to induced seismicity in recent years as it is the most intensely populated area in the world with many induced earthquakes. A list of recent research on the Groningen earthquakes can be found in [2] as well as in [3].

Protection of the heritage buildings from various effects has become even more difficult with the changing climate conditions. It almost is a consensus that the climate change will have severe impact on the world heritage. Several studies report the effects of the climate change on the heritage structures, from the perspective of changing environmental conditions but also the increased risk of natural hazards such as heath waves, floods and extreme rains [4–7].

This paper presents monitoring results from Fraeylemaborg, a heritage structure from North Netherlands. Fraeylemaborg is a noble house built inside a manmade lake in Slochteren, south of Groningen. It is located in an estate. The house dates back to the 14th century and reached its current form at the end of the 18th century. The structure was built in the 14th century as a house, a defensive dwelling, and grew into an impressive residence by an influential resident. After 1670 the two wings were added giving its U-shaped shape (Fig. 1). Following change of owners and a major restoration in 1973, Fraeylemaborg became a museum.

The paper uses the seismic and environmental monitoring system installed at Fraeylemaborg, combining the induced seismicity and climate change effects for explaining the cracks appeared on the structure in the summer of 2018. The results show that a monitoring system considering also the environmental parameters, such as ground water depth and meteorological data, becomes vital if a detailed analysis of the climate change effects are sought. The paper presents, for example, that the 2018 summer was a harsh year with extreme drought affecting the heritage structure in question. There was a severe drought and a sudden rain in mid-August, which demonstrated itself as cracks on the structural system, probably combining with the effects of the small earthquakes as well.

2 Fraeylemaborg in North Netherlands

Fraeylemaborg is surrounded by a manmade lake with a water depth of approximately 1.5 m. The main structure has a U-shaped plan consisting of a partial basement, two floors, roof attic and a clock tower (Fig. 1). The construction material of the load bearing walls is clay brick with additions of stones in the corners, and metal ties and timber elements in the roof. The brick-walls are solid and of varying thickness (40 to 80 cm) in different parts of the structure and the bricks are laid in English bond pattern. Six bricks, retrieved during the previous restoration works, were subjected to compression tests.

Their compressive strength was 0.25 MPa in average (standard deviation 0.052 MPa) [8], a value considerably lower than those obtained from recent experimental studies [9–12] on clay bricks currently used in the construction in Groningen. These findings highlight the low capacity of the masonry walls of the structure and raise the question of structural vulnerability.

The timber elements of the floors are poorly connected to each other and thus a diaphragmatic action is not ensured. Numerous steel anchors exist at various locations of the structure in order to connect the floors to the peripheral walls. The structural elements of the roof are timber beams transferring the loads to the peripheral walls.

The structure went through a serious renovation in 1973, including structural interventions in the retaining walls outside as well as in the floors and connection details inside the building. There is no written report from that period, but photographs of a private archive have been used to identify the nature of the structural interventions. Bricks from damaged masonry walls were removed and replaced, however the cause of these damages are unknown. The foundations at the perimeter of the building are also made of brick masonry. They were repaired by using new bricks. A reinforced concrete floor was added above the main entrance, right below the tower. Steel profiles were added at the base of the tower to stabilize it. Finally, all masonry retaining walls were repaired, missing parts were added, and new steel anchors were placed behind the walls.

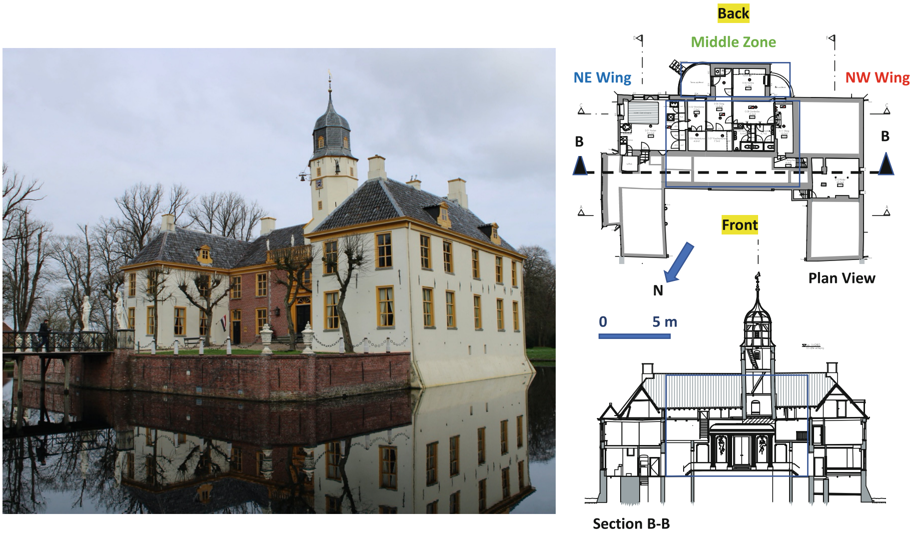


Fig. 1. Fraeylemaborg (left) and its plan views (right).

3 Induced Earthquakes Affecting the Structure

There have been 32 earthquakes above magnitude ML 2.0 since 2012, in epicentral distances 3 to 23 km to the structure. Structural damage and cracks were observed in an increasing pace between 2014 and 2015. There was a serious restoration in 2015, which included interventions on the front façade of the structure where extensive cracks had been formed, while the cracks on the internal walls of the structure were repaired during the 2017 restoration. These cracks were mostly vertical and partly horizontal and diagonal, concentrated on the Northwest (NW) wing as well as on the front façade of the middle zone (see Fig. 1) of the structure. The cracks were as wide as a couple of millimetres in some regions. The plaster was removed, and the damaged bricks were replaced during the 2015 restoration.

The structure received more cracks in mid-August 2018. In search of the reason of these new and surprising cracks, an investigation on the monitoring data started. The shape and location of these cracks, shown in Fig. 2, did not resemble earthquake-related cracks because most of them were in vertical direction, with a larger width close to the base and smaller widths in higher elevation, while diagonal X-shaped cracks, the standard sign of in-plane masonry response to lateral earthquake loading, were not observed in the structure. The existing cracks reminded more the type of cracks caused by soil movements rather than by seismic loads. After the end of restoration, the manifestation of new cracks in the summer of 2018 in the most problematic part of the structure, i.e. the façades of the NW wing, was puzzling given the relative limited seismic activity in that period. However, after monitoring results have been combined together with finite element analyses and observations in the field, it was possible to reach a plausible explanation for the old (prior to 2015 and in 2015) and the new (summer 2018) damage in the building, as discussed further in this paper. More details are given in [8 and 13].

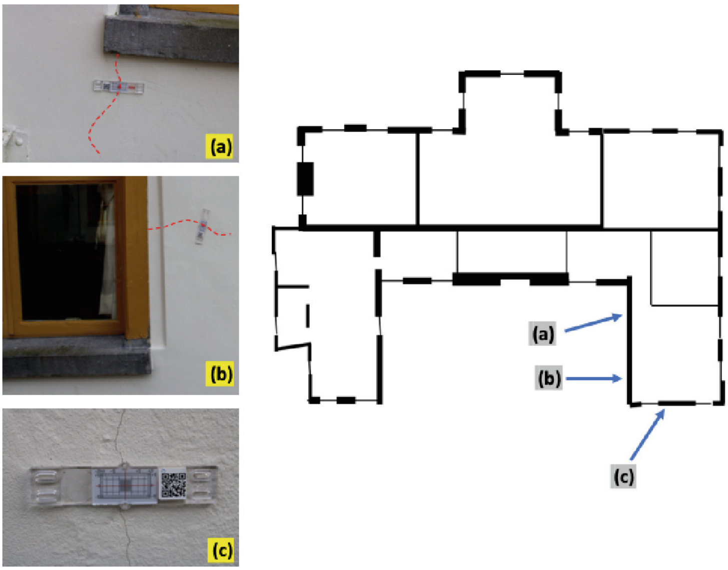


Fig. 2. Minor cracks appeared in August 2018 (left) and their locations on the plan view (right).

The monitoring data, which consist of the acceleration data collected from the structural health monitoring system as well as the tiltmeter data coming from the cellar of the structure, have been analyzed for understanding the relevance of the earthquakes to the observed cracks. Although an earthquake event usually precedes the appearance or deterioration of cracks in the tiltmeter data, it is difficult to establish such an association from the overall plot of tilts. However, focusing on event-based results, better explanations can be obtained that highlight the difference in monitoring when small induced earthquakes are concerned. Two earthquakes were selected for a closer look: the 8th of August 2018 Appingedam earthquake with magnitude ML 1.9 and an epicentral distance of 12 km from the site in the Northeast of the Groningen gas field, and the 22nd of May 2019 Westerwijtwerd earthquake of ML 3.4 in an epicentral distance of 16 km from the site in the Northwest of the gas field. After the former, some damage was reported (see Fig. 3), while the day of the latter, as well as a week before and a week after, the crack rulers were photographed, with no movement or additional crack being detected. Considering that the purpose of this paper is to discuss the different methodologies needed for understanding seismic events in combination with climate change effects, these two earthquake events constitute a good comparative example as explained below in detail.

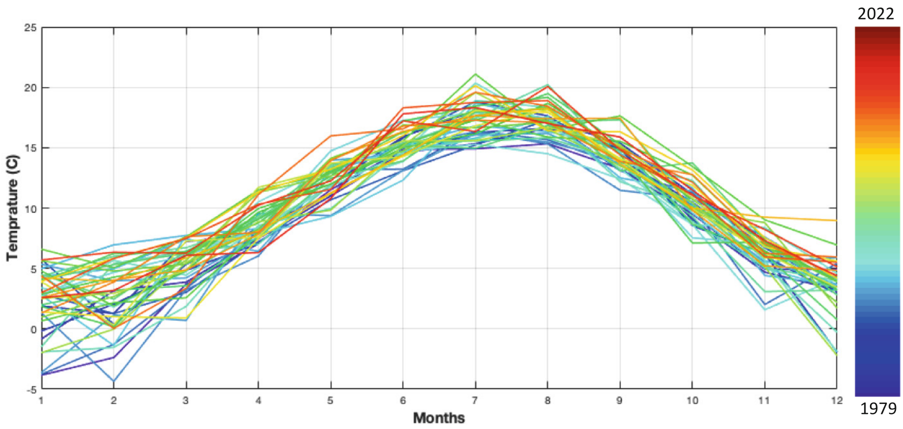
The Appingedam earthquake (ML 1.9) was recorded by the accelerometers in the building (the full dataset is available online in open source by [18]). The time-histories at the basement, at the roof level on the two wings of the structure, as well as at the tower, are given in Fig. 8. The presented time-histories are baseline corrected and bandpass Butterworth filtered between 0.1–20 Hz. The motion was detected by the sensors although the maximum accelerations do not exceed 1 cm/s^2 (0.001 g). The tower amplified the input motion approximately 3 times, while the structure itself amplified it 2 times, both still remaining well below the horizontal acceleration levels that would normally cause any cracks.

4 Climate Change Effects and Their Relevance to Damage

Here the results from a single meteorological station in Slochteren, North Netherlands, where Fraeylemaborg is situated, are presented to better understand the local effects of the global warming and climate change. A trend in increasing average temperatures can be seen both figures in Fig. 3 for Slochteren. The average temperature has increased more than 2 degrees Celsius in the last 44 years. This increase has inevitable effects on rain rate, ground water table, soil humidity and eventually on the soil-foundation-structure interaction.

It should also be noted that the gas extraction activities caused a soil subsidence in the giant Groningen Gas Field, resulting decameters of settlement in the entire area, thus an increase of the ground water level in respect to the ground surface. This is the reason why the heritage structures in the region are more vulnerable to soil-water-foundation interactions as compared to the time these heritage structures were constructed. The reason of the damages that occurred in mid-August 2018, thus, may well be the harsh climate effects. In order to understand this, all monitoring data have been scrutinized as explained below.

The tiltmeter data, in combination with the accelerometers data from 8th of August 2018 earthquake (see Sect. 2), indicate that the foundation of the NW wing and the soil beneath have played an important role in the cracks that appeared in August 2018. It is difficult to explain the exact contribution of soil-related parameters since fundamental



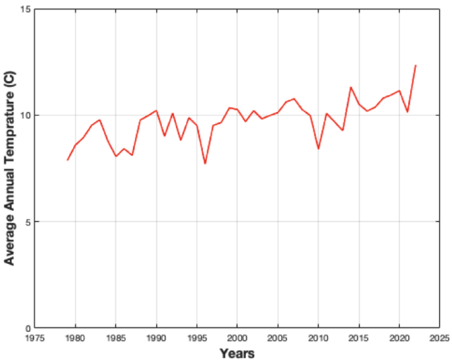


Fig. 3. Monthly and annual change of the average temperature in the Slochteren meteorological station, North Netherlands.

data, such as the potential existence and the situation of piles, are unknown. Speculation about possible explanations regarding the soil effects are provided below.

As mentioned before, soil properties of the site were determined by using 8 boreholes and CPT tests. The two boreholes right next to the NW wing, where the damage concentration occurred, revealed a different soil profile in the first 6m from that in the NE side. NE side is mostly sand, while NW side consists mostly of loam, silt and clay (pot clay or "potklei" in Dutch) layers dominating in the first 2–6 m. More details on the structural and soil properties can be found [13] (Fig. 4).

The shrinking or/and the expansive behavior of the clay layers may be responsible for the structural cracks considering that clay soils can be responsive to moist cycles. Certain clay types are expansive soils, and early studies have identified potential problems for the foundations sitting on such soils [14]. When shrinking or swelling, certain clay soils apply a level of pressure to the environment, including structural foundations [15]. Specific clay types can also crack due to lack of water, up to some meters of depth [16],

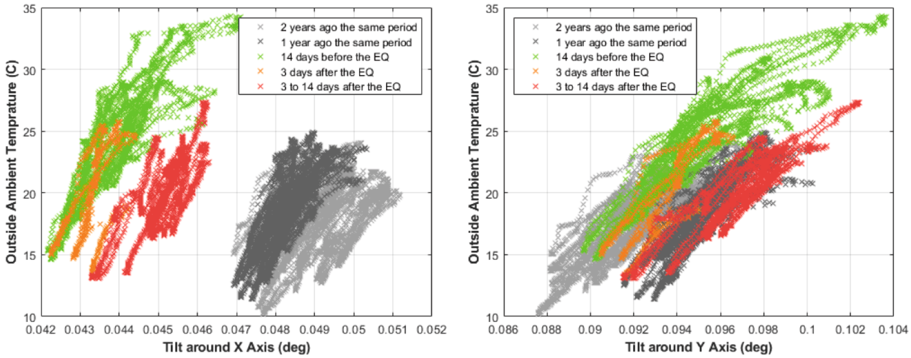


Fig. 4. Tilt angles recorded +−15 days from the earthquake and last two years before.

decreasing the bearing capacity substantially. There are several regions with similar soils in the Netherlands [17].

Part of the NW wing of the structure sits on pot clay layers of several meters thick, a highly impermeable and stiff clay material. Swelling tests conducted on pot clay layers in the region[1] show that expansion can be limited to less than 1% in volume, but considerable shrinking is possible when the layers dry out completely. Due to the high impermeability water is hindered and thus the expansion is limited. Shrinking, however, can still be an issue for pot clay.

Another possible explanation may be related to the piles under the foundation. Due to the weak soil conditions in the region, it is almost impossible to construct any structure without piles. It is thus expected that Fraeylemaborg, being a relatively heavy structure as compared to the modern ones, would also be sitting on some sort of pile grid. Because of the historical identity of the building, access to certain parts is not allowed, thus the existence of the piles is not confirmed. Nevertheless, the common construction practice in the region dictates that some wooden piles must exist under the foundations. If this is the case, especially the old wooden piles need to be under water for protection from deterioration. It is known that draught causes adverse effects on wooden piles in historical buildings.

The scenarios for relating the soil response to structural cracks given above are based on water conditions. One may consider that the structure is surrounded by a manmade lake thus the soil layers are always under water, however this is not granted since the dominating layers are highly impermeable clays and thus the soil layers right beneath the foundations may still be dry in case of draught.

The ground water movement in the same days of the damages was also investigated. The rain rate is plotted in Fig. 5 together with the ground water measurements, in order to decouple possible ground water raise due to the earthquake action. The ground water is monitored in the monitoring well with approximately 4 m total depth. Due to the monitoring setup, the sensors used and the sampling rate (2 h), the monitoring data can provide only slow movements of ground water and not the changes during the seconds of the earthquake motion.

[1] Personal communication with Onno Dijkstra from Fugro in Groningen.

Figure 5 reveals a very dry period from mid-March to mid-August in 2018, reported as a disastrous period for the farmers in the region due to the extremely dry soil. It was also witnessed in soil drilling works that the clay layers were hard and dry due to lack of rain for a very long period. As seen in Fig. 5 the start of the rainy period coincides with the earthquake (in fact, a couple of days later). When other rainy periods in the data are examined, tiltmeter data are found mostly insensitive to the rain. Furthermore, the out-of-the-ordinary movement (i.e. change in tilt baseline) in the tiltmeter data starts right after the earthquake, proving that the movement is related to the earthquake motion too.

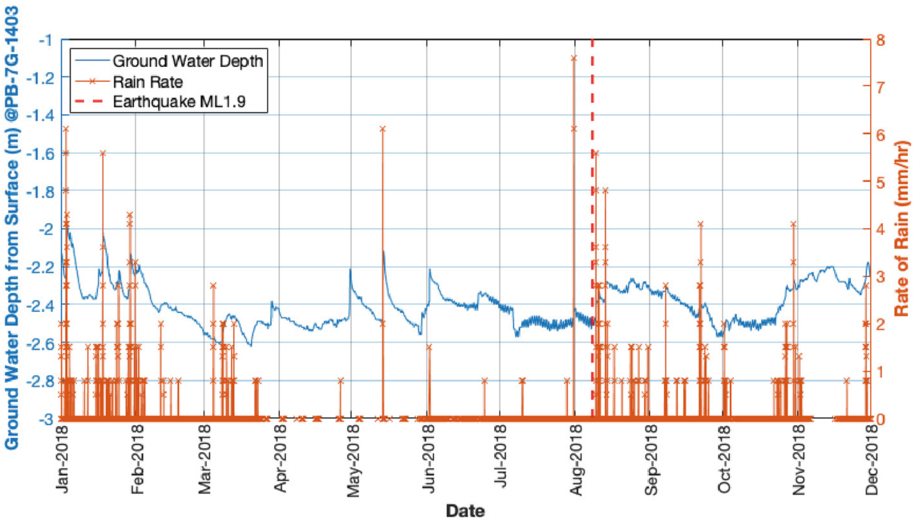


Fig. 5. Ground water depth from the surface and the rate of rain in 2018 in the monitoring well 600 m south of the site.

The structure has light floors and a light timber roof, while the bearing walls are relatively thick. In-plane cracks would not be expected in this structure during such small earthquakes. One possible explanation is that the soil parameters such as shrinking of water-sensitive soil layers and/or response of piles, in combination with a small distant earthquake, caused settlements and/or increased the stress levels on foundations. In other words, the soil effects might have superimposed with the earthquake motion and caused the small cracks. Nonlinear finite element analyses have also been run for supporting this scenario, as presented in [8 and 13].

5 Conclusions

Based on all available data, the damages at Fraeylemaborg are studied. It was concluded that the in-plane cracks observed in mid-August 2018 would not be expected in this structure during a couple of small earthquakes that were recorded around that period. One explanation could be that the soil parameters, such as shrinking of water-sensitive soil layers and/or response of piles, in combination with a small distant earthquake, caused settlements and/or increased the stress levels on foundations. The climate effects might have superimposed with the earthquake effects causing small cracks.

It is shown in this paper that the climate-related effects may seriously affect the heritage structures. This is because the climate change effects alter the environmental parameters, such as rain rate and temperature, which have indirect effects on the soil-foundation interaction as well as on the structural response of the heritage structures.

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