The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

The role of excavation-induced pore water pressure reduction in the damage assessment for buildings: an application of the GIBV method

Une application de la méthode GIBV pour une évaluer rapidement les dommages causés aux bâtiments par une activité d'excavation

Luca Piciullo, Stefan Ritter, Jenny Langford & Farrokh Nadim
Norwegian Geotechnical Institute, NGI, Norway, luca.piciullo@ngi.no

ABSTRACT: This paper presents an application of the GIBV methodology for the rapid assessment of building damage caused by an excavation as proposed in Piciullo et al., 2020. The combination of the Ground-work Impact (GI), in terms of induced greenfield displacements, and the Building Vulnerability (BV) form the basis for the GIBV damage assessment method. The impact of the groundwork is evaluated considering both short-and long-term displacements. The GIBV method has been implemented in a GIS tool to predict damage classes for buildings exposed to excavation-induced settlements. A well-documented case study in Norway was used to compare the predicted impact classes with the measured settlements for two cases: high (Case 1) and low (Case 2) pore pressure reduction. Case 1 represents no mitigation measures for pore water reduction and Case 2 simulates the use of mitigation measures. Both scenarios resulted in conservative predictions as is the intention of this early-stage assessment procedure. It was found that the results of Case 2, which replicated the reality, were in a good agreement with the field observations. The result of this application highlights that the GIBV method provides effective means to communicate the impact of different design solutions for a deep excavation on its surrounding. The paper also shows the importance of employing mitigation measures (i.e., infiltration wells and rock grouting) to reduce unwanted effects caused by pore water pressure reduction.

RÉSUMÉ : Cet article présente une application de la méthode GIBV proposée par Piciullo et al. (2020), pour une évaluer rapidement les dommages causés aux bâtiments par une activité d'excavation. La méthode GIBV est fondée sur la combinaison de 1) l'impact causé par les travaux souterrains (Ground-work Impact, GI) en terme de déplacements de surface, et 2) la vulnérabilité des bâtiments (Building Vulnerability, BV). L'impact des travaux souterrains est évalué en considérant à la fois les déplacements au court-terme et au long-terme. La méthode GIBV a été intégrée à un système d'information géographique (GIS) afin de prédire des classes de dommages pour des bâtiments exposés à des déplacements dus aux activités d'excavation. L'analyse s'est appuyée sur un cas d'étude norvégien bien documenté, afin de comparer l'impact prédit avec le déplacement mesuré, ceci dans le cas d'une forte (cas 1) ou d'une faible (cas 2) réduction de la pression porale. Le cas 1 représente une situation sans mesure particulière, tandis que le cas 2 simule une situation où des mesures sont mises en place pour réduire la pression porale. Les deux scenarii ont conduit à des prédictions conservatives, ce qui était souhaité à ce stade précoce du processus d'évaluation. Dans le cas 2, plus proche du cas réel, les résultats étaient en accord avec la situation observée sur le terrain. Les résultats de ce cas d'étude soulignent le fait que la méthode GIBV permet de générer des données qui pourraient argumenter les discussions sur l'impact de différentes solutions de conception dans le cadre d'excavation profondes. Cette étude montre également l'importance d'employer des mesures, telles que la mise en place de puits d'infiltration ou la cimentation de roches, pour réduire les effets indésirables causés par la réduction de la pression porale.

KEYWORDS: building damage assessment, settlements, excavation, building vulnerability

1 INTRODUCTION

A potential solution to overcome the lack of urban space is to use the subsurface. Exploring the underground will require excavation activities such as tunneling and deep excavations. In soft soils, these excavation works can cause ground movements, which may affect surrounding infrastructure.

Analyzing the impact of excavation-induced subsidence on adjacent buildings is a crucial part of the design of urban excavation works (Son and Cording, 2005). It generally involves the evaluation of the initial movements of the ground as the excavation is constructed, and frequently adopts empirical formulations for the greenfield (e.g. Peck, 1969, Goldberg 1976; Clough and O'Rourke 1990; Karlsrud, 1997; Bentler 1998; Long 2001; Moormann and Moormann 2002; Konstantakos 2008). Long term effects such as ground movements due to changes in pore water pressure are often neglected. However, in geological conditions with fine-grained soils such as silts, clays and peat and abrupt changes of the underlying geology significant differential soil displacements due to consolidation effects can occur. These long-term settlements can affect an extensive area adjacent to a deep excavation, as reported by Langford et al. (2016).

Early-stage methods to assess building damage due to subsidence aim to identify buildings at unacceptable risk in order to subsequently perform more detailed assessments. Son and Cording, 2005, Aye et al., 2006, and Giardina et al., 2010, adopted a three-stage method, following the approach previously described by Mair et al., 1996. Most of the preliminary assessments, however, neglect the vulnerability of buildings to excavation-induced ground displacements. Vulnerability is here calculated as function of physical building characteristics and it represents the building predisposition to damage. The damage assessment, proposed by Clarke and Laefer, 2014, comprises two parts, damage and vulnerability predictions. However, in their method the vulnerability is based on community status and current condition, mixing in a given way vulnerability and risk acceptance.

Another limitation of previous assessment procedures, is that the potential impact of mitigation measures on the risk of building damage has been widely neglected. Especially, the effectiveness of employing measures to reduce the impact of excavation-induced pore pressure reductions has, so far, received scant attention. This shortcoming may result in unreliable early-stage damage assessments when mitigation measures are adopted.

This contribution introduces a recently developed framework to conduct an early-stage assessment of potential building damage due to excavation-induced subsidence which considers short and long-term ground movements and the vulnerability of buildings to subsidence damage. This so-called GIBV method (Piciullo et al. 2020) assess the Ground-work Impact (GI) by combining empirical observations of settlements and pore water pressure reduction adjacent to a deep excavation with a soil stratification model to evaluate excavation-induced soil displacements. In addition, it provides a qualitative assessment framework to conduct a first-pass evaluation of the Building Vulnerability (BV). This paper explores the versatility of this methodology to illustrate and communicate the impact of different scenarios on the potential building damage. More precisely, the effect of mitigation measures to decrease the lowering of the pore water pressure and the associated impact on surrounding structures is explored. In the following section, the GIBV method is briefly reviewed, after which the considered Case history is described. Then results of the application of the GIBV to the study area are shown and discussed. Finally, conclusions are drawn.

2 THE GIBV METHOD FOR THE BUILDING DAMAGE ASSESSMENT

The GIBV methodology provides an early-stage assessment framework to identify buildings at risk of excavation-induced damage. The methodology combines an evaluation of the potential excavation-induced settlements (i.e. impact) with a qualitative assessment of building vulnerability to settlement damage. Figure 1 provides a schematic overview of this methodology.

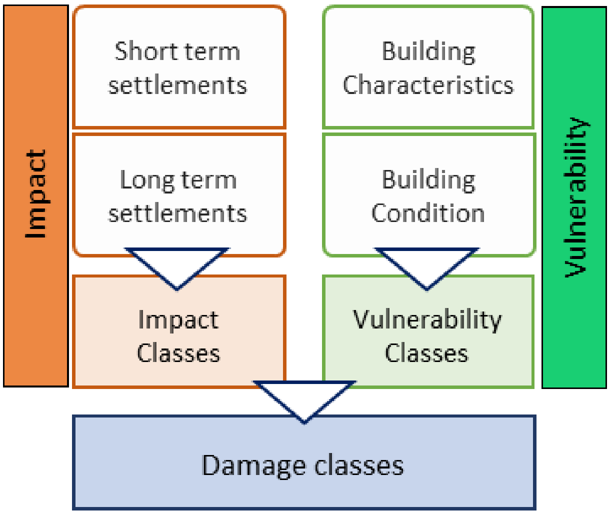


Figure 1. Ground Impact and Building Vulnerability (GIBV) methodology.

The excavation-induced ground movements are quantified with respect their temporal appearance. The short-term settlements are approximated by using empirical data from excavations (Langford et al., 2016b). Long-term ground movements due to pore water pressure reductions are often neglected in previous assessment method but can result in severe impact in areas with subsidence prone soft soils and varying depth to bedrock.

The GIBV method merges a soil stratification model, observations of pore water pressure reductions adjacent to excavation works and consolidation theory to derive long-term displacements. The method implements the upper and lower bound curves shown in Figure 2.

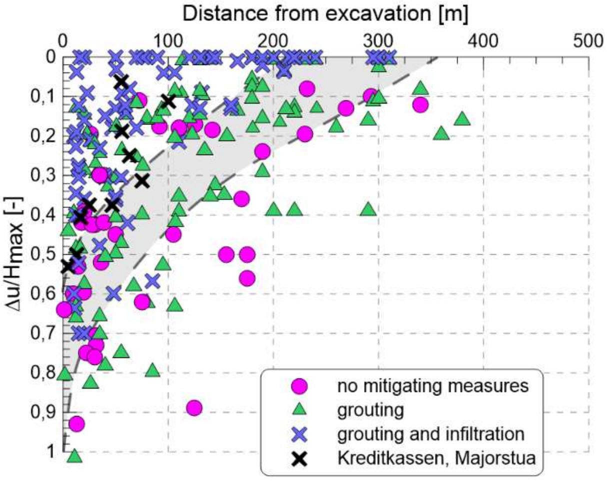


Figure 2. Database of pore water pressure reduction due to excavation works in Norway: Δu = pore water pressure reduction in m measured at the base of clay stratum, Hmax = depth of excavation base beneath initial ground water surface (adopted from Langford et al. 2016a).

The lower bound curve is representative of the use of measures, including both grouting and infiltration wells, to limit the pore water pressure reduction. The upper bound curve represents the Case of no mitigation measures. The curves show the maximum expected reduction of pore water pressure as a function of the excavation depth below the groundwater level (Hmax) and the distance from the excavation. To evaluate the settlements due to pore water pressure reduction, Janbu's modulus concept was used (Janbu, 1970).

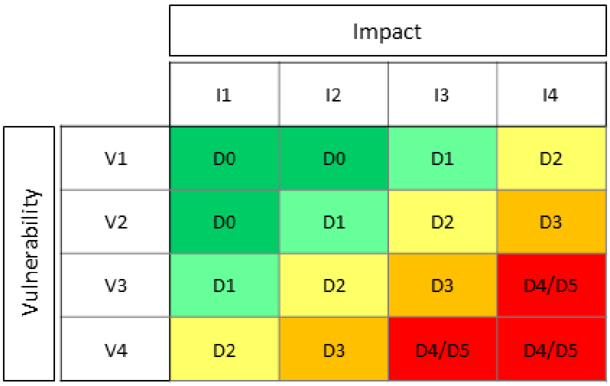
For each building corner point, the short and long-term displacements are combined and used to compute to the maximum building settlement and rotation of a building wall. These parameters are then classified accordingly to the four categories proposed by Rankin (1988) and used to derive an impact class for each building (Table 1).

Table 1. The maximum slope and the maximum settlement are categorized in four level of impact (Adapted from Rankin, 1988).

Impact level	Maximum rotation (θ_{max})	Maximum settlement ($\delta_{V,max}$)
1. Negligible	< 1/500	< 10 mm
2. Slight	1/500-1/200	10-50 mm
3. Moderate	1/200-1/50	50-75 mm
4. High	> 1/500	> 75 mm

To account for a building's predisposition to damage when it is subjected to ground movements, a qualitative rating method was adopted. This framework evaluates the characteristics and condition of a building considering geometrical (i.e. length and shape), structural (i.e. structure and foundation type) and condition (visual damage) parameters. A detailed description of this rating method is described elsewhere (Piciullo et al. 2020).

After each building is categorized with respect to its impact and vulnerability, a risk matrix (Figure 3) is employed to obtain the potential damage. For a given building, the GIBV method predicts a building damage class based on the *ease of repair* of the visible damage of masonry structures (Burland et al. 1997). Piciullo et al. (2020) provide a detailed description of the GIBV method and its validation using two Case studies.



		Impact			
		I1	I2	I3	I4
Vulnerability	V1	D0	D0	D1	D2
	V2	D0	D1	D2	D3
	V3	D1	D2	D3	D4/D5
	V4	D2	D3	D4/D5	D4/D5

Figure 3. Expected damage classes and classification of the matrix cells. The 4x4 matrix plots the vulnerability against the impact classes.

The GIBV method has been implemented in an ArcGIS tool. The aim is to provide a practical tool for rapid and early-stage analysis of buildings exposed to damage from groundwork-induced displacements. The tool is programmed in Python and is directly accessible from the interface of the commercial software ArcGIS Pro Advanced and Standard. The required inputs necessary for running the short-term impact analysis are:

- shapefile polygon with the location of the excavation;
- shapefile polygon containing all buildings to be investigated;
- depth of the excavation (m).

The building and excavation feature classes must be in the same projected coordinate system. If the user enables the option "Long term settlement calculation" (optional), then few additional inputs are needed:

- raster showing depth to bedrock in metres;
- geotechnical characteristics of the main soft soil layer: thickness of dry crust (m), depth to groundwater table (m), total unit weight of soil (kN/m3), overconsolidation ratio (-), pore water pressure reduction nearby the excavation (kPa), Janbu reference vertical stress, pr (kPa), Janbu m value.

The "Vulnerability analysis" option is also available. To run this option, the user needs to specify the columns of the building feature class that contain vulnerability information. If the user does not specify any column for one or more vulnerability parameters (see Table 1), then those parameters are simply omitted from the index evaluation. Values/characteristics in the GIS shapefile attribute table must be specified for each vulnerability parameter. If the value is not part of the domain, the default value (maximum vulnerability class) will be assigned.
Once all the inputs are inserted, the tool can be run. The ArcGIS tool produces a shapefile with the maximum vertical settlement (δv,max) and maximum wall slope (θmax) for each building. The shapefile contains the values for the short-and long-term displacements separately. The buildings are classified into four impact classes, according to the highest calculated displacements, and four vulnerability classes. The impact and vulnerability classes are finally combined in a matrix to obtain the expected damage class (see Fig. 1) for a given building.

3 STUDY AREA

The GIBV method was applied to a Case history of an excavation pit for a basement of building with dimensions of approximately 100 x 150 m. The excavation pit was in a typical urban setting with adjacent buildings that are prone to subsidence damage. The support system consisted of a sheet pile wall to bedrock, tie-back anchors and a grouted curtain, as can be seen from Figure . The site geology is characterized by a surficial urban fill, which is underlain by a 1-2 m thick dry crust clay. Beneath this dry crust clay, a stratum of normally consolidated soft clay is encountered and underlain by bedrock at varying depth. The soft clay strata below 8 m depth can be described as a quick clay. Drilled steel core piles provided the main foundation of the building. A summary of the main parameters used as input for the impact assessment analysis of this case study are summarized in Table 2.

Table 2. The input parameters for Jong-Asker and Kredittkassen case studies.

Variable	Unit	Kredittkassen
Depth of excavation	[m]	16
Dry crust thickness	[m]	3
Groundwater depth	[m]	2
Soil unit weight	[kN/m^3]	19
Overconsolidated ratio	[-]	1
Janbu's modulus number	[-]	19
Pore water pressure reduction at the bedrock	[kPa]	98

The main construction activities for this deep excavation were carried out between 1990 and 1994. Notable pore water pressure reductions and respective consolidation settlements were measured throughout the excavation works. Consequently, mitigation measures in form of several infiltration wells and additional rock grouting were carried out and proved successful to reduce the impact on the surrounding.

An extensive monitoring program including precise levelling and pore water pressure measurements resulted in instrumental data to evaluate the performance the GIBV method. Specifically, the settlement data of the surrounding structures are adopted in this work. Further detail about this excavation pit is provided in Karlsrud et al. 2014 and Langford et al. 2016a.

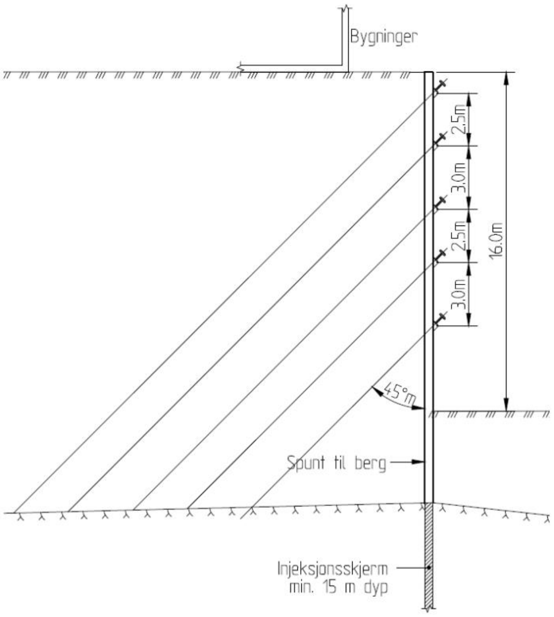


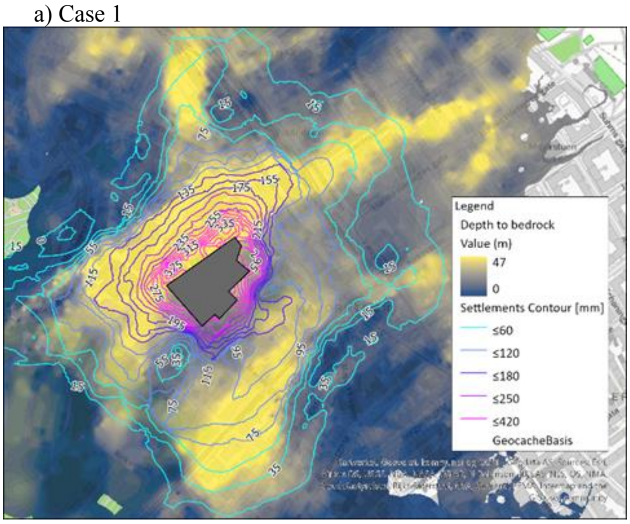
Figure 4. Deep excavation of study area: bygninger = building, spunt til berg = sheet pile wall to bedrock, injeksjonsskjerm min. 15 m dyp = grouted curtain min. 15 m deep (from Karlsrud et al. 2015)

4 RESULTS

The buildings corner points were considered for the evaluation of the impact. Short and long-term displacements were summed up for each building corner point and were used to compute the building settlement. Then, the settlement value of each corner point was interpolated using the *Kriging* method (Matheron, 1963) and settlement contour lines were derived for cases of low and high pore pressure reduction (Figure 5). The case of low pore pressure reduction is representative of a situation where mitigation measures have been employed (such as, grouting and infiltration), on the contrary high pore pressure reduction represents the case of no mitigation measure (see Figure 2).

Figure 5 shows the extent and the impact (short and long-term settlements) due to the excavation in the case of high (Case 1) and low (Case 2) pore pressure reduction. As expected, Case 1 shows a larger influence of the excavation and higher vertical settlements than Case 2, highlighting the importance of mitigation measures to reduce the excess pore water pressure generation.

a) Case 1



b) Case 2

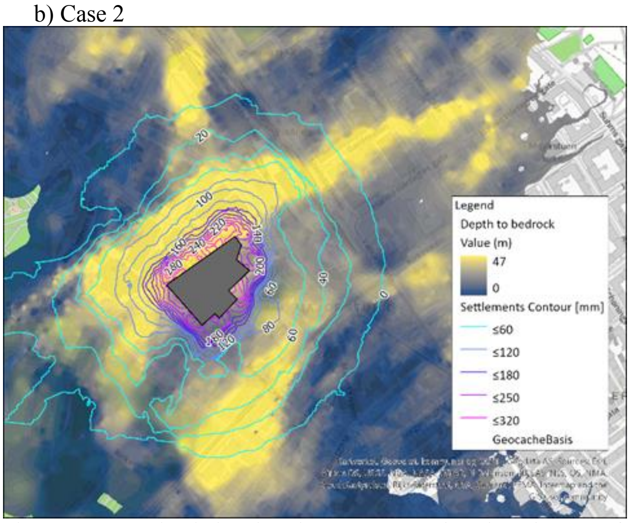


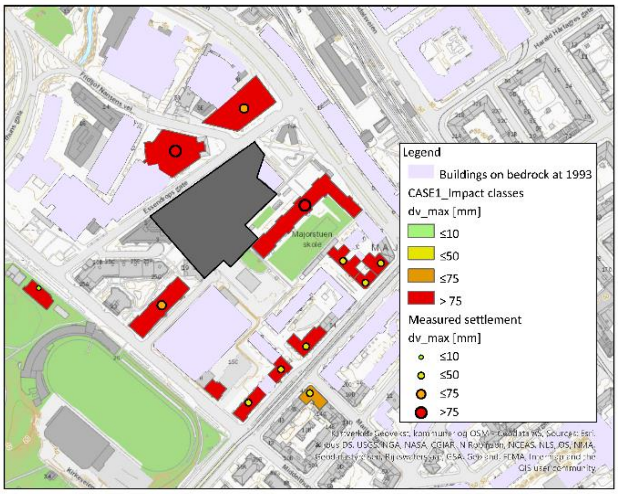
Figure 5. Excavation-induced settlement contours based on the sum of short and long-term impacts for (a) the Case of high (Case 1) and (b) low (Case 2) pore pressure reduction.

The results of the impact analysis, considering Case 1 and Case 2, are plotted in Figure 6. For Case 1, a higher number of buildings are in the highest class of impact (class 4, see table 1) compared to Case 2. In the scenario without implementing mitigation measures, almost all the buildings would have been influenced by settlement values corresponding to the high class of impact (Figure 6-a).

The available monitoring data for the study area was utilised to obtain measured maximum settlements for each considered building. These values were then compared with the settlement thresholds listed in Table 1 to obtain a measured impact class per building. The result of this classification is shown in Figure 6, where the dots represent the classification according to the measured settlements.

A more direct comparison between the two cases was carried out by evaluating the prediction accuracy index (PAI), as defined by Schuster et al. (2009). The PAI is calculated for each building by taking the difference between the predicted and the measured impact classes. The index indicates the number of impact classes a building is under- or overestimated. The value is positive for overestimation and negative for underestimation.

a) Case 1



b) Case 2

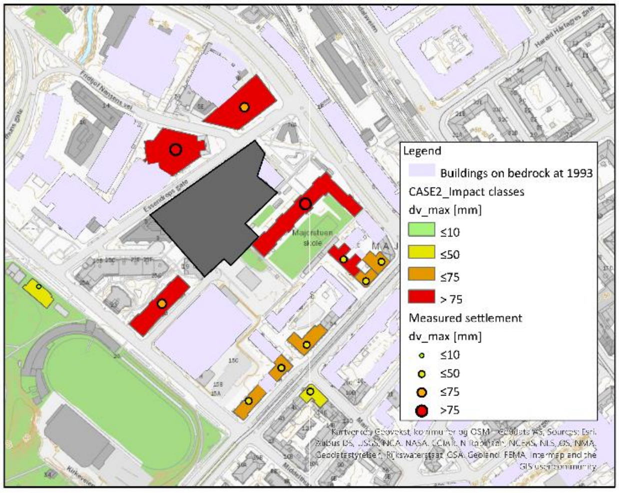


Figure 6. Application of the ground impact analysis of the GIBV method to the Kredittkassen case study: (a) impact classes in the Case of high (Case 1) and (b) low (Case 2) pore pressure reduction. The building colours represent the predicted impact classes while the dots indicate the impact classes derived from measured settlements.

Figure 7 shows the PAI for both cases. The results indicate that all the predictions tend to be conservative which is the purpose of this early-stage assessment method. For Case 2, a lower number of overestimated buildings were observed, indicating that the predictions are closer to the measured ones. In the case study, in fact, mitigation measures were employed to reduce the effect of drainage (see Section 3). The comparison between Case

1 and 2 highlights the importance of mitigation measures to counteract pore water pressure reductions due to excavation works and to avoid building damage. The results further imply that it is vital to design excavation support measures such as internal struts which limit potential leakage into the excavation and associated pore water pressure decrease. Further measures to avoid the risk of pore water pressure reduction and subsidence adjacent to deep excavations were provided by Langford et al. (2016a).

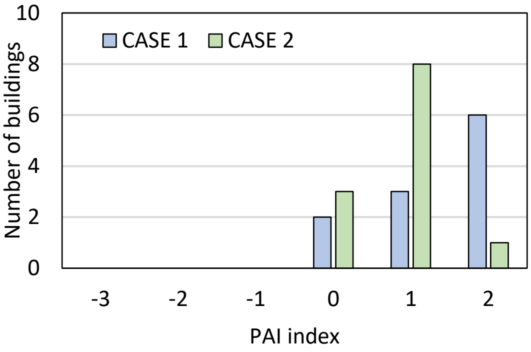


Figure 7. Kredittkassen case study. The performance analysis has been carried out comparing the impact classes predicted considering Case 1 and Case 2. The prediction accuracy index (PAI), as defined by Schuster et al. (2009) has been evaluated.

5 CONCLUSIONS

An original methodology for the assessment of building damage due to excavation-induced displacements called GIBV was described. The impact (i.e. short- and long-term displacements caused by the excavation) and the vulnerability of the buildings surrounding an excavation are considered in the GIBV damage assessment method. Considering long-term settlement and vulnerability of buildings in the damage assessment is an innovative aspect of the methodology.

The GIBV method was implemented in ArcGIS software using Python scripts, providing a user-friendly tool for the preliminary evaluation of buildings prone to damage due to excavation-induced displacements. The GIS environment enables conducting a rapid assessment for a considerable number of buildings, which is particularly crucial for pre-construction damage assessment of infrastructure projects in urban settings.

The tool was applied to a well documented case of a deep excavation in Oslo, Norway, which caused a substantial pore water pressure reduction and associated consolidation settlements in its vicinity. In this contribution, two cases with differing pore water pressure reductions were presented to show both the versatility of the GIBV to account for different scenarios and the importance of avoiding leakage due to excavation activities. Case 1 replicated the scenario of a high pore pressure reduction, while Case 2 considered the use of mitigation measures to reduce the impact on the adjacent pore water pressure regime. The latter scenario represents the real scenario that occurred for the Kredittkassen case study.

The outcome of the GIBV predictions for the two considered cases were compared to monitoring data. Both scenarios resulted in conservative predictions as is the intention of this early-stage assessment procedure. It was found that the results of Case 2, which replicated the reality, were in a good agreement with the field observations. For Case 1, which neglected mitigation measures, the predictions showed a greater impact on the neighboring structures. The application of the GIBV method to these two cases highlights that this methodology provides effective means to communicate the impact of different design solutions for a deep excavation on its surrounding. The considered case study further indicates the importance of employing mitigation measures (i.e., infiltration wells and rock grouting) to reduce unwanted effects caused by pore water pressure reduction.

This application of the GIBV method focused on the impact of excavation-induced subsidence on buildings by considering both short and long-term effects. A more detailed assessment of potential building damage should also consider the characteristics and condition of the affected buildings. The suggested framework of the GIBV method provides the possibility to combine a settlement impact evaluation with a building vulnerability assessment.

6 ACKNOWLEDGEMENTS

The research activities carried out to define the methodology and implement the tool have been developed within the research project BegrensSkade-II/REMEDY (https://www.ngi.no/eng/Projects/BegrensSkade-II-REMEDY-Risk-Reduction-of-Groundwork-Damage). The authors gratefully acknowledge the Research Council of Norway for financing the project 267674, and, all the partners for their fruitful contribution.

The authors would like to acknowledge the municipality of Oslo, in particular: Eriksson, I., Adamou, S., Sæther, M. M., for sharing the digitalized data of the depth to bedrock, used for Kredittkassen case study.

7 REFERENCES

Aye, Z.Z., Karki, D., Schulz, C., 2006. Ground Movement Prediction and Building Damage Risk-Assessment for the Deep Excavations and Tunneling Works in Bangkok Subsoil. International Symposium on Underground Excavation and Tunnelling, Urban Tunnel Construction for Protection of Environment Sponsored by International Tunnelling Association (ITA/AITES), 2-4 February 2006, Bangkok, Thailand, pp. 281-297.

Bentler, D.J., 1998. Finite Element Analysis of Deep Excavations. PhD thesis, Virginia Polytechnic Institute and State University.

Burland, J.B., Broms, B., DeMello, V.F.B., 1977. Behaviour of foundations and structures: state of the art report. In: Proceedings of 9th International Conference on Soil Mechanic and Foundation Engineering, vol. 3, Balkema, Rotterdam, pp. 495–546.

Clough, G.W., O'Rourke, T.D., 1990. Construction induced movements of in situ walls. In Proc. ASCE Design Performance Earth Retaining Struct., eds. P. C. Lambe and L. A. Hansen. Ithaca, NY, June 18–21, pp. 439–470.

Giardina G., Hendriks M. A. N. and Rots, J. G., 2010. Numerical analysis of tunnelling effects on masonry buildings: the influence of tunnel location on damage assessment. In Advanced Materials Research. X. Gu and X. Song, Shanghai, 133, pp. 289-294. 10.4028/www.scientific.net/AMR.133-134.289

Goldberg, D.T.; Jaworski, W.E. and Gordon, M.D., 1976. Lateral support systems and underpinning. Report FHWA-RD-75-128, Federal Highway Administration, Washington D.C., 1, 312.

Janbu, N., 1970. Grunnlag i geoteknikk. Trondheim: Tapir forlag Brinkgreve, R.B.J. 2002. PLAXIS 2D – version 8. A.A. Balkema Publishers. The Netherlands

Karlsrud K., Langford J., Lande E.J. and Baardvik G. 2015 Vurdering av skader og deformasjoner knyttet til utførelse av stagforankring og borede peler i byggegroper. BegrensSkade Delrapport nr. 1+2.4. (in Norwegian)

Karlsrud, K., 1997. Some aspects of design and construction of deep supported excavation, Discussion leader's contribution. Proc. 14th Int. Conf. on Soil Mech. Found. Eng. Hamburg. 4, pp. 2315-2320.

Konstantakos, D.C., 2008. Online database of deep excavation performance and prediction. 6th international conference on Case histories and geotechnical engineering. Arlington, paper 5.16 (1-12).

Langford J., Baardvik G. and Karlsrud K. 2016a. Pore pressure reduction and settlements induced by deep supported excavations in soft clay. In: Proceedings of the 17th Nordic Geotechnical

Meeting, NGM 2016 Reykjavik.

Langford, J., Karlsrud, K., Lande, E.J., Baardvik, G., Engen, A., 2016b. BegrensSkade – Limitation of damage caused by grou ndworks. In Grundläggningsdagen GD2016. Stock-holm, Swede n.

Long, M., 2001. Database for retaining wall and ground movements due to deep excavations. J. Geotech. Environ., 127(3), pp. 203-224. ISSN: 1090-0241

Mair, R.J., Taylor, R.N., Burland, J.B., 1996. Prediction of Groun d Movements and Assessment of Risk of Building Damage. Geotechnical Aspects of Underground Construction in Soft Gr ound, Balkema, Rotterdam, pp. 712–718.

Matheron, G., 1963. Principles of geostatistics. Economic geology, 58(8):1246-1266.

Moormann, C., Moormann, H.R., 2002. Study of wall and ground movements due to deep excavation in soft soil based on worldwide experiences. Geotechnical Aspects of Underground Construction in Soft Ground, Toulouse, Spécifique, Lyon, pp. 477-482. ISBN 2-9510416-3-2

Peck, P.B., 1969. Deep excavations and tunneling in soft ground. In: Proceedings of 7th International Conf. on Soil Mechanics and Foundation Engineering, Mexico City, 3, pp. 225–290.

Piciullo L., Ritter S., Lysdahl A.O., Langford J. and Nadim F. 2021 Assessment of building damage due to excavation-induced displacements: The GIBV method. Tunnelling and Underground Space Technology. 108 (2021) 103673.

Schuster, M.J., Kung, G.T.C., Juang, C.H.& Hashash, Y.M.A. 2009. Simplified model for evaluating damage potential of buildings adjacent to a braced excavation. J. Geotech. Geoenviron., 135(12), 1823–1835. DOI: 10.1061/(ASCE)GT.1943-5606.0000161

Son, M., Cording, E.J., 2005. Estimation of building damage due to excavation-induced ground movements. J. Geotech. Geoenviron., 131(2), 162-177. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(162)