Jenny Langford, Stefan Ritter, Asgeir Kydland Lysdahl, Eivind Wiik Ånes, Luca Piciullo

Assessing potential building damage caused by leakage to urban tunnels

[Untertitel:optional, einzeilig – bitte nur nach Rücksprache mit der Redaktion verwenden]

Building damage is a major risk for urban tunnelling. In areas with soft soil conditions, water ingress to bedrock tunnels can cause significant pore pressure reduction, consolidation settlements and damage to nearby buildings and infrastructure. In Norway, guidelines to determine leakage limits are based on a national database, containing data on water ingress, pore pressure reduction and influence zone. To support future projects, the database has been implemented into an ArcGIS-tool and merged with the Ground Impact and Building Vulnerability (GIBV) method to assess potential building damage at early project stages. This paper presents the adopted methodology and shows its application for a new subway tunnel in Oslo, Norway.

Keywords urban tunnelling; soft soil; subsidence; pore pressure reduction; building damage assessment

Beurteilung möglicher Gebäudeschäden aufgrund von Wasserzutritt im innerstädtischen Tunnelbau

Gebäudeschäden stellen ein beträchtliches Risiko im innerstädtischen Tunnelbau dar. In Gebieten mit weichen Böden kann das Eindringen von Wasser in Festgesteinstunneln zu einer erheblichen Verringerung des Porendrucks, zu Konsolidierungsssetzungen und zu Schäden an angrenzenden Gebäuden und Infrastruktur führen. In Norwegen basieren die Richtlinien zur Bestimmung der Wasserzutrittsgrenzen auf einer nationalen Datenbank, die empirische Daten zum Wasserzutritt, zur Porendruckverringerung und zur Einflusszone enthält. Zur Unterstützung künftiger Projekte wurde die Datenbank in eine ArcGIS Plattform implementiert und mit der sogenannten „Ground Impact and Building Vulnerability“ (GIBV) Methode zusammengeführt, um potenzielle Gebäudeschäden bereits in frühen Projektphasen zu beurteilen. Dieser Beitrag stellt die angewandte Methodik und ihre Anwendung für einen neuen U-Bahn Tunnel in Oslo, Norwegen, vor.

Stickworte: Innerstädtischer Tunnelbau; weicher Boden; Setzungen; Porendruckreduzierung;

1 Introduction

Tunnelling in rock-masses with considerable soft ground deposits above the tunnel can cause pore pressure reduction and extensive settlements of adjacent areas [1][2][3]. Related building damage can increase the project costs [4]. Hence, a vital part of urban tunnelling projects is to assess the potential impact on nearby structures to identify the most critical areas, to set limits to water ingress, design mitigation measures such as pre-excavation grouting (performed by pumping cement-based grout with high pressures into the rock-mass surrounding the tunnel to reduce water ingress) and artificial water infiltration (infiltration of water into bedrock wells to counteract water ingress), as well as suggesting a plan for monitoring schemes. This paper presents how the so-called Ground Impact and Building Vulnerability (GIBV) method [5] was adopted to bedrock tunnelling.

2 Subsidence caused by tunnelling

Water ingress to tunnels can cause unacceptable settlements in urban areas with subsidence prone soft clay. Figure 1 illustrates the problem, with drainage to a tunnel, causing pore pressure reduction at bedrock level. With time the pore pressure reduction propagates upward in the clay layer, and consolidation settlements develop. The magnitude of the settlements depends on the amount of pore pressure reduction, Δu_F, the thickness of the clay layer and the consolidation parameters of the clay.

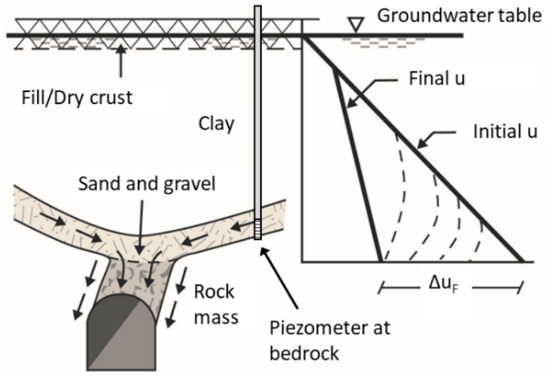


Figure 1 Pore pressure reduction due to tunnel water ingress. **Source:** from [3].

To avoid unacceptable settlements, typically limits are set to tunnel water ingress rates using, for example, the Norwegian industry standard [3], which is based on a database from completed tunnelling projects, recently updated [5]. Figure 2a shows the relation between water ingress rates, q, and pore pressure reduction at bedrock level, Δu_F, over the centre line of the tunnel. Naturally, the data has a large scatter [5], and curves are sketched for "upper" and "lower" bounds. Figure 2b shows pore pressure reduction at bedrock level with distance from the tunnel centre line. These data indicate that the influence zone for pore pressure reduction may exceed 500 m. Current practice for estimating the zone of influence is to assume a decline of Δu_F equal to 20 kPa per 100 m distance (dashed lines in Figure 2b).

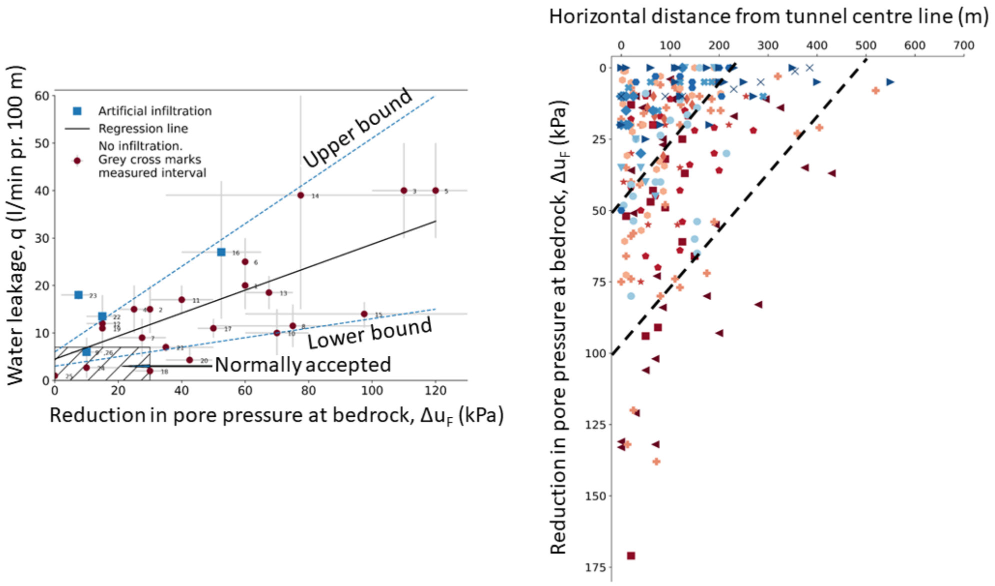
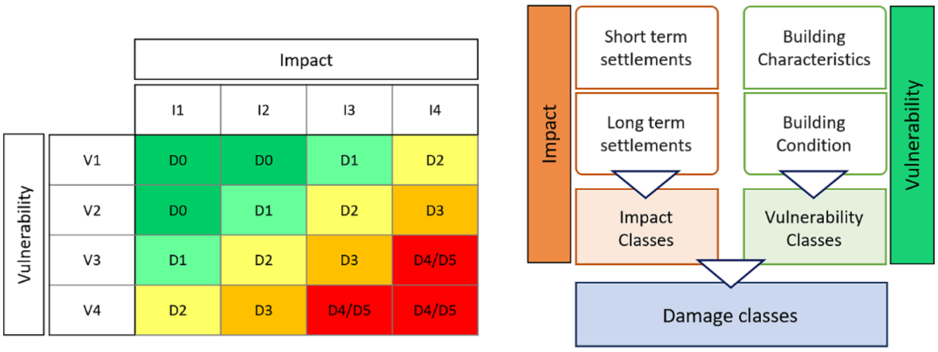


Figure 2 a Measured water ingress to tunnels related to pore pressure reduction at bedrock level over the centre line of tunnel (left), **b** measured pore pressure reduction at bedrock level with increasing distance from tunnel centre line (right). **Source:** from [6].

3 GIBV tool implemented into ArcGIS

The GIBV method, was originally developed to assess building damage due to ground-induced displacements from deep excavations. It has been described in detail by Piciullo [5][7], including validation on two case histories. Thus, only a brief introduction to the method is given herein with focus on the expansion to bedrock tunnels. The method has been implemented into ArcGIS [8] using a Python script. The script for the tool can be downloaded from the open-source platform GitHub [9].

In short, the method enables prediction of a building damage class, D1 to D4/D5, based on the evaluation of Impact classes I1 to I4, and Vulnerability classes V1 to V4, as illustrated in Figure 3a. The impact class is determined by assessing the expected short-term settlement due to stress changes surrounding an excavation and long-term (time dependent) settlements caused by groundwater drawdown and consolidation (Figure 3b).



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

Figure 3a Damage class assessment based on impact and vulnerability classes (left), **b** GIBV model methodology (right). **Source:** from [5].

Deformations when tunnelling in hard bedrock overlain by soft, low permeable clay, will be dominated by consolidation settlements in the clay (i.e., long term settlements). These settlements can be calculated using the Janbu modulus concept [10], which is the standardized Norwegian method for calculating settlements in clay. The method describes the resulting vertical settlement in a soil profile, caused by a change in effective vertical stress, taking into account the preconsolidation stress in the clay. Short term settlements can be included in the impact assessment following a widely used empirical method based on a Gaussian distribution [11][12].

The following input is required in the ArcGIS-tool, to enable impact assessment:

- A geo-referenced bedrock map and terrain model, to interpolate the thickness of the soil deposits in the area to be assessed.
- A map with all surrounding buildings, from which building corner points are generated.
- Settlement input parameters for the Janbu model.
- Expected water ingress to the tunnel, or expected pore pressure reduction at bedrock level, at the centre line of the tunnel.

Running the tool, settlements are calculated at corner points for all considered buildings, based on the interpolated depth to bedrock, given pore pressure at bedrock level and zone of influence, according to Figure 2. The impact class for each building is then evaluated considering the maximum calculated settlement at the corner points, $S_{v,max}$. The impact classes are adapted from Rankin [13] who proposed four impact categories ranging from <10 mm (negligible) to >75 mm (high), as shown in Table 2.

The assessment of vulnerability classes for the buildings is based on a rating system adapted form Dzegniuk et al. [14], where the building geometry, type of foundation, building material, and building condition can be considered. For the case presented in this paper only the foundation type is considered, by neglecting buildings founded to bedrock.

4 Case study: Majorstuen metro tunnel and station

4.1 Project overview

A new subway tunnel and upgrade to the existing Majorstuen station in central Oslo is planned to increase the capacity of the subway system. The new tunnel will be built parallel to an existing subway tunnel, as shown in Figure 4. The buildings in the area consist of historic three to five story buildings, dating from 1880-1950, as well as modern apartment and office buildings. One of the main challenges of the project is the proximity to buildings and infrastructure.

4.2 Ground conditions and building conditions

Figure 4 shows an overview of the project area, the location of the new tunnel and existing tunnel, the surrounding buildings and registered depth to bedrock. The bedrock consists of Cambro-Silurian sedimentary rocks, mainly limestone and shale, with frequent occurrence of igneous dikes, where the transition zone between the bedrock types often is water bearing ([15][16]). The soil conditions are typical for Oslo, with depressions of soft soil on top of the bedrock, with a maximum registered depth of about 40 m. The top layer is man-made fill and dry crust clay, over marine normally consolidated clay, with an apparent over-consolidation ratio (OCR) of about 1.2. The groundwater table is registered at 1-2 m under the terrain, with a pore pressure distribution which is lower than hydrostatic due to drainage to the existing tunnel. The buildings in the area have a variety of foundation types, depending on the size and age of the building, as well as the depth to bedrock. For this early-stage analysis, the vulnerability of the buildings has not been assessed in detail. The buildings have been split into two categories as shown in Figure 4; buildings founded on bedrock (piles to bedrock or shallow foundations on bedrock, marked in green) and foundations on or in clay (shallow foundations, wooden foundations and friction piles, marked in purple). The relatively complex tunnel layout with three parallel tunnels has been simplified with a single tunnel with a width corresponding to the perimeter of the three single tunnels.

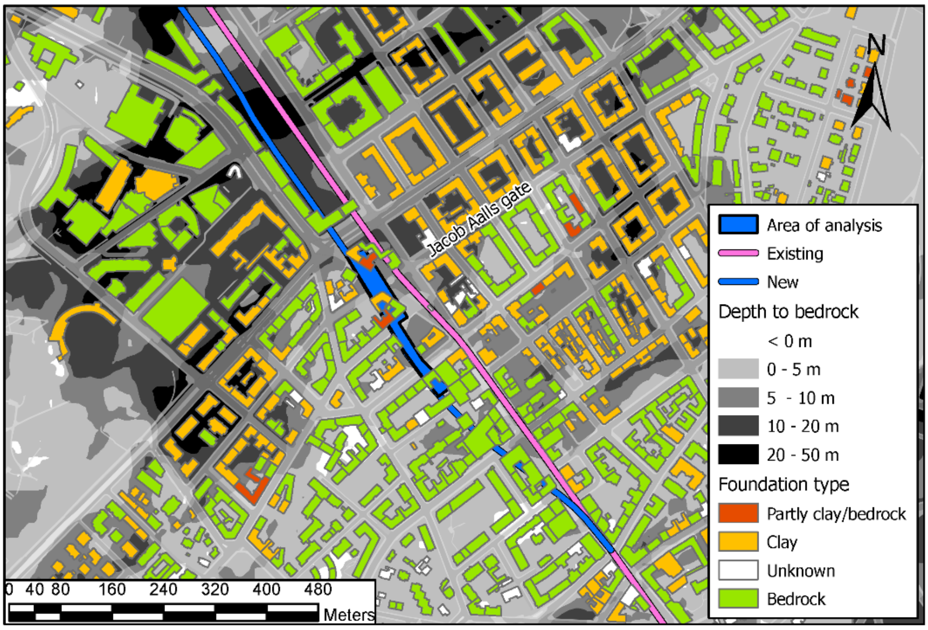


Figure 4 Project area with tunnel location, depth to bedrock map and buildings with different foundation type.

4.3 Tunnel

Only the most critical tunnel section (Figure 4) was assessed in the first planning phase. This section had especially challenging conditions for pre-grouting of the bedrock, with three parallel single-track tunnels and low bedrock cover (4-6 m). The bottom of the tunnel is located about 10 m under the existing groundwater head measured at bedrock. A cross-section through the tunnel at Jacob Aalls gate (see Figure 4) is shown in Figure 5.

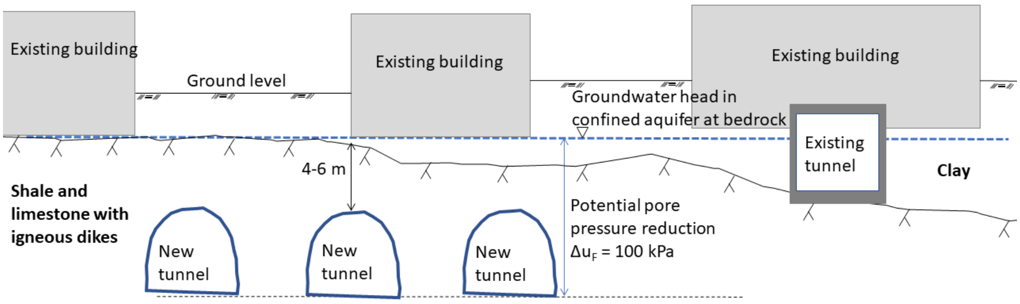


Figure 5 Illustration of new tunnel cross-section with three parallel tunnels and limited bedrock cover.

4.4 Analysis and input data

Input data was obtained from field investigations in the area from previous projects. The bedrock map is generated based on an extensive database with historic field investigations, from the Oslo municipality [17].

The following parameters were assigned as a basis for the settlement calculations:

- Clay soil density: 1,85 kg/m^3
- Depth of the groundwater table below the ground surface: 2 m
- Janbu settlement parameters (constant values) evaluated from constant rate of strain laboratory tests on undisturbed clay samples: OCR=1.2; reference pressure p_r=5 kPa; modulus number m=30; stiffness constant $M_{OC}/(p'_c \cdot m)=4$, where M_{OC}=modulus in the over-consolidated stress range, p'_c= the pre-consolidation pressure

4.5 GIBV-analysis and discussion

To assess the building damage potential for the planned tunnel section, two different scenarios were chosen as given in Table 1.

Table 1. Description of scenarios for pore pressure reduction.

Scenario	Δu_F [kPa]	OCR [-]	Description
A	100	1.2	Unsuccessful pre-grouting, resulting in pore pressure reduction to the base of the tunnel excavation
B	50	1.2	High quality pre-grouting achieved, limiting pore pressure reduction

The settlements are calculated for full consolidation time, i.e. assuming a permanent pore pressure decrease. For both cases buildings not founded to bedrock are considered, in total 284 buildings. The assessed impact maps for the two scenarios are shown in Figure 6. A summary of the results is given in Table 2. As a reference 80% consolidation will be achieved after about 10-20 years of consolidation.

The result for scenario A is shown in Figure 6a, where the assumed pore pressure reduction of 10 m will result in settlements of 10-50 mm for a large extent of the buildings in the areas of clay depressions. Some buildings closer to the tunnel are expected to experience settlements over 50 mm. As can be seen from the figure, the zone of influence is larger than 400 m. The result of scenario B with 5 m pore pressure reduction at bedrock is shown in Figure 6b. The number of buildings with moderate impact (10-50 mm settlement) is substantially decreased to only 7 buildings. It is very clear that the quality of the pre-grouting and the resulting pore pressure reduction has a large impact on the risk of building damage in the area, as a larger pore pressure reduction significantly increases the settlement impact on the buildings and the damage potential.

Table 2 Summary of assessed impact classes (adapted from [13]) for buildings not founded on/to bedrock, assuming permanent pore pressure reduction.

Scenario	**Number of buildings in each impact category**			
	Negligible **< 10 mm**	**Slight** **10 - 50 mm**	**Moderate** **50 - 75 mm**	**High** **> 75 mm**
Scenario A (Δu = 100 kPa)	137	141	6	0
Scenario B (Δu = 50 kPa)	277	7	0	0

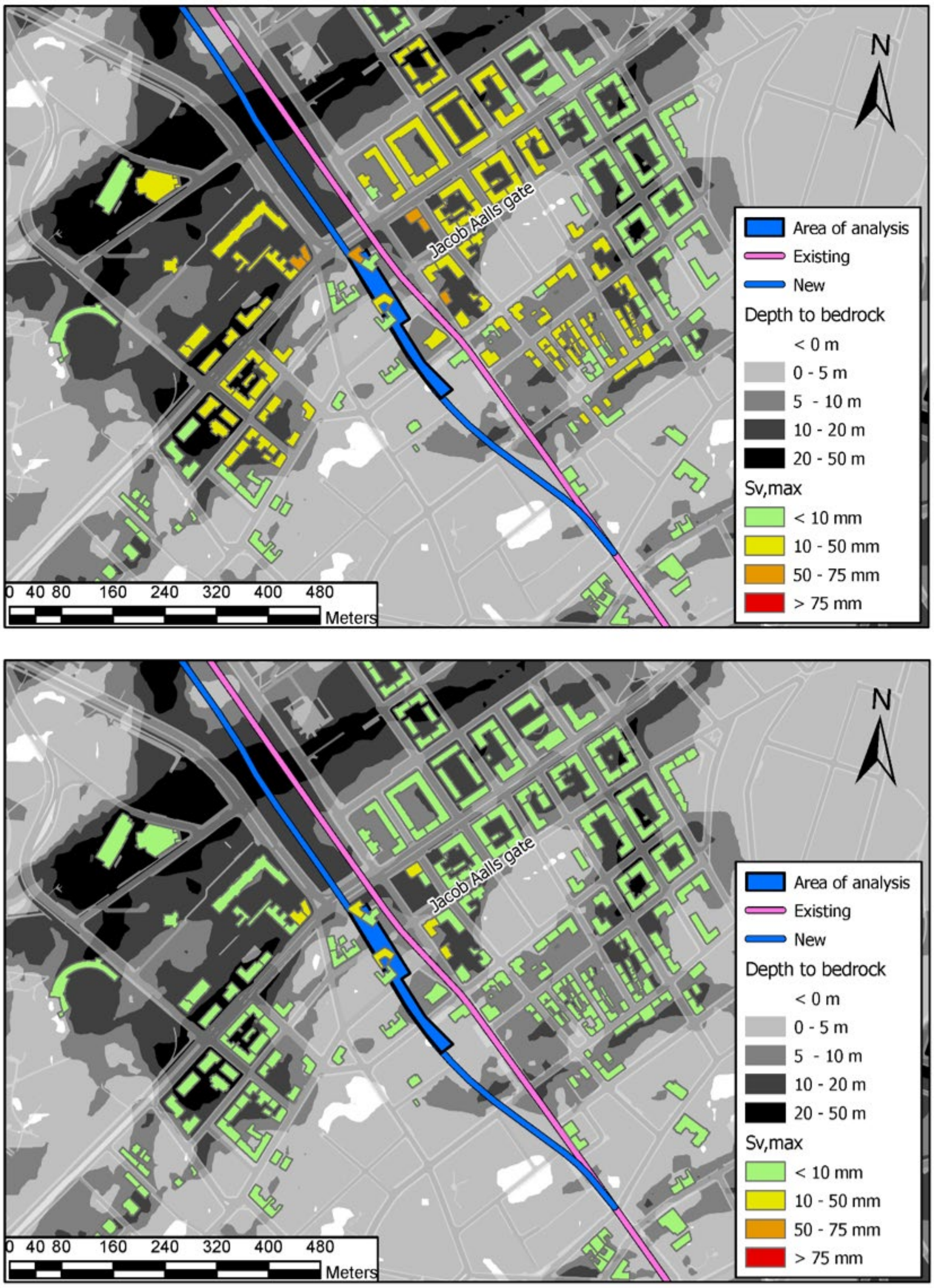


Figure 6 Result of impact classes only showing buildings that are not founded to/on bedrock, long-term scenario assuming permanent pore pressure reduction a) top: scenario A (Δu_F = 100 kPa), b) bottom: scenario B (Δu_F= 50 kPa).

5 Conclusions and final remarks

This paper presents a case study where the GIBV tool has been adopted and applied to an urban tunnel excavation. The conducted early-stage assessment provides insight into the effects of different scenarios for pore pressure drawdown and shows, as expected, the importance of limiting pore pressure reduction to reduce building damage potential. The results provide valuable input for the planning of pre-excavation grouting, including identification of specific buildings, which require additional investigations and more detailed assessments. In addition, the results indicate focus areas for monitoring and artificial water infiltration.

To improve the assessment tool, further work should be undertaken to be able to assign different parameter-sets to different areas to account for changes in the ground conditions. In addition, the GIBV tool for deep excavations [5] should be merged with the tunnel tool, to be able to assess projects with both cut and cover sections and bedrock tunnels.

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Authors

Dr. Jenny Langford (Korrespondenzautor)
jenny.langford@ngi.no
Norwegian Geotechnical Institute (NGI)
Sandakerveien 140
0484 Oslo
Norway

Dr. Stefan Ritter
stefan.ritter@ngi.no
Norwegian Geotechnical Institute (NGI) and Oslo Metropolitan University
Sandakerveien 140
0484 Oslo
Norway

Mr. Asgeir Kydland Lysdahl
asgeir.kydland.lysdahl@ngi.no
Norwegian Geotechnical Institute (NGI)
Sandakerveien 140
0484 Oslo
Norway

Mr. Eivind Wiik Ånes
eivind.wiik.anes@ngi.no
Norwegian Geotechnical Institute (NGI)
Sandakerveien 140
0484 Oslo
Norway

Dr. Luca Piciullo
luca.piciullo@ngi.no
Norwegian Geotechnical Institute (NGI) and Oslo Metropolitan University
Sandakerveien 140
0484 Oslo
Norway