Innovative Ways of Dealing with Existing Problems

How to reliably Assess the Cause of Damage of Masonry Structures in an Area with Man-induced Earthquakes?

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Innovative ways of dealing with existing problems: how to reliably assess the cause of damage of masonry structures in an area with man-induced earthquakes?

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Abstract

Groningen, a province in the northern part of the Netherlands, suffers from earthquakes because of gas drilling. The residential building stock in Groningen was not designed for these loads. Over the years a lot of smaller and larger damage has developed, possibly - but not necessarily - caused by the effects of gas drilling. Delft University of Technology was asked by the Dutch government to come up with a method to reliably assess the cause of damage of masonry structures in Groningen. This paper discusses the developed approach for reliably assessing the causes of failure of masonry structures in earthquake-prone areas and the way innovative monitoring techniques were applied.

Keywords: forensic engineering, damage investigations, masonry structures, cracks, monitoring techniques

1 Introduction

In 1959, natural gas was discovered in the soil in Groningen, a province in the northern part of the Netherlands. Soon after this, extensive gas exploitation commenced. After approximately 1990 however, small induced earthquakes as a result of this exploitation were observed, increasing in frequency and magnitude. The largest earthquake until now occurred in 2012 in Huizinge, with a magnitude of 3.6 on the Richter scale and a maximum peak ground acceleration of 0.087 g.

The current residential building stock in Groningen consists to a large extent of masonry houses. During design and construction of these residential buildings, earthquake actions were not taken into account. Dutch masonry structures usually have slender masonry cavity walls of clay brick or calcium silicate and many of these buildings have strip foundations. They are prone to damage such as cracks.

Figure 1: Damage inspection of masonry house in Groningen

Over the years a comprehensive dispute developed between citizens and gas extracting companies regarding the cause of damage. Citizens had the opinion that the majority of damage was related to the gas drilling activities, while gas extracting companies pointed out that, especially at some distance of the epicentre, the influence of earthquakes was often too small to result in damage and that in the majority of cases other causes were determining, like shrinkage and soil settlements.

Many consultants, for both parties, prepared reports regarding the cause of damage. These reports were sometimes based on limited amount of information, and consultants often seemed to jump into conclusions, without proper substantiating their findings. It should be noted that consultants often needed to prepare these reports, in a period when the understanding of the influence of seismic vibrations, especially of low velocities, still was very limited in The Netherlands. Experts were searching for 'typical earthquake damage', based on internationally available literature on natural earthquakes, but in reality often rivalling explanations for 'this 'typical earthquake damage' could easily be formulated. Furthermore, the damage reports usually focused on single causes of damage, while it would be more realistic to include multiple-cause scenarios in the analyses.

Therefore, Dutch government asked Delft University of Technology (DUT) to elaborately determine the cause(s) of damage of a limited set of houses with complex damage, in order to improve understanding of the influence of mining activities (not limited to gas drilling) in relation to other potential causes. For every selected house in this project one or more earlier investigation reports by consultants were available. The focus of the research needed to be on causality and accountability of individual causes. In order to do so, DUT first needed to develop an investigation method. This paper explains the various aspects of this method and will provide an answer to the main research question: to what extent do innovative methods and techniques contribute to reliable damage investigations?

2 General approach

Forensic investigations usually follow steps of orientation, data collection, hypotheses generation, hypotheses testing and findings reporting [1,2]. The generation of hypotheses (for the causes of failure and sequence of events) and testing of these against the available data, is similar to a general scientific approach [3]. To determine the causes of damage of masonry structures in Groningen, DUT used this general scientific approach as a starting point.

Damage is regarded in this study as a visual manifestation of a lack of performance of a building structure or parts of it. It is not necessarily a lack of safety. Three types of visual damage are included: cracks, permanent deformations (in plane or out of plane without loss of integrity) and permanent displacements (like rotation or settlement) exceeding limits of acceptance.

Elaboration of the general scientific approach was done by implementing insights from two more specific methods focused on damage in masonry.

First, TNO (Netherlands Organisation for Applied Scientific Research) drafted an investigation method in 2009 to determine the cause of cracks of masonry structures [4]. This method included the collection of data regarding context, building and damage. It used a comprehensive list of possible causes as starting point. By analysing context and building characteristics the list of possible causes could be reduced through falsification. Consequently, it was needed to verify which of the remaining causes could adequately explain the observed damage. The method includes the possibility of setting up scenarios consisting of one or more individual causes. The approach of TNO, using falsification based on building and context characteristics, together with the possible list of causes, has been included in our approach.

Second, de Vent developed a diagnostic decision support tool to determine the cause of structural damage in masonry [5,6]. In this approach de Vent focused on symptoms, causes and context conditions. For symptoms of damage she set up a list of 60 commonly found damage patterns (with position, orientation and course of the crack/settlement). Given specific context conditions, she identified that every symptom of damage could only be caused by a limited number of causes. For our purposes, the method of de

Vent was adapted, to match the list of possible causes according to TNO. It appeared that de Vents method could not be used to effectively decrease the list of possible causes given a damage pattern, because every damage pattern still resulted in a long list of potential causes. However, the starting point to first carefully examine the symptoms of damage and classify the damage in predefined damage patterns, has been included in our approach.

Figure 2 presents the basic overview of the approach as used by DUT for the research in Groningen.

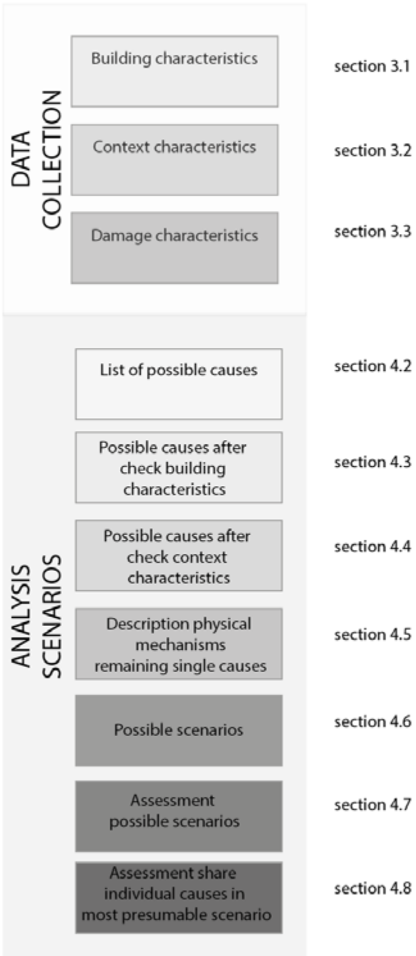

Figure 2: Overview of investigation approach and sections where steps are discussed in this paper

In the following sections the various steps of the approach are discussed and the way they were implemented in this project.

3 Data collection

3.1 Building Characteristics

For the building characteristics various information needed to be collected, like:

- Age of the building
- Function of the building
- General set-up of the building
- Applied building materials and construction method
- Description of structure, foundations and load bearing behaviour
- Level of maintenance
- Proneness to leakage, rain water accumulation
- Changes/renovations after construction
- Other specifics that might be relevant

The building characteristics were retrieved from the original inspection reports that were available, by requesting files from local Building Authorities, by observations during our own inspections, and interviews with house owners. It was acknowledged that foundations could play a major role in the damage, and information regarding the foundations was usually lacking. Therefore, for a large number of houses it was decided to determine the actual appearance of the foundations by digging until the foundation was made visible.

3.2 Context Characteristics and use of innovative techniques

For context characteristics the following information needed to be collected:

- Soil characteristics
- Ground water levels
- Presence of trees in proximity of building
- Observed settlements of area
- Presence of road and rail traffic
- Presence of building and industrial activities
- Calamities (like collision, explosion, lightning, fire)
- Maximum vibration velocity by earthquakes

The majority of data was collected from local authorities, water boards, google earth (for position of trees and position of roads and rail way tracks), own inspections (where soil samples were taken) and interviews with house owners. The collection of two types of data is highlighted here, because innovative ways were used.

First, it was considered relevant to know the rate and amount of settlement of at the position of the buildings. In many areas though, these settlements had never been measured. A relatively new technique provides opportunities to measure settlements of an area: Interferometric Synthetic Aperture Radar (InSAR), where geometry changes of the earth's surface are observed from an orbiting satellite. The precision of these geometry change measurings is in the order of millimetres. Since radar images have been archived since the early 1990's there is a potential for retrospective analysis [7]. As there are some limitations of these techniques (for instance, the necessity to have adequate reflection points on a building or the surroundings), the technique can be regarded as a valuable complementary component to other analyses.

For every house in this research the InSAR analysis was done and information about the settlement and changes in settlement over the last 10 years were listed. Furthermore, information about the horizontal strains could be derived. Complementary to this InSAR analysis, the level of the bed joints was measured in situ, for every house, which data provides a valuable indication whether or not a building was subject to large unequal settlement.

Second, to be able to give an assessment on the influence of earthquake vibrations on damage, it was necessary to know the maximum experienced vibration velocity at foundation level of a house. In the region of Groningen an elaborate sensor network is present. TNO has installed a system with about 240 sensors in buildings. KNMI has a system with about 50 stations with 3 sensors (Accelerometers or geophones) on surface level [8]. Some of these sensors recorded over 1400 earthquakes during approximately 30 years. As these sensors are usually at some distance from the houses under study, a modelling approach with attenuation curves was used to estimate the probability of exceedance of a maximum velocity threshold at ground floor level of the houses under study. This state of the art information regarding vibration velocities was not available to earlier investigations.

3.3 Damage Characteristics

For damage characteristics the following items were documented:

- Position of damage
- Moment of first detection of damage. Development of damage over time
- Deformation in-plane and out-of-plane
- Skewness of floor/building

And for cracks:

- Length, width and depth of cracks (depth usually not recorded)
- Displacement in the crack (in or out of plane)
- Crack width over the length of the crack
- Damage pattern, possible relation between damages (e.g. inner and outer face of a wall)
- Dirt in cracks. Erosion and color of crack surface (indications of age).
- Finishing or repairs applied on cracks

While the initial data collection was based on the available inspection reports, it appeared that a large number of reports only showed photos of the damage and very limited descriptions. Sometimes, especially indoors, it was impossible to determine the position of cracks from the reports. In these situations additional inspection was performed to determine the position of cracks. In the data reports, the plans of the building were provided with location of the cracks and additionally wall drawings were made with the position of the cracks, based on the available pictures and descriptions, highlighting possible relations between damages.

Furthermore, in a large number of houses the levelness of the floors was measured.

4 Analysis

4.1 Investigators

As the work load for the analysis of approximately 70 buildings with in average 30-40 damages was high, it was decided that the investigation team needed to be extended with external experts. DUT remained responsible for the methodology and quality assurance of the implementation of the method and external experts would perform the actual analysis. These experts were, supervised by DUT members who had visited the buildings. Independent checking was performed by a group of internal and external experts.

4.2 List of possible causes

Based on the initial list of TNO [4] the following categories of causes were identified:

- Insufficient resistance of the structure (initial, renovation, aging)
- Overloading due to use (normal use, renovation/extension)
- Overloading due to vibrations (road or railway traffic, seismic, industrial or building activities)
- Overloading due to accidental loads (impact/collision, explosion, rain/snow, storm, lightning)
- Obstructed (hindered) deformations (initial, rebuilding/ extension, aging/ deterioration)
- Imposed deformations (initial, rebuilding/ extension, corrosion, tree roots or branches)
- Autonomous settlements (unchanging loads)
- Settlements because of load changes on sub soil (rebuilding, extension, different function, new adjacent buildings, excavation)
- Settlements because of changes in subsoil (local changes water level, vibrations by traffic, activities or earthquakes)

This list was used as a starting point for possible causes for every case.

4.3 Falsification with building characteristics

Based on building characteristics, it had to be checked if one or more of the possible causes could be eliminated. Some examples:

- If a house has a sloped roof, the cause of rainwater ponding can be eliminated
- If a house has no metal elements, corrosion can be excluded
- If a house was not renovated or extended, all causes related to these events can be eliminated

4.4 Falsification with context characteristics

Based on context characteristics, it had to be checked if one or more of the possible causes could be eliminated. Some examples:

- If the maximum measured seismic vibration velocity is lower than 0.5 mm/s, it can be assumed that seismic vibrations did not cause the damage, because this value is of the same order of magnitude as vibrations caused by normal use of a building.
- If no trees are found in the proximity of the building, imposed deformations by tree roots and local changes in ground water levels by trees can be falsified.
- If no records of explosions or impacts are reported (especially by house owners), it can be expected that these did not play a role (although the house owner, might not know what happened 30 years ago).

It is clear that in these situations possible causes can be excluded.

4.5 Verification of possible causes: description physical mechanisms

After the falsification with building and context characteristics, it was of importance to verify whether the remaining possible causes might have caused the damage. An integral analysis had to be made for every remaining cause how it could physically cause the damage. If such an explanation could not be given, than these causes could be falsified. If for instance a local crack only in one brick near a gutter at 3.0 meter height was analysed, it could be assumed that settlements cannot physically cause this local crack.

To determine causality of an event one should look for (after: [9,10]):

1. An event A
2. That is prior to the occurrence of damage
3. That is such that if event A had not occurred, the damage would not have occurred (all other things being equal)
4. And if event A had occurred in other similar circumstances, the damage would have occurred

It is important to check the necessity of event A for explanation of the damage (requirement 3). This requirements is also called the 'sine qua non' principle. This can be tested with the 'but for' test, where one imagines if the damage would have occurred if the event had not occurred. Furthermore, it is needed to check if event A is sufficient to explain the damage. For instance, a small vibration can trigger damage or can amplify damage (meets requirement 3), but cannot explain the damage without another contributing factor (if it had occurred in similar circumstances, but without another possible cause, damage would not occur: does not meet requirement 4). In such situations, there is a need to combine events in a scenario.

4.6 Listing possible realistic scenarios

From the remaining single causes, scenarios were composed. A scenario is a sequence of events that provides an explanation for the observed damage. In our study the order of events was not included, for reasons of efficiency (so no difference was made if there was first a seismic vibration and then a hindered deformation, or the other way around). Furthermore, repetition of events was not included both for reasons of efficiency, as well as because currently there is a lack of knowledge on the real behaviour after for instance repetition of small vibrations.

In this research, scenarios are combinations of single causes. If all combinations were included, for a situation with 4 single causes, already $2^n-1=15$ scenarios can be composed. Therefore, it was decided to only include scenarios, that were deemed realistic. Realistic scenarios should meet the requirements for causality.

4.7 Causality: Determining most presumable scenario

To determine the most presumable scenario, it needs to be assessed what scenario (that meets the requirements regarding causality) is likely to best explain the damage. The likelihood of a scenario is dependent on the (prior) probability of the scenario to occur, and the (conditional) probability of damage given that the scenario occurred. The experts could choose one scenario to be the most presumable, to choose for two scenarios that were both most presumable or to point out that they did not have sufficient information to determine the most presumable scenario. The experts were stimulated to include earthquake vibrations in the most presumable scenario, unless it was evident that these could not play a role. This was done, because part of the focus was on the role of earthquake vibrations. If the role appeared to be (very) small, this would be revealed in the next step, accountability.

4.8 Accountability: Determining share individual causes in most presumable scenario

Finally, the experts were asked for the most presumable scenario to identify the relative share of the individual causes in the damage. The relative share in the damage was operationalized as the relative share in the maximum strains of the masonry. It is not easy for the investigators to give an indication of this share, without any guidance. Therefore, the investigators were provided with a framework for the relative share of earthquake vibrations, based on the maximum velocities, the maximum crack width, and the presence of other determining causes. This framework was based on some non-linear models of single walls with openings. These walls were subjected to various types of vibrations, settlements and imposed/hindered deformations. It appeared that smaller vibration velocities (<5 mm/s) had a one or two orders of magnitude smaller influence on the strain than realistic settlements or hindered deformations.

With this preliminary framework for an indication of the influence of the vibrations due to earthquakes, it was possible for the investigators to indicate the relative share of the various causes in the most presumable scenario.

The research team was aware of a lot of uncertainties regarding actual loads, material characteristics and resulting strains in the masonry. On the other hand, it was desired to give an impression of the importance of various influencing factors. To acknowledge the high level of uncertainty, the influence of the various single causes was finally rephrased on a qualitative scale (from very small influence, to very high influence). Furthermore, in every step the investigators had the possibility to conclude that they were not able to come to a conclusion based on the available information and knowledge.

5 Evaluation of the method

At the time of writing of this paper, the phase of data collection is almost finished and experts have started the analysis. The majority of data could be collected, although additional inspections and interviews were needed, because of a lack of information regarding the damage in the original inspection reports. For elaborate falsification of context conditions, a lot of information needed to be collected from various sources. Now the analysis has started, it becomes apparent that the method is useable and leads to useful results.

This extended method is far more time consuming than general intuitive approaches, where after data collection investigators intuitively come to conclusions, often based on experience combined with some analysis. However, it is believed that this method also provides more reliable outcomes.

Reliability of the method means that it will lead to similar results when the method is repeated or when the assessment is performed by another investigator. Several measures were implemented to increase reliability.

First, a structured, stepwise approach was followed with a clear distinction in phases of data collection and analysis. Authors believe that acceptance of the outcomes of an investigation by housing owners will be improved by a verifiable approach, with transparent and explicit steps. Second, elaborate data collection was done, where all data wa presented in a separate data collection report, stating clearly the various resources. Furthermore, the falsification of possible causes by building and context conditions was made explicit. By using the template during the analysis phase, the choices during this phase were made explicit and verifiable.

To reduce the 'inter investigator variability' it was needed to spent a lot of time in explaining the experts the format of investigation, during start of the analysis phase. During this introduction, experts asked for a clear template, where the major information of the data collection phase was included, and where the possible influence of earthquakes was already given at the start of the analysis (based on maximum measured velocities). By using this template, by discussing unclear issues and by checking (more severe checking during the start of the analysis) it is believed that reliability of the analysis is higher than with traditional, more intuitive approaches.

This elaborate investigation shows that to come to more reliable conclusions regarding the cause of damage, a lot of data needs to be collected and elaborate analysis needs to be done. At the start of the investigation it is not always clear what information is relevant and what information is not.

Authors are aware that in many situations investigators are not provided with the same amount of time as this investigation team was. In many situations investigators are urged to come to quick conclusions based on a limited amount of data. During the first phase of our project, we checked if our elaborate method would give similar results as a more intuitive method. In many situations, the main outcomes (and main categories of causes) were properly addressed, although some possible (minor) explanations were missed. It is recommended to decide in what situations an elaborate approach is needed and in what situations a 'light' version can be used.

6 Conclusions and recommendations

The main research question of this paper was: to what extent do innovative ways contribute to reliable damage investigations? The INSAR data was interesting additional information, but was outperformed in relevance by the combination of measuring the levelness of the bed joints, taking samples of the soil at the position of the house and digging to determine the real state of the foundation. However, INSAR in some cases had the useful advantage of allowing looking back in time. Furthermore, information about the horizontal elongation of soil could be derived based on INSAR data.

The calculation of the maximum values of the velocities of earthquakes based on attenuation curves was indispensable for this research. Without this information no reliable conclusions could be drawn.

At the end, it can be concluded that, for a thorough investigation, still a lot of strenuous, time-consuming hands-on activities are needed, that can be supported by some more innovative tools.

It is acknowledged that the level of investigation-efforts in practice somehow needs to match the apparent level of damage. Therefore, new affordable ways of monitoring need to be explored, like placing reflectors on edges of roofs to provide more reliable reflection points for satellites. Furthermore, it might be possible to cast sensors in the masonry (or additives in the mortar) providing data regarding strains and stresses (see e.g. www.kcaf.nl). Finally, a way of periodic self-monitoring of damage by housing owners who use a web based application to upload data regarding damage in a central system, might be an affordable and sufficiently reliable way to monitor progression of the damage.

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