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# Combined subsidence phenomena in high-rise built urban areas: numerical study for Frankfurt am Main

## Subsidence combinés dans les zones urbaines construites: étude numérique pour Francfort-sur-le-Main

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**ABSTRACT:** In many megacities, excessive population growth and urban development have brought to heavy concentration of structural loads and marked increase of water demand leading to huge ground water extraction. This paper addresses the effects of both factors on ground settlement magnitude in areas where high-rise buildings prevail. For this purpose, referring to the case study of Frankfurt am Main (Germany), a numerical analysis of soil settlements under structural loads was performed for a selection of high-rise buildings resting on combined pile-raft foundations in overconsolidated clays. Then, at the scale of the single building, the contribution of groundwater withdrawals to the total predicted settlements was quantified via 2D-FEM model, thus highlighting the key role of pore pressure changes on settlement occurrence.

**RÉSUMÉ:** Dans de nombreuses mégapoles, la croissance démographique excessive et le développement urbain ont entraîné une forte concentration de charges structurelles et une augmentation marquée de la demande en eau, entraînant une extraction massive des eaux souterraines. Cet article traite des effets des deux facteurs sur l'ampleur de la colonisation dans les zones où les immeubles de grande hauteur prédominent. À cette fin, en se référant à l'étude de cas de Frankfurt am Main (Allemagne), une analyse numérique des dépôts de sol sous charges structurelles a été réalisée pour un groupe d'immeubles de grande hauteur reposant sur des fondations combinées de pieux en argiles surconsolidées. La contribution des prélèvements d'eau souterraine aux totaux prévus a été quantifiée via un modèle 2D-FEM, soulignant ainsi le rôle clé des changements de pression interstitielle sur la présence de peuplements.

**Keywords:** subsidence; hige-rise buildings; construction loads; water withdrawals.

## 1 INTRODUCTION

Subsidence threatens many megacities worldwide – especially fast growing cities in deltaic areas with soft soils – annually resulting in billions of dollars lost due to structural damage and high maintenance costs to structures and infrastructure network (Deltares, 2013). Subsidence can have natural as well as anthropogenic causes. Among the latter, compression of shallow layers by loading (e.g., buildings), or drainage and subsequent oxidation and consolidation of organic soils and peat, or extraction of oil, gas, coal, salt and groundwater can be mentioned. Main related effects can be: *i)* damage to buildings, infrastructure (roads, bridges, dikes) and subsurface facilities (drainage, sewerage, gas pipes); *ii)* increased flood risk; *iii)* disruption of the water management. In many cases, multiple causes may be contributing to these effects. An efficient subsidence risk mitigation plan should comprehensively account for all of the relevant above-mentioned aspects, supported by appropriate modelling and datasets concerning soil properties, underground water regime, building/foundation properties and loads, displacement data. With reference to the case study of Frankfurt am Main (Germany), the present study investigates the relative and combined contribution of both concentrated construction loads and groundwater table lowering on settlement magnitude in an area where high-rise buildings prevail.

## 2 FRANKFURT CASE STUDY

Frankfurt am Main is the fifth largest city in Germany. In 1961, the first building with 20 stores was constructed and in 1969 the first Commerzbank Tower (130 m high with 30 floors) was completed. In the 1970s and early 1980s, several other skyscrapers were built with heights ranging up to 150–180 m. All those buildings were founded in the very settlement-sensitive Frankfurt Clay (Katzenbach, 2005). In this context, settlements due to building construction loads and groundwater extraction are hereafter analyzed in a specific area of the financial district of the city.

### *2.1* Soil model

The Frankfurt subsoil (Hemsley, 2000) consists of quaternary terrace sand and gravels down to 6-10 m below the surface, underlain by tertiary sediments (see Figure 1). These latter, in turn, consist of Frankfurt clay overlying Frankfurt limestone. This overconsolidated clay is an alternating sequence of stiff and semi-solid clay, wherein hydrobiasands, limestone and dolomite bands are embedded. The limit between Frankfurt clay and Frankfurt limestone is approximately around 40 m b.g.l. The limestone layers within the Frankfurt Clay mostly form unbroken and unweathered plates, but cannot be used for building foundations. As for the Frankfurt limestone – composed by massive limestone and dolomite layers, algal reefs, marly calcareous sands and silts and marly clay – it is a strong and stiff formation with respect to Frankfurt clay extending to depths of about 120 m (Katzenbach et al., 2005). According to these considerations, for the purpose of the present analysis the compressibility of the limestone is assumed similar to that of the sand. The marl is a material with a particular behaviour placed at a depth of over 110 m; its compressibility parameters were assigned as falling within the range of sand parameters. Strength parameters of both Frankfurt Clay and sand are reported in Table 1 as provided by Amann et al. (1975).

*Table 1. Frankfurt's subsoil hydro-mechanical properties.*

| | **E** [Mpa] | **k** [m/day] | **ν** | **γ** [kN/m$^3$] | **c** [kPa] | **φ′** |
|---|---|---|---|---|---|---|
| sand | 75 | 86 | 0.25 | 18 | 0 | 32.5 |
| clay | 50 | 8,64E-3 | 0.15 | 19 | 20 | 20 |

In order to generate the numerical model, owing to the limited information about compressibility parameters, correlation formulas were used. As for the sand, literature values (Hemsley, 2000) were integrated with the values provided by the tables of Dutch standards (NEN, 2016) entering with the Young's modulus value (from Table 1).

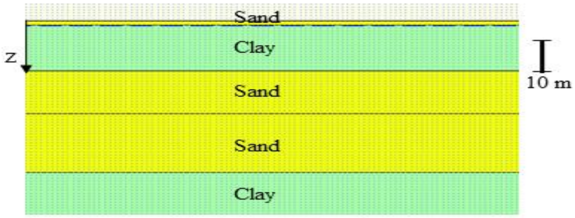


*Figure 1. Subsoil model.*

As for the Frankfurt clay, the compressibility parameters were determined assuming the material as perfectly elastic. By combining Terzaghi's law for small strain increments and Hooke's law, the CR value was derived. According to the NEN-Bjerrum theory, RR has been obtained from the CR parameter (see formulas in Table 2). Finally, $C_\alpha$ has been derived by the Dutch standard tables. Then, in order to pass from the compressibility parameters of the NEN-Bjerrum model to those of the Isotache model (a, b, c) (Den Haan, 1996) - which is implemented in the used D-Settlement software (Visschedijk et al. 2016) - the relations proposed by Den Haan (1996) and Den Haan and H. Sellmeijer (2001) were used. Furthermore, the compressibility parameters of the Isotache model allowed retrieving those ($\lambda^*$, $\kappa^*$, $\mu^*$) of the Soft Soil Creep model (SSC) (Brinkgreve et al., 2006) – which is implemented in Plaxis – via the relations formuled by Brinkgreve et al. (2006).

Table 2 summarizes formulas and values of compressibility parameters used in both numerical models performed via D-Settlement (for a group of buildings) and via Plaxis (with reference to two selected buildings for which more information is available).

The groundwater level is placed at 6m b.g.l., as indicated by Reul (2003).

## 3 RESULTS

### 3.1 *Effect of construction loads*

The effects of construction loads were analyzed on a part of the financial district of Frankfurt city (Figure 2a). This area contains several high-rise buildings that were built at relatively close distances. The area (443,683 $m^2$) also includes medium- to low-rise buildings. The shape of the analyzed area was reviewed because D-Settlement software allows applying only circular or rectangular loads (the latter with sides parallel to the reference axis).

Low-rise buildings in the area are basically historical buildings, so their loads can be considered as a sort of pre-loading.

In order to compute the preloading as an average loading over the area associated with the old buildings, the total real footprint area of the buildings (87,124 $m^2$) was multiplied by the average height of the old buildings and divided by the fictitious footprint area (the whole area minus the park area) to derive the fictitious average building height (give value m). This latter was then multiplied by an assumed load of 3 kN/$m^2$ for each m of building heigth to determine the load spread over the fictitious footprint area (indicated in orange in Figure 2b) that equalled 15.70 kN/$m^2$ with the exclusion of the park area.

*Table 2. Values of the soil compressibility parameters for the Frankfurt case.*

| | **CR**<br>$\frac{2.3\sigma'}{E_{ed}}$ | **RR**<br>$\frac{CR}{5}$ | **Cα** | **a**<br>$\frac{RR}{\ln(10)}$ | **b**<br>$\frac{CR}{\ln(10)}$ | **c**<br>$\frac{Ca}{\ln(10)}$ | **λ***<br>$\lambda^*=b$ | **k***<br>$\kappa^*=2a$ | **μ***<br>$\mu^*=c$ |
|---|---|---|---|---|---|---|---|---|---|
| sand | 0.0023 | 0.0008 | 0 | 0.00035 | 0.001 | 0 | 0.001 | 0.0007 | 0 |
| clay | 0.011 | 0.0022 | 0.0011 | 0.00095 | 0.0048 | 0.00048 | 0.0048 | 0.0019 | 0.00048 |

*Figure 2. a) the study area; b) low-rise buildings (in orange) whose loads are spread over the test area (framed in blue) with the exclusion of the park; c) the area where the pre-consolidation load was applied (in orange), the footprint area of high-rise buildings (in gray) and the reference axis (in red).*

Secondly, the loads transferred by the high-rise buildings on their specific footprint areas were calculated. Figure 2c shows four orange rectangles representing the area where the pre-consolidation load was applied and in gray the footprint areas of the high-rise buildings. In this area, in order to handle problems in foundation design for high-rise buildings on settlement-sensitive soils, the combination of conventionally bored piles with a raft foundation (combined pile-raft foundation, CPRF) was successfully used during the last two decades (Katzenbach, et al., 2005). According to its stiffness, a CPRF transfers the total vertical load of a structure $R_{tot}$ to the subsoil by the contact pressure of the raft ($R_{raft}$) as well as by the piles $\Sigma R_{pile,i}$.

$$Rtot = Rraft + \Sigma\, Rpile, i \qquad (1)$$

The distribution of the total building load between the different bearing elements of a CPRF is described by the CPRF coefficient ($\alpha_{CPRF}$) which defines the ratio between the amount of load carried by the piles $\Sigma R_{pile,i}$ and the total load of a building $R_{tot}$.

$$\alpha_{CPRF} = \frac{\sum R_{pile,i}}{R_{tot}} \qquad (2)$$

For a number of instrumented high-rise buildings in Frankfurt (Katzenbach, et al., 2000), the coefficient "$\alpha_{CPRF}$" value is about 0.80. For this reason, it was assumed 20% out of the total load to be transferred by the raft and 80% by the piles, whose contact surface was set at 2/3 of the pile length according to the method of the equivalent plate. As for the length of piles, a linear regression relating the depth of the pile tip from the soil surface vs. the height above ground of the buildings was derived based on available data (Figure 3). This allowed deriving, in a very simplified way, pile depths also for those buildings for which this information was lacking.

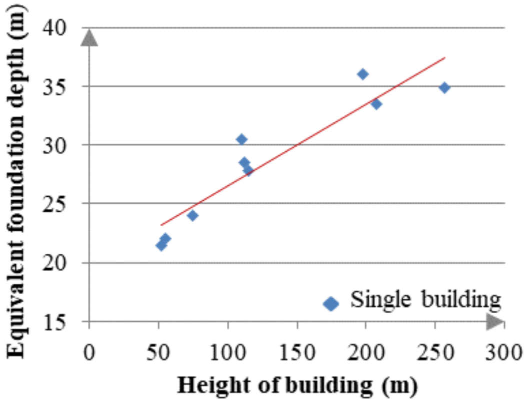


*Figure 3. Equivalent foundation depth (foundation depth + pile length) vs. building height.*

Then, the settlements after 10000 days, as estimation of the time whereafter limited residual settlements occur, were calculated using the software D-Settlement (Visschedijk et al, 2016) – which evaluates the distribution of loads in the ground, using applicable theory of Boussinesq or Buisman – along 400 vertical profiles (drawn with a spacing of 2 m, see Fig.4a) passing parallel to the reference axes (x and z). Afterward, the obtained settlement values were spatially interpolated with Surfer software to derive the contour map of the subsidence index ($I_s= w/w_{max}$, see Figure 4b). The pre-consolidation load (associated with the old buildings) induces settlements as high as 5% (Is=0.05) of the maximum settlement ($w_{max}$). Furthermore, the presence of the high-rise buildings contributes to settlements in their surrounding area that are up to 10% (Is=0.15) higher than those caused by the presence of only the low-rise buildings. Finally, the highest cumulative settlements ($I_s$=1) are recorded in correspondance of a building with shallow foundations, as expected for structures lacking the benefit of CPRF system (Katzenbach, et al., 2005).

## 3.2 *Effect of groundwater extraction*

To investigate the effects of groundwater extraction on settlements, a numerical analysis was carried out at more detailed scale with reference to two high-rise buildings (i.e. Eurotheum and Main Tower located in the study area). The mean features of these buildings are reported in Table 3 (Hemsley, 2000).

*Table 3. Information on buildings (Hemsley, 2000).*

| **Building Data** | **Main Tower** | **Eurotheum** |
|---|---|---|
| Construction period | 1996-99 | 1997-99 |
| Floors above ground | 57 | 31 |
| Basement floors | 5 | 3 |
| Foundation area [m$^2$] | 3800 | 1830 |
| Foundation depth [m] | -21 | -13 |
| Raft thickness [m] | 3.4 | 1.75 |
| Number of piles | 112 | 25 |
| Pile length [m] | 25 | 27,5 |
| Pile diameter [m] | 1.5 | 1.5 |

A 2D Finite Element Method analysis was performed in Plaxis to generate a consolidation model. Figure 5 shows the subsoil model and the input data; compressibility parameter of SSC model are included in Table 2.

The results of the consolidation with reference to both Eurotheum and MainTower models were validated by comparing short-term settlements with ground measurements (Reul, 2003). These latter (see Table 4) for the Main Tower refer to the construction completion (time set to 0), thus a time period of 30 days was considered for the consolidation analysis. As for Eurotheum, 1-year measured settlements are available, thus this time-span was considered for validating the numerical model results.

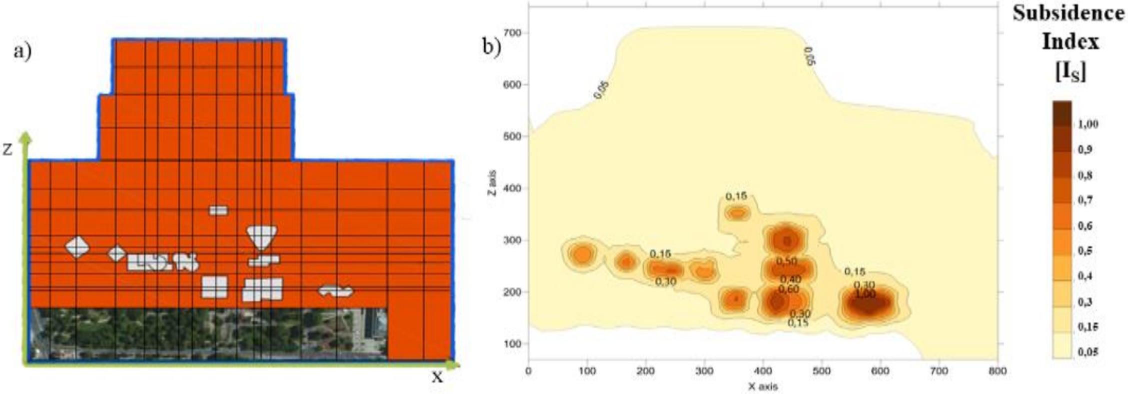
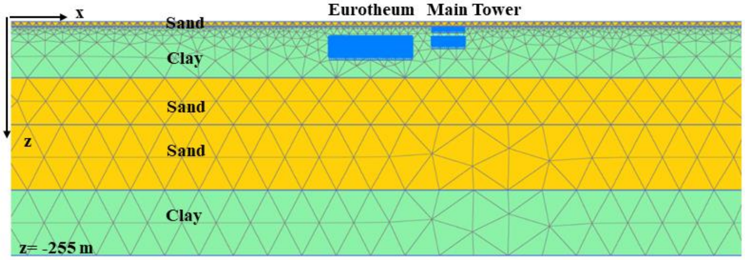


*Figure 4. a) map of sections used for cumulative settlement computation via D-Settlement software; b) contour map of $I_s$ over 10000 days in Frankfurt financial district.*



| General data | |
|---|---|
| **Soil model** | Soft Soil Creep |
| **Consolidation model** | Biot |
| **Strain model** | Natural |
| **Type of Load** | Uniform |
| **Magnitude of load** | 3 kN/m$^2$ each m of building heigth |
| **Water load** | -1 m$_{H20}$/ year |
| **End of settlements calculation** | 36500 days |

*Figure 5. 2D subsoil model and input data for the numerical analysis carried out with Plaxis. Compressibility parameter of SSC model are included in Table 2.*

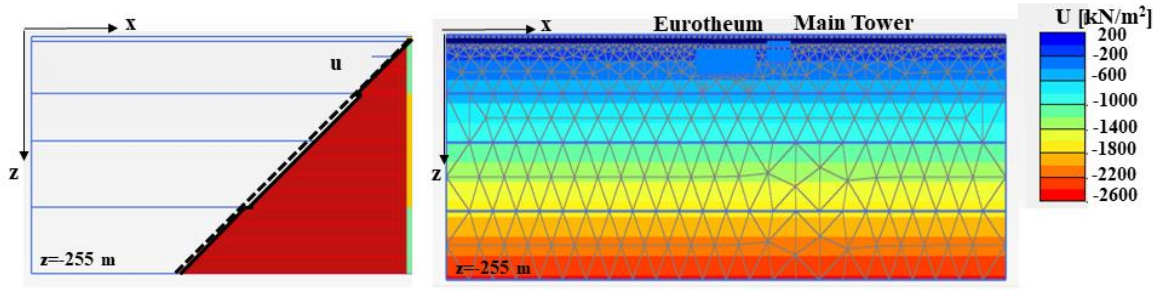


*Figure 6. Pore pressure before and after the groundwater extraction. (Dotted line: pore pressure without groundwater extraction; continuous line: pore pressure with groundwater extraction).*

As for the water table lowering, a back-analysis was carried out to fit the measured settlements reported in Table 4. The results in Figure 6 refer to a water pumping at 60 m b.g.l. in the sand layer resulting in a lowering of hydraulic head of one meter in 1 year. Figure 7 shows the settlement profile in correspondence of the two buildings after both 1 month and 1 year with water pumping.

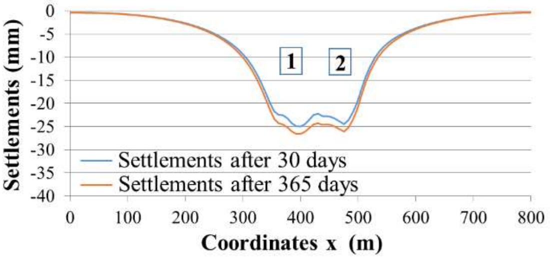


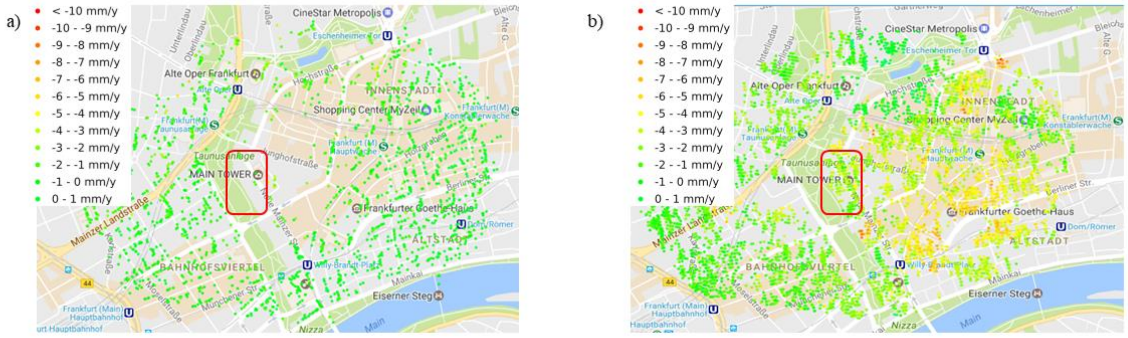
*Figure 7. Short-term cumulative settlement profile with vertical loads transferred by two buildings in Frankfurt: Main Tower (1) and Eurotheum (2).*

Finally, the results of the comparison between measured and predicted settlements for the two analyzed buildings are displayed in Table 4.

*Table 4. Comparison between predicted and measured settlements for the two analysed buildings in Frankfurt.*

| Building | Time | Predicted settlement [mm] | Measured settlement [mm] |
|---|---|---|---|
| Eurotheum | 1 year | 27.5 | 29 |
| Main Tower | 1 month | 25 | 25 |

As for long-term settlements, a validation test was carried out with satellite Diffential Interferometric Synthetic Aperture Radar (DInSAR) data. The use of DInSAR data has been extensively proved in the scientific literature (Peduto et al., 2017a, 2017b, 2018) as a valuable tool to accurately monitor settlements



ERS-2: period1995-2001

Sentinel 1: period 2014-2017

*Figure 8. Settlement rate maps of Frankfurt city (courtesy of SkyGeo company, Delft, The Netherlands).*

of both buildings and infrastructure. For this study, two datasets – provided by SkyGeo company – were used for Frankfurt city: ERS-2 covering the time period 1995-2001 (Fig.8a) and Sentinel 1 (Fig.8b) covering the time period 2014-2017.

In particular, the DInSAR-derived average velocity in the red area in Figure 8 (i.e., including Eurotheum and Main Tower) were compared with the predicted settlement rates of the two buildings deriving from the 100-year settlement computation (see Fig. 9) in order to avoid an overestimation due to primary consolidation effect. Figure 9 shows the predicted settlements accounting for either only vertical loads or the combined effect of water pumping and vertical loads. It can be noticed that the groundwater extraction in the sand layer induces a significant settlement increase (up to about 56%).

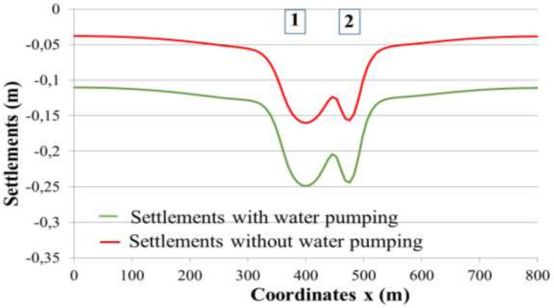


*Figure 9. Long-term settlements under MainTower (1) and Eurotheum (2) induced by construction loads and water pumping.*

The comparison between DInSAR-derived average velocity and the results of the numerical analysis (Table 5) points out that the settlement rates pertaining to the combined effect of water pumping and vertical loads are within the range of remote sensing measurements both with reference to ERS-2 dataset (covering a time span that is contemporary to the building construction) and the more recent Sentinel-1 measurements.

*Table 5. Comparison between DInSAR-measured settlement rates and the predicted ones accounting for both water pumping and vertical loads.*

| Settlement rates [mm/year] | | |
|---|---|---|
| Computed velocity | ERS-2 data | Sentinel 1 data |
| 1.6 | 0-2 | 0-3 |

## 4 CONCLUSIONS

The present study addressed the concurring effects of building loads and water pumping on the magnitude of total subsidence in the high-rise built up Frankfurt city financial district. The results of numerical modelling – although following a very simplified approach – and available monitoring data highlighted that *i)* the group effect caused by the high-rise buildings on the settlement magnitude cannot be ignored since it can determine settlements in the nearby urban area up to 15% of the maximum building settlement; *ii)* the magnitude of computed settlement rates seems to approximate monitoring data when the effects of groundwater extraction are considered in the numerical model. The effects of groundwater extraction and the weight of high rise buildings were nearly equally important in the considered case.

## 5 ACKNOWLEDGEMENTS

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