Artificial groundwater recharging for important civil engineering projects
Réalimentation de la nappe durant la construction des ouvrages d'Art

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SYNOPSIS : Artificial groundwater recharging has been applied for the construction of sea-locks at Zeebrugge and Berendrecht. Based on the obtained experience different improvements of the recharging technique have been introduced. At Berendrecht an extensive control system has been installed to record continuously the waterlevels underneath the nearby refinery. By the progressive installation of the groundwaterlowering system and the systematic back-calculation of the realised lowering it has been possible to optimize the installation time and the location of the recharge wells.

INTRODUCTION

Groundwaterlowering may cause important settlements when very compressible deposits, such as peat layers, are encountered. For construction sites, located in the immediate neighbourhood of residential or industrial buildings, special precautions have to be taken in order to avoid unacceptable settlements.

Different techniques are available to minimize the disturbance of the natural watertable during the execution of large civil engineering works, such as, excavation under compressed air, ground freezing, installation of diaphragm walls or flexible cut-off walls.

For most problems an economic solution can be obtained with the technique of a groundwaterlowering, associated with the reinjection of a fraction of the pumped water in wells located outside the excavation. In Belgium artifical groundwater recharching has been applied for the construction of sea-locks at Zeebrugge and Berendrecht and for the execution of several tunnels in urban areas.

CONSTRUCTION OF SEA-LOCKS AT ZEEBRUGGE AND BERENDRECHT

During the seventies a new sea-lock for ships of 125000 DWT has been built at Zeebrugge on the belgian coast in the vicinity of the village. In the Zeebrugge area one finds very compressible peat and clays overlaying a layer of coarse sand. A first design provided for a general groundwaterlowering over more than 20 meter. Soon after starting the groundwaterlowering, damages were observed at several buildings in the borough of Zeebrugge, some occuring at quite large distance from the building site. So the original design had to be abandoned and special measures were taken in order to limit the groundwater drawdown in the borough of Zeebrugge. Vertical bentonite-cement screens, resp. reinforced concrete diaphragm walls, were installed to limit the drawdown almost to the deep construction pits of the lock heads, resp. for the cellars of the basculating bridges. Furthermore a recharge of the groundwater table was performed. The design of the refeeding installation was principally based on a judicious extrapolation of the results of previously performed pumping tests. For this extrapolation a computer program based on the theory of De Glee has been elaborated (Berleur and al., 1981). The work has been achieved without further difficulties.

In 1981 the construction of the Berendrecht sea-lock, situated 20 km north of Antwerp has been started. This lock (length between the lock gates = 500 m and width between walls = 68 m) will be the largest in the world. The lock is built in an open trench. Therefore the groundwater had to be lowered about 25 m. As a refinery and large storage tanks are located in the immediate neighbourhood of the construction site, special measures had to be taken. These measures consist in the installation of a bentonite-cement cut-off wall combined with artifical recharge (fig. 1) (Goetinck et al., 1983). In the initial stage 70 recharge wells with a capacity of 5 m3/h had to be installed 10 m behind the bentonite-cement-wall at intermediate distances of 10 m and 30 m. The installation of 70 additional recharge wells was foreseen in the specifications. However the location of these additional recharge wells was not fixed.

Due to budgetary constraints, the installation of the bentonite-cement cut-off wall and the artificial groundwater recharging system were regulated by a separate tender before the construction of the lock itself was started. In order to avoid possible interference between the groundwater recharging system and the groundwaterlowering for the construction of the sea lock, preference has been given to a complete independent recharging system, with discharge wells installed in the lower waterbearing stratum at a short distance in front of the betonite-cement wall.

From different investigation campaigns (CPT-tests, borings with prelevation of disturbed and undisturbed samples and laboratory tests) the following composition of the subsoil was deduced (fig. 2) =

- from about +9,00 m to about +2,00 m (meters above sea-level) : Fill installed by different methods (in the dry and hydraulic) and very heterogeneous
- from about +2,00 m to about -2,00 m
  Quaternary holocene formations consisting of former "polder" deposits, a compact peat layer with a maximum thickness of 3 m and stratified clayey and sandy layers
- from about -2,00 m to about -22,00 m
  Quaternary pleistocene fine eolian sands, with a maximum thickness of 7 m and Tertiary Upper Pliocene fine glauconitiferous sands

- from about -22,00 m to about -24,00m
  Tertiary Upper Pliocene fine glauconitiferous sands, with shells and numerous clay layers. The thickness of the clay layers generally varies between 1 and 1,5 cm but may locally reach 20 cm. The vertical permeability, determined in the laboratory on five undisturbed samples varied between $1{,}49.10^{-7}$ and $8{,}31.10^{-9}$ m/s.

- from about -24,00 m to about -50,00 m
  Tertiary Upper Pliocene sands, Tertiary Lower Pliocene and Tertiary Miocene fine to medium fine glauconitiferous sand with shells dispersed in the sand and concentrated in different layers

- underneath -50,00 m
  Tertiary Oligocene stiff fissured overconsolidated clay (Boom clay)

Long term pumping tests have been performed in the sand layer between -2 m and -22 m and in the sand layer between -24 m and -50 m. From the results of these pumping tests the following hydro-geological parameters have been deduced :

- hydraulic resistance of the holocene deposits between +2 m and -2 m

  $$C = \frac{D}{k_v} = 690 \text{ to } 750 \text{ days}$$

  with D = aquifer thickness
  k_v = vertical permeability of the considered layer

- horizontal permeability of the waterbearing stratum between -2 m and -22 m

  $k_h = 0{,}79$ to $1{,}04.10^{-4}$ m/s

- hydraulic resistance between -22 and -24

  $$C = \frac{D}{k_v} = 400 \text{ to } 460 \text{ days}$$

  $k_v = 5{,}06$ to $5{,}79.10^{-8}$ m/s

- horizontal permeability of the waterbearing stratum between -24 m and -50 m

  $k_h = 4{,}88$ tot $6{,}86.10^{-5}$ m/s

Before any groundwaterlowering was started, three different water tables were encountered

- a suspended water table in the fill layers, situated between +7,15 m and +7,50 m

- a water table in the upper waterbearing stratum between -2 m and -22 m varying between +2,60 m and +4,60 m in sympathy with the tide in the River Scheldt and the variations of the dock level

- a water table in the lower waterbearing stratum between -24 m and -50 m varying between +3,80 m and +4,60 m, also in sympathy with the tide in the River Scheldt and the variations of the dock level.

A preliminary refeeding test has been performed in order to check :

- the capacity and the influence radius of the refeeding wells.
- the ability of the water extracted from the lower waterbearing stratum for recharging
- the type and evolution of the well clogging
- the frequency of the necessary cleaning of the wells and the planned cleaning method

For the execution of the preliminary refeeding test a discharge well, four recharge wells and several piezometers in the two waterbearing layers have been installed.

During a period of 2 months water has been recharged into the four refeeding wells at a total rate varying between 50 and 60 m3/h.
A complete analysis of the pumped water showed that the content of Fe 2+ ions varied between 50 and 250 mg/liter and that the oxygen content was very low (0,24 mg/liter). Consequently special precautions had to be taken in order to avoid the aeration of the pumped water and prevent the deposit of ferrugeneous salts.

Furthermore a large number of tests were performed to control the possible clogging of the recharge wells. The presence of fine particles (Membrane Filter Index) and the gas content have been checked regularly. The obtained results showed that the pumped water contained only very few fine particles and that the gas content was very low.

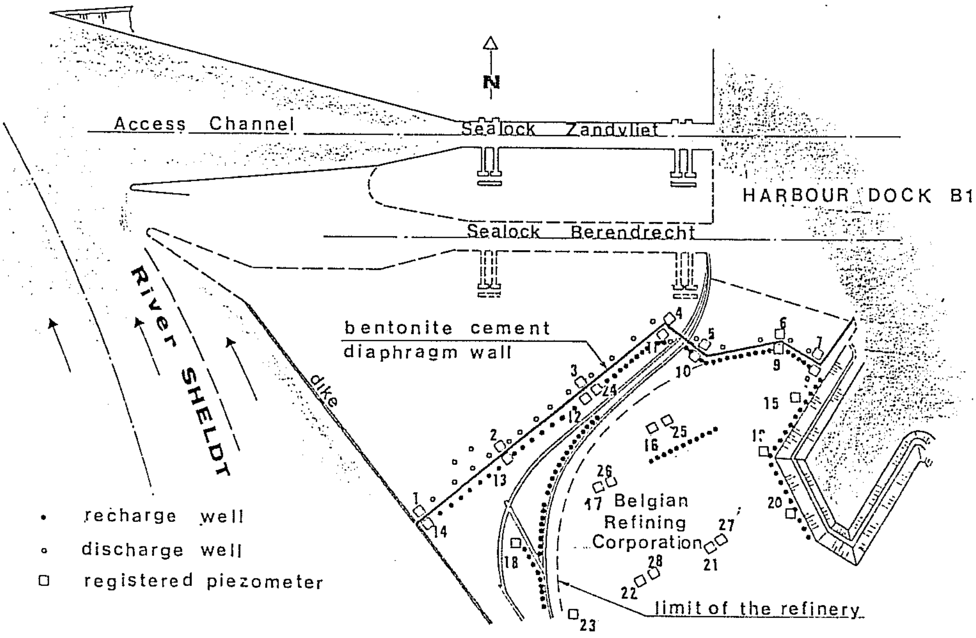

Fig. 1 : Berendrecht : Situation of the bentonite-cement diaphagm wall, groundwater recharging system and registered piezometers

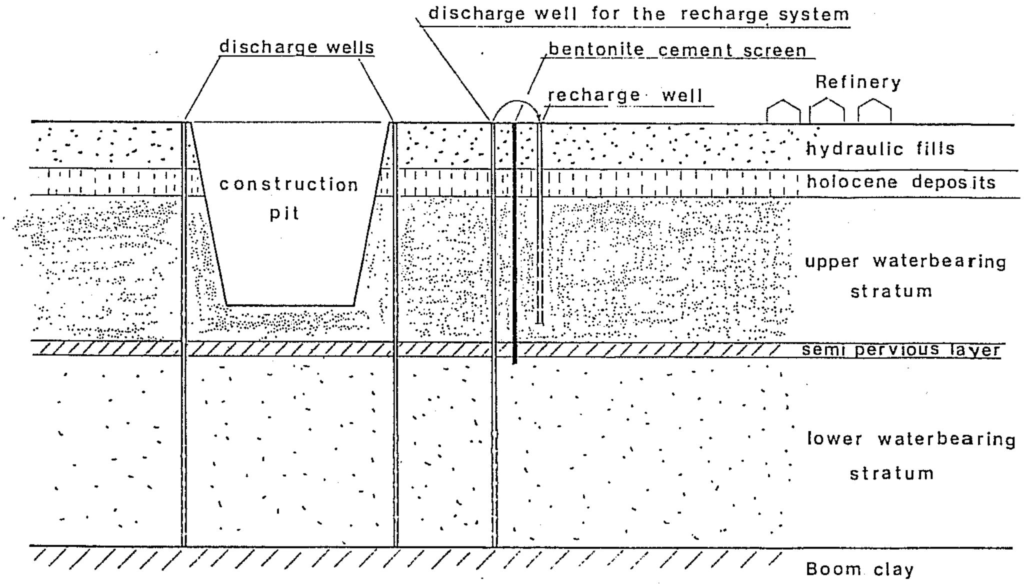

Fig. 2 : Berendrecht : schematic cross-section of the groundwater recharging system and of the groundwaterlowering system for the construction of the new sea-lock

After a period of 40 days the refeeding water for one recharge well has been aerated on purpose. After one day this recharge well was already completely clogged. After cleaning of this refeeding well by extensive pumping, its capacity was restored to only 85% of its initial capacity. This proved that special measures to avoid aeration are an absolute necessity.

The cross section of the installed recharge wells is given on fig. 3. They consist of a PVC-tube with an inner diameter of 150 mm and a filter length of 10 m, between the levels -11 m and -21 m. The borehole with a diameter of 0,40 m was drilled according the direct flush method. The discharge wells consist of a PVC-tube with an inner diameter of 235 mm and a filter length of 11 m, between the levels -38 m and -49 m. The borehole with a diameter of 0,40 m was drilled by the direct flush method. In order to avoid aeration of the pumped water the capacity of these wells has been limited to 35 m3/h, nd preference has been given to a direct connection between the discharge wells and the recharge wells. So each discharge well was connected with 7 recharge wells.

For the control of the groundwaterlevel along the bentonite-cement-wall and underneath the refinery, 28 piezometers have been installed (see fig. 1). The piezometers 1 to 23 have their filter section in the upper waterbearing stratum (-2 m to -22 m) and the piezometers 24 to 28 have their filter section in the lower waterbearing stratum (-24 m to -50 m). The waterlevel is measured with vibrating wire pressure transducers suspended in PVC-tubes with a diameter of 0,20 m.

Under normal circumstances measurements of the waterlevel are performed every 15 minutes, with the help of a micro-computer. The results of these measurements are stored on magnetic tape. On one cassette 950 readings can be stored. Normally the cassette is changed every week. The results already stored on the cassette can be reproduced on the wharf quite rapidly in tabular or graphic form.

Before the construction of the new sea-lock was started, a certain number of conduct pipes had to be diverted. Therefore two excavations with a depth of about 30 m were made. Shortly after the start of the dewatering a sharp lowering of the waterlevel underneath the nearby refinery was observed, especially in piezometer 16. As the waterlevel underneath the refinery continued to draw-down, even when the groundwater recharging system was started, it was decided to install the 70 additional refeeding wells, provided in the specifications.

The data obtained by the registered piezometers were extremely valuable. From the regular control of these data it could be assumed that the waterlevels in the piezometers 16 and 25 installed at small intermediate distances resp. in the upper and lower waterbearing stratum, presented always smaller differences than the other couples of simular piezometers. This permitted to assume that the clayey layers between -22 m and -24 m doesn' t exist over a certain zone near to the piezometer 16. This hypothesis was confirmed by the execution of additional CPT-tests.

The groundwaterlowering system installed for the diversion of the conduct pipes had to be extended for the construction of the new sea-lock. With the help of a mathematical model, following the finite element method, it has been checked that the existing groundwater recharging system would still continue to give satisfaction for the construction of the downstream head of the sea-lock and for the construction of the quay walls in the access channel to the River Scheldt. (Raedschelders et al., 1986). For the construction of the upstream head, 56 additional recharge wells have been installed in order to avoid an excessive lowering of the groundwaterlevel underneath the refinery. The most efficient place to locate the additional recharge wells was deduced from the calculations with the mathematical model.

At the 1st december 1986 the construction of the Berendrecht sea-lock is almost completed.
The major part of the groundwater recharge system has been in operation for more than 5 years without considerable interruptions. The specifed capacity of 5 m3/h is still available for all recharge wells. The amount of repair and maintenance work was very limited.

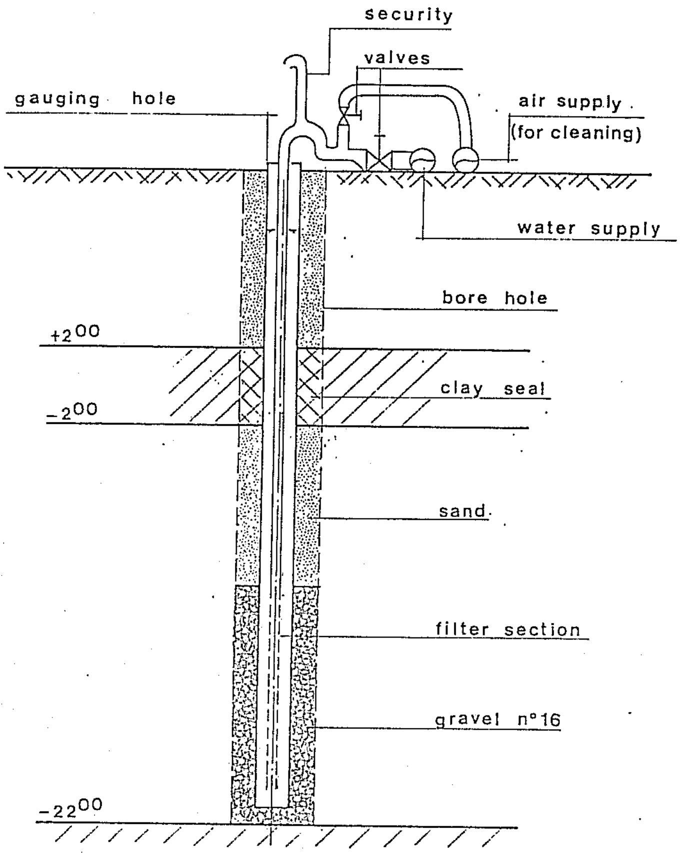

Fig. 3 : Berendrecht : Recharge well

GAINED EXPERIENCE

a) Preliminary studies

The hydro-geological conditions have to be known very accurately. Therefore the execution on the site of a pumping test is absolutely necessary.

The execution of a preliminary recharge test contributes largely to the reliability of the groundwater recharge system. It permits to check the quality of the pumped water (determination of the Membrane Filter Index and of the gas content).
It permits also to adapt the composition of the recharge well as much as possible to the local conditions (water quality, grain size distribution of the soil in situ...) and to check the efficiency of the system designed to unclog the screens.

b) Control system

It is always necessary to install an extensive control system.
Preference has to be given to a system with continuously registered piezometers. In this way very useful information can be obtained during the initial phase of the groundwaterlowering and for irregularities in the dewatering processus. These data permit to readjust the hydraulic parameters by comparing the measured levels with the groundwaterlevels calculated with the mathematical model.

c) Installation procedure

The progressive installation of the groundwaterlowering system and the systematic back calculation of the realized lowering permits to optimize the installation time and the location of the recharge wells.

Preliminary calculations with a mathematical model provide only indicative values of the expected waterlevels. It is always necessary to readjust the hydraulic parameters of the model and also the boundary conditions by comparing the measured waterlevels with the calculated ones. This readjustment is only valuable when the groundwaterlowering system and recharge system are installed progressively.

GENERAL CONCLUSIONS

The groundwater can be lowered over an important depth in the vicinity of existing constructions or installations, founded on compressible layers. An adequate control of the realised groundwaterlowering is necessary.

Very good predictions of the expected groundwaterlowering can be obtained with a well calibrated mathematical model, even in very complex situations.

Recharge wells can be used over a period of more than 5 years without considerable loss of capacity, if all necessary precautions are provided.

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