# Monitoring and Regulating Tidal Influenced Groundwater Heads During Reconstruction Works of a Hydraulic Barrier Structure at the Eider Estuary in Germany

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**Abstract.** The "Eidersperrwerk" is the largest coastal protection construction in Germany located at the estuary of the River Eider into the North-Sea. The "Eidersperrwerk" consists out of five chambers with a length of 40 m and a width of 35 m. In the chambers the water level usually fluctuates between 3 and 5 m due to the tidal movement. At the bottom of each chamber there's a reinforced concrete slab with a thickness of 0.8 m founded on piles which are driven into bearing sands. This sand aquifer is hydraulically connected to the tidal influenced North-Sea. Hence, the groundwater heads are corresponding with the water levels of the North-Sea. Recently, an overhaul of the construction was necessary. Over the last five years one chamber after the other was completely emptied over a period of several months. Due to the missing water load the stability of the concrete slab against uplift was only guaranteed at a certain hydraulic head in the sands. In this context a groundwater monitoring system was established to observe the groundwater heads as well as the deflection of the slab. Also, a pressure relief system was installed to regulate the groundwater heads if necessary. This system is taking advantage of the existing hydrogeological boundary conditions. The supervision and the control of the monitoring system as well as the visualization of the measured data were realized over a webserver with an intuitive graphical interface. Operating this system it was possible to carry out the overhaul without any disturbance due to stability problems caused by hydraulic conditions.

**Keywords:** Groundwater monitoring · Stability proof · Hydraulic uplift · Tidal movement · Hydraulic barrier · Overhaul

## 1 Introduction

The Federal Waterway Administration of Germany (WSV) is responsible for numerous ship locks, weirs and hydraulic barrier constructions located all over Germany. For the maintenance and inspection they have to be emptied completely on a regular base. Since the stability of the constructions has to be guaranteed at any time, the


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geotechnical proof of stability need to be fulfilled for the emptying procedure as well as for the empty state. In most of the cases the water pressures underneath the constructions are unknown, so that rough assumptions are common sense. Usually those estimations result in unrealistic high water pressure loads, so that in many cases the safety against hydraulic heave cannot be proven. In this context, it seems to be necessary to measure the actual water pressure to determine the actual load and to assess the stability of the construction appropriately [1]. In some cases counteractions (e.g. lowering the groundwater heads by pumping) are necessary to adjust the water pressure to fulfil the stability proof [2].

In this paper a monitoring- and pressure relief system is presented, which was used during overhaul measures at the largest hydraulic barrier construction (Eidersperrwerk) of Germany. With that each chamber of the “Eidersperrwerk” had to be emptied completely over several months. Over the whole time of the overhaul a system was required to monitor and to take counteractions if necessary.

## 2 The “Eidersperrwerk”

### 2.1 Location and History

The hydraulic barrier “Eidersperrwerk” is the biggest coastal protection construction of Germany. It is located at the Westcoast of the German state Schleswig-Holstein in the estuary of the river Eider. With a length of approx. 188 km the Eider drains an area of 3.275 $km^2$ covering almost the entire northwestern part of Schleswig-Holstein. Its tidal influenced estuary starts close to the city of Tönning and it can be characterized by a length of 9 km and a width of 2 km. The river Eider dewaters into the North-Sea.

In the year 1967 - after one of the most severe storm surges of the younger history - different measures to improve the coastal protection of the estuary of the river Eider were discussed. The chosen solution was the construction of a dam and of a hydraulic barrier. Here, the coastal protection line was shortened from originally 60 km down to 4.8 km. With a construction time of 7 years the dam and the “Eidersperrwerk” were finalized in 1973.

### 2.2 Construction and Geological Situation

The total length of the “Eidersperrwerk” is 240 m and it consists out of five chambers. Each chamber ranges over a length of 40 m and a width of 35 m. The chambers are usually filled with water. Due to the tidal movement the water level in the chambers fluctuates between 3 and 5 m. Each chamber is lateral bordered by concrete carriers. A massive concrete beam including a street-tunnel spans over the entire construction (Fig. 1). At both sides of each chamber there are steel gates between concrete carriers which can be closed independently from each other, so that a double dike-safety is given.


**Fig. 1.** Aerial photo of the “Eidersperrwerk” (source: WSA Tönning).

The bottom of each chamber is constructed out of a reinforced concrete slab with a thickness of 0.8 m founded on 42 piles which are driven into bearing sands. Underneath the concrete slabs there’s a sand aquifer with a thickness of approx. 5 m followed by an aquiclude existing out of a clay soil layer also with a thickness of approx. 5 m. The concrete slabs are completely surrounded by sheet pile walls which are embedded into the clay soil layer, so that the sand aquifer underneath the slab is vertically and horizontally isolated by a hydraulic barrier (Fig. 2).

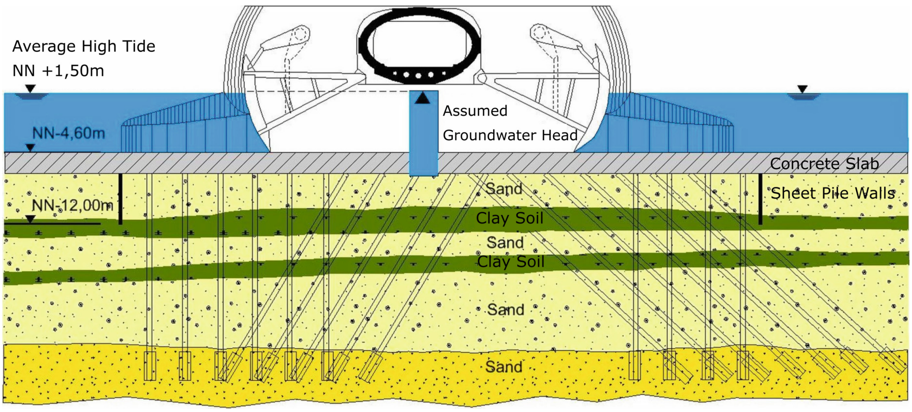


**Fig. 2.** Cross-section of the “Eidersperrwerk”.

Nevertheless, groundwater observations in the early 1990ties indicated that there's a hydraulic connection between the sand aquifer and the tidal influenced North-Sea. The groundwater heads in the sands show a damped reaction to the tidal influenced water levels of the North-Sea.

### 2.3 Overhaul Measures in 2014 to 2018

Between 2014 and 2018 extensive overhaul measures of the "Eidersperrwerk" were conducted including the renewal of the coatings of the steel parts. At first, the removal of the old coating was necessary. Since the old coating was containing PCBs the steel parts had to be covered completely by tents. In those tents under pressure conditions were initiated to withdraw the residues of the coating. For that, it was necessary to empty the chambers completely. Since those measures are highly time consuming and the functionality of all five chambers had to be guaranteed from October until March there were only short time-slots left for the overhaul. Also, it was only possible to close one chamber at a time. Closing more than one chamber leads to a hydraulic overburden of the riverbed. Scours would develop and endanger the stability of the whole construction requiring extensive safety-measures [3].

## 3 Monitoring

### 3.1 General Approach and Set-Up

According to the stability proof, whilst an empty chamber the stability of a concrete slab against uplift is only guaranteed at a groundwater heads in the aquifer of NN +1.30 m. At the "Eidersperrwerk" the average high tide is NN +1.50 m. Sometimes even water levels of NN +2.20 m occur between April and October.

Since it is known that the groundwater heads underneath the slabs are influenced by the water level of the North-Sea it has to be assumed that under certain high water conditions the critical hydraulic heads of NN +1.3 m underneath the slabs could be reached [4]. Therefore, it is required to observe the groundwater heads during an overhaul continuously. Furthermore, it is necessary to make the results directly open to all project participants to be able to initiate counteractions in the case that the critical groundwater heads are passed.

Thus, pressure probes are installed in the corners of each chamber to monitor the hydraulic heads during the overhaul. Here, vibrating wire probes made by Geokon, USA are used. The measuring range of these probes is between 0 and 1 bar and the accuracy is < 0.5% of the final value. Vibrating wire probes are chosen because of its high reliability and longevity.

In addition, two extensometers are installed in the middle of the concrete slab in order to measure the movement of the slab directly. Here, two telescopic rods with a length of approx. 5 m are installed. They are fixed between the spanning concrete beam and the concrete slab. The resolution of the extensometers is 0.1 mm. The telescopic rods are equipped with temperature sensors for compensation of the temperature influences on the measurements. With the combination of both measuring systems a monitoring of the structural safety redundantly is possible. Also, the water level in the chamber as well as of the river Eider and the North-Sea are measured. The water levels of the Eider and the North-Sea are used from the online service “Pegelonline”. Also, a climate station is set up. With this approach it was possible to relate the measured hydraulic heads to the other hydraulic boundary conditions (Fig. 3).

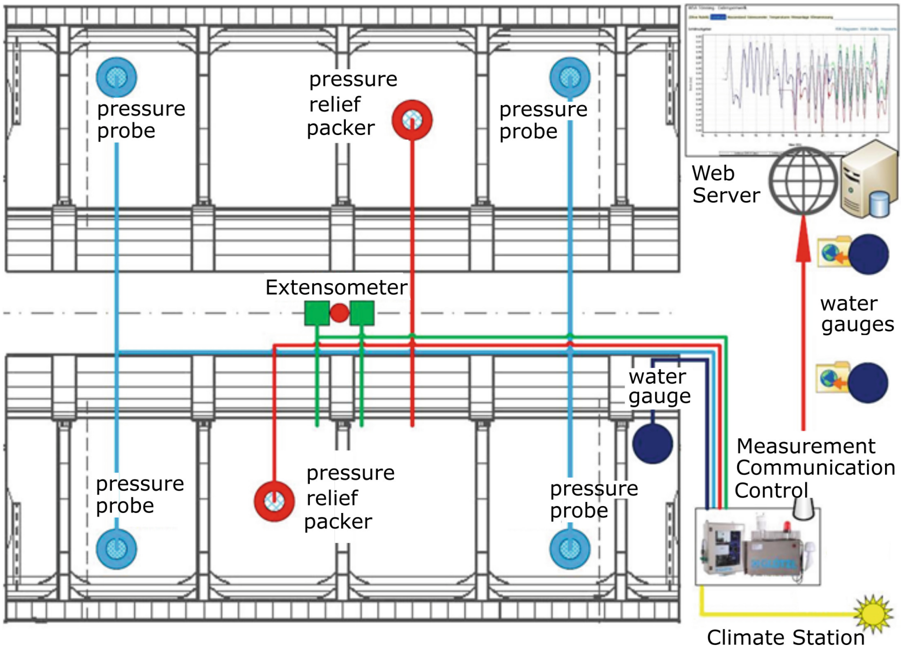


**Fig. 3.** Set-up of the monitoring system (top-view).

As counteractions either a flooding of the chamber or a relief of the groundwater heads in the sand layer underneath the concrete slab are eligible. Since a flooding of the chambers must be avoided during the overhaul, a pressure relief system was chosen. Here, the concept of the pressure relief system is based on the geohydraulic conditions. It was assumed that the sand aquifer was nearly hydraulically isolated due to the low-permeability clay layer (aquiclude) and the sheet pile walls, so that after a pressure relief the original hydraulic heads would only be restored after a longer period of time. Also, due to the artesian groundwater conditions a passive groundwater extraction is possible. Due to the confined groundwater conditions, a low specific storage coefficient can also be assumed, so that even a small groundwater abstraction can provide sufficient relief for the hydraulic heads [5, 6]. During the overhaul, those assumptions have to be verified by hydraulic tests in order to proof the effectiveness of the pressure relief system.

The measuring system, the pressure relief system and the data storage are controlled online via a central server, where the recorded data are imported, displayed and stored.

Here, the data are made available in the form of an ASCII file in an FTP directory. The data are scanned by the system at regular intervals, read out and transferred to the web-server as well as converted to a uniform data format and integrated into a database. The data are accessed to an existing FTP directory making it available to a publicly accessible address. Here, it was made directly accessible to all project participants via a web interface in the form of freely definable evaluation representations (e.g. hydrographs). In addition, message chains have been programmed which are activated if the critical hydraulic heads are exceeded. In this case, the responsible participants are notified via SMS or e-mail immediately.

### 3.2 Measuring Interval

In Germany, a tidal cycle lasts about 12 h and 25 min and can be simplified as a sinus function. In order to record and evaluate the tidal influence on the groundwater heads measurements with an appropriate temporal resolution are necessary. If a measuring interval that is too large is chosen, a fluctuation of the hydraulic heads would be determined with a higher frequency. The so-called alias-effect can be avoided by selecting a measurement interval with a frequency that is at least twice as high as the frequency of the signal to be measured. This frequency is called the Nyquist frequency [7]. To determine the tidal dynamics with an accuracy of a few centimeters, measurement intervals are required that are far greater than the Nyquist frequency, since the accuracy increases with the sampling frequency.

Comparing the areas enclosed by a curve, which can be reconstructed on the basis of the measured values with the area enclosed by the curve of an original signal, the relationship between measurement interval and accuracy can be determined. With this approach approx. 40 measurements per tidal cycle are required to reconstruct the original curve with an accuracy of 1 cm. This results in a measuring interval of at least 18 min. Considering that a small measuring interval does not present a major challenge for today's measuring and logging technology, a measuring interval of 5 min was chosen.

### 3.3 Packersystem

For various reasons, the installation of stationary measuring points and a permanent monitoring system is to complex and to expensive, so that the pressure probes are temporarily installed in special packer systems. In addition to a controlled and safe installation, the pressure probes can thus be dismantled and reused for the subsequent overhaul of the other chambers. Also, it is possible to restore the original condition of the concrete slab after the completion of the overhaul.

The packer systems used here consist out of so-called borehole packers, which are inserted directly into boreholes, and smaller packers which contain the pressure probes. These so-called measuring packers are inserted into the borehole-packers. The packer systems were developed by the company Comdrill, Heilbronn in Germany in cooperation with the BAW.

The borehole packer has a removable tip at its lower end, into which 4 filter stones are embedded. Inside the tube there is a locking pin for fixing the second smaller measuring packer (Fig. 4). After inserting the borehole packer, the tube is pressed onto a pressure plate and a rubber is pressed against the borehole wall. This ensures a complete sealing of the borehole during the overhaul.

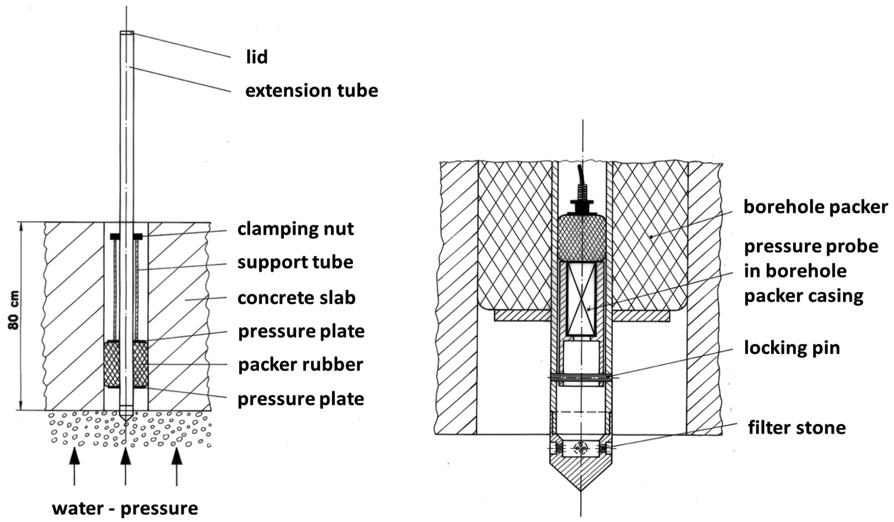


**Fig. 4.** Borehole packer (left) and measuring packer installed in the borehole packer (right).

After the installation of the borehole packer, the measuring packer is inserted with a special rod. Here, also a rubber is pressed against the inner wall with the help of the special rod by a rotary movement. The main advantage of this double packer system is that if the pressure probe fails, the pressure probe can be replaced without a flooding the chamber. Thus, an undisturbed overhaul and continuous monitoring of the groundwater heads can be guaranteed.

The pressure relief packers consist of modified borehole packers, which are equipped with a 20 cm long filter tube between the tip and the packer rubber (Fig. 5). Since the sand aquifer is made of fine and medium sand, appropriate slot widths of 0.2 mm were selected to prevent material discharge during the operation of the pressure relief. On the top there’s a valve to open and close the pressure relief packer. Additionally there’s an electronic valve head which can be controlled via the existing measuring system online.

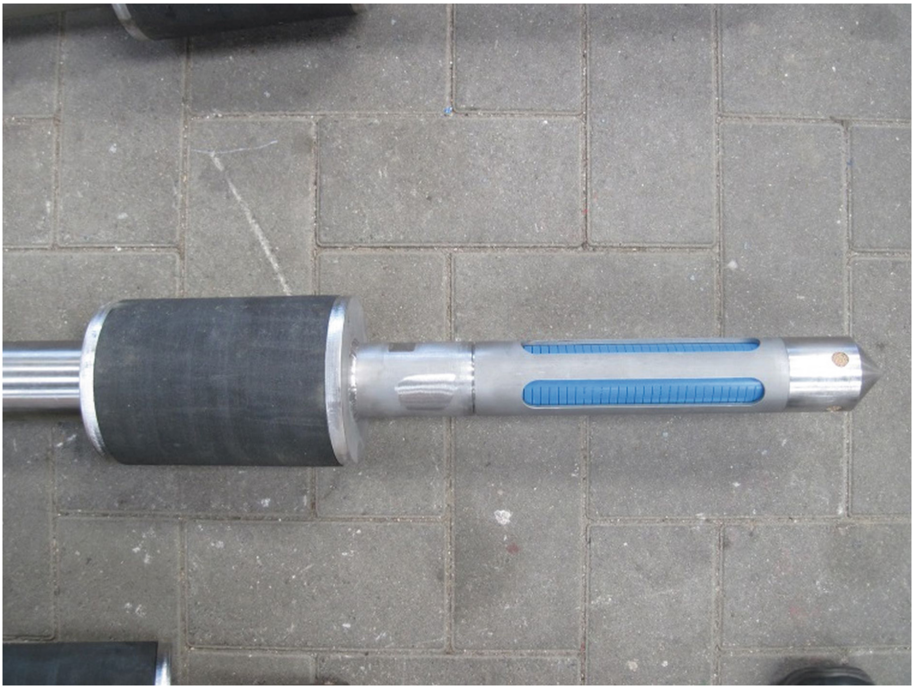

**Fig. 5.** Pressure relief packer.

## 4 Installation

Figure 6 shows the different working steps of the installation. First, scuba divers drill through the 0.8 m thick reinforced concrete slab with a single core barrel (D = 116 mm) using a hydraulically operated underwater drilling rig. For ballasting, the drilling rig is fixed to a concrete block, which is lowered into the submerged chamber and positioned by a crane. A drilling under water load was necessary, so that a hydraulic induced discharge of soil material from the sand aquifer into the chamber is prevented. Ideally, the drilling should be carried out during a tidal flooding so that a high water load is present. After the completion of the drilling, a borehole packer or a pressure relief packer is inserted into the borehole. After that, divers have to fix the packer. The measuring packer will be inserted into the borehole packer from the working pontoon level using a special rod. Immediately, after a measuring packer has been inserted and connected to the monitoring system the measurements started. After the complete installation of the packer systems, the extensometers and the water gauge in the chamber as well as after the entire set-up of the monitoring system, the chamber can be emptied for several months so that the overhaul can be started.

After the completion of the overhaul, the chamber was filled with water again, so that the packer systems and the other components of the measuring system can be removed completely. Finally, sealing packers were installed into the borehole immediately after the removal of the borehole packers. At last, the boreholes are filled with special concrete so that the original conditions are reconstructed.

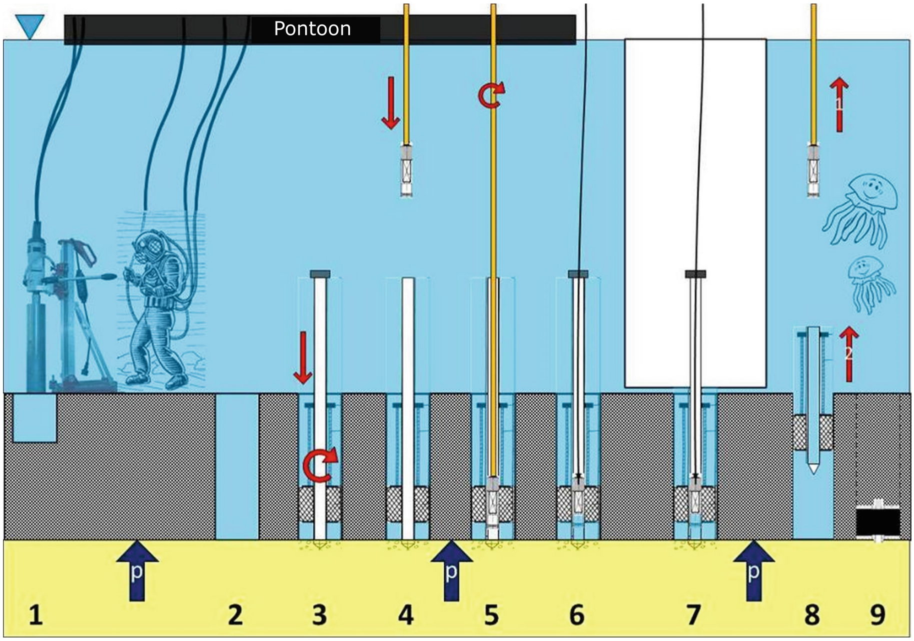


**Fig. 6.** Working steps of the installation.

## 5 Results and Discussion

Looking at the recorded groundwater heads during the overhaul of all chambers, a differentiated analysis of the chambers 1 to 3, chamber 4 and chamber 5 is required.

Figure 7 shows an exemplary hydrograph for the overhaul of the first chamber carried out in 2014 including the water levels of the chamber and the North-Sea. Over the whole observation period the groundwater heads were far below NN +1.3 m. Thus, the safety against an uplift of the concrete slab was given at all times during the overhaul of the chamber 1. Also, the hydrograph shows that the tidal dynamics of the North-Sea is reflected damped in the groundwater heads. The damping before (pre-phase) and during and after the emptying of the chambers differentiate. This difference is due to the fact that before emptying, additionally to the pressure propagation caused by the water level changes of the North-Sea, the influence of the water load within the chamber also has an effect on the groundwater heads. It can also be seen that the groundwater heads drop during the emptying of the chamber. This drop is due to the removal of the water load and the resulting stress changes in the sands.

At the beginning of the overhaul phase, the relief packers were opened for a test run of 45 min. This resulted in a drop of the groundwater heads by approx. 2 m. During the overhaul a second test run was carried out, in order to proof the effectiveness of the pressure relief system. Here, a specific storage coefficient for the sands of $S_s = 5.5\ 10^{-4}\ m^{-1}$ was estimated. Since the re-increase afterwards occurred over several weeks it was shown that the sheet-pile walls and the clay layer underneath the sand aquifer are characterized by a low hydraulic conductivity.

The measurements made during the overhaul of the chambers 2 and 3 in 2015 and 2016 confirmed the observations described above. The groundwater heads recorded during the overhaul of chamber 4 show a totally different behavior (Fig. 8). They are also damped in comparison to the tidal influenced water level of the North-Sea. But as soon as the chamber is emptied the groundwater head drops completely and converges to the water level within the chamber. Here, a hydraulic connection between the chamber and the sand due to a leak in the concrete slab was identified. To find the leak colored water was infiltrated into the sand aquifer using the pressure relief packers as infiltration wells. Here, the colored water flew out at two spots of a joint of the concrete slab so that the leak could be localized and fixed.

During the overhaul of chamber 5 the hydrographs showed a very low damping so that a hydraulic isolation of the sand aquifer was not existent (Fig. 9). Here, either leakage through the sheet pile wall or a high hydraulic conductivity respectively a small thickness of the clay layer is assumed. Nevertheless, because of the low damping high groundwater heads were expected during high water events of the North-Sea. Here, the groundwater heads had to be lowered for 16 times during the overhaul of chamber 5 by using the installed pressure relief system successfully.

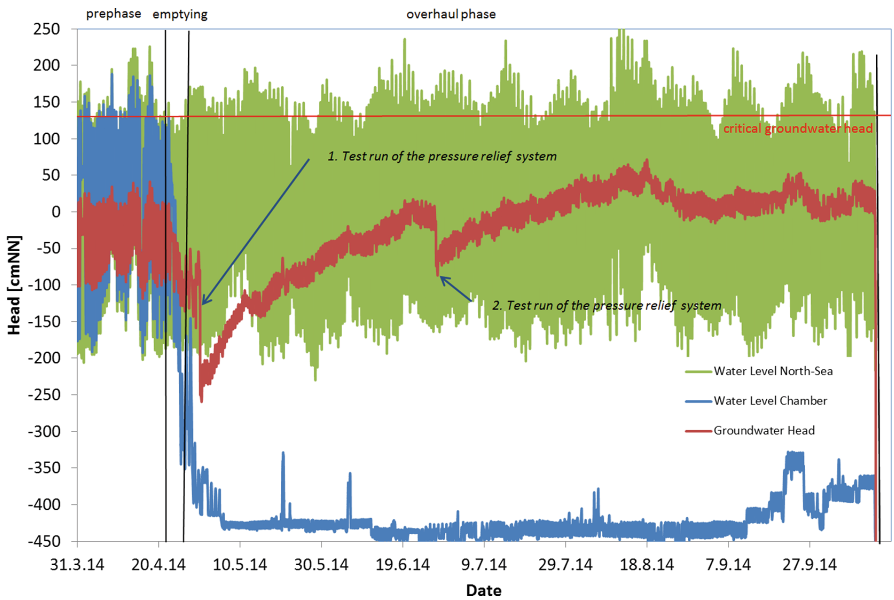


**Fig. 7.** Hydrographs for chamber 1.

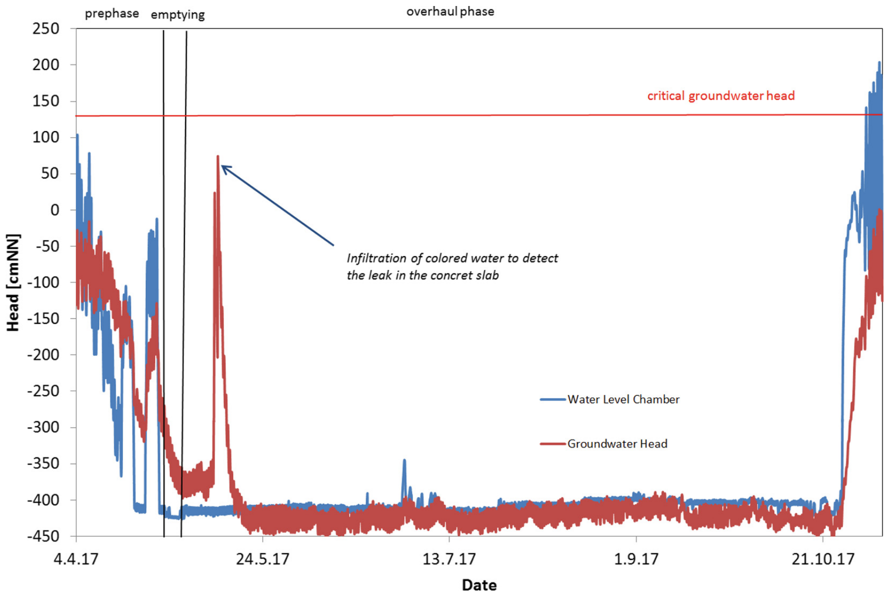


**Fig. 8.** Hydrographs for chamber 4.

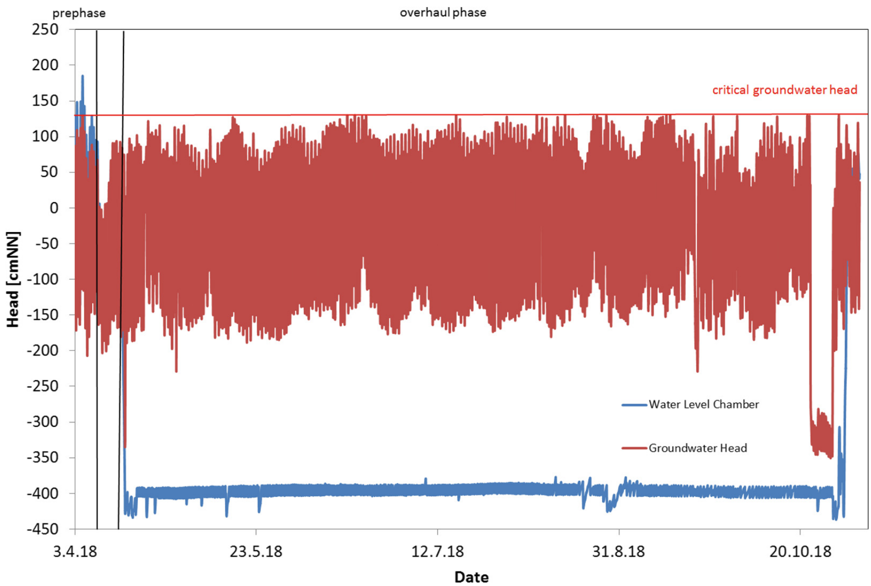


**Fig. 9.** Hydrographs for chamber 5.

## 6 Conclusions and Outlook

The operation of the monitoring and relief system described above enabled a safe overhaul of all five chambers of the "Eidersperrwerk". Using the system during the overhaul, the groundwater heads were far below the permissible values so that a controlled overhaul could be ensured. The hydraulic effectiveness of the pressure relief system could be proven for each of the chamber, whereas the pressure relief system had to be used during the overhaul of chamber 5 several times. Also, an imperfection of the concrete slab of chamber 4 was detected using the monitoring systems. The damped course of the groundwater heads as well as the effectiveness of the relief wells depends on the low hydraulic permeability of the existing adhesive layer and the existing sheet pile walls. In general, using the system floodings of the chambers could have been avoided and the expensive overhauls which were conducted under an intense time pressure were finished successfully. Also the monitoring system was running stable. Over a project time of five years there were no malfunctions of the system.

By evaluating the recorded data it was also possible to determine the values for the hydraulic conductivity of the sand aquifer, as well as of the hydraulic isolating clay-layer and sheet-pile wall. Here, a general idea of the system behavior could be gained which will be used for future measures, where an emptying of the chambers might be possible.

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