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Evaluating the effects of a deep excavation on monumental buildings: MarmorKirken station in Copenhagen

Évaluation des effets d'une excavation profonde sur des bâtiments monumentaux: gare MarmorKirken à Copenhague

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ABSTRACT: This paper describes the Building Risk Assessment (BRA) process implemented during the design and construction of MarmorKirken metro station in Copenhagen. Being the box station very near the monumental church, the evaluation of the effects induced by the excavation on the church was a key issue of the design. Surveys, structural and geotechnical investigations were carried out to setup reliable structural and geotechnical numerical models on which BRA, at the design stage, was based. During construction works, design predictions were systematically compared with monitoring measures, allowing to update the BRA. According to BRA results, no significant effects of construction works on the church was observed.

RÉSUMÉ: Cet article décrit le processus d'Evaluation des Risques liés aux Bâtiments (BRA) mis en œuvre lors de la conception et de la construction de la station de métro MarmorKirken à Copenhague. Le box étant très proche de l'église monumentale, l'évaluation des effets induits par les fouilles sur l'église a été un enjeu clé de la conception. Des études, des investigations structurelles et géotechniques ont été réalisées pour établir des modèles numériques structurels et géotechniques fiables sur lesquels BRA, au stade de la conception, s'est basé. Lors des travaux de construction, les prévisions de conception ont été systématiquement comparées aux mesures de suivi, permettant ainsi de mettre à jour le BRA. Selon les résultats du BRA, aucun effet significatif des travaux de construction sur l'église n'a été observé.

Keywords: Deep excavations; soil-structure interaction; numerical analyses.

1 INTRODUCTION

Deep excavations and tunnelling in the urban environment require a careful evaluation of the effects of works on existing structures. Very often, the building risk assessment (hereinafter referred to by the acronym BRA) process plays a major role in design, especially when monumental structures are involved.

In this case, at a given design stage, numerical analyses with different levels of complexity are carried out, geotechnical and structural aspects of the problem needing to be properly addressed (Rampello et al., 2012; Burghignoli et al., 2013; Pascariello et al., 2023). Expected building damage may be then evaluated by looking at stress and strain fields or patterns in the structure.

During construction stages, monitoring data are of primary importance to assess numerical predictions and, when needed, to update the BRA.

This paper describes some features of the BRA process carried out for the construction of MarmorKirken metro station in Copenhagen.

2 MARMORKIRKEN STATION

Marmorkirken station box is about 35 m in depth; diaphragm walls have a length of 40 m. The retaining walls are located only 3 m away from the foundations of the church (Figure 1). A full top-down construction technique was adopted to minimise excavation induced settlements of the church.

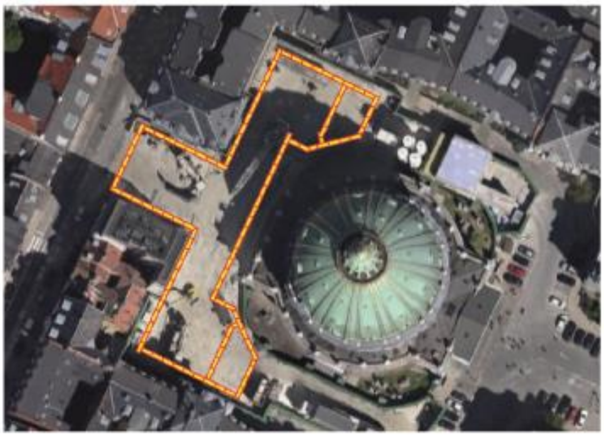

Figure 1. View of MarmorKirken area.

3 BRA PROCESS

The BRA process carried out consisted of different stages, starting from the acquisition of relevant data used for the setup of numerical models. BRA was based on the evaluation of predicted stresses and strain field changes due to construction activities. The interpretation of monitoring measurements allowed for checking and updating the BRA during construction works.

3.1 Survey and testing

It is worth noting that reliable structural and geotechnical numerical models should be based on reliable structural and geotechnical investigations, the first of them being rather difficult to be obtained for monumental buildings, often due to conservative issues. For MarmorKirken, the following activities were addressed:1) historical research (drawings and texts); 2) a laser scanner survey to define geometry; 3) endoscopy and lab testing on cored samples (marble); 4) flat jack and sonic tests on walls (masonry);
Before the construction activities, no significant crack patterns were observed in the structure.

The geotechnical investigation (boreholes, piezometers, seismic tests and samples tested in the laboratory) allowed for a reliable geotechnical characterization of the foundation soil. Boreholes and excavation pits enabled to identify materials and depth of the ring foundation of the Church.

3.2 Structural and geotechnical model

The church may be broadly divided in four main parts: foundation level (rock blocks), entrance level (marble blocks, for both inner and outer structure), drum and dome (masonry). The ring foundation has a thickness of about 3 m, with an inner and outer diameter of about 25 and 50 m, respectively. The dome has a diameter equal to 31 m, ant it reaches a height of about 46 m.

About 50000 finite elements were used to define the structural model of church (Figure 2). Both masonry and marble were modelled using a linear, isotropic elastic model due to the expected small strain levels. The estimated total load acting at foundation level was about 300 MN.

Figure 6 shows soil profile and geometry of the excavation in front of the church. Foundation soils, below shallow units of made ground (FY) and a clayey silt (ML), are constituted by a medium to dense sand and gravel level (DS/DG) with a thickness of about 9 m. At a depth of 13 m (10 m a.s.l.), the basal limestone formation, with increasing stiffness and strength properties with depth (UCL-HP, UCL, MCL), is found.

Figure 2. Structural model of the church (SAP2000 code).

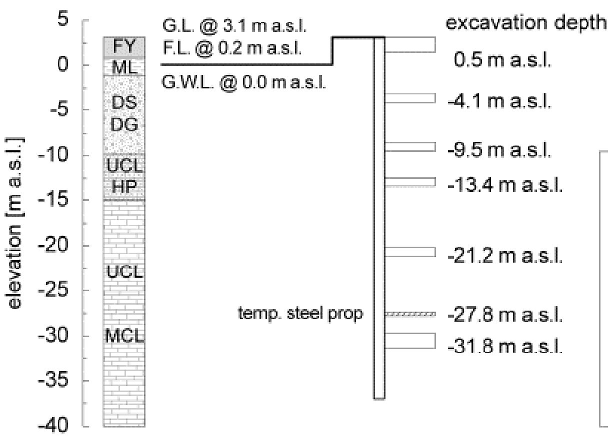

Figure 3. Soil profile and top-down excavation stages in front of the church.

Figure 4 shows the three-dimensional (3D) FEM computational mesh of the geotechnical model of both the excavation and the church. The church is modelled by an equivalent embedded linear elastic solid (Rampello et al., 2012), on which the average dead loads obtained from the structural analysis are applied. The HSM nonlinear, plasticity hardening model (Schanz et al., 1999) was used for soil and rock units. Calculation steps of the analysis followed, after the in-situ stage and the simulation of retaining walls construction, the top-down sequence depicted in Figure 3. Predicted maximum settlements of the Church were very small: about 0.5 mm due to retaining wall construction and about 1.7 mm at the end of excavation stages. Full details on soil parameters, numerical modelling approach and results of the 3D numerical soil-structure interaction analysis (class A prediction) are described in Soccodato and Tropeano (2021).

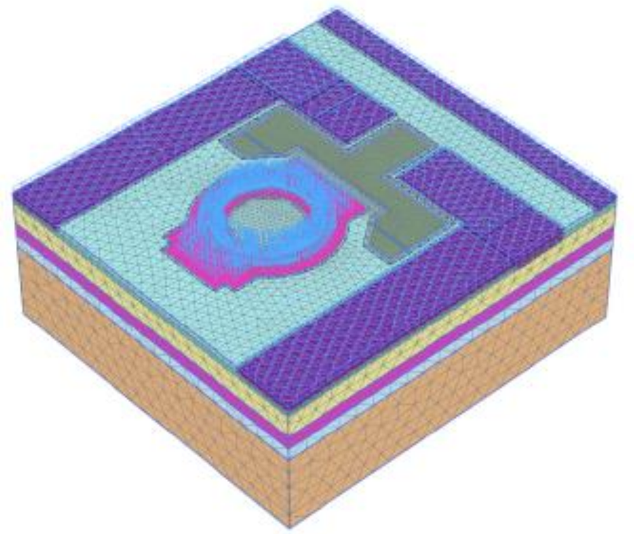

Figure 4. Geometry and mesh of the geotechnical model (PLAXIS 3D code).

3.3 Monitoring system

The project included a detailed monitoring plan, with an automatic remote acquisition system (KRONOS) to provide real-time information about the effects of construction activities. Precision levelling points were placed on the church structure and inclinometers were installed inside the retaining walls and in the soil behind (Figure 5).

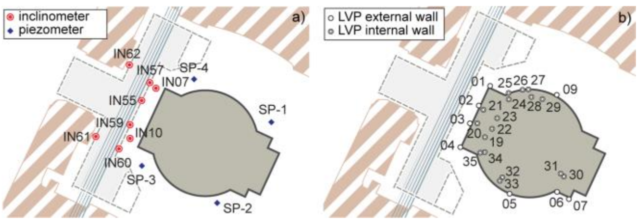

Figure 5. Monitoring system: a) inclinometers and piezometers; b) levelling points.

3.4 Evaluating the effects of construction

Settlement fields applied to the bottom nodes of the structural model of the church are shown in Figure 6. The reference stage is represented by the self-weight (SW) condition before the construction works. Predicted settlement field at the design stage (G1) was then applied, evaluating changes in stress and strain values.

During construction works, monitoring system recorded higher settlements than those predicted. Firstly, wall installation in front of the Church caused a maximum settlement of about 3 mm (KRONOS): a first correction to the applied settlement fields (G2) was thus considered, by adding to the actual settlement field recorded by measurements (KRONOS) the predicted settlement field induced by excavation stages. Furthermore, first excavation stages also gave rise to settlements of the church higher than those predicted. Considering the 'at time' available monitoring data compared to predictions, the settlement field obtained from numerical geotechnical analysis for the excavation stages was increased by a factor equal to 4, giving rise to the final settlement field (G3) used for BRA updating.

Maximum measured settlements of the church at the end of works were about 7 mm, in close agreement with the G3 displacement field used for BRA (Soccodato and Tropeano, 2021). It is worth noting that nearly one half of the total observed maximum settlement was due to retaining wall construction.

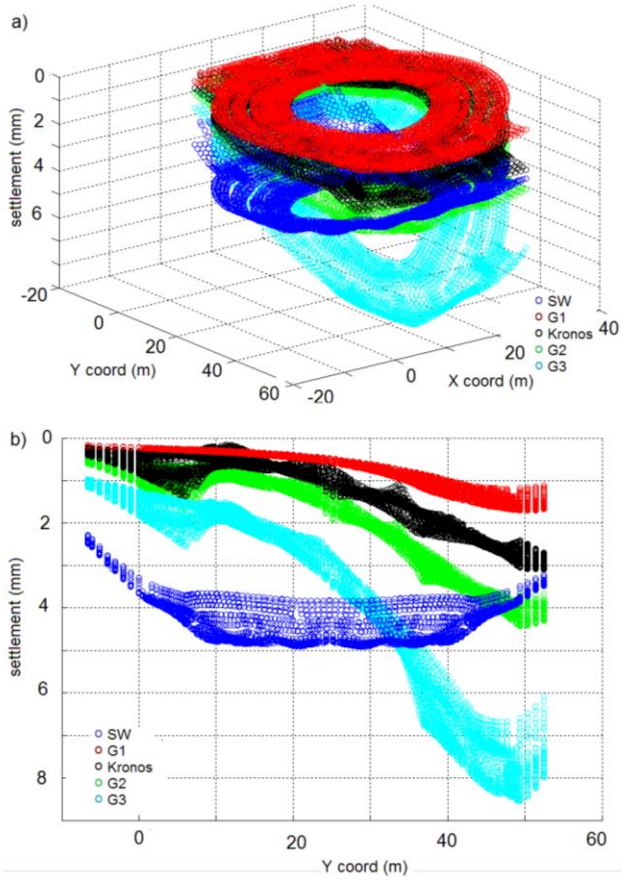

Figure 6. Foundation settlement fields used for BRA: a) 3D view; b) longitudinal view toward box station excavation.

As stated before, BRA was based on the comparison of stress and strain fields under different settlement fields, taking as reference the SW condition.

Figure 7 shows, as an example, the frequency distribution of principal tensile strain obtained from the structural model in the dome elements and in the inner structure. Maximum strain values are very small ($< 3\cdot10^{-4}$) and significantly lesser than those associated to 0.1 mm width cracks in masonry structures. Furthermore, changes (in value and frequency) due to construction works (both for G2 and updated G3 settlement fields) are quite limited, allowing for the estimation of a negligible damage induced by the excavation.

Figure 8 shows the stress values for the inner structure, which allowed for a preliminary identification of the parts of the structure potentially affected by cracking.

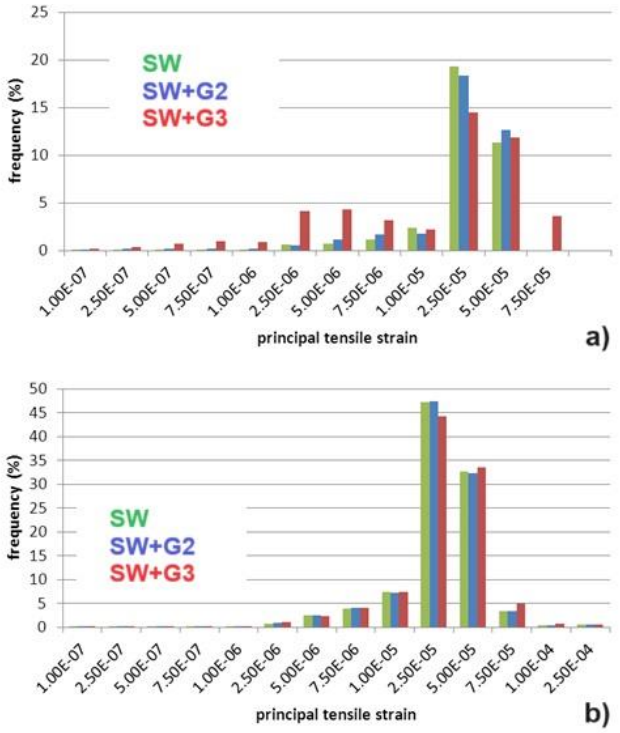

Figure 7. Distribution of principal tensile strain: a) in dome elements; b) in the inner structure (masonry).

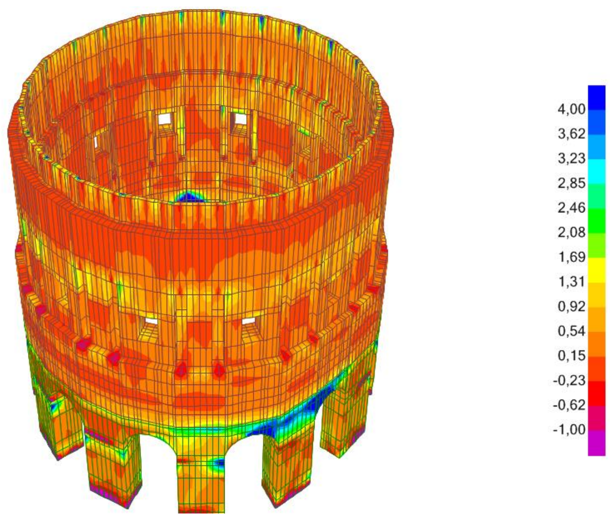

Figure 8. Inner structure, SW+G3 settlement field: maximum principal stresses (units: daN/cm^2, tensile if >0).

4 CONCLUSIONS

The Building Risk Assessment process carried out for MarmorKirken has been a very challenging task: archaeologist, structural and geotechnical engineers collaborated to define reliable models to be used in the evaluation of the excavation induced effects on the church. Negligible effects of construction activities on MarmorKirken were predicted at the design stage, as well as negligible damage appeared in MarmorKirken at the end of works. During construction, the real time automatic monitoring system allowed for successfully updating the Building Risk Assessment, pointing out the importance of real time measurements and of their interpretation in this kind of process.

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REFERENCES

Burghignoli A., Callisto L., Rampello S., Soccodato F.M., and Viggiani, G.M.B. (2013). The crossing of the hystorical centre of Rome by the new underground Line C: a study of soil–structure interaction for historical buildings. In *Geotechnics and Heritage: Case Histories*, E. Bilotta et al. (eds), CRC PRESS, pp. 97-136.

Pascariello, M.N., Luciano, A., Bilotta, E., Acikgoz, S. and Mair, R. (2023). Numerical modelling of the response of two heritage masonry buildings to nearby tunnelling. *Tunnelling and Underground Space Technology*, 131:104845. https://doi.org/10.1016/j.tust.2022.104845.

Rampello, S., Callisto, L., Viggiani, G. and Soccodato, F.M. (2012). Evaluating the effects of tunnelling on historical buildings: the example of a new subway in Rome / Auswertung der Auswirkungen des Tunnelbaus auf historische Gebäude am Beispiel einer neuen U-Bahnlinie in Rom. *Geomechanik Tunnelbau*, 5: 275-299. http://doi.org/10.1002/geot.201200017.

Schanz, P.A., Vermeer, P.A., and Bonnier, P.G. (1999). The hardening soil model: Formulation and verification. In *Beyond 2000 in Computational Geotechnics*, pp. 281-296. Balkema, Rotterdam.

Soccodato, F. M. and Tropeano, G. (2021). Numerical analysis of a deep excavation in front of MarmorKirken, Copenhagen. In *Challenges and Innovations in Geomechanics,* M. Barla et al. (eds.), Lecture Notes in Civil Engineering, Springer, Vol. 126, pp. 223-230. https://dx.doi.org/10.1007/978-3-030-54518-3_27.