Barriers of Low Permeability to Water – Technical Solutions

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Abstract. The need of creating the barrier for inflow, access, flow-through, efflux, outflow, or lastly the effect of ground waters and dissolved solids results from as numerous (or surely more numerous) necessities as the number of “flows” specified above. Anti-filtration barriers can be grouped in many ways depending on the fundamental purpose required in hydraulic engineering and geoengineering. The study presents various aspects of creating waterproof barriers in the ground in the short and long term, discusses the most commonly used technological solutions, and finally provides examples of such actions and warns about possible consequences.

1. Introduction

Waterproof barriers can be divided into those visible units, which are hydraulic constructions, like embankments, dams, weirs, and other ones used to regulate watercourses. There are many barriers invisible to the eye, such as tight cores in the bodies and aprons on water-contacting batters of flood embankments or earth dams, or tight separation of excavations and dumpites: sheet pilings and diaphragm (slurry trench) walls, palisades of concrete piles or soil-concrete-bentonite walls (in various proportions) made by deep mixing or ground injection. Here, we should also mention the barriers around landfill sites, which aim at stopping osmotic migration of potential pollutants outside the separated area, even if there is no intense flow of ground waters.

You can't also forget about barriers protecting hydraulic structures (e.g. weirs) against such phenomena as suffosion (scouring) in the ground around weir structure at a constant difference of levels and resultant pressure gradient. The requirements for the barrier result from its function: apart from the obvious criterion of tightness, the conditions on its strength and durability (resistance to mechanical damages or corrosion) can also be imposed. Another, although no less important factor refers to the possibility of “unsealing” when restoration of the original hydrogeological conditions is finally required. Such a situation takes place, for instance, when the barrier is of temporary nature for the time of work carried out below the groundwater table.

Without going into details (available are books on hydro-engineering), it can be summarized that anti-filtration barriers are aimed at eliminating or just slowdown the flow, which is accomplished by partitioning or substantially elongating the filtration distance.

1.1 Threats related to water flow in ground

The cutting-off function enabling to run construction work in a separated space down to the depth below the known groundwater table is well known and requires no detailed description. Interesting discussions were opened about real tightness of barriers (“must sheet piling be tight?”) in respect of possible evacuating leakages, using installation which was primarily used to remove static water and then rainwater out of the working space throughout the entire investment period. As always, a
compromise is required between expenditures on “quality and certainty of trench shoring” and possible cost of effective dewatering the excavation during earth and foundation work [1].

Design engineers should also always take into account the phenomena related to groundwater filtration and its effect on the structure. Water flow (movement) called filtrating or percolating depends on the ground medium composed of separate grains and particles with pores therebetween filled with water or gas (air, water vapour). An adverse phenomenon caused by water movements can be suffosion, i.e. removing small soil particles by filtering water. A measure of potential suffosion predisposition of ground may be its uniformity coefficient d60/d10 where d60 and d10 are diameters of particles corresponding to 60% and 10% (respectively) of thinnest fractions in the material analyzed. This parameter is often defined in technical specifications of embankments referring to its minimum value (most often c. 4-6), which should ensure good compatibility. The upper limit of this parameter, which specifies the risk of suffosion is less often defined. As a result of suffosion, water flows faster through soil medium causing generation of cavities (empty spaces) or channels in the soil and degradation of its strength. The final and most dangerous stage of suffosion is a hydraulic breakdown. This phenomenon leads to creating a channel filled in with soil of affected structure inside soil mass. At the surface area, this process appears as so called springs. Usually, it takes place in low cohesion grounds. To avoid these phenomena, it is usually necessary to make anti-filtration barriers that totally cut off water flow or considerably impede it.

Paradoxically, the problem can be when water flow exists and also when it is absent. Please bear in mind that higher water pressure would not disappear with constructing a barrier and in fact, it can start to rise due to continuous supply while no easy outflow/flow through is possible. Then, water damming starts, and questions appear about the effectiveness of the barrier with a predetermined crown level. Such a phenomenon is already observed in centers of large cities where building plots at rivers are used to construct apartment buildings with “water front” and underground car parks causing to cut off the natural flow of ground water to the river. It causes the cellars in buildings situated further away from the river to become contaminated by moisture or even flooded. This can also lead to problems in the new project when raised water level exceeds the highest values provided by hydrogeological documentation to design engineers.

On the efficiently dewatered side, one should take into account the possibility of ground settlement. Settlements may be caused by the absence of hydrostatic lift on granular soil structure (soil skeleton) in non-cohesive soils, and by increased resultant vertical stresses (which are observed in the vicinity of deep excavations). In cohesive soils with high plasticity index, such long term limitation of water supply causes overdrying and contraction leading to settlements as well.

The problem of long-term operation of the barrier and its after-effects on hydrogeological conditions in the longer term as outlined above is partially referred to in the regulation on geotechnical investigation and designing. Provisions of regulation directly require the design engineer to predict future phenomenon in ground related to project implementation, including those which concern a change of ground conditions. Interesting examples from the area of Poland were presented in the conference “Geoengineering in construction. VII Conference”, Krakow on 6-7 December 2017.

1.2 Application areas of anti-filtration barriers

Anti-filtration barriers can be conventionally divided into horizontal and vertical ones. Those vertical ones are made as being penetrated to a natural impermeable layer or as extending the filtration path (suspended). They are made, for instance, to protect excavation, around permeable grounds and foundation excavations, or as additional sealing the body and bedding of dams and flood banks. In the case of damming structures, the application of the anti-filtration barrier improves their stability and prevents the suffosion phenomenon from appearing due to the long-year use of structures. They are also used, for instance, in waste collecting areas. Correcting the errors made at design and execution stages (e.g. improper investigation of the subsoil) can result in serious and costly consequences. The geotechnical investigation includes determination of groundwater level, setting down filtration coefficients of soil layers, and chemical composition of waters. Important is also information on
mining damages and obstacles in subsoil (rocks, underground services). Also the level of impermeable layers should be determined along the barrier under the planned barrier.

1.3 Deep excavations
Basic problems with ensuring safety and stability of excavation sidewalls need to be, at the same time, dealt with the analysis of foundations of neighboring structures, and possible strengthening them at the stages of installing the excavation protection walls, progressing the excavations and constructing basement storeys [2,3]. A separate problem refers to the necessity of constructing underground storeys below the level of local groundwater. This requires long-term lowering of water table inside excavation while at possibly limited intervention in hydrological regime beyond the project in progress. In river valleys, such as “hoarding off” the excavation and cutting off groundwater leads to temporary or permanent disturbances of groundwater run-off and local swellings. A traditional way to protect vertical fault and simultaneously to cut-off groundwater inflow consists of the application of steel sheet pilings [4-6].

They enable to construction of monolithic reinforced concrete structures of underground storeys thus ensuring both their tightness and high rigidity of foundation. Depending on the situation, steel sheet pilings can be in retrieving or staying-in-place versions. Fig. 1 presents a view of deep excavation: upper ground anchors line is above the water table and the lower ones must have a waterproof head at a connection with the sheet piles.

Figure 1. Deep excavation supported by sheet piles. (own photo)

1.4 Hydraulic structures
Water filtration must be dealt with by contractors of any work related to, for example, construction or modernization of hydrotechnical objects and landfills [7, 8]. As these works concern large volumes and – fortunately – there are no limitations for dimensions of the machinery used, the most often such work is carried out to create anti-filtration barriers in form of deep slits filled with material of very low filtration coefficient [9-12]. Such structures can be made as relatively thin bentonite barriers or much thicker “walls” constructed as continuous units (with trencher (Fig. 2) or dug), segmented units (Cutter Soil Mixing CSM using dredgers for diaphragm walls) or as palisade walls (Deep Soil Mixing or of bentonite and reinforced concrete). Application of specific technology depends on its effectiveness (in respect of scheduled service time), feasibility (that’s why large projects often include testing stage prior to starting with work) and finally (though at the end, in general) on the economic considerations.

Barriers with the cement-bentonite binder are often used during bank modernizations. Elongated filtration path and improved stability are then achieved. Most flood banks were constructed long years ago and over their life they subjected to intense filtration phenomena in their subgrades and bodies during freshets. Over the years water became soak through bank bodies causing local flooding. It is for this reason, among other things, the plan of embankment sealing is currently carried out all over
Poland. One example of such action is the 3rd stage of the project of expanding and protecting against filtration for 35 km of embankment in the Sub-Carpathian region started in January 2020. The value of this investment is app. USD 7 million. The scope of work includes, among other things, anti-filtration barrier on the left bank of San River at a length of nearly 4.5 km.

The sealing structure was designed as a vertical barrier at least 0.4 m thick and with depths of 14 m (km 0+000 1+300) and 12 m (km 1+300 2+960) in the bank axis. The barrier will be constructed using one method of deep soil mixing. Bentonite-cement mixtures are to be used. Another example of using the anti-filtration barrier is the project of 3.4 km embankment in Zembrzyce, Lesser Poland. The left-hand flood bank of Skawa River was constructed there, which then is continued as the right-hand embankment of Paleczka Stream (the Skawa tributary). To limit water filtration through embankments, a bentonite-cement barrier was made 50 cm wide and 6 m deep. Another example of a filtration barrier application is the project implemented within the reclamation of the Slabomierz–Krzyzowka Landfill (Municipal Services in Zyrardow). Here, a vertical anti-filtration barrier nearly 1.5 km long was made in diaphragm wall technology. The minimum depth of these barriers was 3 m, and the maximum one about 13 m.

1.5 Environmental protection

Waterproof barriers are constructed to prevent harmful substances from penetrating into ground and ground waters in many other types of landfills or structures which could be adversely affected by ground waters (Fig. 3).

Figure 3. Protection against effluents from garbage dump

Very good knowledge of soil conditions is necessary to ensure proper design of the anti-filtration barrier and to adopt optimum solutions matched to specific circumstances. Interesting examples of research related to this subject were conducted at Warsaw University of Life Sciences – SGGW [13-19].

2. Materials and methods

There are many ways in which the barriers can be executed depending on soil conditions and the intended application. This paper is focused on several most often used technologies: Deep Soil Mixing (DSM), Cutter Soil Mixing (CSM), Continuous Deep Mixing Method (CDMM - Trencher), Diaphragm (slurry trench) Wall technology and Steel Sheet Piles. Some attempts were introduced to replace cement binders with fly ashes that can reduce the total carbon footprint of the conducted works [20, 21].

2.1 Deep Soil Mixing (DSM)

This technology consists of creating a cement-soil composite in a form of secant columns. Natural soil is mixed with a specially prepared binding medium (Fig. 4.).
Columns are made in several stages during which the mixer is alternately elevated and plunged until the column attains uniform structure. The columns are made so as they overlap each other to get better tightness. The thickness of such a barrier equals to 0.6-1.0 m approximately. A drawback of this method is limited depth to a dozen or so meters. Difficulties with drilling are to be taken into account for deeper operations (Fig. 5.).

2.2 Cutter Soil Mixing (CSM)
This technology consists of creating a cement-soil composite (see Fig. 6. on the previous page) in a form of barrette (rectangular panel). Similarly to DSM, natural soil is mixed with the hydraulic binding medium by ground cutting wheels. Panels may be made in several stages during which the mixer is alternately elevated and plunged in.

2.3 Continuous Deep Mixing Method (CDMM)
The CDMM barrier consists in cutting of natural soil and mixing it with in situ made slurry without getting out the soil to surface. The slurry is fed, via pumps and pipelines, to a trencher where it is mixed with soil. In the case of these anti-filtration barriers, a cement-bentonite slurry is most often used. Such barriers are characterized by continuity and constant thickness (Fig. 7). The advantage of CDMM over the other methods consists in a short time and high quality of execution.

2.4 Diaphragm walls and slurry trench walls
The inflow of ground waters into excavation can be limited also by constructing diaphragm walls. Usually, they reach impermeable soil layers or are “suspended” to extend the filtration path. In case the poorly permeable soils are deposited at considerable depth, the horizontal barriers can be also
used. To reduce water inflow into an excavation, the bottom may be sealed with a concrete “plug”. Vertical panels (barrettes) are excavated under stabilizing slurries using mechanical/hydraulic clamshell grabs (Fig. 8) or (in the case of rocks) a hydromill cutters to form a continuous cut-off, retaining and/or structural wall. Diaphragm walls are constructed using grabs (Fig. 9) or cutters to create a narrow trench excavation into the ground. The trench is supported to be an engineered slurry. Generally, diaphragm walls are made from reinforced concrete, though unreinforced walls can also be used. Joints in adjacent panels are formed using either an over-cut (secant) technique or via temporary stop-ends.

2.5 Sheet pile walls
Steel sheet piles are also commonly used to protect deep excavations. According to work [3], the advantages of steel sheet piles worth to emphasize are as follows:

- when the steel sheet piles can be retrieved, the costs are substantially reduced and the project impact on the environment is limited as the water relations can be regenerated totally or to a considerable extent (limitation of damming);
- they can be easily joint together; the profiles, length, level of wall crown and the shape of the footprint of future excavation can be flexibly selected;
- they can be easily transported and installed using up-to-date and highly efficient equipment for driving them in, vibration pressing and pressing; (reduction of work scope at foundation construction area – starting from the moment when material unloading is completed, the construction site is occupied just by pile driver or pressing machine with a crane which handle the sheet piles;
- sheet pilings have quite flexible work schedule – there is no risk related unplanned downtime; sheet piles can be pulled out and driven in again;
- when a transfer of vertical forces is planned, they have high bearing capacity at low settlement; after they are driven in immediate loads can be applied;
- they have high durability, proved in practice, also under severe conditions of use; observations made for over hundred-year-old embankments or equally old communication structures allow to say that steel elements in soil ensure sufficient durability in adverse environmental conditions, often without proper maintenance;
- they ensure clean site area, and – what is important – limit traffic of heavy vehicles (concrete mixer vehicles) because steel sheet piles are delivered with one transport.

Application of steel sheet piles have also some constraints:

- Standard impact or vibratory methods of sheet pile driving are inevitably connected with the dynamic impact of vibrations that must be somehow controlled [22-25].
• Steel sheet piles have limited length, which results both from transportation reasons and from the limited height of pile-driver masts. In special cases, this may cause the necessity to “lengthen” the wall of sheet piles using the palisade of injection piles. Such solutions have already been successfully implemented.

• Occasionally, it is impossible to immerse the sheet piles with conventional methods. Then, drilling or water jetting is necessary to assist in immersing. Such actions reduce soil strength at contact with the wall and can cause higher pressures than those in design assumptions.

• Steel sheet piles can, when they encounter obstacles in soil, be destroyed or partially disconnected in interlocking joints. When the wall shall pay the role of sheet piling, a “window” is then created and the ground water will flow into the excavation.

3. Results and Discussion

The inflow of ground water creates a considerable threat to civil structures during their construction and usage. For this reason, the anti-filtration barriers which cut off or limit water flow are of great importance. Although large machinery is used to construct them, this work must be accurate and precise. The protection of structure against the action of ground water ensures its durability, strength, and stability over long years. This is why it is so important to commission them to the best contractors.

To get the maximum possible use of construction plots in densely populated cities, design engineers place car parks in underground floors. This involves the need to solve many geotechnical problems including those caused by water migration (inflow during construction) and later constant groundwater pressure.

Figure 10 illustrates an example where water inflow to excavation (after pumping is turned off) caused water rise much above the higher level recorded in the ground around the excavation. It can lead, according to Archimedes’ principle, even to driving up the underground structure. In this situation, removal of the shielding or at least unsealing it could be the solution. It should be highlighted that such situations are not uncommon and low water volume between structure wall and the excavation protecting wall (usually out of steel sheet piles) does not change the buoyancy as it is dependent on water column height only.
Figure 11 shows an example of the problem with unbalanced water pressure on the ground-bearing floor slab. Global stability to the driving up is ensured using deep immerse (anchorage) of diaphragm walls but the force balance causes bending of the whole structure upwards.

It should be mentioned here that the solution would be to cut off, durably and effectively, the inflow of ground water below the slab, which can be assumed by the design engineer, but as indicate numerous experiences, it is rather impossible to achieve.

In such a situation, the solution may be the dewatering system which reduces water overpressure under the slab. However, it would be then necessary to maintain such a system lifelong, so significant costs would be involved.

Figure 12 illustrates an example of the problem with water pressure on the floor slab of the building with variable height. The global stability for buoyancy is ensured, like in the situation of Fig. 11., with structure weight (located off-center with respect of the structure projection center) and with deep immersion (anchorage) of diaphragm walls. In such a situation, the force balance causes a rotation of the whole structure. In this case, it is not necessary to ensure the ground water inflow under the slab to be durable and effective cut-off, however, structure tilt can be expected and also such bending schemes of foundation slab which were not foreseen by the design engineer. As a consequence, scratches in the slab may appear and water may inflows to the basement floor.

In such a situation, the remedy can consist of a dewatering system that reduces water overpressure under the slab. However, it would be then necessary to maintain such a system lifelong, so significant costs would be involved.
4. Conclusion

The abovementioned issues emphasize the role of various aspects of creating waterproof barriers in the ground in the short and long term. Given the technology description and some examples of such actions presented in section 5 presents possible consequences of building barriers of low permeability to water using various special geotechnical technologies.

This complexity brings the need for an experience based geotechnical education of students but also practicing engineers with regard to new technologies and design solutions [26].

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