SETTLEMENT OF HIGH-RISE BUILDINGS IN ROTTERDAM
TASSEMENT DE GRATTE-CIELS EN ROTTERDAM

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SYNOPSIS: A great number of high-rise buildings has been realized in Rotterdam over the past few years. Due to the ground conditions and the load from the building, settlements occur of overconsolidated loam layers at about 40 m below ground level. The paper presents the results of settlement measurements of a number of projects. Two projects are discussed in more detail. These projects offer data of the time-settlement behaviour during the contruction period, and of the stress distribution in the subsoil. The realization of both projects involved the jacking-up of neighbouring structures. The presented data inspire confidence in the accuracy of the predicted settlements. Uncertainties however, continue to exist, especially in relation to the time-dependency of the settlements. This underlines the necessity of continuing the measurements after completion of a high-rise building.

INTRODUCTION

Many high-rise buildings have been realized in Rotterdam in recent years. High-rise buildings, like most other structures in Rotterdam, are founded in a sand layer on piles with a base-level of about 25 m below sealevel. Due to the load, high-rise buildings cause settlement of overconsolidated loam layers at about 40 m below sealevel. Adjacent structures undergo these settlements as well, due to the stress distribution in the subsoil. The prediction of the settlements of high-rise buildings in Rotterdam used to be a problem. Nowadays the settlement predictions are based on the results of measurements as more data become available. The paper describes the interpretation of the available settlement measurements of high-rise buildings for prediction purposes.

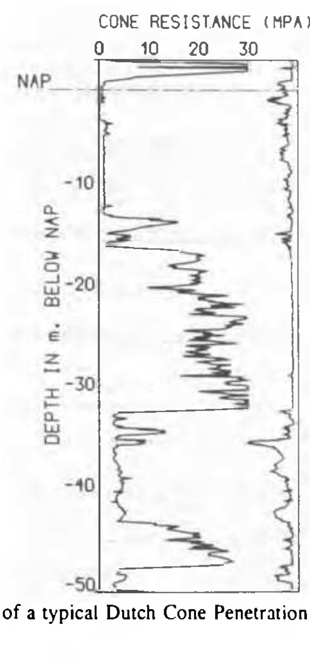

Fig. 1. Result of a typical Dutch Cone Penetration Test in Rotterdam.

SUBSOIL

The majority of the high-rise buildings is located in the City-centre. The groundlevel in the centre of Rotterdam is a few meters above sealevel (N.A.P.). The subsoil consists of soft holocene clay and peat layers to a depth of 17 m below sealevel. Below this level fine to medium coarse pleistocene sand is found up to 35 m below sealevel. There a firm 10 m thick layer of loam is present, that is part of the Formation of Kedichem. The level of the top of the Formation of Kedichem varies. North of the river Nieuwe Maas this level is generally 35 m below sealevel, sometimes 30 m. South of the river this level is higher, sometimes even higher than 25 m below sealevel. At many places a second sand layer occurs below the loam layer. In Figure 1 the result of a typical Dutch Cone Penetration Test (D.C.P.T.) is presented. The groundwater table varies around sealevel.

SETTLEMENT DATA

Predictions of settlements of high-rise buildings in Rotterdam based on consolidation tests used to differ much from the measured settlements. This was caused by the great difficulty of taking and testing of undisturbed samples of the loam layer at 40 m below sealevel. In order to use the measured settlements of already realized high-rise buildings it is necessary to evaluate the available data paying special attention to:
- composition and properties of the subsoil;
- geometry of the building and the foundation;
- effective load of the high-rise building;
- stress distribution in the subsoil;
- time-dependency of the settlements.

Table 1 presents the available settlement data of high-rise buildings in Rotterdam. The data come from various sources, are not complete and differ in quality. The results of settlement measurements of the Medical Faculty and of a tall apartment building in the Prins Alexanderpolder gave for a long time the most important data about the settlement behaviour of high-rise buildings in Rotterdam, because of the long measuring period (Joustra et al, 1977). The magnitude of the measured settlements however, differ much.

Table 1. Settlement of high-rise buildings in Rotterdam

Structure	Building period	Building area (m2)	Load (kPa)	Maximum height (m)	Maximum number of stories	Load depth (m -N.A.P.)	Depth of loam layer (m -N.A.P.)	Measured maximum settlement (mm)	Measuring period
Dijkzigt Hospital and apartment building for nurses	1953 - 1956		100		12	18		47	1955 - 1969
Medical Faculty	1965 - 1968	80 x 38	255	110		18	32,5 - 40,5	130	1966 - 1985
Apartment building Prins Alexanderpolder	1972 - 1974	25 x 47	250	67	22	25	40 - 48	42	1972 - 1987
Office-tower Shell	1974 - 1976	25 x 35	372	90	27	20	39 -	11	1977 - 1982
World Trade Center	1983 - 1986	30 x 48	143	93	29	20	39,5 - 49,5	40	1984 - 1988
Head-office Nationale Nederlanden	1988 - 1990	1000	309	150	41	27	40,5 - 51	48	1989 - 1991
Weena-tower	1988 - 1990	30 x 35	311	106	33	22	40,5 - 51	41	1988 - 1990
Apartment building D.W.L.	1989 - 1990	28 x 29		70	22	20	33,5 -	32	1989 - 1990
Building Hietkamp	1989 - 1990	23 x 25	156	47	16	20	27 - 34,5	45	1990 - 1991
G.E.B.-building	1989 - 1991	14 x 51	200	65	16	24,5	33 - 55	41	1990 - 1991

The Medical Faculty settled about 130 mm at maximum, and the apartment building about 50 mm at maximum. Also the time-settlement behaviour differs much. The settlement after completion of the Medical Faculty amounted to 35% of the extrapolated settlement within 30 years. This percentage amounted to 50% for the apartment building. Table 1 shows that a number of high-rise projects has been realized in Rotterdam recently. These projects have been monitored and give additional data. The building area of the projects varies generally between 500 and 1,000 m2. The load of the World Trade Centre is distributed over a larger area to reduce the settlements. The loads on the subsoil vary between 250 and 350 kPa for the 100 m tall buildings. The load depth in Table 1 represents the level from where the loads on the foundation piles are distributed into the deeper layers. The top of a characteristic hard peat layer is taken as the upper level of the compressible layers of the Formation of Kedichem. The settlements were generally only measured during the building period. The average maximum settlement of about 50 mm is therefore not a figure to rely upon. The projects Weena-tower and Head-office Nationale Nederlanden offer well-documented and interesting settlement data, and are discussed in more detail. Both projects are located at the Weena (see Figure 2).

WEENA-TOWER

The Weena-tower at the Weena consists of office-space and living-apartments. The 33 stories are in total 106 m high. The smallest distance to the Underground-tunnel is 7 m. Due to the load on the subsoil the neighbouring Underground-tunnel and the Weena-house will undergo settlements. Fortunately only limited measures were necessary for the Underground-tunnel, but the foundation of the Weena-house was constructed in such a way that settlements could be adjusted by means of flat jacks. The Weena-house was built in the period 1985/1986. The building activities on the Weena-tower started in october 1988 and were completed in november 1990. The settlements of both the Weena-tower and the Weena-house were measured during the building activities. The Weena-tower settled about 40 mm in the period from december 1988 to june 1990, the moment that the highest point of the tower was reached. The Weena-house settled due to the load from the Weena-tower about 25 mm at maximum in the period from december 1988 to august 1990. A jacking-up operation of the Weena-house took place in august 1990 up to a maximum of about 50 mm. The over-compensation was meant to avoid if possible, another jacking-up operation in the future. The ground-plan with the Weena-tower and the Weena-house is given in Figure 3. Figure 4 shows the settlements of the north and middle section of the Weena-house in the period from december 1988 to august 1990. Figure 5 shows time-settlement-diagrams of two characteristic points as well as the progress of the building activities. No results of settlement measurements were available from the period after august 1990.

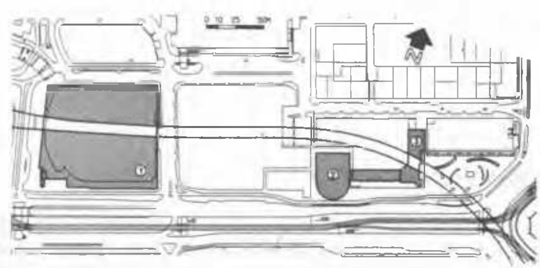

Fig. 2. Situation Weena.
1 = Head-office Nationale Nederlanden
2 = Weena-tower
3 = Weena-house

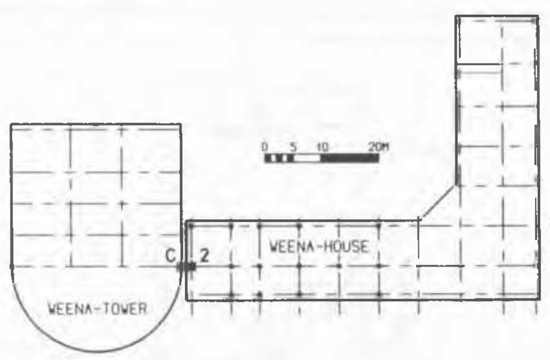

Fig. 3. Ground-plan with Weena-tower and Weena-house.

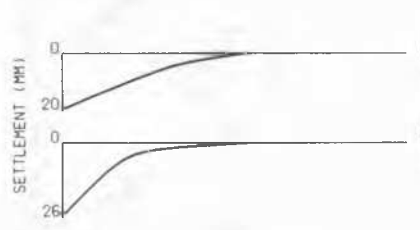

Fig. 4. Settlement of the Weena-house.

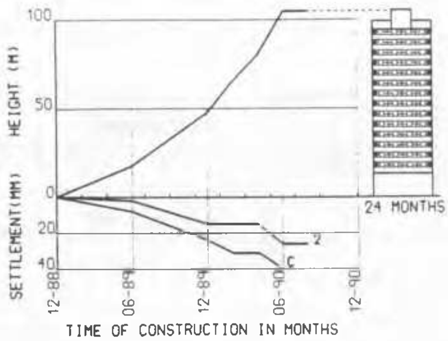

Fig. 5. Time-settlement diagram of measuring points 2 and C.

HEAD-OFFICE NATIONALE NEDERLANDEN

Near the Central Station of Rotterdam, an insurance company, Nationale Nederlanden, has built its new head-office at the Weena (see Figure 6). This office consists of a number of buildings over and next to the Underground-tunnel. The most striking part is a 150 m high tower which stands immediately beside the tunnel. Despite a basement directly over the tunnel, significant settlements of the tunnel were expected. After studying various measures, a solution was selected that made it possible to correct the position of the tunnel any time the settlement would require so. Therefore jacks were installed in such a way that they were accessible for a long time (Feijen, 1990). Because of the close interrelation and mutual influence of tunnel and high-rise building, the execution of both works was done by the same contractor. The building activities on the new tunnel foundation started in november 1988 and were completed in the second half of 1989. The high-rise building was completed in 1991. The settlements of both the Underground-tunnel and the high-rise building were measured during the building activities. The high-rise building settled about 50 mm at maximum in the period from october 1989 to march 1991. The Underground-tunnel settled about 25 mm at maximum in the same period. Jacking of the tunnel took place in july 1990 and january 1991 up to a maximum of 15 mm in total. The ground-plan with the high-rise building, the Underground-tunnel and the jacking points is given in Figure 7. Figure 8 shows the settlements of the north and south side of the Underground-tunnel in the period from october 1988 to november 1992 as well as the total correction of the settlements by the two jacking-up operations. Figure 9 shows time-settlement-diagrams of some characteristic points on the high-rise building and the Underground-tunnel. It is assumed that the building has settled about 5 mm before the measurements started. It is remarkable that the settlement process of the Underground-tunnel has almost stopped after completion of the high-rise building. The measurements have to be continued however, to confirm this behaviour.

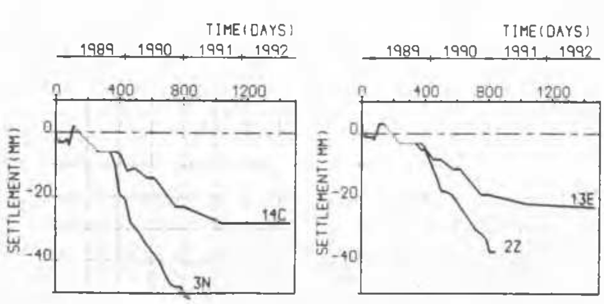

Fig. 9. Time-settlement behaviour of measuring points 3N, 14C, 2Z and 13E.

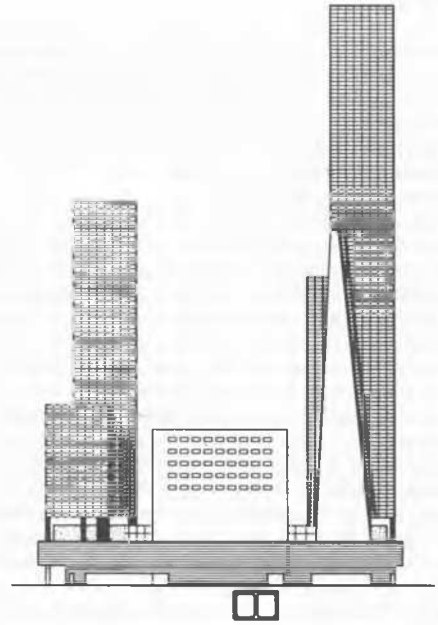

Fig. 6. Head-office Nationale Nederlanden.

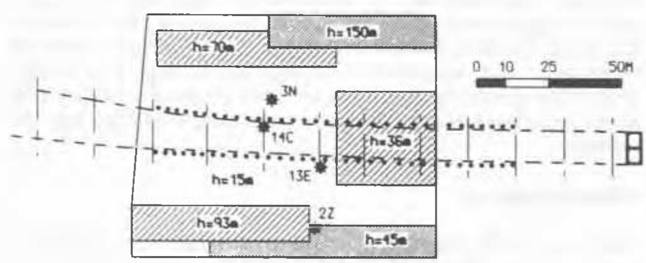

Fig. 7. Ground-plan Head-office Nationale Nederlanden.

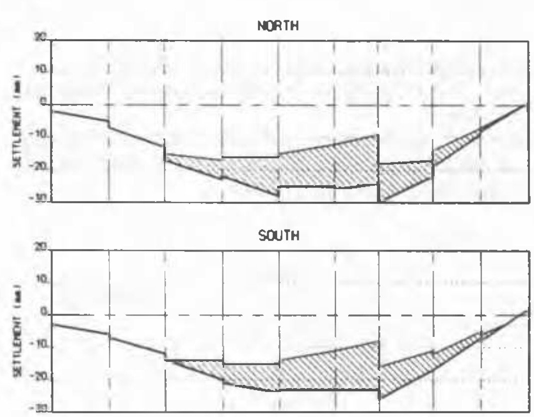

Fig. 8. Settlement of the Underground Tunnel.

EVALUATION

The presented data do not give additional information of the time-settlement behaviour of high-rise buildings. The settlement properties of the loam layer of the Formation of Kedichem can be back-calculated, but the accuracy of the parameters is limited due to variations in the:
- ground-plan of the buildings;
- level, thickness and properties of the loam layers;
- time-dependency of the parameters.

However, the measurements of the Weena-house offer an excellent opportunity to analyse the stress distribution in the subsoil. Normally the stress distribution is determined according to the formula of Boussinesq. It can be questioned whether the stiff sand layer in which the foundation piles are driven, resting on the overconsolidated loam layer is causing another stress distribution in the subsoil. Figure 10 shows the measured and calculated settlements of the middle section of the Weena-house. For comparison it is assumed that the final settlements are equal to 1.5 times the measured settlements. The calculated settlements are based on a stress distribution according to the formula of Boussinesq. In case the upper pleistocene sand layer is significantly stiffer than the lower compressible loam layer the stresses and settlements in the lower layer beneath the loaded area are reduced considerably. However the stresses and settlements in the lower layer at larger distances are in that case increased. Figure 10 shows that the shape of the measured and calculated settlements are corresponding well. It can therefore be concluded that the stress distribution in the subsoil of Rotterdam can be assessed sufficiently accurate by the formula of Boussinesq when calculating the settlement of high-rise buildings.

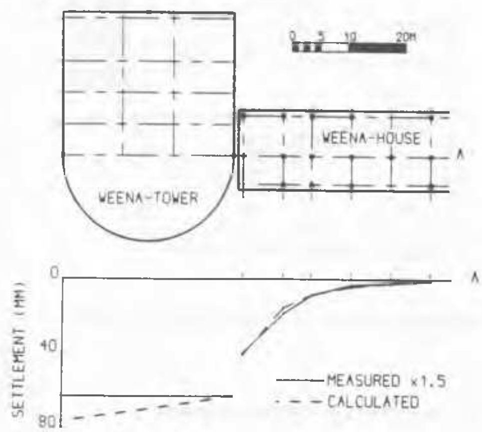

Fig. 10. Measured and calculated settlements of the Weena-house.

CONCLUSIONS

Final settlements of 100 m high buildings in Rotterdam with a smallest cross-side of 25 to 30 m will generally be restricted to 100 mm at maximum. Stress distribution in the subsoil due to the weight of the high-rise buildings can sufficiently accurate be calculated by the formula of Boussinesq. Insufficient data are available of the time-settlement behaviour in the period after completion of the high-rise buildings. It is strongly advised that consultants, contractors and local government increase their efforts to continue measurement programs after completion of the high-rise buildings.

Acknowledgements

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