Settlement analysis of the storage depot Noord-Oost Abstpolder in Rotterdam

Analyse des tassements du dépôt Noord-Oost Abstpolder à Rotterdam

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ABSTRACT: The city of Rotterdam has established a 40 ha storage depot to store low level, hazardous soil waste and moderately contaminated soils. A total amount of 2.4 million m^3 of contaminated soil was deposited from 1992 to 2001. The load imposed by the storage depot is resulting in severe settlements in the subsoil below the landfill. Final settlements are expected up to 5 m. The base of the contaminated material is required to be at least 0.7 m above the groundwater level. Settlements are monitored frequently to provide reliable information on the settlement process. The filling plan is updated and revised, as more data becomes available.

RESUME: La ville de Rotterdam a établis un 40 ha dépôt pour le magasinage des déchets de sols un peu nocif et des sols pollués modéré. Une quantité totale de 2.4 million m^3 de sol pollué était emmagasiné dans la période 1992-2001. La charge exercée par le dépôt amenera des tassements sévères dans la formation au-dessous du dépôt. Des tassements finals jusqu'à 5 m sont expecté. Une condition nécessaire est que la base du matériau pollué sera permanent au moins de 0.7 m au-dessus du niveau de la nappe souterraine. Des tassements sont mesuré fréquemment afin de fournir des informations sur les tassements. Le plan de remplissage est révisé au fur et à mesure que l'information devient disponible.

1 INTRODUCTION

In the 1960's the need to dispose of harbour sludge in the region of Rotterdam increased. One site that was used for the disposal of harbour sludge was a polder situated in the north of the city. After twenty years of sludge disposal, the total thickness of the sludge became about 6 m. Towards the end of the 1980's the need for storage of contaminated soil increased. Plans were made to utilise a part of the old sludge landfill for the permanent disposal of contaminated soil. In the early 1990's the landfill "DOP NOAP" for contaminated soil was established by the city of Rotterdam to store low level hazardous soil waste, and moderately contaminated soils. The total area that is being used for storage is 40 ha. The disposal site has a final storage capacity of 2.4 million m^3. Filling the disposal site has been taking place gradually, from 1992 onwards. The site will eventually be full in 2001. Capping the disposal site starts in 2001.

According to Dutch regulations, the contaminated soil is required to stay at least 0.7 m above the highest groundwater level. Flow of the percolate to the subsoil is not allowed, and spreading of the contaminants should be avoided. Important geotechnical issues in this respect are:

- What is the magnitude of the settlement at the base of the fill?
- How can the groundwater table in the fill be regulated, and thus leakage or infiltration?
- What is the effect on the groundwater flow in the environment?
- To what extent can spreading of the contaminants through the groundwater take place?

For the design of the storage depot several options for the cap and the base of the fill have been studied to prevent spreading of and contact with the contaminants. The settlement issue however, is dominant in this project: will the base of the fill finally be above the groundwater level? Dutch regulations demand a consideration on the reliability of the used calculation methods and models. Generally it is expected that settlements may be 30% bigger or smaller than the calculated settlements. Therefore, the settlements have been monitored during filling. The paper will show a comparison of predicted and measured settlements. Whether the condition of hydrologic isolation is met, will be evaluated. The consequences of changes in the filling plan during exploitation will be described.

2 PROJECT DATA

The storage depot is built upon an old depot for moderately contaminated sludge. The sludge pit was filled from 1967 to 1986. Filling of the storage depot with soils started in 1992, initially the filling rate was large, but was gradually decreased. The increase of the stored amount was measured in tons at the entrance to the landfill (table 1). The specific weight of the fill material varied, but was estimated at 18 kN/m^3 on average at the entrance of the landfill.

Table 1: Supply of fill

Year	1993	1994	1995	1996	1997	1998	1999	2000
Stored Volume %	24	41	50	56	63	75	81	88

2.1 *Design Philosophy*

Hydrologic isolation is a significant element of the design of the storage depot (Hannink, 1991). No provision at the base of the fill means that on the long run a situation may be created in which the percolate water with contaminants will flow to the subsoil. Because the design prevents the infiltration of water by incorporating an HDPE-liner at the top of the fill, the amount of percolate will be minimal. As a result the groundwater table will gradually drop to the piezometric head in the underlying Pleistocene sand that is 3.5 m below sea level. A drainage system at the base of the fill will collect and remove the consolidation water during the expected consolidation period of at least 60 years, together with the percolation water during the filling period. By removing the consolidation and percolation water, the contaminated soil will remain above the groundwater level during the consolidation period. Finally, when settlements are over, the contaminated soil will remain at least 0.7 m above the groundwater level. The design was based on the worst case assumption: the required 0.7 m must be available in case the calculated expected settlements + 30 % safety margin are taken into account.

The 1.26 million m^3 of moderately contaminated soil is according to this philosophy directly placed in the depot without a bottom liner. Leachate from this soil is not expected to influence the level of contamination in the groundwater because of the described hydrogeologic mechanisms. The 1.14 million m^3 of hazardous soil however, is placed in a section of the depot provided with a 2 mm HDPE liner on the bottom, to create additional safety. After completion of the waste loading, a 2 mm HDPE top cover is placed over the entire depot to prevent further infiltration from percolation and precipitation.

2.2 *Soil Investigations and expected settlements*

Soil investigations for the design of the fill comprised of 44 Cone Penetration Tests (CPT's) and 3 borings. In a later stage 44 additional CPT's were carried out. In the area of the site 28 piezometers were installed to monitor the groundwater levels. In the laboratory 25 consolidation tests and 11 triaxial tests were performed.

The ground level was about 2 m above sea level in 1990, before filling of the depot. The thickness of the rather impermeable sludge is 6 m. Below this layer about 12 m of uncontaminated Holocene peat and clay layers are found to a depth of 17 m below sea level. Below this level fine to rather coarse Pleistocene sand is found down to 30 to 35 m below sea level. The phreatic groundwater was 1 m above sea level in 1990. The phreatic water is not in hydraulic continuity with the underlying Pleistocene sand in which another water regime is found. The piezometric head in the Pleistocene sand is 3.5 m below sea level.

Together with the in-situ present clay and peat layers of the Holocene sediment, this made up a 15 to 20 m thick layer of almost impermeable compressible layers. The 15 to 20 m's combined layers of peat, clay and sludge will consolidate from the weight of the disposal. The calculated final settlements were 4 m on average. The load from the waste on the sludge, peat and clay creates a temporary upward gradient in groundwater flow from 50% depth of the total 15 to 20 m consolidating layer (7.5 to 10 m), making it impossible for leachate from the depot to enter and contaminate the groundwater. Since the peat and clay are natural materials, the consolidation water that is forced downward due to the waste is not contaminated.

3 MONITORING

A monitoring program during the filling period of the depot was mandatory. To monitor the settlement 146 settlement gauges were placed. The settlements were initially measured once or twice a month, and eventually 8 times a year. The settlement gauges were also used to monitor the increase in height of the depot at that particular location. Groundwater levels are normally measured 12 times a year in 65 gauges in several layers: near the surface, in the Pleistocene sand layer at the site, and at a number of distant locations. Groundwater pressures are monthly measured in compressible layers at 10 locations. Each observation location contains gauges at 4 different depths. Inclinometers were installed at 11 locations near the slope of the storage depot to monitor the deformations in the subsoil during the period that the storage depot was filled. The frequency of these measurements was also monthly.

The maximum storage level amounted to 13 m above sea level at the end of 2000, with a maximum thickness of the deposited soil of 15 m. At this time 3,200 days had passed since the storage depot had opened, and a maximum settlement of 3 m. Figure 1 shows a characteristic settlement-time diagram.

The phreatic groundwater level in the storage depot was, as expected, high during filling. The piezometric level of the groundwater in the Pleistocene sand layer varied during the filling period, and was at the site 3 m below sea level on average at the end of 2000. Excess pore pressures in the Holocene clay and peat layers were limited during filling.

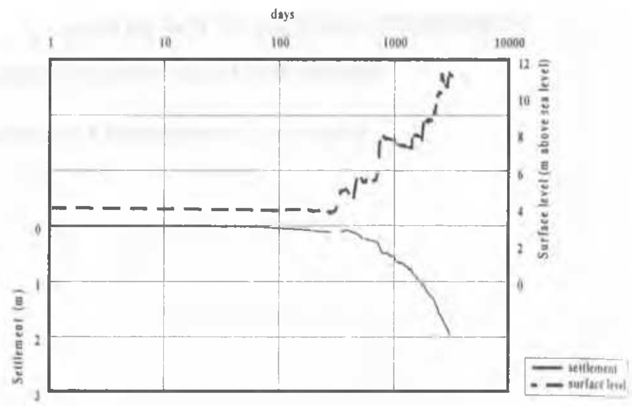


Figure 1. settlement-time diagram (settlement and surface level).

4 INTERPRETATION OF SETTLEMENT DATA

Settlement data, which have been collected during the filling period, are used to verify the calculated settlements. Because the site has gradually been filled during the last ten years, this has resulted in complicated settlement behaviour in the area. The gradual increase of the load is documented in the surface level monitoring. As there is no vertical drainage system in the compressible layers, only about 50% of the final settlements have occurred in 2001 which makes the interpretation of settlement monitoring data an important issue. Comparisons of calculated and measured settlements were also hampered by differences between locations of CPT's and settlement gauges. The best way to calculate the expected settlement for a monitoring spot, is that each increase of load in time should have it's own time-settlement curve. The total settlement is the superposition of all time-settlement curves. It appeared to be impractical to perform this for each monitoring point.

4.1 *Original Approach*

Interpretation of the settlement data started in 1994, by considering the data of 1993 and before. Interpretations of settlement data were after that repeated every year. Until 1998 a rather simple procedure was consequently followed to check the settlement predictions. The following data were determined at each settlement gauge (see Figures):

1. original ground level (2.16 m above sea level) and the thickness of the compressible layers (15 m; average $c_v = 5 \times 10^{-8}$ m^2/s), based on surrounding CPT's
2. thickness of the landfill in m (10.57 m), based on the present ground level (10.42 m above sea level), the original ground level (2.16 m above sea level) and the measured settlement (2.31 m)
3. final settlement (4.02 m), that goes with the present load (10.57 m), based on a linear interpolation of the initially calculated final settlement (4.28 m) that goes with the finally expected load (11.27 m)
4. loading period (2214 days) based on the data of the settlement gauges
5. expected consolidation grade (61.5 %) based on the time-settlement curve
6. expected present settlement (2.47 m) based on the expected consolidation grade (61.5 %) and the expected final settlement (4.02 m).
7. ratio (0.94) of measured settlement (2.31 m) and expected settlement (2.47 m).

A ratio smaller than 1 indicates an area which will settle less than calculated. Likewise, a ratio bigger than 1 indicates an area with a tendency to settle more than calculated.

This approach has the advantage of being simple. A different settlement behaviour of the gauges is relatively easy to distinguish and trends in general settlement behaviour with advancing years are clearly demonstrated. However this approach has also some disadvantages:

- a linear relationship is assumed between load and final settlement. This is not correct; a smaller load than the final load goes with a relatively bigger final settlement. The followed approach will lead to some underestimation of the final settlement that goes with the present load. The underestimation will however decrease with increasing load.
- the effect of the drop of the phreatic groundwater level is not taken into account. This will lead to an overestimation of the final settlement that goes with the present load. The overestimation will increase with increasing loads, but partly decrease with the settling level of the drain layer.
- the moment of loading is taken as the point in time of the first significant loading. This will lead to an overestimation of the consolidation grade. The overestimation will decrease with advancing years.

4.2 *Refined Approach*

The original approach for analysing the settlement data was followed until 1998. As the exploitation period of the disposal site was nearing its end, several uncertainties and unknown factors needed verification or refinement:

- The permitted amount of contaminated soil could not be stored without revising the settlement calculations, as the landfill should stay 0.7 m above the defined highest groundwater level.
- Due to changes in legislation the aftercare plan had to be revised, based upon the revised settlement predictions incorporating reliability contours.
- The design of the capping structure needed an indication of differential settlement to make an economic and efficient capping structure.

As a solution for these problems a better settlement prediction was made, indicating the spatial dependency of the settlements, and quantifying the differential settlements, needed for dimensioning the cover structure (Spruit et al, 2000).

The imaginary starting date of the filling sequence was adjusted by a sudden complete application of the total load based on calibration with the results of representative monitoring points. It appeared to be accurate enough to apply a standard adjustment of the loading time to all the monitoring points.

The spatial dependence of the settlements has been defined using GeoEAS software. With a modelled spatial dependence, the expected settlement and its corresponding bandwidth have been defined for each measuring point.

4.3 *Horizontal displacements and water pressures*

In the design stage horizontal displacements of 300 to 600 mm were calculated at the edge of the fill, using the Plaxis code. The measured horizontal displacements amounted to about 350 mm at one section at the end of the year 2000. The maximum displacement speed in this section amounted to about 20 mm/month during filling, and measures were taken to decrease this speed. Other sections showed less displacement than calculated.

Pore pressures were less than expected. Only the section with the large horizontal displacements showed remarkable excess pore water pressures. In the other areas excess pore water pressures were measured of 0 to 50 %. In the design stage excess pore water pressures of 50 to 70% were expected at the final stage of the filling.

5 EVALUATION

Due to the large number of settlement prediction and measuring points, an interpretation regarding the site as an entity is evident.

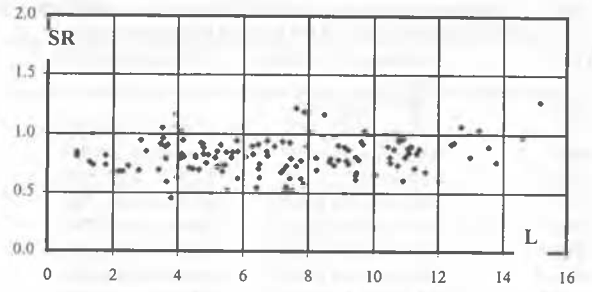


Figure 2. Settlement Ratio (SR) versus actual Load (L) in meters

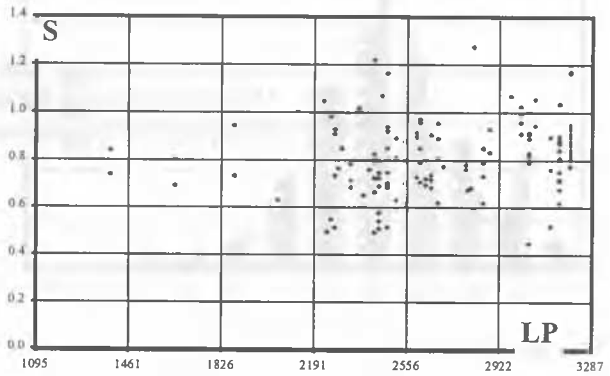


Figure 3. Settlement (S) ratio versus Loading Period (LP) in days

Parallel to the local settlement interpretations, an integral site interpretation has been made yearly since 1994. The following relations were investigated:

- settlement ratio versus actual load
- settlement ratio versus loading period
- settlement ratio versus measured settlements
- settlement ratio versus thickness of compressible layers
- settlement ratio versus measuring period

These relations show the following trends:

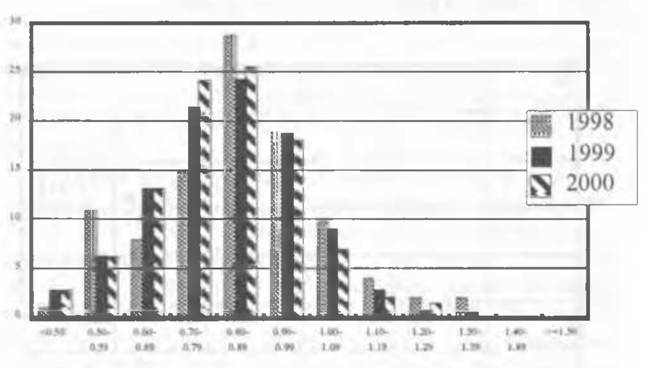
- the settlement ratio is more or less constant with increasing load (Fig. 2)
- the settlement ratio increases a little with increasing loading period (Fig. 3)
- the settlement ratio increases with increasing measured settlements
- the settlement ratio is a little bigger when the thickness of the compressible layers is more than 17.5 m compared to less than 17.5 m
- the settlement ratio is bigger and the standard deviation is smaller if only the areas are considered where filling has started in the first year, and therefore where data are available from the beginning. This is illustrated in table 2 where the average of all settlement ratios and standard deviations as established every year, is compared with the same data of areas where the eldest fill is present.

In the original approach more ratios were calculated than settlement gauges were available, because settlement monitoring data were sometimes related to several predictions based on surrounding CPT's. As becomes clear in table 2, the final settlements will be less than initially accounted for. The difference in settlement ratios based on the original and the refined approach do not differ much. There is a small difference if only the settlement ratios based on the data of the eldest loads are considered. The present data indicate an overestimation of the expected settlements of about 15 %.

The spreading in the settlement ratios based on the refined approach is shown in Figure 4. The initial design had a 30% bandwidth for the expected settlements. By applying the original approach for processing the settlement monitoring data, the

Table 2: Settlement ratios and standard deviations as established from 1993 to 2000 (between brackets the number of data considered)

Year	Average all settlement ratios	Average eldest fill
1993	1.08 +/- 0.39 (90)	
1994	0.92 +/- 0.30 (155)	1.05 +/- 0.29 (75)
1995	0.93 +/- 0.29 (198)	1.09 +/- 0.29 (78)
1996	0.95 +/- 0.31 (212)	1.04 +/- 0.27 (78)
1997	0.89 +/- 0.28 (214)	0.97 +/- 0.21 (78)
1998	0.87 +/- 0.26 (215)	0.93 +/- 0.20 (78)
1998 *	0.85 +/- 0.20 (142)	0.89 +/- 0.14 (51)
1999 *	0.83 +/- 0.16 (143)	0.88 +/- 0.14 (51)
2000 *	0.81 +/- 0.15 (145)	0.86 +/- 0.13 (49)



* = refined approach

Figure 4. Settlement ratios in the period 1998-2000

bandwidth of the settlement prediction hardly decreased (33 to 30 %) in the period 1994-1998, if the average of all settlement ratios were considered. If only the data of the eldest loads were considered, a decrease of the bandwidth of 28 to 22 % is apparent. By applying the refined approach to the settlement data as described, the bandwidth of the settlement prediction is reduced to less than 20% with a reliability of 95%. Together with the adjusted (lower) settlement expectancy, the worst case settlement is much smaller than in the initial design.

6 CONLUSIONS

1. Even with intensive monitoring, it takes time before settlement predictions can be revised. In this case the data of 1997 confirmed in 1998 the expectation that settlements would be smaller than initially calculated. This is 6 years after the start of the filling. At that time filling was at 75 % of its completion.
2. The original approach for checking the settlement predictions shows a clear downward trend in settlement ratios with advancing years. The results show also that only considering data of the eldest loads leads to somewhat bigger settlement ratios. The standard deviation of the settlement ratios hardly decreased with advancing years.
3. The refined approach shows to be very useful, because it shows the quality and density of the data and attaches a reliability to the results.
4. Without the intensive monitoring of the settlements, it would not have been possible to define a spatial dependence of the settlement behaviour. There would have been no way to indicate the reliability regarding the groundwater clearance.
5. The adjusted settlement predictions show that the hydrologic isolation of the disposal site can be realised according to the design philosophy.

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