OPTIMIZING SEISMIC ASSESSMENT AND RETROFIT: A MULTI-LEVEL APPROACH

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Abstract: *The Groningen region in the Netherlands has been experiencing subsidence phenomena and induced seismicity due to gas extraction. Since 1991, seismic events have been recorded, causing damage claims to buildings and discontent among the population. The 2012 Huizinge earthquake of magnitude 3.6 led to public debate, and in 2014, a reduction in gas extraction began. As 90% of buildings in the region are made of masonry and were not designed to withstand seismic loads, a campaign to assess their seismic vulnerability began parallelly to the reduction in gas extraction. The aim was to identify any critical issues and reinforce damaged and potentially vulnerable buildings. Groningen region is populated by a heterogeneous stock of structures exposed to a spatial and time dependent seismic hazard within the gas field area. Therefore, to reduce time and costs associated with seismic assessment and optimize retrofit interventions, a multi-level assessment procedure has been proposed. This step-by-step approach starts with simpler analysis methods and moves to more complex analysis methods associated with different levels of accuracy and precision. A core feature of the proposed multi-level procedure is the use of a dynamic tool which allows the non-linear time history assessment of out-of-plane loaded masonry elements. This method leads to a better estimation of the seismic behaviour of these elements with an overall reduction of the retrofit needed. This is a key factor since in recent years the retrofit demand is mainly governed by out-of-plane failures as a result of the decrease of seismic input, related to the reduction of gas extraction. In conclusion, the proposed multi-level procedure not only offers a practical approach to assess the seismic vulnerability of buildings in the Groningen region, but also allows for an efficient use of resources by investing computation time only for the more vulnerable structures and avoiding overestimation of the retrofit needed. This method ensures the safety of the population in the event of future seismic events while minimizing unnecessary costs and efforts.*

1 Introduction

A significant problem in recent years has greatly affected the Groningen region in the Netherlands. This issue involves earthquakes that are caused by extracting gas on land. Groningen, one of the twelve provinces of the Netherlands, is situated in the northern part of the country and it is home to approximately 570,000 inhabitants. The province is uniquely positioned above the largest natural gas field in Europe and the tenth largest in the world, making it a vital player in the country's energy sector.

The discovery of this vast gas field dates back to 1959, and extraction operations commenced in 1963. The recoverable volume of gas was estimated at approximately 2,800 billion cubic meters, with 60% of this resource already extracted. However, the extraction process has not been without consequences, as since 1991, induced seismic events have been plaguing the Groningen region. These seismic events have been directly linked to the ongoing conventional gas extraction activities in the area. Over the past three decades, as reservoir extraction continued, the frequency and magnitude of these seismic events have been steadily increasing, posing significant challenges to the safety and stability of the region.

The risks associated with these induced seismic events and the growing discontent in the population, prompted the Dutch government to take action. In 2014, they initiated a policy to gradually reduce gas extraction, and in parallel, in 2016, an extensive campaign was launched to evaluate the seismic vulnerability of existing structures within the Groningen region. The objective was to identify structural weaknesses and reinforce buildings as necessary.

To this end, the Dutch government asked NEN (i.e., Royal Netherlands Standardization Institute) to create guidelines specifically for designing and evaluating buildings in the Groningen region, tailored to the typical structures there. These guidelines, known as NPR 9998 (NPR), focus on ensuring the structural safety of buildings facing earthquake loads in the region. The NPR guidelines have undergone several updates over the years to incorporate new developments and findings regarding the seismic performance of buildings. The latest version was released in December 2020.

Assessing and reinforcing a significant number of structures within a limited timeframe brought about several complex challenges. Key among these challenges included a shortage of engineers and building companies, a tight schedule, the need to minimize disruptions for the local population, cost considerations, and the necessity to avoid unnecessary retrofitting for economic and sustainability reasons.

2 The Groningen building stock

The province of Groningen, though mostly rural and less crowded than other parts of the Netherlands, is globally important due to being densely populated over a natural gas field. With over 250,000 buildings, around 150,000 of which are regularly occupied, the region is primarily residential, with over 80% of structures being homes, often terraced or semi-detached.

Historically, the Groningen region and the Netherlands as a whole were not known for their susceptibility to tectonic earthquakes. Consequently, local building stock primarily consisted of structures designed to handle vertical loads and withstand wind forces, with limited lateral load-resisting capabilities, leaving them highly vulnerable to earthquakes. This seismic vulnerability has become a critical concern, given the increased seismic activity in the area.

Most of these buildings, more than 90%, are made of unreinforced masonry (URM). Residential structures, making up the majority of housing, fall into three main categories: independent buildings, terraced houses (common in the second half of the 20th century), and barn houses (i.e., buildings with attached barns) Figure 1 illustrates the different types of structures commonly found in the Groningen region.

Figure 1. Images of common residential building layouts in the Groningen region.

2.1 Walls

The primary lateral load-resisting systems in typical Groningen region buildings are URM walls, classified as either cavity or solid walls, constructed mainly with clay and calcium silicate brick units. The material properties varying depending on the year of construction, their mean values are summarised in Table F.2 of Annex F of NPR.

Cavity walls, used for thermal insulation, generally consist of two 100 mm thick masonry leaves with a 60 to 100 mm gap. Typically, the inner layer bears the vertical load, while the outer layer is non-structural and acts as an outer veneer. Though there are steel tie elements connecting the layers, they often lack sufficient strength for effective connection. This type of wall results being particular vulnerable since only the inner masonry leaf is load bearing and the outer leaf mainly acts as additional inertial mass.

Solid single-leaf walls are typically 210 mm thick for perimetral use and 100 mm internally. In some cases, thinner walls can be found with non-structural function, either 70 mm or 50 mm masonry walls could be observed in structural surveys. The reduced thickness of these walls increases vulnerability to lateral forces, especially those acting out-of- plane.

2.2 Foundations

Various foundation types are present, including shallow brick masonry strip footings, deep foundations (concrete or timber piles with concrete cap beams), and occasional pad footings. Masonry strip footings are typically 400 mm wide and 300 mm deep. Regardless of being shallow or piled, these foundations were not originally designed to withstand uplift or significant lateral forces.

2.3 Diaphragms

The type of horizontal diaphragm solutions is heavily influenced by the type of structure and its construction era. In older structures, such as detached houses in rural areas, timber floors with basic timber beams topped by planks are commonly found, exhibiting limited in-plane stiffness. Occasionally, if these structures underwent retrofit interventions, the timber diaphragms may feature one or two layers of oriented strand board (OSB) panels, resulting in increased stiffness.

In more recently constructed structures, particularly terraced houses, diaphragms are often realised using hollow core precast elements. Two main types of these elements can generally be distinguished: NeHoBo, which involves hollow brick units connected with cement mortar (common between the late 1950s and early 1980s), and pre-stressed hollow-core floors from the 1980s onward, which are often considered to be infinitely rigid. Furthermore, cast-in-situ reinforced concrete (RC) diaphragms can also be found in more recently built structures, and these elements can similarly be regarded as infinitely rigid in their respective contexts.

The in-plane stiffness of diaphragms is crucial for seismic response as it governs in-plane distortions and the coupling of lateral resisting walls. Properly assessing and determining the accurate value of in-plane stiffness in existing diaphragms, especially timber ones, is essential in order to choose the most appropriate type of analysis for seismic assessment.

2.4 Roofs

Roofs are often gabled or pitched, while flat roofs with concrete slabs or timber floors are less common. Although the roof itself is not a significant problem, it is important to consider that many of these roofs have a gable. The lateral forces that the roof transmits to the gable make the entire system vulnerable especially considering the significantly in-plane flexibility of timber roof.

3 Multi-level procedure

Sismica360, a consulting firm based in Pavia, Italy, specializing in civil and seismic engineering, has been actively engaged in significant projects related to the seismic evaluation and retrofitting of existing structures subjected to induced seismicity in the Groningen region since 2018. Sismica360 collaborated on these endeavours with two Dutch companies, EconStruct and A&I Seismic. The consortium's primary activities involved conducting surveys, assessments, and designing retrofit solutions for existing URM structures.

In early 2021, the National Coördinator Groningen (NCG), the organization responsible for coordinating seismic investigations of existing buildings, issued a directive to perform seismic assessments using Non-Linear Time History (NLTH) analyses instead of the previously standard Non-Linear Pushover (NLPO) analyses. This decision was primarily driven by the belief that employing NLTH analyses would help reducing the extent of retrofitting required.

The guidelines for engineers participating in the seismic assessment of existing structures in the Groningen region have undergone continuous changes since the initiation of the assessment campaign in 2015. The Dutch national guidelines NPR9998, initially introduced in 2015, were subjected to several revisions over the years. In terms of the overall capacity of URM structures, there has been a significant increase in ultimate displacement capacity. This increase has led to more structures aligning with code-based verification, especially considering that assessments up to that point primarily utilized NLPO analyses. Furthermore, the initial release of the guidelines in 2015 lacked a methodology for assessing local out-of-plane (OOP) failure. This aspect was introduced in 2017, initially allowing for the assessment of one-way-bending mechanisms. In 2020, this capability was expanded with the incorporation of a new methodology for evaluating two-way-bending failure mechanisms. The definition of earthquake loads has also been subject to updates over the years, initially to incorporate new seismic source models and later to reflect changes in the extraction scenario related to the cessation of gas extraction mandated by the Dutch government. Consequently, while there has been an increase in structural capacity, there has also been a reduction in seismic input. This has resulted in a general decrease in the number of structures not complying with the building code requirements and therefore an overall decrease of retrofit interventions.

The experience gained between 2018 and 2021 through the seismic assessment of hundreds URM structures in the Groningen region highlighted a trend where structures were predominantly globally verified using NLPO analyses. This trend was more pronounced especially in recent years due to the evolving code and seismic input requirements, eliminating the need for more time-consuming and costly NLTH analyses. However, the same trend did not apply to OOP assessments, a critical aspect for existing URM structures in the region. This is primarily due to the slenderness of URM elements, low axial loads, and the presence of cavity walls. These considerations underlined that the request for full NLTH analyses in the seismic assessment of URM structures in the Groningen area would have been exaggerated and it would have drained resources which would have been better spent in assessing more structures considering the limited number of available engineers.

In response to the NCG request to use NLTH for seismic assessments of existing URM structures, Sismica360 and its partner companies proposed a multi-level assessment procedure. This methodology was grounded in the notion that an initial assessment of an existing structure should employ a simplified method before resorting to more complex and time-consuming approaches. The former, characterized by a higher safety factor, tends to provide more conservative results, overestimating a structure's vulnerability. If a building fails to meet standards in the initial assessment, engineers can then transition to more advanced methods to refine the safety margin and gain a more accurate understanding of its vulnerability.

In the context of the Groningen earthquake issue, where limited engineering resources are available, such an assessment procedure could prove valuable by saving time and enabling the evaluation of a greater number of structures. The proposed multi-level assessment procedure comprises three levels, each addressing both global and local mechanisms. Global analyses consider the overall structural behaviour, assessing the loss of load-bearing capacity, while local assessments investigate the OOP response of individual masonry elements, including walls and parapets. Examining potential local OOP failures is crucial in seismic evaluations of URM structures, as the premature activation of such mechanisms could impede the structure from realizing its full global capacity and lead to local failures and structural collapse.

3.1 Level 1

The first level of the procedure involves higher safety factors, and it utilizes the less time-consuming types of analyses. At this level, NLPO analyses are applied to assess the seismic global in-plane structural capacity of a building, represented by the pushover capacity curve. It's important to note that for URM buildings, there are two types of NLPO analyses.

The first type involves analysing the entire building as a unique unit and it is suitable for structures with rigid diaphragms, such as those with reinforced concrete diaphragms or timber diaphragms reinforced with OSB panels if there are adequate connections between the boards and beams. The second type of NLPO analysis, termed single wall analyses, is employed when the floors are flexible. This flexibility, often found in existing URM buildings in the Groningen region, results in low in-plane stiffness, preventing the coupling of lateral resisting walls and the transfer of shear forces between different walls of the building. In such instances, each wall behaves independently, requiring NLPO analyses on each wall. The latter employs a tributary area method to determine seismic inertia and loads without applying any amplification of torsional phenomena, as specified by the NPR guidelines (paragraph G.9.5.3.1).

Once the structural capacity is computed, the seismic demand (i.e., the performance point) must be evaluated. Various methods can be utilized to calculate the seismic demand. The NPR specifies the use of the Capacity Spectrum Method (CSM) while discouraging alternative approaches. To compute the displacement demand, the necessary data include the capacity curve and the seismic input provided by the NPR Webtool, in the form of an elastic response spectrum. If the seismic displacement demand is less than the displacement capacity, the structure is deemed compliant with NPR standards from a global perspective.

The NLPO method discussed above should be combined with OOP (i.e., local) assessment methods to analyse the potential occurrence of local failures.

NPR in Annex H dedicate a specific section to present a simplified methodology for assessing OOP mechanisms. This method is known as the Non-Linear Kinematic Analysis (NLKA), it estimates the acceleration required to induce the collapse of a masonry element through predefined graphs. The acceleration value is then compared with the acceleration demand to determine whether the masonry element can withstand OOP forces. This assessment method is used to investigate one-way-bending mechanisms. Additionally, the Annex H provides a second methodology which assess two-way-bending mechanisms which is based on the Virtual Work Method and which is used to estimate the cracking resistance of URM panels. This second methodology is more complex, and it must be applied to elements not passing the NLKA assessment and which present at least one vertical restraint.

In Annex H, the NPR dedicates a specific section to introduce a simplified methodology for evaluating OOP mechanisms. This method, known as Non-Linear Kinematic Analysis (NLKA), estimates the acceleration necessary to induce the collapse of a masonry element using predefined graphs. The calculated acceleration value is then compared with the acceleration demand to determine whether the masonry element can withstand out-of-plane forces. This assessment method is primarily employed for investigating one-way-bending mechanisms. Moreover, Annex H introduces a second methodology for assessing two-way-bending mechanisms, based on the Virtual Work Method. This methodology is used to estimate the cracking resistance of URM panels. The second methodology is more complex and time consuming and NPR suggest applying to those elements not passing the NLKA assessment. The matter methodology can only be applied to elements presenting at least one vertical restraint.

If both the global (i.e., NLPO) and local (i.e., NLKA) verification methods meet the NPR standards, the multi-level procedure is concluded, and the seismic assessment is completed. However, if the structure is not deemed compliant, further levels are pursued.

3.2 Level 2

The second level of the procedure comes into play when the evaluated structure successfully passes the in-plane assessments but falls short during out-of-plane checks. In such instances, the outcomes of the global verification from Level 1 persist, while OOP loaded URM elements that do not meet the criteria outlined by NLKA are subject to evaluation through a dynamically calibrated Single Degree of Freedom (SDOF) tool known as "Trilly". This tool was purposefully designed and calibrated based on experimental tests conducted on URM panels akin to those present in the structures within the Groningen region.

This SDOF is based on the representation of the response of specific URM components as a mass/non-linear spring/dashpot system and it can successfully simulate the OOP dynamic response of single leaf and cavity walls, parapets, gable walls, roof systems and chimneys as presented in Tomassetti et al. (2018, 2019-1 and 2019-2). The SDOF equation of motion is solved adopting the Newmark linear acceleration-integration scheme implemented in the non-iterative formulation. This is, in essence, a local NLTH analysis.

The model was extensively validated in several works including comparison with respect to damped free-vibration responses of Sorrentino et al. (2008) trigonometric models for a parapet wall and a vertical spanning strip wall, see Tomassetti et al. (2018). A further validation of the model is given in Tomassetti et al. (2018) comparing the amplitude-dependant rocking period of free vibration with that derived by Housner (1963) in closed form.

The authors incorporated the application of the equivalent SDOF dynamic tool within the framework of Annex F of NPR9998 which outlines all the guidelines for conducting NLTH analyses. Trilly assesses the OOP response of a wall in terms of normalized displacement for a given accelerogram. This metric represents the ratio of the OOP displacement of the wall to the limit displacement, beyond which the wall would collapse. This limit displacement is dependent on the specific characteristics of the wall element, such as being a parapet wall or a vertical spanning strip wall. To introduce a safety margin, the authors decided to consider any wall with a normalized displacement greater than 0.8 as vulnerable to collapse. This decision aimed to account the absence of an inherent safety margin in the dynamic OOP assessment procedure. Additionally, the authors chose to use 11 input ground motions, following NPR9998's recommendations, and determined that a URM element would not pass the dynamic check if it exhibited a normalized displacement exceeding 0.8 for at least one of the 11 input ground motions. Despite NPR9998's guidance, the authors dismissed the option of employing an average response to the 11 ground motions for the OOP assessment procedure. This choice was influenced by the understanding that averaging the OOP displacement loses its physical significance when dealing with walls experiencing collapse.

It is essential to emphasize that Trilly can be employed for evaluating the OOP dynamic behaviour of URM panels situated either at the ground floor or at higher levels within the structure. In the former scenario, the SDOF tool is supplied with input ground motions as specified by NPR9998. For URM elements positioned at higher levels, the authors have devised an additional tool. The latter utilizes output data from NLPO analyses, including parameters such as the vibration period, failure type, and displacement profile across the height, to generate floor motions that consider structural amplification.

The second level, the most recurrently employed in practical applications, proves crucial. As previously highlighted, in recent years, many structures have generally met the code requirements at a global level but exhibited localized OOP failures. By combining NLPO analyses with localized NLTH analyses, the assessment process becomes more efficient. This method enables a targeted evaluation of the structure's critical aspects, offering time and resource savings compared to a comprehensive NLTH assessment.

3.3 Level 3

Finally, the last level is applied when the global verifications carried out with NLPO analyses are not compliant with the NPR guidelines. This level involves a full NLTH analysis of the structure from both global and local perspectives.

The global dynamic response of the buildings is evaluated using multi-degree-of-freedom (MDOF) finite element models based on the equivalent frame approach available in the TREMURI software Lagomarsino et al. (2013). The non-linear macro-element model implemented in TREMURI, described by Penna et al. (2014) and enhanced by Bracchi et al. (2017), enables a reliable simulation of the cyclic response of URM walls without imposing a heavy computational burden. This model accurately represents stiffness and strength degradation, incorporating the main masonry failure mechanisms: bending-rocking, shear-sliding, and their mutual interaction. These characteristics are in line with the requirements of the NPR. The numerical models are exposed to 11 sets of acceleration time histories (in three directions: x, y, and z) in line with the prescriptions of Annex F of NPR9998. The code-compliance of the structure is performed by verifying that the displacement demand for the input ground motions remains withing the limits imposed by the Dutch guidelines.

The TREMURI software does not allow the direct execution of OOP verifications for URM panels. Consequently, the local assessment employs the SDOF tool utilized in Level 2. In contrast to the preceding level, in the case of panels situated above ground level, the input ground motions utilized for OOP assessments are derived directly from the NLTH global analyses.

4 Insights from Sismica360's analysis of buildings in the Groningen region

Sismica360, in collaboration with its Dutch partners, has actively participated in the seismic assessment of buildings in the Groningen region since 2018. The multi-level procedure, presented in the above paragraphs, was implemented at the beginning of 2021 and it was applied starting in May of the same year, leading to the analysis of approximately 200 buildings to date. Most of these structures were detached houses or barn houses, with a smaller yet significant proportion being terraced houses. The majority of the assesses buildings were characterized by the presence of timber diaphragms composed of timber beams topped with timber planks (i.e., with low in-plane stiffness). Consequently, from a in-plane point of view, most buildings were analysed using single wall pushover analysis rather than global ones.

Out of the 200 structures seismically assessed since the spring of 2021 almost the totality of the buildings was found to be code-compliant from a global point of view. In rare cases, less than 5% of structure, a few walls were found to be non-code-compliant, but in such instances, the same wall was also not passing the local OOP verifications. Therefore, in terms of the multi-level procedure, the assessment was usually halted at the second level of the procedure, as conducting full NLTH analyses would not have yielded any substantial improvement. This led to the conclusion that there was no need for overall reinforcement (i.e., major reinforcement measure).

Concerning the OOP stability of masonry elements, the 200 structures assessed underlined some main trends. Generally, the most vulnerable elements according to the code-based assessment procedure, were gable walls. These elements, in typical Dutch houses are quite tall and slender, and in many cases are cavity walls where the outer leaf acts as additional mass without helping the overall stability. Additionally, these elements are located at the upper levels of the structure were a the seismic input in terms of acceleration is higher due to structural amplification. Other URM elements particularly vulnerable are walls spanning parallelly to the diaphragms loading direction, especially in case of perimetral cavity walls characterized by 100 mm thickness.

In the framework of the multi-level procedure it was observed that the application of the Level 2 (i.e., the use of the dynamic OOP assessment tool Trilly), allowed to significantly reduce the number of URM elements to be reinforced. A large number of elements not passing the NLKA assessment were then assessed using the NLTH approach and found to be passing the OOP check. As a results, it was necessary to prescribe retrofit interventions for a limited number of URM elements generally being gable walls characterized by large size (especially tall ones).

Within the context of the multi-level procedure, it was noted that implementing Level 2, which involves utilizing the dynamic OOP assessment tool Trilly, led to a substantial decrease in the quantity of URM elements requiring reinforcement. Numerous elements that failed the NLKA assessment were subsequently evaluated using the NLTH approach, revealing compliance with the OOP criteria. Consequently, retrofit interventions were only deemed necessary for a limited number of URM elements, primarily those comprising gable walls of considerable dimensions, especially in terms of height.

Previously, it was noted that in 2021, the NCG, the government agency responsible for seismic assessments in the Groningen gas field area, mandated the use of NLTH analyses for assessing structures. The rationale behind this decision was the belief that employing NLTH analyses would result in fewer retrofit interventions. However, based on our experience from evaluating 200 projects since spring 2021, the insistence on full NLTH analyses seems to be excessive, as it appeared unnecessary.

For in-plane seismic assessment, NLPO analyses have proven effective in verifying structures in nearly all cases. The few instances of unverified structures typically required localized intervention on a single wall, often susceptible even to out-of-plane issues. Implementing Level 3 in the multi-level procedure (i.e., full NLTH analysis) over the years has been basically unnecessary. Moreover, the associated time and financial costs for such analyses seemed disproportionately high compared to actual requirements.

It's important to emphasize that the time and costs linked to NLTH analyses are significantly greater than those associated with NLPO analysis. Additionally, not all engineers possess the necessary skills to perform NLTH analyses critically, and enforcing the use of such a powerful tool may lead to unreliable assessment results. Another consideration is that the level of detail required for proper NLTH analysis is much higher than that needed for simpler assessment methods. Consequently, incorporating NLTH analyses into seismic assessments would substantially increase the time and cost associated with the structural survey and inspection of the structures under evaluation.

The multi-level procedure has proven to be a very effective approach in assessments. Unlike conducting full NLTH analyses on all buildings, it allocates more resources to those that are most critical and vulnerable. The procedure has its key feature in employing a more detailed analysis method (NLTH) for assessing the most vulnerable (local) type of failure and employing simpler analysis methods (NLPO) for the less vulnerable (global) structural feature. This procedure helped to reduce costs and time needed for less vulnerable structures while increasing them for more critical ones. In 2022, even NCG has acknowledged the validity of a cascading approach and requested a procedure similar to the one proposed in this paper as an entry requirement in procurement competitions for project distribution.

The mentioned observation can be further elucidated by presenting the outcomes of three projects used as case studies. In Figure 2 (left), the seismic assessment results of three structures are depicted, illustrating the cost of seismic assessment (x-axis) plotted against the cost of the resulting retrofit intervention (y-axis). Different markers denote the three levels of the multi-level procedure: a circle for Level 1, a triangle for Level 2, and a square for Level 3. Notably, a significant reduction in retrofit cost is evident when transitioning from Level 1 to Level 2, despite a slight increase in engineering cost. Conversely, implementing a full NLTH analysis (Level 3) results in a marginal decrease in retrofit cost.

For the first case study, represented by the blue line in the left image, the right part of Figure 2 illustrates the cumulative costs of retrofit (blue) and engineering (grey) for the three assessment levels. It is notable that with Level 3, no retrofit intervention is recommended, but the cost of employing full NLTH analysis exceeds the combined engineering and retrofit costs associated with Level 2. This reinforces the notion that for structures like the one considered in the case study, which are abundant in the Groningen region, opting for Level 2 is more pragmatic than Level 3. Not only does Level 2 result in cost savings for engineering, but it also allows a reduction in assessment time. This efficiency is particularly significant in situations like Groningen, where a substantial number of buildings need evaluation, and there is a constraint on the availability of engineers.

It is important to emphasize that the retrofit costs indicated in Figure 2 pertain solely to the assessment results and do not include fixed intervention costs or costs related to interventions associated with pre-existing damage in portions/structural elements of the building. Additionally, engineering costs have been averaged based on experience gathered over the years working on projects in the Groningen region. Furthermore, it should be noted that the three case studies involve residential detached houses, and the aforementioned considerations may vary for specific buildings, such as historical structures, for which NLTH might be the only reliable option for seismic assessment.

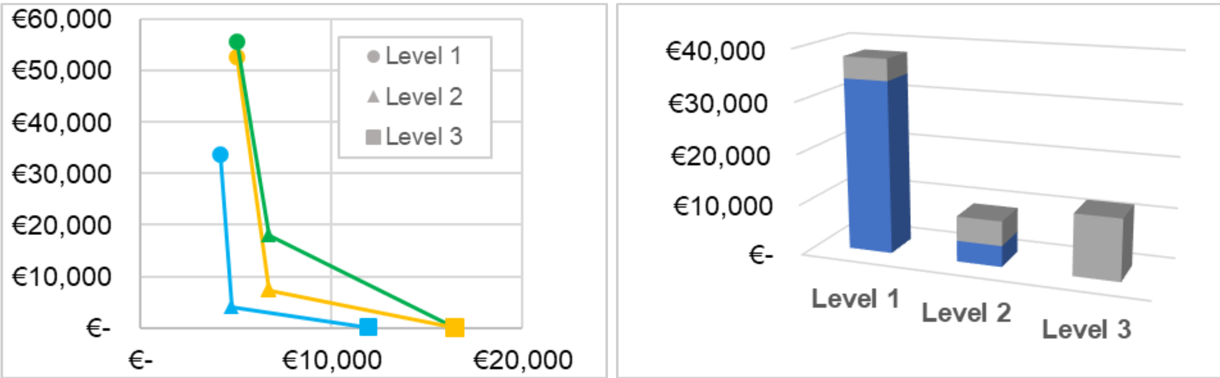

Figure 2. Depiction of engineering vs. retrofit costs for three cases study for the different levels of assessment (left) and impact of the engineering costs (grey) for case study 1 (right).

The efforts undertaken by Sismica360 in collaboration with its Dutch partners since 2018 have revealed additional critical aspects related to the management of the overall seismic assessment campaign. These aspects extend beyond those previously mentioned.

Typically, there has been a lack of systematic prioritization in both seismic assessments and retrofit interventions. Projects were often assigned without a clear and objective prioritization based on the vulnerability and seismic risk of individual buildings. Instead, decisions were made using unclear logic and criteria. The insistence on the necessity of full NLTH analyses has exacerbated the issue of prioritization compelling many engineering firms to invest significant resources, both in terms of time and money, in advanced methods for buildings that are minimally or not vulnerable. Consequently, resources were diverted away from genuinely critical structures where the application of more sophisticated analyses could have provided more substantial benefits.

Furthermore, the allocation of structures for seismic assessment was done in project batches that exhibited a considerable heterogeneity in composition. Within a single batch, there could be a mix of structures ranging from 100-year-old buildings to recently constructed ones, encompassing detached/barn houses, terraced houses, and historical buildings like churches. Examining a single project batch didn't reveal a clear rationale for its composition, and it was evident that structures with markedly different seismic vulnerabilities coexisted within the same group. Consequently, it seemed unclear why engineers were mandated to apply the same approach, especially one as time-consuming as NLTH analysis, across all structures.

The policy of not prioritizing buildings based on their vulnerability may make sense in areas with tectonic seismicity, as investigating and intervening in any building can reduce the overall risk for the entire area. However, in cases like the Groningen region, which experiences induced seismicity with decreasing hazard over time, this approach becomes less relevant. Concentrating on strengthening every building in the region is impractical; instead, attention should be directed towards the most vulnerable ones posing a higher risk of both economic loss and human life.

5 Conclusion

The paper sheds light on the seismic challenges faced by the Groningen region in the Netherlands due to gas extraction activities. The proposed multi-level assessment procedure, developed by Sismica360 in collaboration with partners, offers a comprehensive and efficient approach to evaluating the seismic vulnerability of buildings in the region.

The Groningen region, historically not prone to tectonic earthquakes, has experienced induced seismic events linked to gas extraction since 1991. The increasing frequency and magnitude of these events prompted the Dutch government to initiate a reduction in gas extraction in 2014 and concurrently assess the seismic vulnerability of existing structures.

The majority of buildings in the Groningen region, over 90%, are constructed with URM. The building stock, consisting mainly of residential structures, exhibits vulnerabilities, particularly with regard to out-of-plane seismic actions.

The proposed multi-level assessment procedure addresses the diverse seismic vulnerabilities in the Groningen building stock. It employs a multi-level approach, starting with simpler methods and progressing to more complex analyses based on the seismic performance of URM structures.

A core feature of the procedure is the use of a dynamic tool, Trilly, which enables the non-linear time history assessment of out-of-plane loaded masonry elements. This tool facilitates a more accurate estimation of seismic behaviours, reducing the overall retrofit required and aligning with the observed decrease in seismic input due to gas extraction reduction.

The multi-level approach ensures efficient resource utilization by focusing detailed analyses on structures that demonstrate vulnerability in earlier stages. This not only enhances the accuracy of seismic assessments but also minimizes unnecessary retrofitting, optimizing the use of resources and mitigating economic and sustainability concerns.

The paper provides valuable insights from the analysis of approximately 200 buildings in the Groningen region. The multi-level procedure, when applied, often revealed that in-plane compliance was achieved already by assessing the structure with NLPO analysis. Therefore, the use of more time/cost consuming NLTH analysis was in the almost totality of case unnecessary and it would have led to a waste of precious resources which were better employed in assessing a larger number of structures.

The experience gathered on the assessed project underlined that with the current code and seismicity the URM structure located in the Groningen gas field area mainly show local issues of particularly vulnerable elements out-pf-plane, mainly large gable walls. Therefore, the particular attention should be posed in the seismic assessment and reinforcement of these elements.

The proposed procedure not only enhances the safety of structures in the Groningen region subjected to induced seismicity but also contributes to cost-efficiency. By avoiding overestimation of retrofit needs and focusing efforts on critical elements, the approach aligns with the goal of safeguarding the population while minimizing unnecessary costs and efforts.

In conclusion, the multi-level assessment procedure presented in the paper provides a robust framework for addressing the unique seismic challenges faced by the Groningen region, offering a balance between structural safety and efficient resource utilization. The findings contribute to the broader discourse on seismic risk mitigation in regions with induced seismicity due to industrial activities.

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