Memo: Review of “Afronding Lopend IEDB Onderzoek by DAED ingenieurs”

Verification of usage of fragility curves for the probability of damage due to IEDS

Authors: Paul Korswagen, Alfonso Prosperi, Jan Rots - TU Delft

1. Introduction

TU Delft studies have looked at the influence of ground curvatures [2,3] and horizontal strain [3,4] on building damage. The focus of these studies is set on the cracking behaviour of Dutch masonry buildings in response to these soil deformations. The studies have thus produced fragility curves that present the probability of light damage (just visible to minor cracking) for increasing intensity of soil deformations. These curves, when combined with actual values of soil deformations, can be used to estimate damage on Dutch buildings.

The report of “DAED ingenieurs” with main author J.H. van Dalen [1] (hereon “the report”) makes use of the fragility curves that relate ground curvature to building damage probability. Its goal is to compute the probability of damage due to indirect effects of deep subsidence such as lowering of the water table; specifically, the increase in probability of damage due to IEDS is sought.

In this review, therefore, the main question that is answered is:

Are the fragility curves produced by TU Delft [2,3] correctly used in the report from DAED ingenieurs [1]?

A first version of the report was reviewed in an earlier version of this memo. Accordingly, this memo has been updated after careful review of the revised report [1]; comments referring to changes have been includes in *italics*.

2. Brief Overview of the Reviewed Report

In the report and its revision reviewed, the probability of damage due to Indirect Effects of Deep Subsidence (IEDS) is calculated through a combination of geotechnical modelling, structural vulnerability analysis, and statistical evaluation. The methodology can be summarised as follows:

R.1. Groundwater Change and Soil Settlement Modelling

The first step is to quantify soil settlements resulting from changes in groundwater levels due to IEDS. The settlement mechanisms include:

- Compression of soil layers (consolidation),
- Shrinkage of clay layers,
- Oxidation of peat layers,
- Degradation of wooden foundations.

These mechanisms are modeled using soil profiles and settlement formulas, such as those based on the Koppejan or Bjerrum methods. The reviewers lack expertise to fully assess this methodology. In the report, these are not further explained either.

R.2. Structural Response to Uneven Settlements

The calculated soil settlements are used to determine damage. The primary indicator of potential damage is the relative angular distortion (β or βx), which measures the curvature of the building caused by differential settlement.

The most important aspect is that two cases are always analysed, one for the angular distortion generated by autogenous causes (A, for example due self weight) and another for the angular distortion generated by autogenous causes and processes of IEDS (A+IEDS).

R.3. Vulnerability Curves and Probability Distribution of Damage

Vulnerability curves, derived from the computational studies (by TU Delft), relate the angular distortion to the probability of visible or structural damage in buildings. One damage threshold is selected:

- ψ = 1: Just visible cracks (crack width ~0.1 mm).

The probability of damage is represented using lognormal distributions for different types of buildings and damage thresholds. Parameters of the lognormal distribution (mean and standard deviation) are estimated based on the vulnerability studies. This is done for both A and A+IEDS cases. The increase in probability is attributed to IEDS causes. The vulnerability curves are modified slightly to include the influence of earthquake vibrations.

R.4. Monte Carlo Simulations

To account for variability in soil properties, building stiffness, and settlement profiles, Monte Carlo simulations are performed. These simulations generate a wide range of possible settlement scenarios, each linked to a probability of exceeding specific damage thresholds.

R.5. Final Probability of Damage

The output is a probabilistic risk assessment that provides the likelihood of damage for given IEDS-induced settlement scenarios. For example, the probability of exceeding $\psi = 1$ or $\psi = 2.5$ is calculated for buildings with different foundation and structural typologies.

3. Comments and Suggestions

Appendix A provides a point-by-point review of the report. In this section, key points are emphasised.

Greenfield Angular Distortion

It was not entirely clear which angular distortion is calculated in R.1 and which building parameters are being used, if any. If the greenfield distortion is being calculated, then no building parameters are required. In this case, using the fragility curves for Greenfield beta against the probability of damage is correct.

However, several autogenous causes are building-dependent. For example, the consolidation of clay layers depends on the weight distribution of the building. This means that the stiffness (and weight) of the buildings affects the observed angular distortion. Nonetheless, as the studies [2,3] demonstrate, the stiffness of buildings depends on their damage level: a more damaged building will be more flexible and thus lead to an increased angular distortion.

These points are enlightened in the revised report and its extended appendices. While no damage effect is considered, the calculation of the angular distortion has been detailed and exemplified.

Determination of angular distortion

The angular distortion is crucial in estimating the probability of damage. In the report, it is calculated based on the differential settlement and a horizontal distance between foundation elements of 5 meters (with probabilistic variations). This approach is valid for individual footings such as those present in concrete or steel framed buildings; however, masonry buildings have distributed or continuous strip footings. It is possible to consider the direction perpendicular to these strip foundations, but most buildings would only have two parallel walls which cannot be used to determine a distortion.

The fragility curves from [2,3] have been developed for in-plane damage of masonry façades over continuous (masonry or reinforced concrete) footings. Under this premise, it is not possible to determine the angular distortion based on the relative settlement between two points separated by a distance of 5 meters. Moreover, differential settlement alone could be an indication of rigid body motion (tilt) without necessarily observing distortion (angular distortion). It is suggested to refine this calculation to obtain the maximum distortion within and up to the façade or building width. It is advised that this parameter be varied in the Montecarlo simulations.

This point has been addressed in the new Appendix 7 in which the sensitivity analysis shows the impact of choosing a distance of 5 meters. This advice has thus been followed and implemented.

Shape matters

The approach of the reviewed report assumes that for both A and A+IEDS cases the angular distortions can be added. This is a valid yet simple formulation. It must be emphasised that the (greenfield) or applied settlement profile can be unique for each settlement process. This means that the resulting shape may not contain a distortion that is the sum of all cases. Some effects may even counteract each other, or exacerbate the distortion, resulting in settlements higher than their sum.

This point has been clarified.

Sequential Processes

The response of a structure to a new process will depend on its current state; in the TU Delft terminology this is referred to as the Ψ_0. The initial damage condition will have an influence on the damage aggravation. Currently, the fragility curves for soil deformation do not consider expressly a Ψ_0. The approach suggested, of comparing two situations with and without IEDS, is a good workaround.

The methodology has been further illustrated with the new appendixes.

Selected Damage Threshold

The condition for damaged/undamaged is not clear. Two thresholds for Ψ are selected but this is not reflected in the results. It is suggested to make clear which probability, that of entering or leaving light damage, is being calculated.

It is now clear that the analysis in the report refers to Ψ=1.0 for the determination of the damage criterion. However, the way the angular distortion is compared with a limit value is not made explicit. The report seems to sample a critical value from the log-normal distributions provided with the fragility curves; this and the reasoning behind it can be made clearer.

More intermediate figures

The report could benefit from additional figures to illustrate the results corresponding to each section. For example:

- Angular distortion against watertable change,
- Comparison of distribution of angular distortions caused by the various (autogenous) processes,
- Relationship between soil profile and angular distortion,
- Histograms from distributions input and output of the Montecarlo analyses,
- The results are expressed as the relation of Δwatertable and $\Delta p(\Psi)$ but Δwatertable and $\Delta\beta$, in absolute values, is also useful,
- Exceedance curves for the contribution of IEDS to the angular distortion are presented (Figures 6.4-6.7) but the horizontal axis could also be the contribution of IEDS to the probability of damage.

These do not alter the conclusions presented and have not been implemented in the final version.

Reproducibility

The work behind this report cannot be easily reproduced with the current descriptions and explanations. It would be useful to add an example of the calculation for one specific building, from beginning to end, as an appendix. Details on the Montecarlo simulation are needed if the work is to be scientifically replicated. Several parts of the report are not sufficiently commented; they could also be further supported by scientific sources.

The new appendices of the revised report greatly address this point.

4. Discussion

The fragility curves are used correctly in so far the following criteria are also approached correctly:

- The proper curve set and parameters are matched with the adequate intended calculations,
- The input for the curves is compatible with the formulations behind the curves, and,
- The output or results of the curves are interpreted correctly.

As per section 5.3 of the reviewed report, its understanding of the TU Delft fragility curves is correct and it can thus be assumed that its distribution sets are being used correctly in the work reviewed. This means that distribution parameters for e.g. unreinforced foundations are correctly selected.

Many details have been added to the report and its appendices concerning the inputs into the curves. While the curves themselves are used as probabilistic distributions to sample critical values of angular distortion, the calculation of the angular distortion from the differential settlement has been been clarified and the sensitivity in building length has been explored revealing only small effects. Consequently, it can be said that the inputs employed are compatible with the formulations behind the curves except for one point:

The TU Delft study [3] which includes the soil block in its soil-structure interaction models, is explicit about its applicability for subsidence sources outside of the soil block. The models have not been developed nor been verified for in-block sources corresponding to local effects such as clay consolidation underneath the buildings' foundations. The study employing interface soil-structure interaction [2] may be better suited for these cases. The reviewed report employs curves from [3] to determine the relationship between β and damage; here for caution is advised. *The impact of this point is currently under study.*

The two-step approach to determine the increase in probability of damage (A and A+IEDS) is a useful strategy. It would benefit from an uncertainty parameter regarding whether settlement cases can be summed up linearly. It can be argued that a more complex, step-wise approach, using coupled analyses with several phases and Ψ_0, would yield more realistic results. However, such complex analyses would require significantly more work and may prove unfeasible in the short term.

5. Conclusions

This review concludes that the DAED report correctly utilises the fragility curves developed by TU Delft [2,3] to estimate the probability of damage due to Indirect Effects of Deep Subsidence (IEDS). The authors clearly demonstrate an accurate understanding and appropriate selection of fragility curve parameters, specifically for unreinforced masonry buildings and relevant foundation typologies.

However, one significant limitation has been identified: the fragility curves were originally developed and validated for soil deformation caused by subsidence occurring outside the soil block surrounding structures (out-block sources). In contrast, the DAED report applies these curves to deformation originating directly underneath the structures (in-block sources). It is not yet clear whether using the curves in this manner may lead to notable deviations or inaccuracies. Further investigation into the implications of this application is necessary.

Additionally, the methodology of separately evaluating angular distortions for autogenous causes and combined autogenous and IEDS effects provides a practical but simplified approach. It should be explicitly acknowledged that this simplification might not fully capture the interactions and cumulative effects in realistic scenarios, particularly when sequential processes or prior damage conditions (Ψ_0) significantly influence structural responses.

In sum, the revised report addresses the main unclear points originally highlighted and has explored specific sensitivities to further support its conclusions. In this light, it can be concluded that the fragility curves provided and correctly employed.

Lessons Learned for TU Delft

Equivalent building stiffnesses for extensions and curvatures can be determined from the numerical models at various levels of damage. A comparison of these values with traditional or simplified calculations used for geomechanical estimations can be useful. Providing such values will help engineers using this type of equations.

Similarly, in-block sources of settlements should be explored to complement the instrumentarium generated for greenfield strain/curvatures from out-block sources. Sources within the soil block (in-block) are generally addressed as fully-coupled problems since the intensity of the hazard depends on the presence of the building. Out-block sources, like deep subsidence, are not affected by presence of the structure.

6. References

1. J.H. van Dalen. Afronding Lopend IEDB Onderzoek. Spoor 1. Eindconcept - voor intern beraad. 15 December 2024. DaeD Ingenieurs.
   Revisions:
   J.H. van Dalen. Afronding Lopend IEDB Onderzoek. Document nr. A5. Eindconcept - na commentaar. 9 April 2025. DaeD Ingenieurs.
   J.H. van Dalen. Afronding Lopend IEDB Onderzoek. Document nr. A6. Definitief. 7 mei 2025. DaeD Ingenieurs.
2. P.A. Korswagen, M. Longo, J.G. Rots, A. Prosperi (2022). Supporting analyses to determine probability of damage and fragility curves due to indirect subsidence effects. Delft University of Technology. Final Version 2, October 3, 2022.
3. P.A. Korswagen, M. Longo, J.G. Rots, 'Onderzoek naar Gecombineerde Effecten van Meervoudige Mijnbouwactiviteiten (GEMMA)', TU Delft rapport versie 08, september 2024.
4. Rots, J.G., Korswagen, P.A., Longo, M. (2021). Computational modelling checks of masonry building damage due to deep subsidence. Delft University of Technology. Report number 01, Version 05, February 18, 2021.
   Appendixes G, H, and I: Computational modelling checks of masonry building damage due to deep subsidence. Delft University of Technology. Report number 01, Version 01, February 16, 2023.

7. Appendix A

Prior comment: **(contextual addition between brackets)**	**Comment to the current version**
(In section 2.2) It would be more effective to differentiate between the types of consolidation, namely primary consolidation and secondary consolidation (creep).	Point addressed in the current version.
(In section 2.2) It would be helpful to include an additional point addressing potential heterogeneities within the building: not only variations in the foundation but also differences within the structure itself can intensify differential settlement. For example, a two-story building with a one-story annex may experience such effects.	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek”.
(In section 2.4) In the list of “autonomous factors,” it would be valuable to include: settlements caused by construction activities associated with new structures and infrastructure in the vicinity of the building under consideration. Excavations can also play a major role.	Point addressed in the current version.
(In section 2.4) It should be noted that in older buildings, other factors can also cause minor cracking in walls, which may not necessarily be related to settlements. Examples include vibrations from traffic or thermal loads.	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek”.
(In section 3.2) Deze beweging kan jaarlijks optreden als gevolg van seizoensfluctuaties in grondwaterstand, maar wordt verwaarloosbaar gewacht omdat deze een orde 5 tot 10 lager is dan de blijvende zetting die optreedt indien de grondwaterstand een laagste waarde bereikt die eerder nog niet was bereikt.	Point answered in “Reactie op review TU-Delft IEDB Onderzoek”. However, a reference in this section could still be added for clarity.
(In section 3.2) Also: differences in loads over the dimensions of the building.	Point addressed in the current version.
(For equation (1) in 3.3 “Zetting door krimp van klei (mechanisme 2)” and (3) in 4.2 “Veenoxidatie”) Please, provide (inter)national references for this equation.	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek” and in the current version.
(In Section 5.1) It is not clear where the scale of fluctuation of the soil thickness and soil heterogeneity is used. Also, the scale of fluctuation is typically used to measure the variability of the soil properties, rather than the one of the soil thickness.	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek”.
(In Section 5.2) Is it the small magnitude of the horizontal strain being considered, or its influence? A minor horizontal strain can still lead to significant impacts. It could be stated that for buildings settling under their own weight, the horizontal strain values are expected to be considerably lower compared to those caused by activities such as excavation, mining, or tunnelling [1]. However, it is worth noting that horizontal strains have not been measured in cases like groundwater lowering, for example.	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek”.
(for Figuur 5.1 in 5.2) This image is taken from the NEN9997 [1]. A general image is shown in Figure H.1 in the Eurocode 7 [2].	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek”.
(Regarding equation (5) to (6) in Section 5.2) The underlying assumption for this equation is that the relative rotation (or angular distortion) is equal to the rotation.	Although not a major point, it would be better to refer to the definition of Burland et al., 1975.
(In Section 5.4) Here the parameter directly Ψ is used without being introduced.	Not a major point, but the definition of Ψ is available in “Korswagen, P. A., & Rots, J. G. (2021). Monitoring and quantifying crack-based light damage in masonry walls with digital image correlation. In Proceedings of 1st International Conference on Structural Damage Modelling and Assessment: SDMA 2020, 4-5 August 2020, Ghent University, Belgium (pp. 3-17). Springer Singapore.” and could be included for clarity.
(In Section 5.4) It is not clear in this document how the parameters of the fragility curves in Table 5.2 are used. It would be more effective to report the formulation in which the parameters are adopted.	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek”. The determination of the damage criterion (criterium rel. rotatie) is somewhat unclear.
(In Section 6.1) It is not clear how the fragility curves from TU Delft were used to determine if a specific case was damaged or not. The Monte Carlo technique provides a pool of data, for which the differential settlements, and thus β, are computed. For each case, then, my understanding is that the curves from TU were used to determine if a certain case would be damaged or not. However, it is not clear how.	Point addressed in “Reactie op review TU-Delft IEDB Onderzoek”. Also in the new Appendix 8. The determination of the damage criterion (criterium rel. rotatie) is somewhat unclear.
(Regarding the number of the analyses) why 2*104 specifically?	The current reports address this point and specify that it is related to a compromise between the computational burden and reproducibility.