Deformation behaviour of clay due to unloading and the consequences on construction projects in inner cities

Étude du comportement en déformations de l'argile suite à un retrait de charge et conséquences lors de projets de constructions en zone urbaine

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ABSTRACT: In the course of construction projects in many cases the soil is unloaded. For example at the construction of excavations or the deconstruction of existing buildings the soil relaxes due to the reduced stress level. Cohesive soil materials like clay react strongly time dependent. At all construction projects in the city of Frankfurt am Main, Germany, which belong to the Geotechnical Category 3 regarding Eurocode EC 7 the deformation of the soil was measured during and after the construction works. It has to be determined that the settlement relevant soil layer, the tertiary Frankfurt Clay, relaxes time-delayed due to the unloading in the dimension of centimetres. The new acknowledgement of the deformation behaviour of the Frankfurt Clay due to unloading the subsoil is presented in detail by typical projects for the development of the city.

RÉSUMÉ : Il arrive régulièrement dans le cadre de projets de construction en zone urbaine que le sol subisse un déchargement. Dans le cas d'excavations par exemple, le sol se détend suite à une baisse des contraintes appliquées. Le comportement des sols cohésifs tels que l'argile dépend fortement du temps. Pour l'ensemble des projets de construction à Francfort en Allemagne, ces projets étant classés en Catégorie Géotechnique 3 selon l'Eurocode 7, les déformations du sol ont été mesurées pendant et après les travaux. Il est à mettre en avant que le sol de la couche pertinente en terme de tassements, l'argile tertiaire de Francfort (Frankfurt Clay), subit un relâchement différé dans le temps suite au retrait de charge de l'ordre du centimètre. Les nouvelles reconnaissances sur le comportement de l'argile de Francfort suite à un déchargement du sol sont présentées ici en détail pour des projets typiques dans le cadre du développement de la ville.

KEYWORDS: Soil-structure-interaction, Frankfurt Clay, time dependent deformation behaviour, observational method.

1 INTRODUCTION

Since the beginning of the large infrastructure and high-rise building constructions in Frankfurt am Main the bearing and deformation behaviour of the Frankfurt Clay has been scientifically researched intensely (Chambosse 1972, Breth and Stroh 1974, Amman et al. 1975, Sommer et al. 1990, König 1994, Katzenbach and Moormann 1999, Breth and Katzenbach 2000, Katzenbach et al. 2001, Moormann 2002, Katzenbach et al. 2002, Dürrwang et al. 2007, Janke et al. 2010, Vogler 2010, Katzenbach et al. 2011). The first research and experiences made with the Frankfurt Clay result from new constructions, i.e. from high-rise buildings and tunnel constructions.

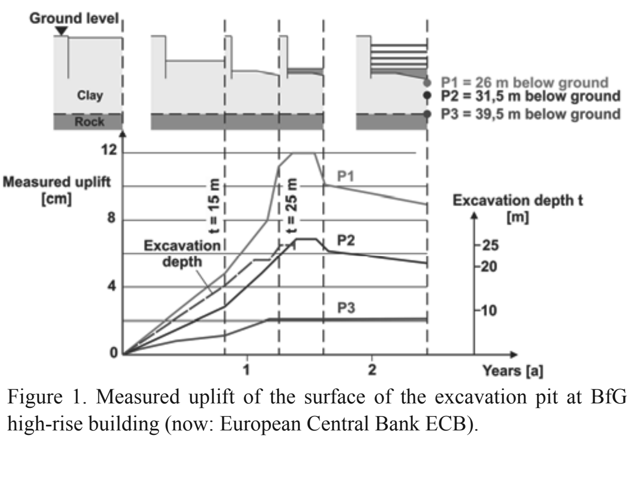

Figure 1. Measured uplift of the surface of the excavation pit at BfG high-rise building (now: European Central Bank ECB).

Due to the development of the city a lot of deconstruction activities occur in advance of new construction projects. In the course of these projects new knowledge about the time dependent bearing and deformation behaviour of the Frankfurt Clay is obtained, especially if there is a larger timeframe between the deconstruction (unloading) and the new construction activity (reloading). In such cases the uplifting is not overlapped or compensated by an early reloading. For example a deep excavation base usually heaves up to several centimetres as shown in Figure 1 (Amman et al. 1974).

The time dependent deformation behaviour of the over-consolidated tertiary Frankfurt Clay is presented in detail by 2 large deconstruction projects. The first project is the deconstruction of the building complex of the Zürich Insurance consisting of 2 high-rise buildings (Zürichhochhaus I and II) and the construction of the new high-rise building Opernturm at the same location. The project is located very close to a tunnel of the metro system. The second project is the deconstruction of an up to 14 storeys high-rise building in the historic centre of Frankfurt am Main. The project is located directly over 2 tunnels and an underground station of the metro system.

2 DECONSTRUCTION OF THE ZÜRICH INSURANCE HIGH-RISE BUILDINGS

The Zürich Insurance building complex was built between 1959 and 1963. It consisted of 2 high-rise buildings (Zürichhochhaus I and II) with heights of 70 m and 63 m and annexe to the high-rise buildings with up to 8 storeys. The complex was founded on a raft in a depth of 7 m below the surface. In the years 2001 and 2002 the complex was deconstructed down to the ground level. The sublevels remained. A cross section through the project area is shown in Figure 2.

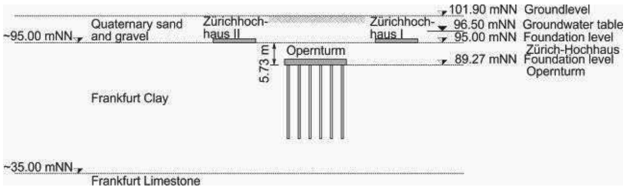

Figure 2. Soil, groundwater and foundation conditions.

5 years after the deconstruction the 177 m high-rise building Opernturm was built. The annexe of the high-rise building is up to 7 storeys high (Fig. 3) and was founded on the existing raft foundation. Under the Opernturm the existing raft was deconstructed and a new sublevel was built.

Figure 3. New high-rise building Opernturm.

The Opernturm is founded on a Combined Pile-Raft-Foundation (CPRF) consisting of a 3 m thick raft and 57 piles with a diameter of 1.5 m and a length of 40 m. For design of the CPRF a whole characteristic load of 1,500 MN was calculated. The bearing behaviour of the CPRF is described by the CPRF-coefficient α_{CPRF}, explained in Equation (1) (Viggiane 1998, Hanisch et al. 2002). The Operturm has a $\alpha_{CPRF} = 0.9$.

$$\alpha_{CPRF} = \frac{\sum_{j=1}^{n} R_{pile,k,j}}{R_{tot,k}} \quad (1)$$

The soil and groundwater conditions are typical for the inner city of Frankfurt am Main:

- 0 m to 7 m: quaternary sands and gravel
- 7 m to 67 m: Frankfurt Clay
- below 67 m: Frankfurt Limestone
- groundwater level in a depth of 5.5 m

The measured settlements during the construction of the Zürichhochhaus I and II as well as the uplift during their deconstruction are depicted in Figure 4. The measured settlements increase continuously up to 60 % of the final settlement during the construction time of the superstructure. Due to the consolidation process the deformation rate decreases continuously. About 5 years after the construction the settlement stopped at 9.5 cm at Zürichhochhaus I and 8.5 cm at Zürichhochhaus II. The deconstruction started in the middle of 2001. In March 2002 the deconstruction was completed. Only the sublevels were kept. After 5 years the measured uplift is in the same magnitude as the settlements before.

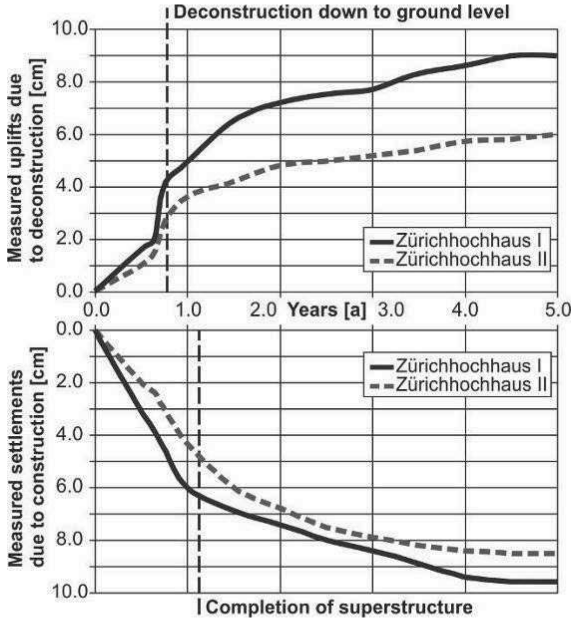

Figure 4. Measured settlements and uplifts of the soil in the area of the high-rise buildings.

The measured time dependent settlement and uplift evolution with reference to the maximum value can be approximately mathematically described by Equation 2. Figure 5 shows the application of Equation 2 to the presented project.

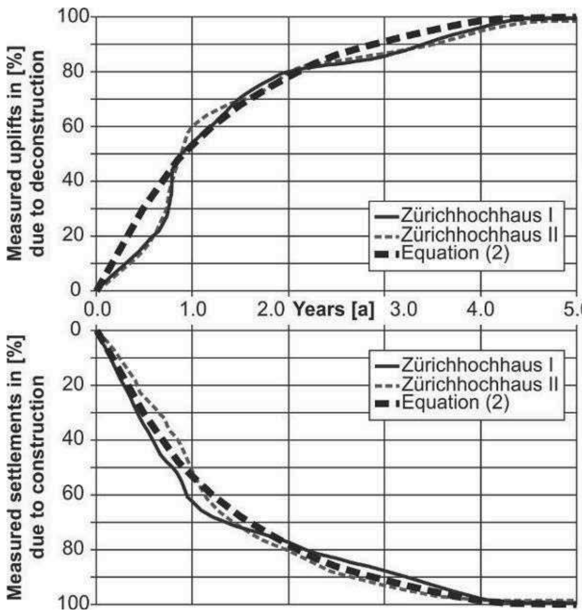

Figure 5. Measured settlement and uplift and correlation to Equation 2.

$$\frac{s(t)}{s_{max}} = k \cdot \left(1 - e^{(-n \cdot t)}\right) \quad (2)$$

where: k = Consolidation factor
here: $k = 0{,}104\,[-]$
n = Time factor
here: $n = 0{,}7\,[-]$
t = Time in years ($t \leq 5$ years)

(3)

$$\frac{s(t)}{s_{max}} = k \cdot \left(1 - e^{(-n \cdot t)}\right)$$

where: k = Consolidation factor

here: $k = 0{,}104\,[-]$

n = Time factor

here: $n = 0{,}7\,[-]$

t = Time in years ($t \leq 5$ years)

To verify Equation 2 the measured time dependent settlement behaviour during the construction of the high-rise building Mainzer Landstraße in Frankfurt am Main is used (Fig. 6). The construction of the 155 m high-rise building began in 1973 and the settlements were measured for 5 years. After this time a settlement of 25.4 cm was measured in the core area of the high-rise building. At the completion of the superstructure after 1.5 years the measured settlement was about 70% of the total settlement. The estimation of the time dependent deformation behaviour can also be described by Equation 2.

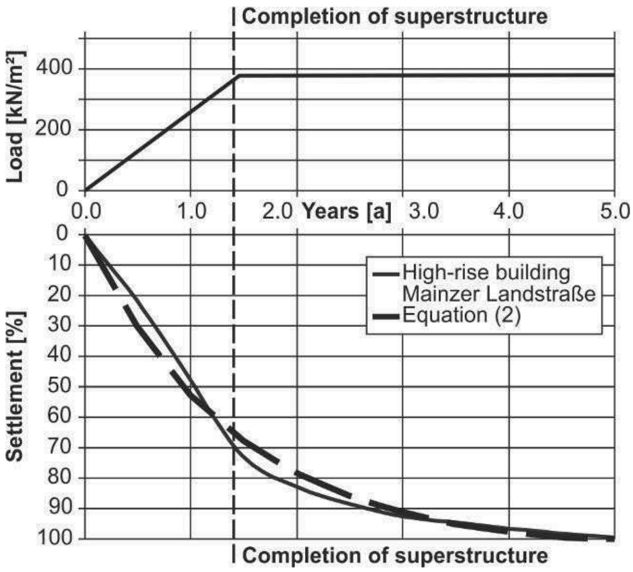

Figure 6. Measured settlement of the high-rise building Mainzer Landstraße.

3 DECONSTRUCTION OF A HIGH-RISE BUILDING FOUNDED ON AN UNDERGROUND STATION

In the context of the urban development the city of Frankfurt am Main plans to redesign the historic centre. Historic façades and buildings will be reconstructed. To create the necessary space on the surface an up to 14 storeys high-rise building was deconstructed. According to the present state of planning the deconstruction was carried out down to the sublevels.

The high-rise building and its underground parking overlay 2 tunnels and an underground station of the urban metro system. The loads of the superstructures are directly transferred onto the tunnels and underground station. Figures 7 and 8 give an overview on the primary situation prior to the deconstruction. The sealing of the structures was made of outside layers of bitumen-based materials. It must be guaranteed that during the deconstruction of the existing high-rise building and the construction of the new buildings the sealing of the underground structures and the sublevels remained intact. For this purpose especially the uplifts due to the deconstruction and the deformations of the underground structures and the sublevels had to be monitored during the execution of the project according to the observational method.

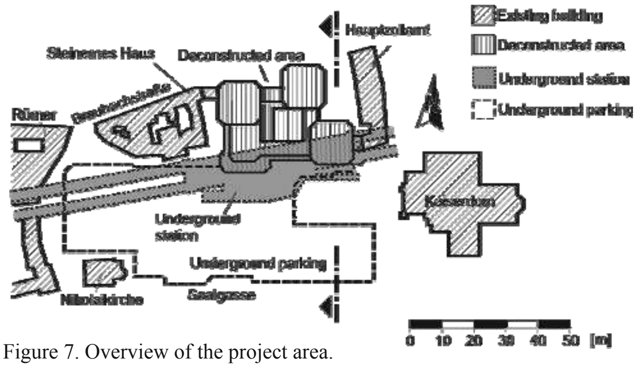

Figure 7. Overview of the project area.

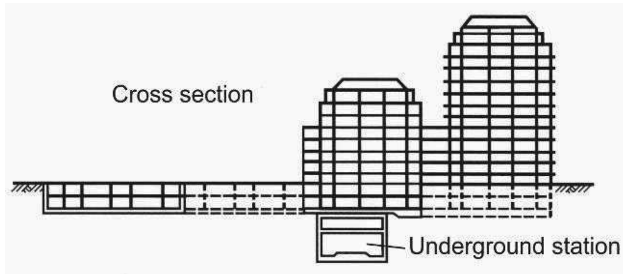

Figure 8. Cross section of Figure 6.

The soil and groundwater conditions are as follows:

- 0 m to 7 m: quaternary sands and gravel
- 7 m to 30 m: Frankfurt Clay
- below 30 m: Frankfurt Limestone
- groundwater level in a depth of 6 m

The groundwater level is influenced by the river Main which is 180 m far away. In the course of the geotechnical survey two aquifers have been encountered. The top aquifer is located in the non-cohesive soil. The lower confined groundwater layer is located in the Frankfurt Clay and in the Frankfurt Limestone.

According to the classification of the project into the Geotechnical Category 3, that is the Category for very difficult projects in EC 7, an extensive geodetic monitoring program with 580 measuring points was installed. 220 measuring points are located around the deconstructed building, 110 are located in the underground parking and in the sublevels of the deconstructed building, 30 are in the underground station and the remaining 220 are located in the tunnels.

The existing buildings were deconstructed down to the 2 sublevels. The uplift that occurred due to the unloaded of the soil is shown on selected points (Figures 9 and 10).

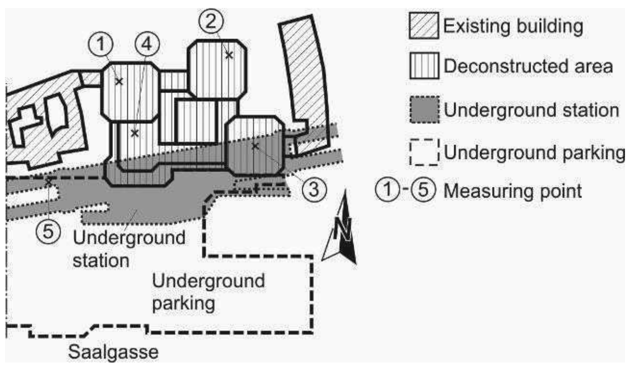

Figure 9. Selected measuring points.

The selected measuring points 1 to 4 are in the sublevel of the former high-rise building. Measuring point 5 is at the transition of the underground station to the tunnel. At the measuring points 1 to 4 uplift between 1 cm and 5 cm was detected in the deconstruction time (March to December 2010). The measured uplift of measuring point 5 is less than 0.5 cm.

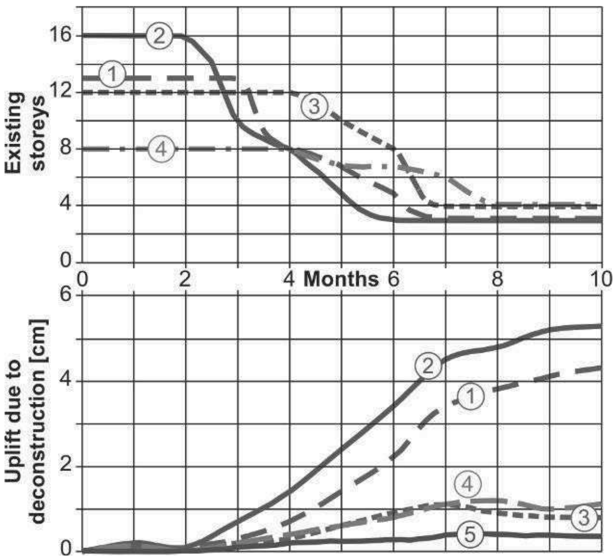

Figure 10. Measured uplift at selected measuring points.

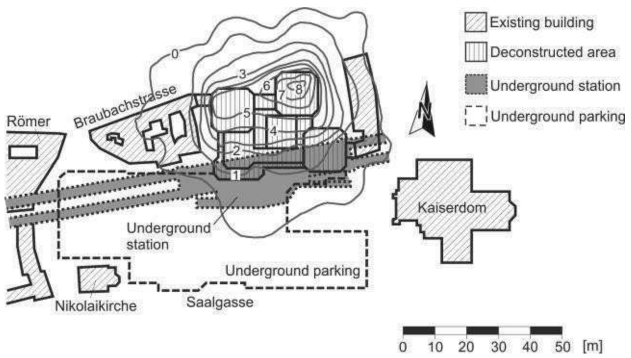

Figure 11. Measured uplift of the whole project area [cm].

After the deconstruction down to the sublevels in December 2010, the modification of the sublevels began. In that phase the loads only were changed insignificantly. The uplift of the whole project area and the neighbourhood in October 2012 is drawn in Figure 11. The uplift due to the reduced stress level of the stress and time related deformation behaviour of the Frankfurt Clay is continuously raising due to the consolidation processes. A maximum uplift of 8.5 cm was measured in the area where the most storeys were deconstructed. The uplifts fade down related to the distance very quickly. So no dangerous deformations of the neighbourhood were measured.

4 CONCLUSIONS

At the construction of excavations or the deconstruction of existing buildings the soil is unloaded and relaxes due to the reduced stress level. Cohesive soil materials like clay react strongly time dependent. For example the tertiary Frankfurt Clay relaxes time-delayed due to the unloading in the dimension of centimetres. Regarding the guarantee of the stability and the serviceability of structures in the neighbourhood the influence of the arising deformation of the soil has to be taken into account during an early planning stage and has to be considered during analyses and design.

For verification of the analyses and to proof the design all projects with large soil deformations have to be monitored by means of the observational method. Only high-level analyses compared with the observational method are the guarantee for a safe construction phase for the project itself and the influenced structures.

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