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# FLOOD EMBANKMENTS MODERNISATION WITH USE OF VERTICAL HYDRAULIC CUT-OFF WALLS FIELD RESEARCH RESULTS

## XVII

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# SPIS TREŚCI

# 1. INTRODUCTION

Researches of the flood banks of Odra river that have been conducted since 1970, including the period after the flood in 1997, show, that the proper functioning of banks is based on the effective operation of hydraulic cut-off walls. Since it was necessary to find an experimental section, in order to test the effects that could be achieved with use of ultrafine binders, we have reviewed the documentation [Arcadis Ecokonrem 1999], [Proxima S.A. 2000], developed to evaluate the technical condition of the flood banks of Odra on the territory of Dolnośląskie (Lower Silesian) Voivodship.

The existing flood banks in the valley of Odra were constructed, and then modernised several times, in various periods of the past. In the 19th century, and in the first half of the 20th century, the flood banks were constructed without a prior detailed evaluation of the subsoil. Hydraulic calculations had not been applied in order to determine the transverse section, and during the construction of the flood banks, proper types of soil had not been selected. When the crown of the modernised banks was raised above the levels of water recorded during subsequent catastrophic floods, the results of increased filtration in the top of the bank were not taken into consideration. During the construction of new banks and following modernisation works, neither uniform technology nor construction solutions were applied, that would consist in the zoning of the transverse section of the bank, e.g. by means of the construction of a core or of a screen to limit the filtration. In most cases the flood banks were constructed with use of the surface layer, approximately 1m deep, of clayey alluvial clays, gathered, in most instances, from the inter-embankment zone. If alluvial clay was unavailable, non-cohesive soils were used. In places of larger leaks, the flood banks were usually strengthened by a buttress constructed on the downstream slope, increasing the stability of the bank and limiting the negative effects of filtration. Most of the flood banks are relatively homogenous embankments, raised with use of local surface soils, covered by a 10–20 cm deep layer of humus, with turf as the top layer.

The analysis of approx. 450 cases of destruction of flood banks in Poland, presented by Król [1983], and conducted in 1980 by CBSiPWM "Bipromel", shows that over 50% of the cases were caused by damages resulting from intensive filtration through the body and subsoil of the banks, while 32% were caused by water overflowing the embankment. Thus, various types of filtration-related damages account for the potentially most significant problem of existing flood banks. Flood freshets usually last from several to over ten days. During the flood in 1997, the period, when the level of water surpassed the alarm level on the section of the river between Brzeg and Głogow, lasted from 23 to 36 days [IMGW 1997]. Long-lasting rise of water intensifies the filtration-related damages. They are particularly dangerous in case of flood banks constructed only from non-cohesive soils or those, which contain only weakly compacted inserts of such soils, which had been often subject ed to suffosion. Following long-term freshets within the embankments, as well as in the soil base, voids and cavities  often appear. They are created as a result of:

- Subsidence of loose soil,
- Elevation by water of soil surrounding the channels bored by mammals living within the embankment (Photo 1),
- Creation of channels and zones of loosened, non-cohesive soil, as a result of water filtration,
- Cavities and exposures of the downstream slope in areas of intensive filtration effusions, and
- Suffosion

a)

b)

Photo 1 (a, b) Embankments of the river Ślęza devastated by boars

Sections, where small ponds of water exist in the direct neighbourhood of the flood banks, are significantly threatened by filtration (Photo 5). Water-soaked areas in the embankment-adjacent areas used as agricultural land, and forests, foster the population of the embankment by amphibious mammals, such as: musk-rats, grubbers; insectivorous and herbivorous mammals such as: voles, hamsters, moles, various species of mice, and other. Flood banks offer these animals comfortable moisture, thermal and trophic conditions, and the absence of human interventions enables them to build complex systems of burrows and nests inside the body of the bank (Photo 3). The perforation of the body of the flood bank creates privileged paths for filtration. Extremely disadvantageous ways of perforation of the whole cross-section of the bank may cause piping. Another problem is caused by rootling boars, which devastate the slopes of embankments in search for food, thus weakening the transverse section of the banks (Photos 1a, b).

In order to improve the safety conditions of existing embankments, repairs and modernisation works are conducted. Repair (reconstruction) encompasses the works performed on damaged sections of flood banks, in order to reconstruct their original geometry and to protect areas of leaks and filtration-related deformations. The basic operation realised during the flood bank modernisation process is caulking. When the banks are founded on a deep layer of clayey alluvial clays, additional sealing is performed only on the body of the bank. It can be realised in form of a screen or cut-off wall located in the axis of the bank. Numerous embankments are situated on highly permeable subsoil; they also cross old river beds that have been filled with dredged sand or sandy soils. During long freshets on the area adjacent to such embankments, intensified effusions occur, which can cause piping on weakly compacted, suffosion-prone soils (Photo 4). Excessive filtration can be limited by means of elongation of the filtration path. This is achieved through the use of such construction elements as screens and horizontal cut-off walls in the foreground of the upstream slope or, more efficient, vertical hydraulic cut-off walls. Suspended vertical cut-off walls can be located inside the foot of the upstream slope and connected with the screen, or in the central zone of the flood bank, in form of a narrow core. It should be emphasised, that the purpose of such solutions is to lengthen the path of filtration, and not to seal the base of the bank all the way down to the impermeable layer, located below groundwater zone. Full sealing of permeable soil restrains the outflow of groundwaters to the river, thus the supply of groundwaters from the valley to the river could be limited or worse, eliminated. This may in turn lead to flooding of the embankment-adjacent areas, in particular during spring thawing. If local conditions force this type of solution, it is necessary to build filtration windows at the point of contact of the cut-off wall with the non-permeable layer in the deep subsoil.

Impermeable screens and cut-off walls are constructed from cohesive soils or from bentonite mats, in rare cases from synthetic geomembranes. In order to install them, the downstream slope of the embankment has to be exposed, and transport of large amounts of soil is required. The main cause for the practical application of these solutions was the lack of access to less invasive technologies. The technological and logistic problems specified hereabove can be minimised through the use of trenchless technologies.

## 1. Condition of the embankments in the valley of Odra

After the disastrous flood in July 1997, research was initiated in order to evaluate the technical condition of embankments on the river Odra. This was the first geological and geotechnical investigation on such a scale conducted in this area. The ice-marginal valley of Odra is a basin eroded in Tertiary silts and clays, which are practically non-permeable. On the breakthrough sections of the river the basin is eroded in formations older than the Tertiary period, located on the depth ranging from several to several tens of meters. The basin is filled with Quaternary sediments accumulated by the glacial process in form of drift clay and free glacier sediments in form of highly compacted gravel and clayey sand-mix gravels interbedded with cohesive formations. In the Quaternary formations a Holocene basin was created, whose bottom is filled with compacted river sediments of the river bed facies, in form of washed-up gravels, gravel-sand mix and sands. Non-cohesive formations are covered by clayey alluvial clays (river clays) – Figure 1.

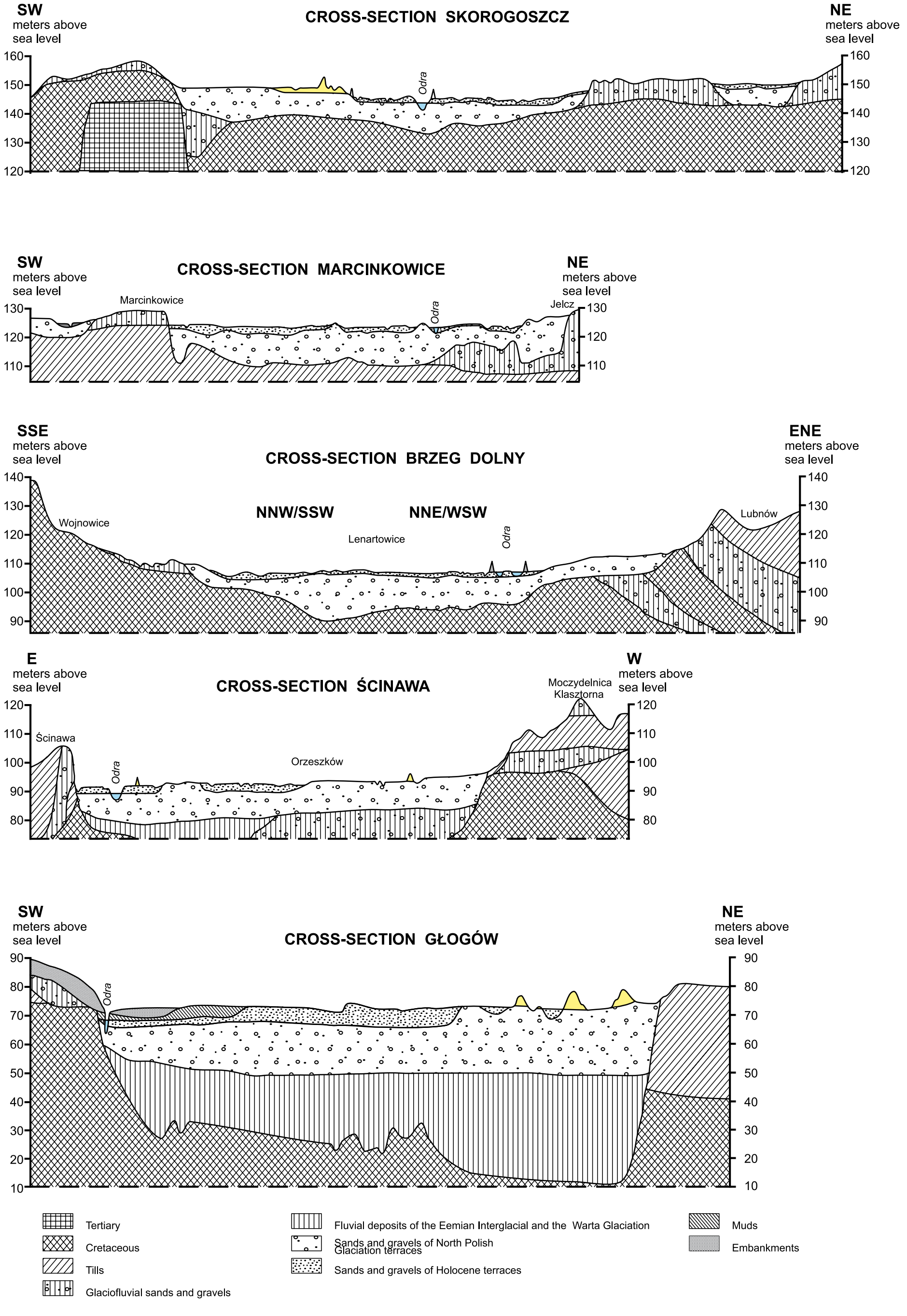


Fig. 1. Geological cross-sections of Odra valley, according to Badura, Przybylski [2000]

The composition of the subsoil, from bottom to top, is following:

- Tertiary clays and glacial clays appear in semi-compact and hard-plastic consistency, only in the top layer of these formations the superficial layer of the depth ranging from ten centimetres to max. 0.5 m has a plastic consistency.
- Glaciofluvial gravels and sand-gravel mix, several to over ten metres deep, formed as a result of the washing-up of glacial formations and their transport from higher areas of the catchment, are compacted, and due to this state can be separated from similarly granulated, later river formations.
- River sands and gravels of the river bed facies located in the area of lower flood terraces, are very well rounded and evenly granulated. Depending on the speed of water in the process of transport, these can be coarse, medium or fine sands. These soils can be washed-up, relatively clean, with small amounts of dust, but also strongly dusty, of varied states of compaction, with a majority of medium-compacted and loose forms.
- Clayey alluvial clays are cohesive river sediments of flood facies, of a depth ranging up to 3.0 m. Their depth most often ranges from 0.5 to 2.0 m, and granulation ranges from that of clayey sands to clays, with a significant majority of dusty clays, cohesive dusty clays and dusts, containing between 2 and 5% of organic elements. The consistency of these soils varies through a wide range, from hard-plastic to soft-plastic, with a majority of $0.3 > I_L > 0.4$.

The level of ground waters contained in non-cohesive formations above the drift clays is of a great significance for the stability of the flood bank and the area adjacent to the embankment. The stable surface of ground water, located in non-cohesive formations on the depth ranging from 0.3 to 2.0 m below ground surface, is of a free nature and depends on the current water level in the river. During freshets the surface of ground waters may be free, or tense, as in most cases of surfaces covered by alluvial clays.

The existing configuration of flood banks on the river Odra is a result of a wide scope of protection and modernisation works initiated after the flood in 1903, conducted basing on the experiences from previous disastrous floods and hydrological data from that period. Depending on the morphological setting of the area of the Odra valley, three major instances of the arrangement of banks can be distinguished:

1 – on the edge of the lowest and medium flood terrace,
2 – in the area of the lowest, flat and wide flood terrace (such banks constitute a majority),
3 – in the area of the lowest, flat and wide flood terrace, but crossing the old river bed.

The direct subsoil of the banks consists of:

- in case 1 – the apex of drift clays or Tertiary formations,
- in case 2 – the layer of clayey alluvial clays or discontinuities thereof, residing on sandy formations.

The depth of alluvial clays, in the area adjacent to the banks, in the middle section of the river, ranges from 1.0 to 1.5 m. Alluvial clays often reside on river sands of varied granulation, often dusty, – in case 3 the crossings of the embankments with old river beds – the old beds have been filled with sandy soils. The existence of aggregate mud in the soil bed leads to the conclusion, that the area was covered by land with use of frontal method, and the material was sprinkled or dredged into water. The flood banks located in these sections manifest lowered levels of the crown, and in the area closely adjacent to the embankment piping occurs more frequently.

The Odra embankments have been repeatedly raised and reinforced. The distance between banks must have been determined basing on property-related aspects, as they run very close to the sides of the riverbed in many instances. The elevation of the crowns over great water was usually designed basing on highest levels recorded during subsequent disastrous floods. Only the "Protokół Bogumiński" from 1819 was the first to determine the standards of the embankments cross section.

Most of the banks that are over 3.0 meters high are equipped with benches constructed from non-cohesive soils, which were first used after the flood in 1854. The embankment associations modernised the banks so that the crown was 2.5 ÷ 3.0 m (8 ÷ 10 feet) wide, the inclination of the upstream slope 1:3, and the downstream slope 1 : 1.5 ÷ 2. Where effusions appeared in the bank, buttreses in the downstream zone increased the stability of the bank and limited negative filtration-related phenomena. The buttresses are equipped with a bench of the width of 3,0 ÷ 4,3 m (10 ÷ 14 feet), situated on the level of 1.8 m (6 feet) above the crown of the banks. Only the funds acquired pursuant to the Act of 1905, destined to regulate the outflow of great waters and the channelling of the river, enabled for a general organisation of the run and geometry of the embankments, which later, with the exception of backwater banks upstream of Brzeg Dolny, remained practically the same until the flood that took place in 1997. The inclination of the slopes of currently existing banks ranges from 1 : 1.5 to 1 : 3, whereas upstream slopes have an inclination of 1 : 2 ÷ 3, and downstream slopes 1 : 1,5 ÷ 2. Sometimes, in case of particularly high banks, two benches are present. The embankments are generally not equipped with a drainage system; this function is performed by sandy buttresses, obviously only in places, where they were constructed.

The analysis of the cataloguing geodetic measurements conducted in 1998–2000 [Arcadis Ecokonrem 1999, Proxima 2000] allowed to determine that:

- above Wrocław to the border of the Opolskie Voivodship – 49.5% of the banks are lower than 2 m; 45.5% are of the height 2 ÷ 3 m and 5% > 3 m;
- below Wrocław to Głogów – 8% of the banks are lower than 2 m, 27% are of the height 2 ÷ 3 m, 34% are 3 ÷ 4 m high, 24% 4 ÷ 5 m high and 7% higher than 5 m;
- the inclinations of the slopes of existing banks range from 1: 1.5 ÷ 3, whereas 88% of the length of upstream slopes are inclined by 1: 3, and the remaining inclinations are higher. 70% of the length of downstream slopes is inclined by 1 : 3; 28% by 1 : 2, and the remaining inclinations are higher.

For the construction of the banks the superficial layer ca. 1 m thick of clayey alluvial clays was used, typically originating from the inter-embankment zone, from the zone above the surface of ground waters. In cases when clayey alluvial clays were unavailable, also non-cohesive soils were used – some of the sections are constructed exclusively from such soils. The identification conducted during the reconstruction of destroyed sections [Balawejder, Kowalski, Molski, Orzeszyna 1999; Garlikowski, Orzeszyna 1998, 1999;

Janiak 1986, 1992, 1993; Kowalski 1984, 1085, 1997, 1998, Orzeszyna 1984, 1992, 2002] and the identification related to the evaluation of the technical condition of the banks [Arcadis Ecokonrem 1999, Proxima 2000] prove, that no uniform technology was used. Neither the body of the embankment nor the subsoil are sealed or compacted. The embankment and the superficial zone of the subsoil are characterised by most varied types and states. The random location of soils within the transverse section of the flood banks was probably determined by the distance of transporting the soil material from the deposit. As horse transport was commonly used (horse carriages, and, in cases where it was convenient, rail transport in dumpers), and, within the embankment also manual transport with use of carriers and wheelbarrows, it seems, that this might have led to the difficulties in controlling the layered material. In the middle zone of the bank lenses may occur, as well as interbedded cohesive and non-cohesive formations. The banks were poured, and the soil did not undergo a consistent compaction.

In the light of current research and requirements, the soils embedded in the flood banks are insufficiently compacted [Garlikowski, Orzeszyna, 1998, 1999; Arcadis Ecokonrem 1999, Proxima. 2000, Conditions…1994; Guidelines…1983]. Sections of banks of such structure may manifest effusions and leaks on the downstream slope, which may, in time, especially during freshets, lead to hydraulic displacements and piping. For the purposes of evaluation of the behaviour of specific sections of the embankments during freshets and of the methods of their protection or modernisation, characteristic cases of the structure of the transverse sections (Figure 2) have been categorised as follows:

Body of the bank constructed from:

1 – non-permeable or low-permeable soils,
2 – permeable soils,
3 – containing various soils randomly located within the cross-section,

The direct soil bed of the bank consists of:

A – a layer of clayey alluvial clays of a large depth, deposited on top of non-cohesive soils,
B – permeable non-cohesive soils,
C – a layer of alluvial clays of a small thickness or characterised by inconsistencies.

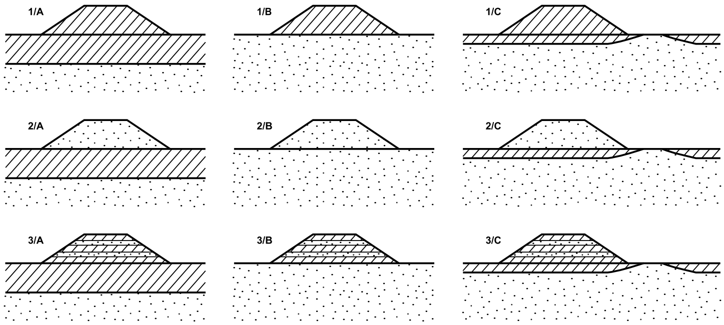


Fig. 2. Characteristic interbeddings of soil within the cross-section of the embankments and their soil beds

Long-lasting freshet intensifies filtration-related damages to the structures cross-sections and soil subbase marked as 2/A, B, C i 3/A, B, C presented in Figure 2.

The above specified structures are often characterised by voids and caverns inside the body, formed:

- as a result of the subsidence of loose soil (Photo 2),
- as a result of the increase in diameter of "channels" bored by mammals populating the embankment (Photo 1),
- channels and zones of non-cohesive soil loosened by filtrating waters (piping), whose outlets in the embankment-adjacent area are visible in form of cones of elevated material (Photo 4),
- external, superficial cavities and exposures of the downstream slope in places, where intensive filtration effusions exist.

A large threat of filtration exists on those sections, where small ponds of water are located in direct proximity of the banks, both in the embankment-adjacent area, and in the inter-embankment zone (Photo 5). In cities, where the embankment adjacent area has been developed, wells are dug, and sewage tanks or underground floors of building objects are often located in the direct proximity of the flood banks. Long-term freshet causes intensive leaks, followed by the elevation of soil in the bottoms of wells, in insufficiently weighed thanks and floors in basements. The locations of such elevations create an "outlet" for the channels of piping.

In the valley of Odra, following the German tradition, during the modernisation of the flood banks system at the beginning of the 20th century, trees were planted on banks located within most cities on the river Odra. In case of long-lasting freshets, during which the bodies of the flood banks become heavily soaked, not even a developed root system, often reaching deep inside the ground, can provide the banks with sufficient stability. Short time, at which such damages occur, practically disables any effective prevention (Photos 7, 9).

The following observations were made on several dozen erosion-related washouts of the flood banks on Odra:

- a significant part of the damages to the banks has occurred in places, where trees were growing on the crown or on the slope of the banks (Photo 9). The root system, besides those roots that penetrated deep in search for water which, grows through the whole body of the bank and the subsoil, down to the surface of ground water, consists of some roots develop ed in the superficial layer, or only in the humus, loosening it significantly.
- the root system of dead trees, that remains inside the body of the flood bank, rotting and decomposing in time, transforms into a system of open channels. Even if the upper part of the root system was removed, and the resulting cavity appropriately filled in, still in a part of the body of the bank the flow would concentrate in a system of channels replacing the roots, instead of slow filtration
- bushes and trees growing in the inter-embankment zone cause a limitation to the hydraulic cross section, which leads to an artificial rise of flood waters, which can then overflow the crown of the bank (Photo 10).

Photo 2. Subsidence of the crown of the bank

Photo 3. Burrows of animals populating the embankment

Photo 4. Zone of non-cohesive soil loosened by filtrating waters (piping)

Photo 5. Small ponds of water in the embankment adjacent area

Photo 6. Subsidence of loose soil

Photo 7. Gap in the flood bank on Odra created as a result of a tree falling down

Photo 8. Trees growing on the embankments

Photo 9. Root systems of trees inside flood banks. Flood bank on Odra – Residential District Zacisze

Photo 10. Inter-embankment zone grown over with trees and bushes

Flooding areas, small ponds in the inter-embankment zone and the area adjacent to the banks, agriculturally used land, forests and developed areas located in the direct proximity of the banks fosters the population of the embankment by such amphibious mammals such as: musk-rats, grubbers; insectivorous and herbivorous mammals such as: voles, hamsters, moles, various species of mice, and other. These animals treat the flood banks as a natural habitat, where they can find convenient moisture, thermal and trophic conditions, whereas the absence of human intervention enables them to build large systems of burrows and nests inside the body of the bank [Adamczewska-Andrzejewska; Pawlat 1990]. The perforation of the body of the flood bank by mammals creates privileged channels for filtration. Openings and tunnels allow the water to penetrate inside the body of the bank, bypassing the filtration through its large part. This radically shortens the time of filtration and of the stabilisation of the water surface inside the body of the bank. In some cases, the filtration curve approaches the downstream slope, or cuts through it on different heights, which may, within a short time, cause a local loss of stability, manifested in form of superficial slides or falls. In extremely disadvantageous cases, the way of perforation throughout the whole transverse section of the body of the bank may cause a piping.

During the last decade of the 20th century, a series of underground infrastructure fittings was constructed, cutting through the banks, including wires, pressure pipelines, sewage outlets of rainwater and drainage water. Some of these installations were constructed lawlessly, without obtaining the required permits. Passages that were built against the rules of construction, are locations of potential damages to the bank and create privileged paths for filtration.

The majority of embankments are not equipped with service roads. Long sections of the crown of the flood banks are sometimes used as local pedestrian passages or cycling roads, and often driven over by cars (Photo 11). Such situation significantly impedes the creation of temporary means of prevention in case of larger as well as longer-lasting freshets.

Photo 11. Crown of the flood banks driven over by cars – lack of service road

# 2. RECONSTRUCTION OF EXISTING EMBANKMENTS

## 2.1. Modernisation and sealing of the flood banks

Apart from financial problems, modernisation works are hampered by a series of construction-related and technological limitations. One of them is the existing infrastructure and various types of fittings located inside the bodies of the flood banks. Another serious limitation is caused by property-related conditions, which often force expensive construction solutions. Often in places, where the problem could be solved by means of installing a drainage system, the impossibility to obtain land to increase the size of the structure forces the construction of complex insulating structures.

After the flood, loose and permeable sandy soils in the subsoil of the washed-out section of the right side flood bank on Odra, near the village Uraz-Raków were strengthened with use of the vibroflotation method. This method enables to strengthen the loose soils along the base of the embankments, although the sealing of the body of the flood bank itself requires the use of different technology. A series of embankment sections were sealed by constructing screens and cut-off walls. If cohesive soils are to be used for the construction, the transportation of large amounts of material and a lot of expensive earthworks will be required. Those cannot be avoided also in cases, when screens from bentonite mats and foil geomembranes are used. Equipment for the construction of poles, slabs, walls and hydraulic cut-off walls with use of the soil-mixing technology has been available in Poland for a few years. In case of flood banks and other earth structures for damming up the water, those technologies ensure the high quality of produced cut-off walls, and the construction works require a small working space.

The idea of soil-mixing *in-situ* emerged in the 1950s. In the following years, several various technologies of dry or wet mixing of soil with different binders were patented [Topolnicki 2003]. In situations when the aim is to solidify the soil base, mostly cement with various additives is used as binder, and for hydraulic cut-off walls, apart from cement, also its mixtures with bentonite, ash and ground slag [Borys 2006].

### 2.1.1. Technologies of construction of hydraulic cut-off walls

Equipment enabling the construction of vertical cut-off walls in form of poles, slabs, walls and hydraulic cut-off walls inside the ground has been available for several decades abroad, and for over ten years in Poland. Basic methods of the construction of cut-off walls consist of dry or wet mixing of soil with binders, production of a uniform cut-off wall, and injecting the soil with grout under high or low pressure. In case of flood banks and dams, where existing working space is limited, these technologies enable the construction of such cut-off wall without the need for excavation. Within the scope of such methods, a series of technologies can be listed, each using suitable, especially designed equipment for the preparation and bringing in the mixture or binders grout into the soil. The binder can consist of a single component or of a mixture of several components. Materials can be applied in dry form, or in form of grout or suspension. The cut-off wall is created as a result of mixing the soil with the binder, or of the direct bringing in of the adhesive into the space where the wall is being constructed. The cut-off wall is formed in a mechanical, mechanical and jetting way, or only by jetting, with mixing at the end or along the pole.

### 2.1.2. Soil mixing technologies

One of the most popular technologies used in the method of mechanical wet soil mixing is DSM (Deep Soil Mixing). The feed-in wet mixing DSM equipment set consists of a drill with a mixer, silos, grout container, agitator and pump. The technology consists of cement grout or a suspension of bentonite and other supplements mixing with soil. As a result of mixing the cement with soil, a new medium emerges, often referred to as cement-soil. It is characterised by significantly higher strength parameters and very low water-permeability. The actual size of the parameters depends on the type of added grout as well as on the type of soil.

The method has numerous technological variations, developed by various enterprises. The differences between these technologies, under different names, such as, e.g. DMM (Deep Mixing Method); COLMIX, CDM (Cutter Soil Mixing); SMW (Soil Mixed Wall), CDMM (Continuous Deep Mixing Method) consist in the construction and manner of operation of the heads used for mixing soil and in the systems of feeding the grout. The soil is mixed with binding components with use of mechanical or mechanical-jet mixers. The immersion of drilling poles, which are used in form of a single or multiple mixers, or of milling-mixing heads, is done by means of drilling the pole into the soil. On the end of the pole there are typically a leading element and a nozzle injecting the grout. After the mixer reaches the set depth, the actual forming of the cut-off wall begins. It is constructed by means of simultaneous elevation of the mixer and release of pressurised grout from the nozzles. Thus, a single column is created, or a rectangular panel, if multiple mixers are used. Single panels or columns are overlaped, forming a uniform cut-off wall, which, depending on the specific technology applied, may reach the depth of 20–30m.

The use of appropriate equipment enables the construction of cut-off walls even to 50 m deep. This method of forming walls is mainly used in linear hydrotechnical structures. One of the newer variants of the soil mixing method is the Continuous Deep Mixing Method (CDMM). Here, the soil is mixed by a special trencher. The mixing element is a moving mill, whose construction and operation resembles that of a chainsaw. Blades attached to the mill destroy the structure of the soil, and later the binder is injected. This technology allows creating cut-off walls approximately 40 cm wide and up to 10 m deep.

All the above specified technologies enable the construction of cut-off walls in practically any type of soil. The reinforcement effect is lower when works are conducted in organic soils. The presence of a large quantity of organic particles, characteristic for peat, aggradate mud and gyttja, significantly limits the process of binding the grout. This in turn leads to much lower strength parameters of the completed cut-off wall. Hence, the usage of methods based on the mixing of soil with cement or bentonite grouts requires a detailed analysis of hydrological and geological conditions.

### 2.1.3. Vibration injection technology

In the VIB cut-off walls technology the cut-off wall is formed in the soil with use of a steel H-beam profile or vibrator/extractor attached to a crane on a self-propelled carriage. The base of the steel profile is equipped with nozzles which inject the pressurised grout into the moved ground. The beam is immersed into the ground from a previously prepared technological trench, with pressure and vibration. When the H-beam is being extracted, the void created around it fills with a mixture of the stabilising material. The finished cut-off wall is 15–30 cm wide. Part of the grout also penetrates into the porous space of the soil and possible voids and caverns. The formation of a fissure in the soil through vibration also causes additional compaction of the soil in the zone adjacent to the cut-off wall. Vibration injection technology is significantly different from soil-mixing technologies, as it allows to construct a homogeneous cut-off wall, wholly consisting of the previously prepared grout. This enables to create a cut-off wall of more consistent parameters than in case of soil-mixing technologies. Local changes in soil characteristics (such as inserts of organic soils) do not affect the process of forming and binding of the cut-off wall material. However, it is difficult to create walls deeper than 20 m with use of this method.

### 2.1.4. Jet-grouting technology

Jet-grouting consists of the mixing of soil with stabilising grout at very high pressure, leading to the formation of cement-soil columns. In case of cut-off walls, apart from cement, the addition of bentonite or other sealing materials are used. Due to the application of very high pressure, ranging from 20–30 MPa, the structure of soil is completely destroyed. The diameter of columns formed by the jet-grouting method depends on the type of soil, pressure, diameter and number of nozzles, as well as on the duration of the injection. The application of this technology enables the construction of columns of the diameter from 0.4 to 2.5 m, which can be connected nearly in any way. This technology enables the construction of columns over 30 m deep. Due to the application of high pressures, this technology is typically used for the stabilisation or sealing of soil located a few meters below the surface. Thus, it is not usually used for the purposes of construction of cut-off walls in the body of the flood banks, although it is successfully applied in areas where energetic infrastructure is located or other, where it is required to seal the contact points between a structure and the soil.

### 2.1.5. Low-pressure injection technology

In case of low pressure injection, the injection grout is introduced into the soil at the pressure of 40–500 kPa. The inject can be applied into loose subsoil, as well as on contact points of soil and objects that have been subject to damages resulting from settlment. This method enables the stabilisation of loose sands, organic soils, peats and aggradate muds, or filling voids and caverns in the subsoil. Structures created in this way serve to stabilise the subsoil underneath various types of constructions, as well as to construct hydraulic cut-off walls. The pressurised inject is dispensed from rotating nozzles mounted in the pole. During the injection, soil is mixed with binder, which, after certain time, creates a strong and tight cement-soil structure of a cylindrical shape.

According to Gruszkiewicz [2003], sections of the flood banks on Wisła, Wilga and Rudawa, in Krakow and the nearby region, modernised after the flood of 1997, where along the axis of the banks cut-off walls were constructed with use of DSM, vibration injection, and jet-grouting technologies, from cement and cement-bentonite grouts, were positively verified during the long lasting freshet in 2001. Similar technology was used for the modernisation of the embankments on Odra. On sections Stabłowice in Wrocław, Kotowice and Oława, above Wrocław, cut-off walls were constructed as follows: the fissure, constructed with use of the vibration method, was then filled with a pressurised bentonite and cement mixture (Photo 12).

Photo 12. Construction of cut-off wall on the flood banks near Wrocław

# 3. EXPECTED RESULTS OF THE USE OF CUT-OFF WALLS CONSTRUCTED FROM ULTRAFINE BINDERS ON THE BASE OF CLAY FOR THE MODERNISATION OF FLOOD EMBANKMENTS

The main cause of most cases of destruction of the flood embankments are the filtration-related damages specified in chapter 1. The construction of the cross-section of most embankments and their direct subsoil, as well as prolonging periods of freshets, will augment this type of damages in the future. The basic action realised in the process of modernisation of embankments is sealing. Typically used method of sealing, resulting mainly from the lack of proper technologies and required specialist equipment, is the construction of screens and cut-off walls on the upstream slope of the embankments. Such watertight elements are made of cohesive soils or bentonite mats. The installation of such structures requires the exposure of the downstream slope of the embankment, and the embedding of large amounts of soil, which often need to be obtained from distant deposits and transported to the construction site. On most sections of modernised flood banks an additional problem will appear, as it will be necessary to construct temporary access roads. The above specified technological and logistic problems can be minimised by the usage of appropriate technology. The popularisation of DSM, vibration-injection and low-pressure injection technologies with use of ultrafine binders based on clay could significantly simplify and hasten the modernisation works.

The expected result of the introduction of suspensions preventing filtration into the body of the flood bank is the filling up of zones consisting of weakly compacted non-cohesive soils creating the body of the bank, and the creation of a low-permeable wall that would cut through the existing paths of filtration in form of horizontal, permeable interbeddings. It is assumed, that such cut-off wall will efficiently cut off the effusions on the downstream slope, move the effusions from the subsoil outside the zone directly adjacent to the embankment, which in turn will improve its stability and increase the bearing capacity of potential service roads located at the toe of the bank. It is expected, that the introduction of injection grout into the central zone of the body of the bank will fill up channels, suffosion caverns, voids replacing decayed roots of trees, as well as holes and burrows dug by rodents populating the bank, which are very difficult to locate inside the body of the bank. Low compaction of soils embedded in the banks leads to the fact that, during the rise of flood freshets the soaked body of the bank does not form good subsoil for the service road on the crown. The improvement of the bearing capacity of the upper layer of the crown road, as well as of the subsoil at the foot of the downstream slope as a potential foundation for unsurfaced roads would create an opportunity to construct, at low cost, an infrastructure of service roads along the flood banks, and to connect them with the existing local road system. The lack of such system of service roads often hampers efficient flood protection. `

# 4. FIELD INVESTIGATION PROJECT

## 4.1. State of the embankments in Kostrzyn on Odra prior to the injections

Flood banks on the river Warta were modernised at the beginning of the 20th century. At that time, flood banks were constructed with use of a technology that consisted in the formation of the body of the bank from soils that were typically obtained from the inter-embankment zone. Subsequent layers of the embankment were created from sand of fine and medium granulation, but occasionally also from clayey sands and sandy clays that were compacted by the wheels of carts delivering subsequent portions of materials. Their present state of compaction is a result of the settlment of the embankment soil under its own weight. As the soils used to form the embankment were obtained from the superficial layer of the inter-embankment zone, they are characterised by a content of organic particles ranging from $2.02 \leq I_{om} \leq 10.43\%$. Photo 13 present the right-side embankment on Warta near Kostrzyn, which was made available by LZMiUW (local water and melioration management office) Inspectorate in Gorzow Wlk. for the purpose of experimental sections of cut-off walls construction in the vibration injection, DSM and low-pressure injection technologies, with injection grouts based on clay from Bełchatów and sludge from Bolesławiec.

The body of the bank on the section to be sealed is built of non-cohesive soils interbedded with cohesive soils (Figure 14). The first geotechnical layer, NIa, is built of medium-compacted fine sands residing under a thin (0.10–0.15 m ) layer of humus. The state of compaction of this layer results from the fact that the crown of the embankment has been periodically used as a road. The strength of this layer is characterised by relatively high angles of internal friction, within the range $38.94 \leq \Phi \leq 43.56°$ and cohesion $0.0 \leq c \leq 5.81$ kPa.

The actual body of the flood bank creates the layer NIb, placed on the natural subsoil of alluvial clays from the river. It consists of loose sands of fine and medium granulation, and on the level of B and D openings also inserts of clayey sand and sandy clay. Fine sands in this layer are characterised by internal friction angle in the range $31.78 \leq \Phi \leq 35{,}03°$ and cohesion of $0.0 \leq c \leq 13.05$ kPa. The strength of this layer is lower than that of layer NIa, which results from a lower state of compaction, which is a result of the fact that soil was poured instead of having been compacted during the construction of the banks.

Photo 13. View of the section of embankment where the section of cut-off wall was to be constructed

The next geotechnical layer determined in the body of the bank (NII) consists of sandy clays and clayey sands of plastic and soft-plastic consistency, existing in form of lenses of thickness ranging from 0.6 m to 1.7 m. These are the clayey alluvial clays from the inter-embankment zone.

The bottom part of the body of the bank with its direct subsoil constitute the layer of clayey alluvial clays in form of clayey sands, sandy clays, dusty clays and cohesive clays – geotechnical layer II. It seems to be the native layer of alluvial clays formed in this area of the valley, on which the embankment was constructed. As this layer under the embankment is elevated by 0.4 to 0.6 m above the current level of ground on both sides of the embankment, it should be assumed, that during the construction of the embankment the adjacent terrain was levelled.

Under the layer of clayey alluvial clays non-cohesive soils are located – forming geotechnical layer III. This layer has not been drilled through. It consists of medium-compacted fine and medium sands interbedded with peats– geotechnical layer IV. The surface of ground water stabilised on the ordinate 11.52 m above sea level is located in the subsoil layer of medium sands, approximately 1.5 m below ground surface.

The conducted analysis of the structure of the flood bank shows, that it is constructed mainly from low-compacted non-cohesive soils. This is proven by the result of tests on undisturbed samples collected from the body of the bank. Bulk dry density of the sands creating the bank ranges from 1.44 to 1.57 g/cm$^3$ (which corresponds to a loose state of compaction). These results correspond with the values of determined permeability coefficient, ranging from 2.90E-03 to 3.75E-03 cm/s.

Photo 14. Bench on the embankment used as unsurfaced road

## 4.2. Aim and scope of the study

The main technical problem of most existing embankments, whose age should be estimated at 100 years and more, is the low state of compaction of the embedded soils and the lack of means to prevent filtration. The consequence of such situation, as well as of prolonged periods of freshets, is the weakening of the bodies of the embankments. Excessive filtration through loosened and water-permeable soils in the transverse section of the banks causes the development of suffosion and piping. The selection of modernisation solution depends on local conditions and on the necessity to maintain the required transverse section of the inter-embankment zone. Such solutions are mainly screens and cut-off walls sealing the embankment, as well as elaborate systems of buttresses and drainages on the downstream slope. The installation of sealing elements requires preparatory works on a large scale, which are difficult from the point of view of logistics. Solutions based only on the capturing of filtrating waters by drainage, apart from the fact that an additional zone of land needs to be occupied for their formation, also require a solution for the system of outflow of the captured waters on the embankment adjacent area. Vibration injection, DSM and low pressure injection technologies create new, less difficult to organise, possibilities for the modernisation of flood banks, free from the inconveniences specified above. Moreover, these technologies offer a realistic possibility to fill and eliminate the voids, caverns and channels bored by mammals populating the embankment and created as a result of the decomposition of roots of trees growing on the banks, which are very difficult to locate during the recognition.

After the preliminary analysis of the above mentioned technologies, it was determined, that, apart from the zonal displacement of loose soils and filling in the voids, the introduction of inject can also lead to the mixing, and thus filling the permeable pores of non-cohesive soils with the inject grout. Mixing the native soil with inject, which will then harden, can also cause it to stabilise, which would be very desirable from the point of view of the bearing capacity of the soil.

In the annual cycle of atmospheric changes, as well as during the period of rise of freshet waters, the moisture content of the soils embedded in the embankment will be subject to changes. In the 1980s, changes in the moisture content of the clays embedded in the core of the bank separating the waters of the rivers Odra and Oława in Siechnice near Wrocław were measured. Figure 3 presents the changes in the moisture content of the clays that occurred during 3 drought years. The conducted measurements show, that significant changes in the moisture content should be expected up to the depth of approx. 1.5 m below the surface of the bank or of the ground.

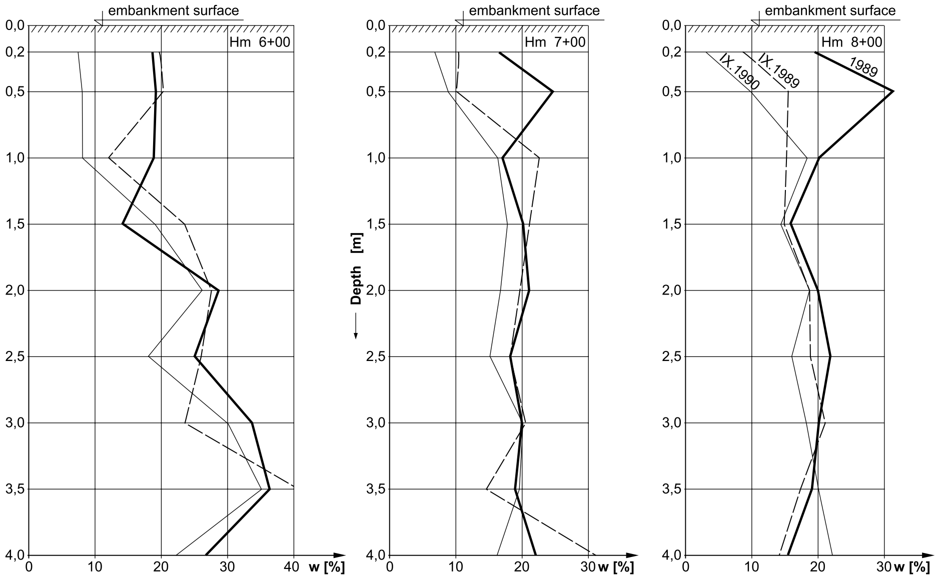


Fig. 3. Changes in the moisture content in the clay core body embedded in the bank separating the waters of Odra and Oława in Siechnice near Wrocław in years 1988–1990

This study, together with many others, proves, that in order to comprehensively recognize the phenomena occurring in the soil embedded in soil structures the best is to conduct *in situ* research in 1:1 scale. Due to that, investigation was planned, in order to recognize the phenomena occurring during the injection of ultrafine adhesives in the construction of hydraulic cut-off walls. The adopted objective encompassed a series of field studies and laboratory tests on samples collected in the field. The research has been conducted within the Sector Operational Programme "Increase in the Competitiveness of Enterprises", in 2004–2006. The project was entitled: "Study of ultrafine binders for the construction of hydraulic cut-off walls". (Project Number: WKP_1/1.4.1/1/2006/69/69/6 23/2006/U/KW/1/2006). The project was realised by a consortium consisting of five following entities:

- Przedsiębiorstwo Robót Geologiczno-Wiertniczych G. Janik & R. Kuś Sp. Jawna – as leader,
- AGH University of Science and Technology in Kraków – faculty of Materials Science and Ceramics,
- Wrocław University of Environmental and Life Sciences – Faculty of Environmental Engineering,
- Institute of Meteorology and Water Management in Warsaw – Centre for the Technical Supervision of Dams,
- Hrabowski – Expertizes and projects in the field of water, land and environmental management and engineering, and control and measurement equipment.

Further sections of this monograph present the result of field studies conducted by the employees of the consortium leader and of Wrocław University of Environmental and Life Sciences.

A series of field studies and laboratory tests was planned and conducted. They consisted of basic and extended studies of the soils embedded in flood banks, injects used for the construction of hydraulic cut-off walls and of mixtures of soils and injects.

The aim of this program was to evaluate and develop the technology, which application prevents filtration-related damages of flood banks and which will fill all types of cavities and lead to a zonal stabilisation of the transverse section, as well as stabilise the subsoil of service roads. The scope encompassed field measurements consisting of two parts. Part one included:

- determination of the geometry of the flood bank in 4 measurement cross-sections,
- probing with dynamic impact probe SL-10 in the above specified cross-sections from the crown of the bank up to the depth of approx. 5.0 m,
- drilling openings along the axis of the bank with use of manual drill, and collecting undisturbed samples and disturbed samples for laboratory analysis to verify macroscopic identification,

The second part of the field research was conducted approximately 50 days after the construction of the cut-off walls. Exposures were created, entering the body of the bank up to the axis, which enabled to uncover and examine soil profiles in the zones of specific injections. The homogeneity of the formed cut-off walls was visually assessed, and samples were collected to determine:

- bulk density,
- natural moisture content,
- shrinkage after drying to air dry state,
- coefficient of permeability,
- strength parameters.

It was planned to measure the Californian Bearing Ratio CBRd with a dynamic plunge on the soils of the embankment and on the constructed cut-off wall. The location of drilling holes and exposures is presented on Figure 4, and the cross-sections of the bank in the evaluated locations are shown on Figures 5 and 6.

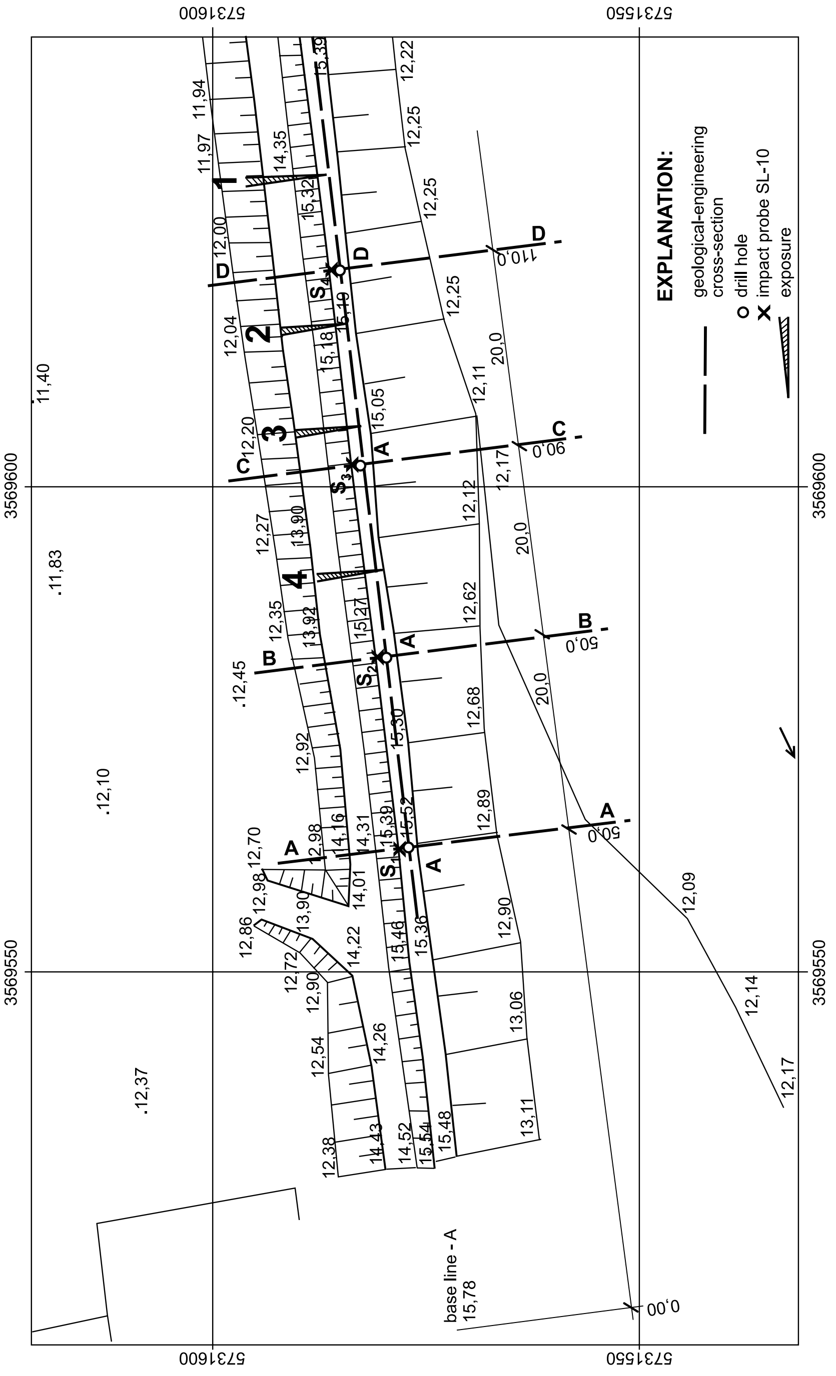


Fig. 4. Location of cross-sections, drills, exposures and probings

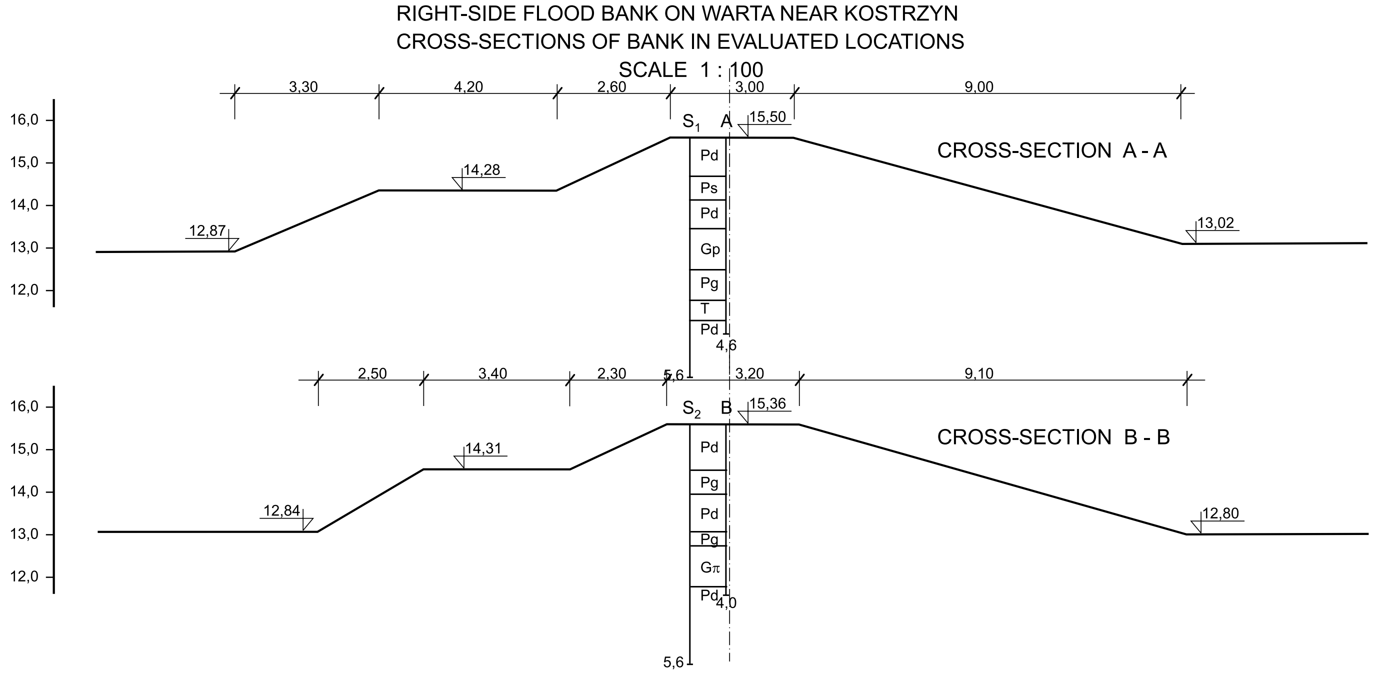


Fig. 5. Cross-sections of the bank in locations of drilling holes

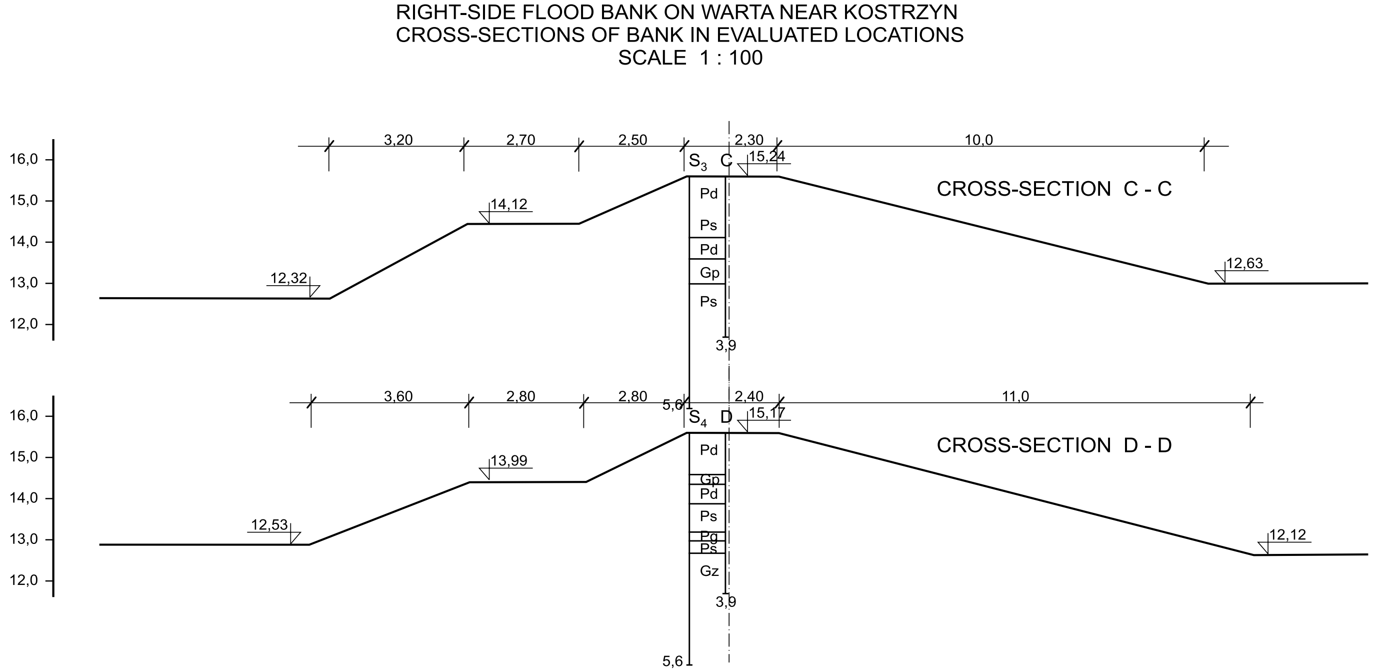


Fig. 6. Cross-sections of the bank in locations of drilling holes

## 4.3. Field investigation

In order to prove the suitability of the binders designed by Przedsiębiorstwo Robót Geologiczno-Wiertniczych as materials for the construction of hydraulic cut-off walls, and to determine the efficiency of their application in the body of the flood bank methods, beside laboratory tests a cut-off wall construction was foreseen in the experimental section.

The right side embankment of Warta near Kostrzyn, where the section for experimental research was made available, is located in the western part of the valley of the river Warta, connecting to the valley of Odra, on the northern side. The valley of Warta constitutes a part of the Torun-Eberswalde Ice-marginal valley, and its final section is approximately 10 km wide. The river bed flows in sandy formations, and slight longitudinal and transverse inclination leads to the fact that the valley is superficially composed of sandy alluvial clays and mineral-half-bog soils, among which shallow peat-bogs are located. The right side embankment is located approximately 5÷6 km away from the river, and above Kostrzyn it approaches the river so that the distance decreases to several hundred meters. Part of the valley in the embankment adjacent area, with the remains of old river beds, is used as meadows and pastures, mechanically drained by a network of channels and ditches.

### 4.3.1. General description of test investigation section

Przedsiębiorstwo Robót Geologiczno-Wiertniczych selected two types of ultrafine injects – one based on clay from Bełchatów, and another based on sludge from Bolesławiec as the main component. The summary of the test results of three types of sediments in the context of their usability as a component for the production of ultrafine binders for hydraulic cut-off walls is presented below:

<u>Clay from Bełchatów</u>
Granulometric composition: fraction over 50 μm – 30.07% by weight;
fraction between 50 – 5 μm – 41.77% by weight;
fraction below 5 μm – 28.16% by weight.
Mineral composition: quartz – 25% by weight;
kaolinite – 2% by weight;
illite – 3% by weight;
calcite – 10% by weight;
montmorillonite and other clayey minerals – 50% by weight.
Ionic interchange and the share of basic ions: $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$;
111.98 mval/100 g.
<u>Sludge from Bolesławiec</u>
Granulometric composition: fraction over 50 μm – 25.71% by weight;
fraction between 50 – 5 μm – 64.97% by weight;
fraction below 5 μm – 9.32% by weight.

Mineral composition: quartz – 18% by weight;
illite – 10% by weight;
calcite – 35% by weight;
dolomite – 15% by weight;
montmorillonite and other clayey minerals – 22% by weight.
Ionic interchange and the share of basic ions: $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$;
97.75 mval/100 g.

Decision was made to test the effectiveness of their application on the experimental section. On the 60-meter-long section of the bank, six 10-meter long sections of cut-off walls were constructed with use of three technologies: vibration injection, DSM and low-pressure injection, with two types of the above specified injects.

Prior to the beginning of the installation of the hydraulic cut-off wall, exploratory research of the soils composing the body of the flood bank was planned and conducted. The aim of this research was to determine the types of soils embedded in the body of the bank, their depth, depth of location, state of compaction and moisture content. The tests consisted in the collection of undisturbed and disturbed samples to determine the physical characteristics and strength parameters of the tested inject and mixtures of soil with inject.

#### 4.3.1.1. Sampling

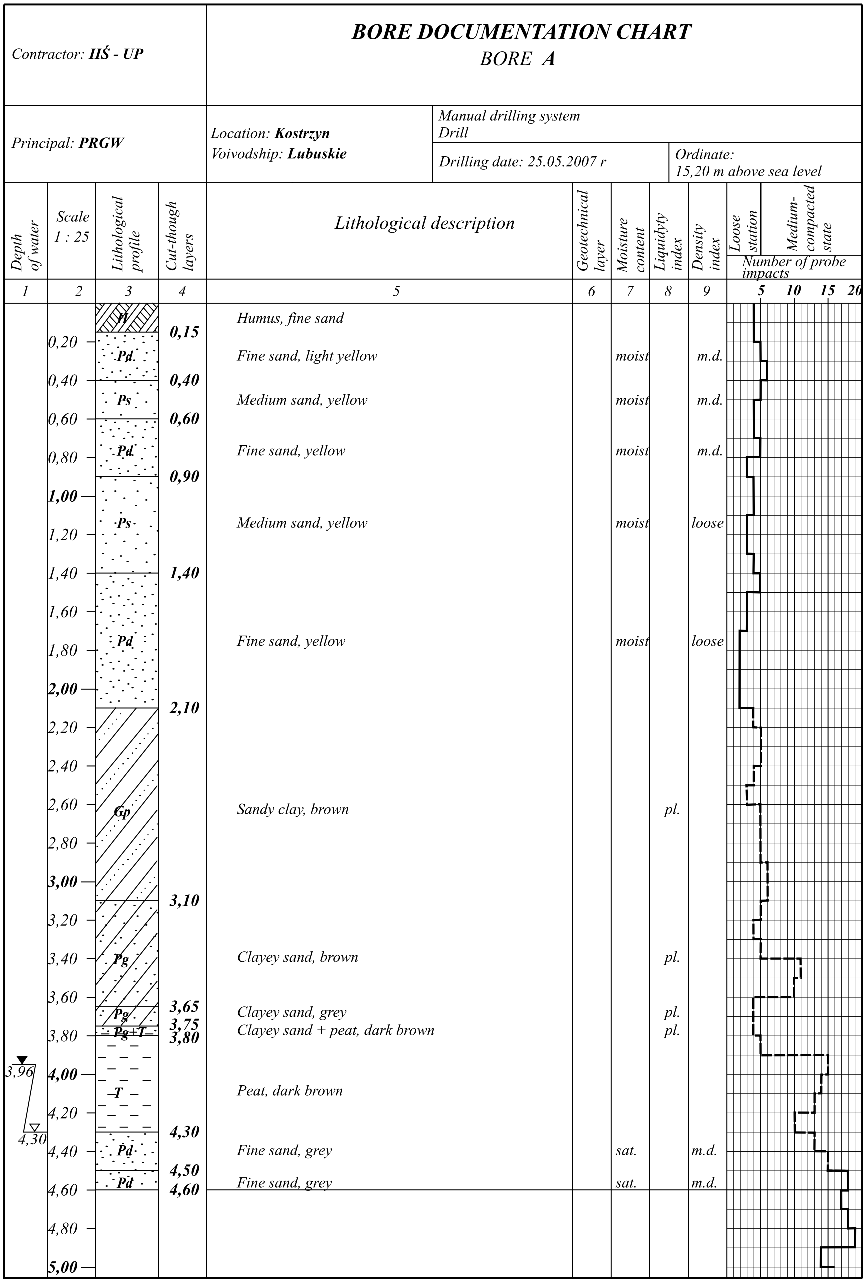
In order to determine the state of compaction of non-cohesive soils constituting the body of the embankment, samplings were conducted with use of dynamic impact probe SL-10, from the crown of the bank, 0.5 m from the edge of the downstream slope. Locations of the probings are presented in Figure 4, and probing graphs are presented along the lines of specific lithological profiles (Figures 7–10). Since correct results of the probings of superficial layers can be obtained after the so-called nominal depth is exceeded, the results obtained during the probings have been corrected pursuant to the recommendations included in the Guidelines … [Wytyczne wykonania... 1983].

The course of the samplings has shown that sandy soils embedded in the superficial 40 ÷ 50 cm layer of the flood bank are in a medium-compacted state, whereas the non-cohesive soils on other routes are characterised by a loose state. The non-cohesive soils in the direct subsoil of the embankment in the cross-section "C" are in a medium-compacted state.

#### 4.3.1.2. Drillings

Drillings in the axis of the crown of the bank were made with use of a manual drill of the diameter of 4 inches. During the drillings, undisturbed samples were collected from various layers of the deep opening, to cylindrical containers of the capacity of 1886 cm$^3$, as well as samples of disturbed structure.

The locations of the drilled holes are presented in Figure 4, and the lithological profiles of the openings are presented in Figures 5–6.



Contractor: **IIŚ - UP**

**BORE DOCUMENTATION CHART**
BORE **A**

Principal: **PRGW**

Location: **Kostrzyn**
Voivodship: **Lubuskie**

Manual drilling system
Drill

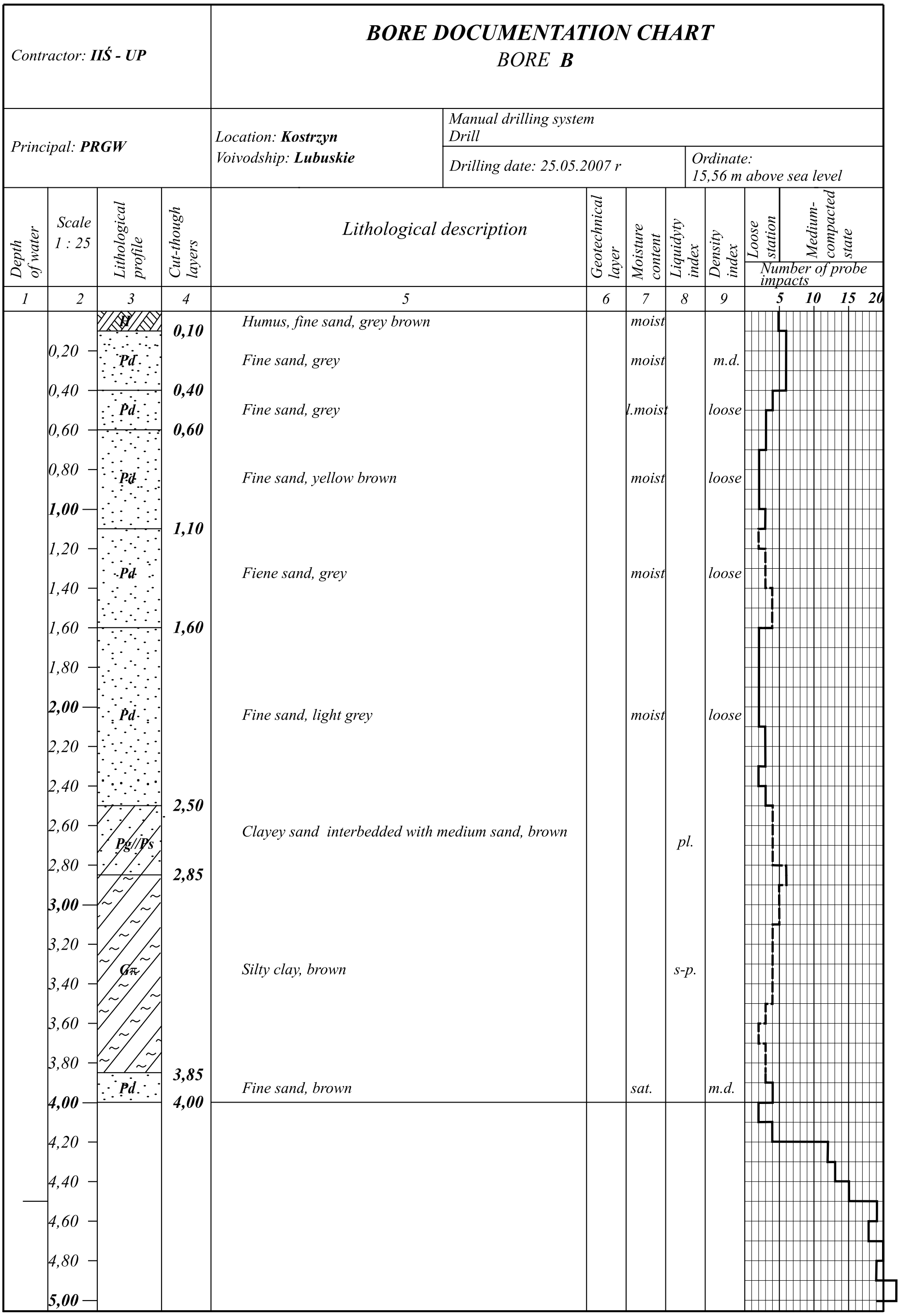
Drilling date: 25.05.2007 r

Ordinate:
15,20 m above sea level

| Depth of water (1) | Lithological profile (3) | Cut-though layers (4) | Lithological description (5) | Geotechnical layer (6) | Moisture content (7) | Liquidyty index (8) | Density index (9) |
|---|---|---|---|---|---|---|---|
| | H | 0,15 | Humus, fine sand | | | | |
| | Pd | 0,40 | Fine sand, light yellow | | moist | | m.d. |
| | Ps | 0,60 | Medium sand, yellow | | moist | | m.d. |
| | Pd | 0,90 | Fine sand, yellow | | moist | | m.d. |
| | Ps | 1,40 | Medium sand, yellow | | moist | | loose |
| | Pd | 2,10 | Fine sand, yellow | | moist | | loose |
| | Gp | 3,10 | Sandy clay, brown | | | pl. | |
| | Pg | 3,65 | Clayey sand, brown | | | pl. | |
| | Pg | 3,75 | Clayey sand, grey | | | pl. | |
| | Pg+T | 3,80 | Clayey sand + peat, dark brown | | | pl. | |
| 3,96<br>4,30 | T | 4,30 | Peat, dark brown | | | | |
| | Pd | 4,50 | Fine sand, grey | | sat. | | m.d. |
| | Pd | 4,60 | Fine sand, grey | | sat. | | m.d. |

m.d. – medium dense, pl. – plastic, sat. – saturated,
l.moist – lightly moist, h-p. – hard-plastic, s-p. – soft-plastic

Fig. 7. Documentation chart of bore A



Contractor: **IIŚ - UP**

**BORE DOCUMENTATION CHART**
BORE **B**

Principal: **PRGW**

Location: **Kostrzyn**
Voivodship: **Lubuskie**

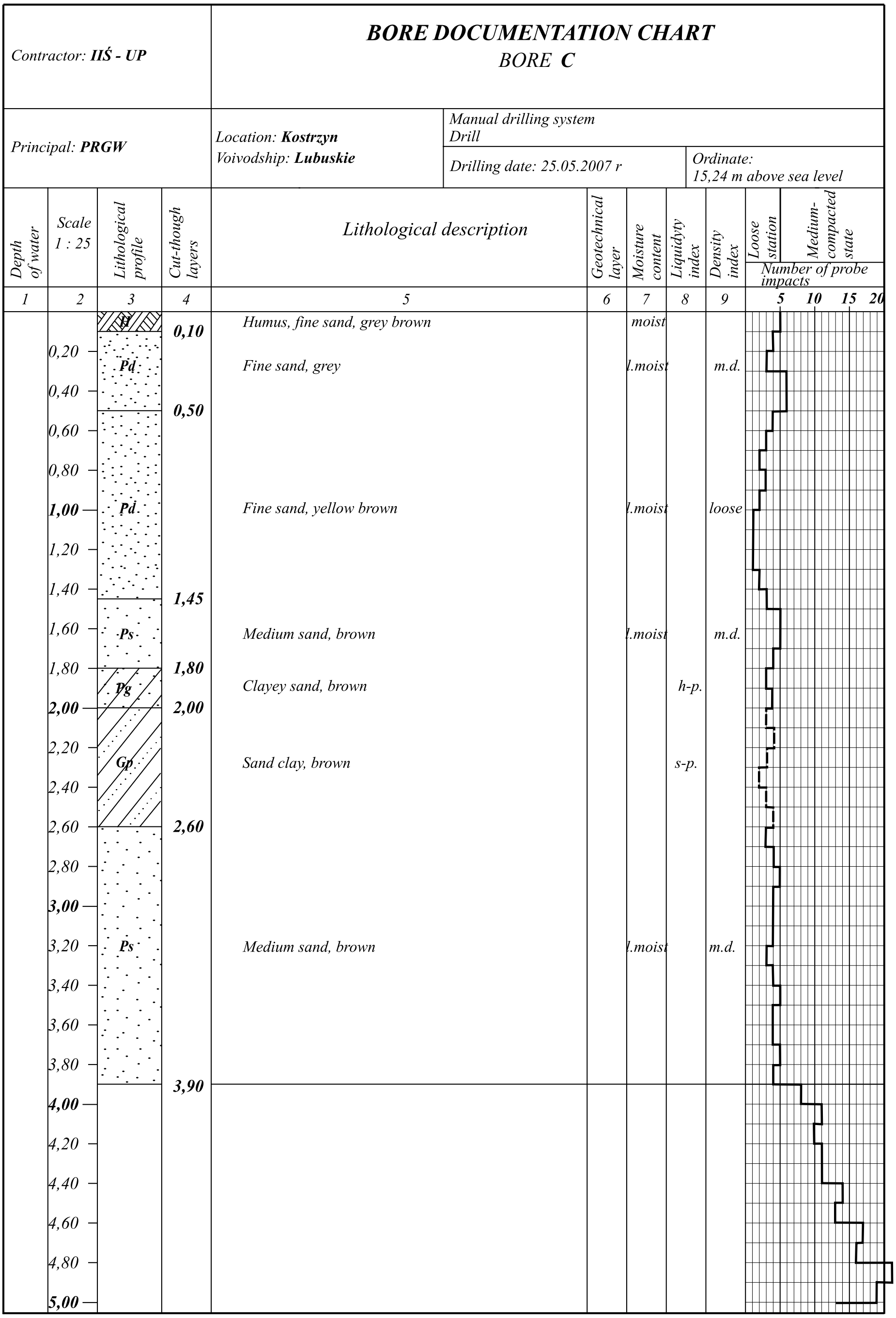
Manual drilling system
Drill

Drilling date: 25.05.2007 r

Ordinate:
15,56 m above sea level

| Depth of water | Scale 1 : 25 | Lithological profile | Cut-though layers | Lithological description | Geotechnical layer | Moisture content | Liquidyty index | Density index |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | | H | 0,10 | Humus, fine sand, grey brown | | moist | | |
| | | Pd | 0,40 | Fine sand, grey | | moist | | m.d. |
| | | Pd | 0,60 | Fine sand, grey | | l.moist | | loose |
| | | Pd | 1,10 | Fine sand, yellow brown | | moist | | loose |
| | | Pd | 1,60 | Fiene sand, grey | | moist | | loose |
| | | Pd | 2,50 | Fine sand, light grey | | moist | | loose |
| | | Pg//Ps | 2,85 | Clayey sand interbedded with medium sand, brown | | | pl. | |
| | | Gπ | 3,85 | Silty clay, brown | | | s-p. | |
| | | Pd | 4,00 | Fine sand, brown | | sat. | | m.d. |

Fig. 8. Documentation chart of bore B

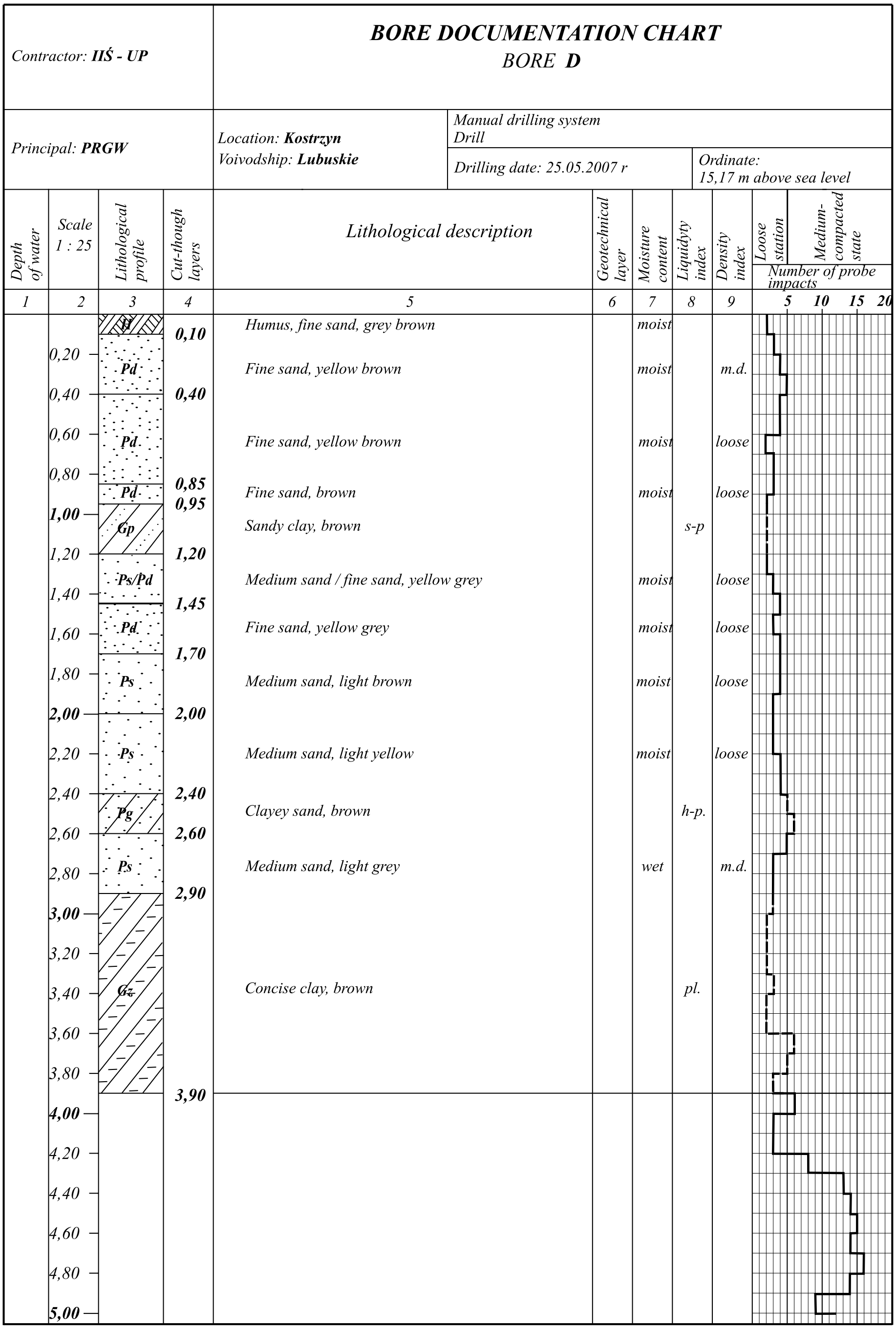


**BORE DOCUMENTATION CHART**
BORE **C**

Contractor: **IIŚ - UP**
Principal: **PRGW**
Location: **Kostrzyn**
Voivodship: **Lubuskie**
Manual drilling system
Drill
Drilling date: 25.05.2007 r
Ordinate: 15,24 m above sea level

| Depth of water | Scale 1 : 25 | Lithological profile | Cut-though layers | Lithological description | Geotechnical layer | Moisture content | Liquidyty index | Density index |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | | H | 0,10 | Humus, fine sand, grey brown | | moist | | |
| | | Pd | 0,50 | Fine sand, grey | | l.moist | | m.d. |
| | | Pd | 1,45 | Fine sand, yellow brown | | l.moist | | loose |
| | | Ps | 1,80 | Medium sand, brown | | l.moist | | m.d. |
| | | Pg | 2,00 | Clayey sand, brown | | | h-p. | |
| | | Gp | 2,60 | Sand clay, brown | | | s-p. | |
| | | Ps | 3,90 | Medium sand, brown | | l.moist | | m.d. |

Fig. 9. Documentation chart of bore C



## BORE DOCUMENTATION CHART

BORE **D**

Contractor: **IIŚ - UP**

Principal: **PRGW**

Location: **Kostrzyn**
Voivodship: **Lubuskie**

Manual drilling system
Drill

Drilling date: 25.05.2007 r

Ordinate:
15,17 m above sea level

| Depth of water<br>1 | Lithological profile<br>3 | Cut-though layers<br>4 | Lithological description<br>5 | Geotechnical layer<br>6 | Moisture content<br>7 | Liquidyty index<br>8 | Density index<br>9 |
|---|---|---|---|---|---|---|---|
| | H | 0,10 | Humus, fine sand, grey brown | | moist | | |
| | Pd | 0,40 | Fine sand, yellow brown | | moist | | m.d. |
| | Pd | 0,85 | Fine sand, yellow brown | | moist | | loose |
| | Pd | 0,95 | Fine sand, brown | | moist | | loose |
| | Gp | 1,20 | Sandy clay, brown | | | s-p | |
| | Ps/Pd | 1,45 | Medium sand / fine sand, yellow grey | | moist | | loose |
| | Pd | 1,70 | Fine sand, yellow grey | | moist | | loose |
| | Ps | 2,00 | Medium sand, light brown | | moist | | loose |
| | Ps | 2,40 | Medium sand, light yellow | | moist | | loose |
| | Pg | 2,60 | Clayey sand, brown | | | h-p. | |
| | Ps | 2,90 | Medium sand, light grey | | wet | | m.d. |
| | Gz | 3,90 | Concise clay, brown | | | pl. | |

Fig. 10. Documentation chart of bore D

### 4.3.1.3. Samples collection from the injected zones of the flood bank in Kostrzyn

Samples for tests were collected from the open pits made by Przedsiębiorstwo Robót Geologiczno-Wiertniczych. The location of pits, in the body of the bank which from samples were collected, is presented in Figure 4. The results of the determination of the Californian Bearing Ratio (CBRd) of soils embedded in the embankment and of the material constituting the constructed cut-off wall, at natural moisture content, are presented in Table 1. Measurement points are shown in Figure 11. The granulation of the tested soils is presented in Figure 12, and the compaction curve of clayey sand in Figure 13.

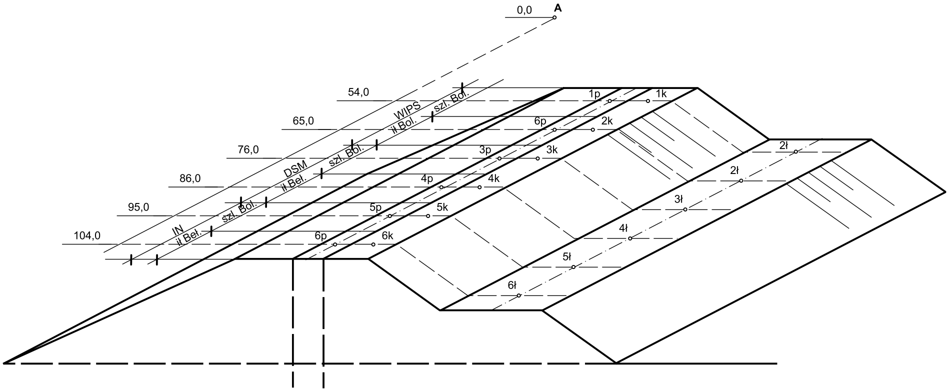


Fig. 11. Location of Californian Bearing Ratio (CBRd) determination places

Table 1

CBRd determination results

| CBRd value determined on the crown of the bank | | | | | | |
|---|---|---|---|---|---|---|
| No. Of sample | 1k | 2k | 3k | 4k | 5k | 6k |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Bulk density ρ [g/cm$^3$] | 1.798 | 1.399 | 1.819 | 1.724 | 1.799 | 1.893 |
| Moisture [%] | 8.67 | 8.15 | 7.59 | 8.22 | 8.76 | 11.2 |
| Dry density $\rho_d$ [g/cm$^3$] | 1.655 | 1.294 | 1.691 | 1.593 | 1.654 | 1.702 |
| CBRd [%] | 12 | 9 | 18 | 15 | 16 | 19 |
| Settlement s [mm] | 23011 | 30.02 | 13.81 | 19.07 | 17.36 | 12.38 |
| CBRd value determined on the crown in the axis of the constructed cut-off wall | | | | | | |
| No. Of sample | 1p | 2p | 3p | 4p | 5p | 6p |
| Bulk density ρ [g/cm$^3$] | 1.588 | 1.761 | 1.799 | 1.556 | 1.786 | 1.949 |
| Moisture [%] | 54.03 | 81.14 | 51.04 | 58.16 | 48.32 | 94.15 |
| Dry density $\rho_d$ [g/cm$^3$] | 1.031 | 0.972 | 1.191 | 0.984 | 1.204 | 1.004 |
| CBRd [%] | 0 | 0 | 0 | 0 | 0 | 0 |

Table 1 cont.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Settlement s [mm] | – | – | – | – | – | – |
| CBRd value determined on the bench of the bank | | | | | | |
| No. Of sample | 1ł | 2ł | 3ł | 4ł | 5ł | 6ł |
| Bulk density $\rho$ [g/cm$^3$] | 1.975 | 1.999 | 2.092 | 1.975 | 2.017 | 2.049 |
| Moisture [%] | 7.65 | 7.73 | 8.4 | 11.21 | 8.15 | 8.9 |
| Dry density $\rho_d$ [g/cm$^3$] | 1.835 | 1.856 | 1.930 | 1.776 | 1.865 | 1.882 |
| CBRd [%] | 37 | 40 | 52 | 29 | 49 | 38 |
| Settlement s [mm] | 4.28 | 3.74 | 2.38 | 6.52 | 2.53 | 4.09 |

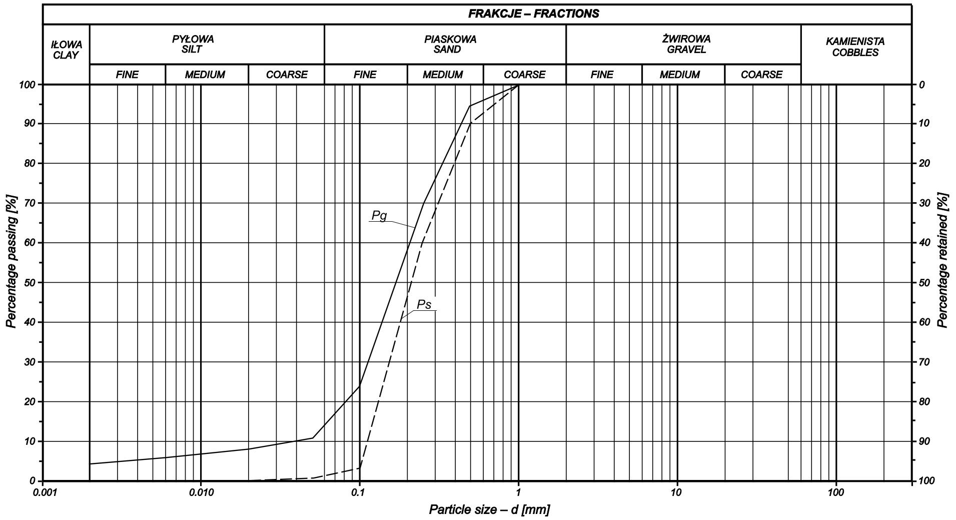


Fig. 12. Grain size distribution curve of the soils collected from the crown (Pg) and the bench of the bank (Ps)

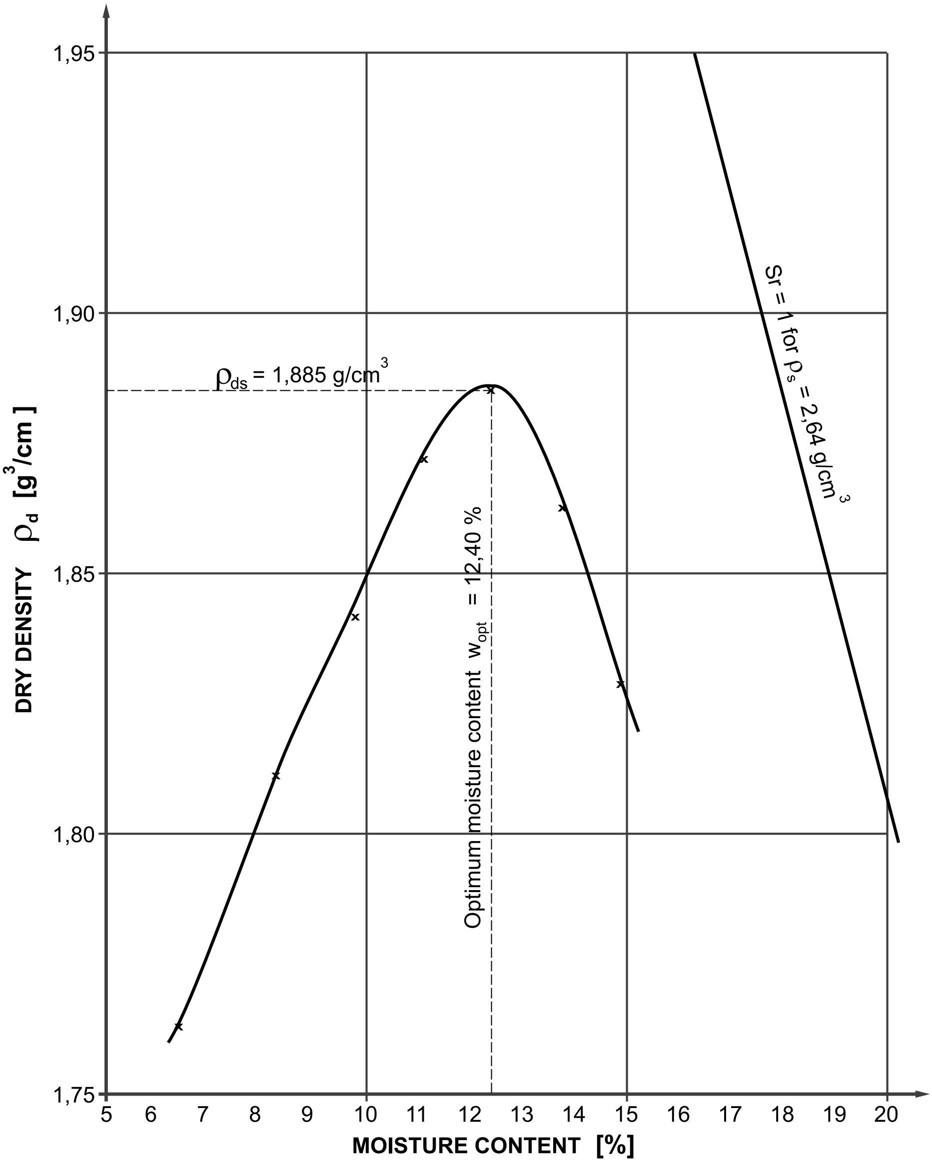


Fig. 13. Compactibility of clayey sand Pg

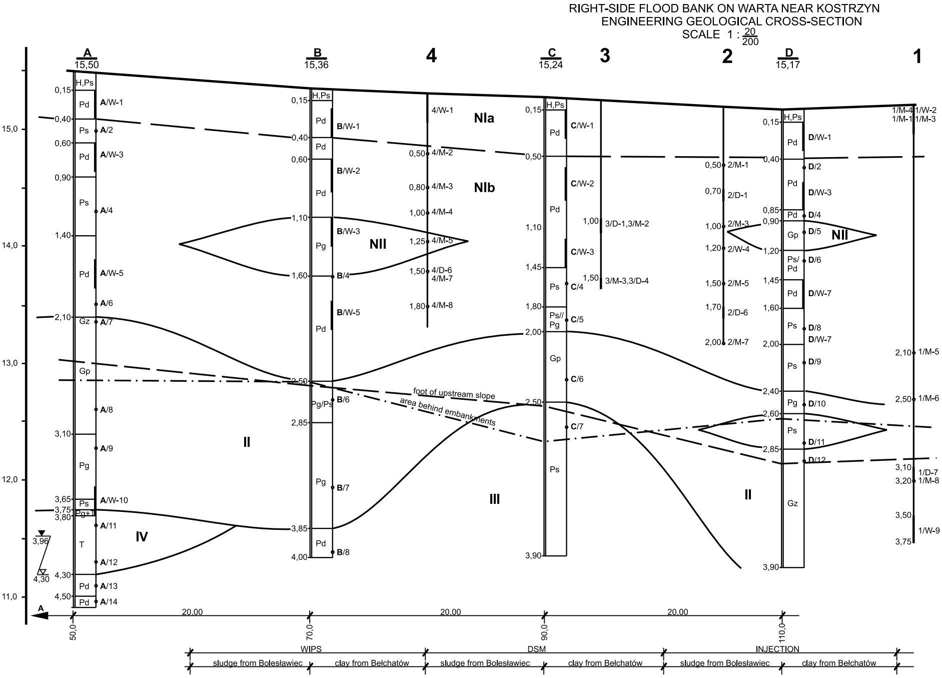


Fig. 14. Engineering geological cross-section of the flood bank on Warta near Kostrzyn, on which the experimental section of hydraulic cut-off wall was constructed with use of vibration-injection, DSM and low-pressure injection technologies

## 4.4. Analysis of the injections

Experimental hydraulic cut-off walls were constructed with use of three technologies: vibration injection, DSM and low pressure injection. Two types of injects were used. The installation used for the preparation of injection grouts is presented in Photo15. Sections constructed with use of each specific technology were 10 m long for each type of inject, which resulted in six different variations of hydraulic cut-off walls. For cut-off walls constructed with use of low-pressure injection, the top layer, 2 m thick, was constructed with use of DSM technology, in order to prevent the outflow of the inject on the crown of the bank during pressure injection. Fragment of the constructed cut-off wall is presented in Photo 16. Then, the constructed cut-off walls hardened for approximately 50 days. Samples for tests were collected from the open pits made by Przedsiębiorstwo Robót Geologiczno-Wiertniczych.

Photo 17 presents open pit No. 1 of the cut-off wall constructed with use of low-pressure injection technology and the clay from Bełchatów. The upper part of the cut-off wall was constructed with use of DSM technology. Exposure No. 2 was excavated on the section of injection made with use of DSM technology, with inject based on sludge from Bolesławiec (Photo 18). A clear border between the cut-off wall and the soil of the bank is visible. The upper part of the body of the cut-off wall is relatively homogenous. In this section the cut-off wall is free from interbeddings of continuous nature. Below, 70 cm underneath the crown of the bank, the cut-off wall becomes more heterogeneous – interbeddings mixed to various extents and inserts of sand are visible (Photo 19).

Photo 15. Equipment for the injects preparation, ready for work on the flood bank on Warta in Kostrzyn

Photo 16. Fragment of the constructed hydraulic cut-off wall

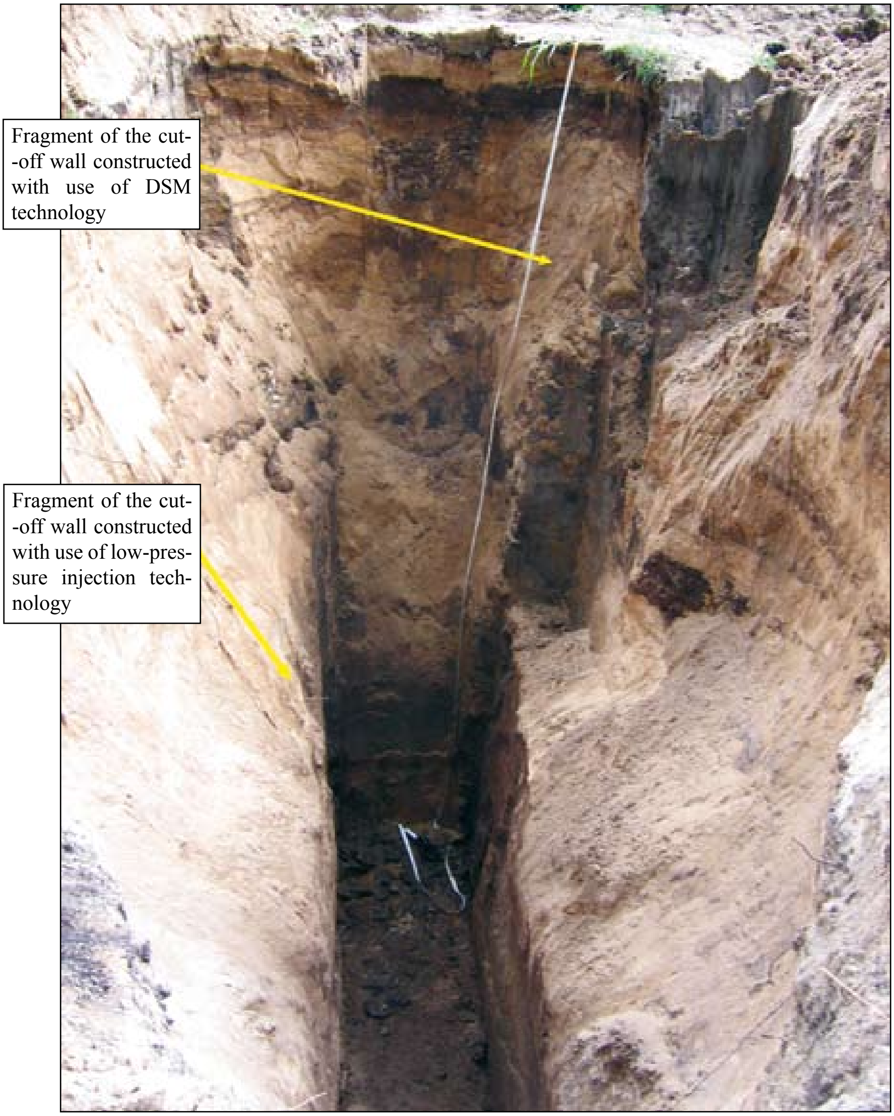


Photo 17. Open pit No. 1

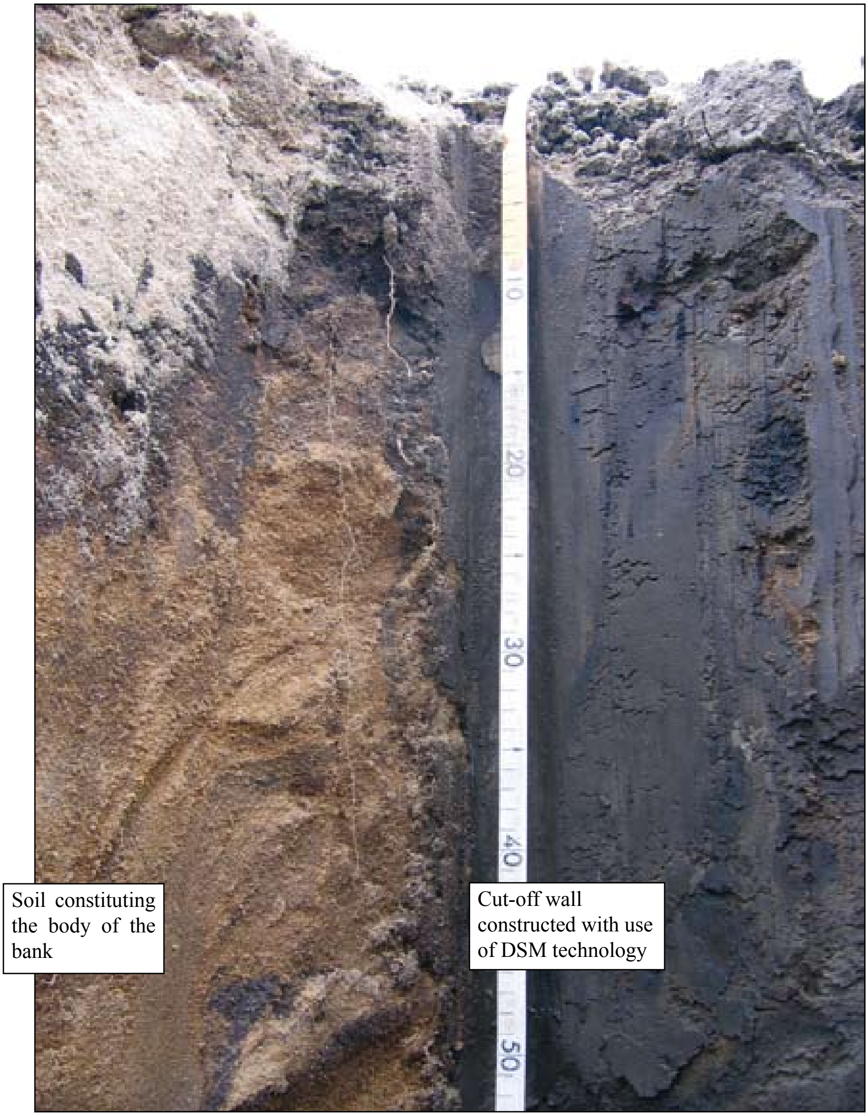


Photo 18. Upper part of open pit No. 2

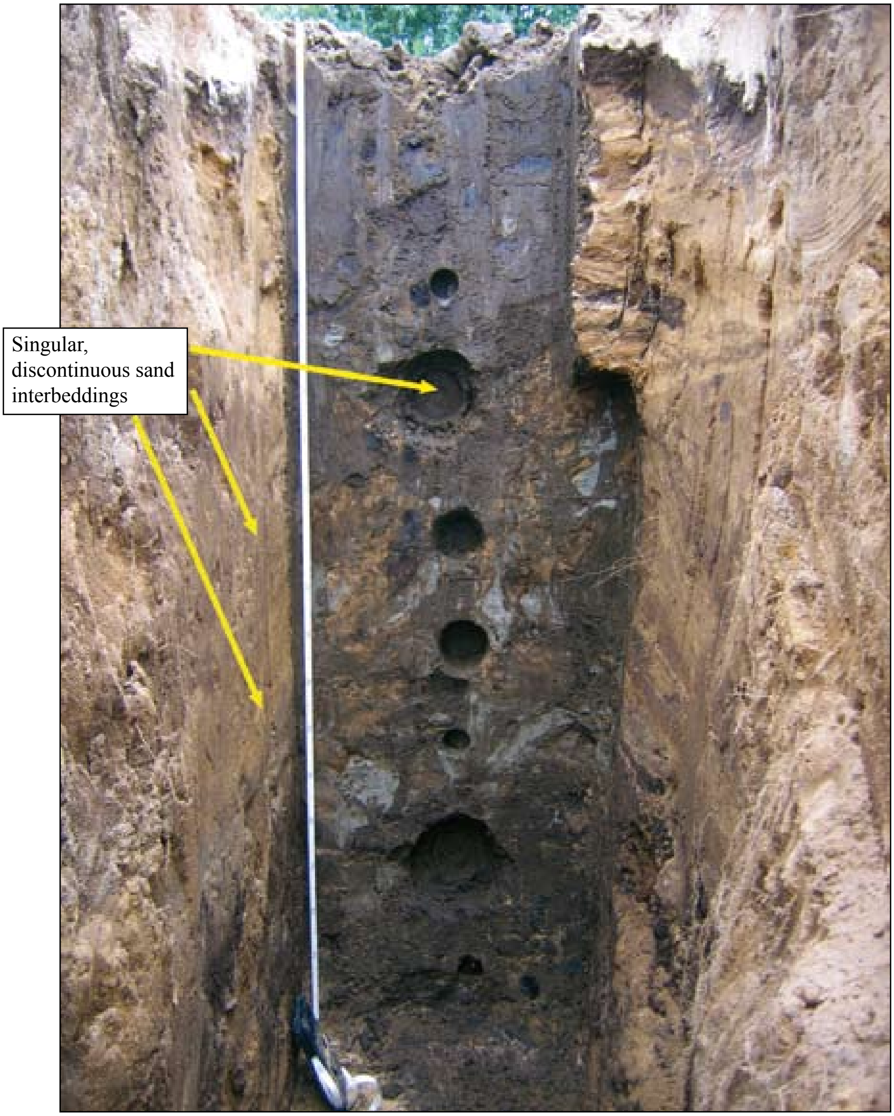


Photo 19. Lower part of open pit No. 2

The membrane cut-off wall constructed with use of the vibration injection technology is approximately 20 cm wide. Photo 20 shows the exposed upper part of the cut-off wall, prepared for the determination of Californian Bearing Ratio (CBRd).

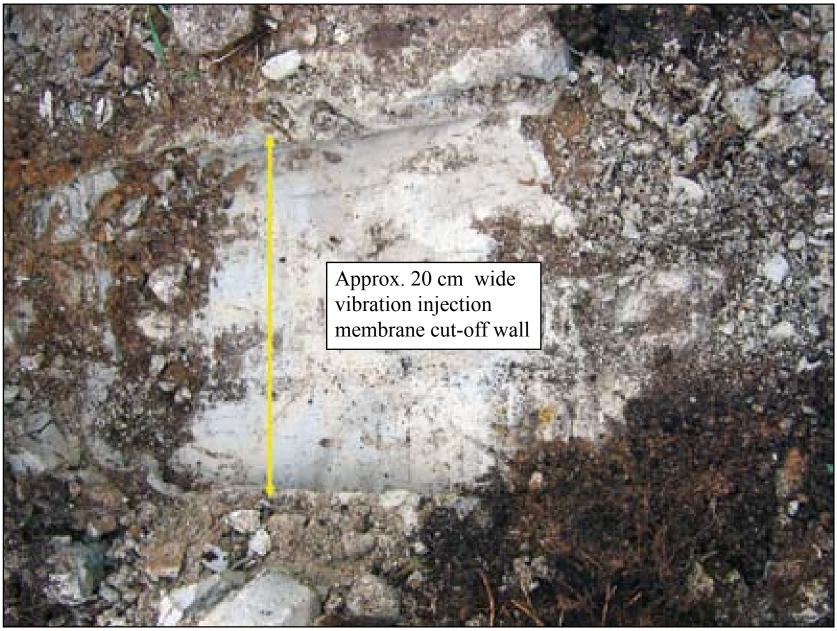


Photo 20. Crown of the embankment: exposed membrane cut-off wall constructed with use of vibration injection technology with the inject made from clay from Bełchatów

The cut-off wall constructed with use of vibration injection technology creates a compact, homogenous wall of the inject (Photo 21). Vibration injection technology enables the construction of very homogenous membrane cut-off wall, since during the application of this method, the soil is moved to the side, not mixed with inject, as in DSM technology. The form of the cut-off wall is the same, regardless of the type and state of soils, where it is applied, and thus it allows for the construction of a wall of isotropic characteristics (Photo 23). It effectively cuts through both non-cohesive and cohesive soils. A clear boundary is created between the cut-off wall and the soils constituting the bank – the soil of the embankment does not create any inserts or interbeddings (Photo 22).

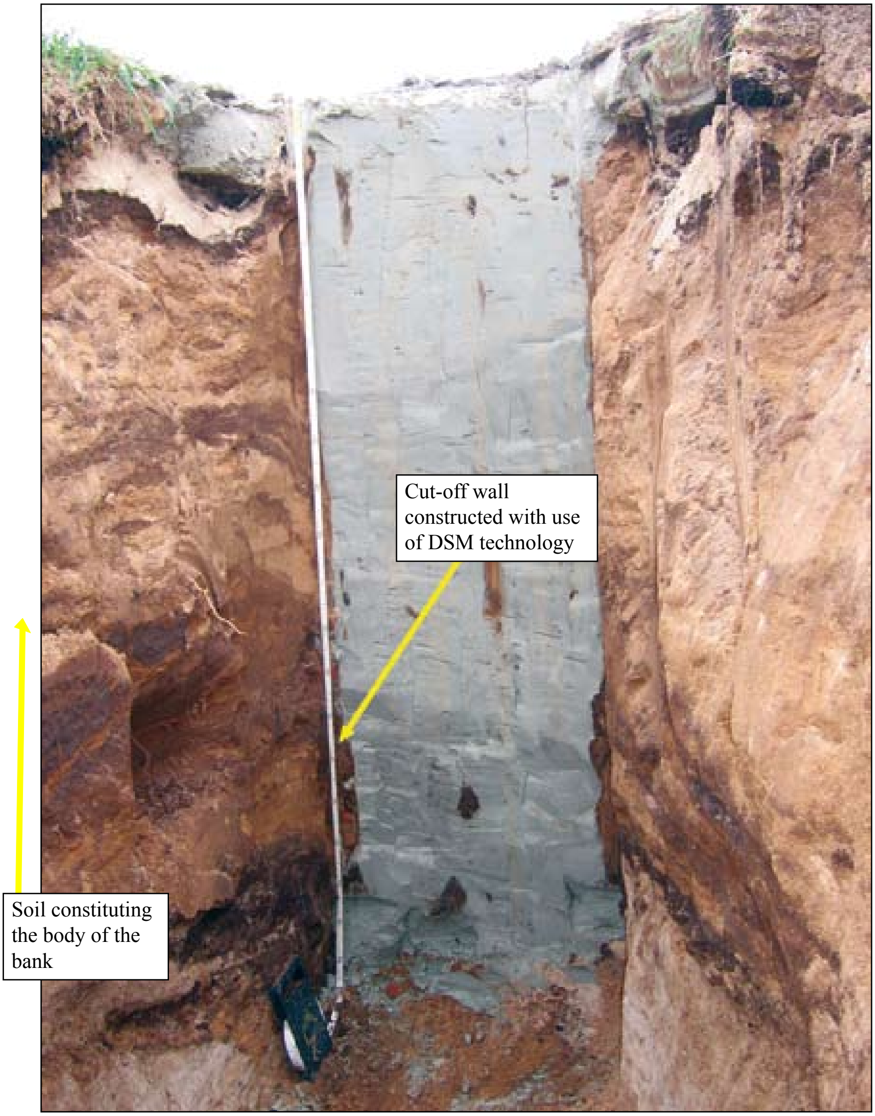


Photo 21. Open pit No. 4 – cross-section through the cut-off wall constructed with use of DSM technology grout based on clay Bełchatów

Photo 22. Boundary between the cut-off wall and the soils forming the embankment

Photo 23. Open pit No. 4 – exposed cross-section through the bank on the contact point with the cut-off wall constructed with use of vibration injection technology from grout based on clay Bełchatów

### 4.4.1. Analysis of the constructed cut-off walls characteristics

The macroscopic evaluation carried in open pits proved, that the inject in the cut-off walls constructed with use of DSM and low pressure injection technologies had not hardened to the expected extent. In the macroscopic scale, the construction material of cut-off walls constructed with use of DSM technology presented the characteristics of plastic soil, and with low pressure injection technology – of soft-plastic soil. On the other hand, injects introduced into the cut-off wall with use of vibration injection technology showed characteristics typical for soils in semi-compacted state. This state is different from that from previous experiments. It is probably a result of the mixing of injects with the soils embedded in the flood bank. Most of these soils contained significant amounts of organic particles. The content of organic particles $I_{om}$ ranged from 2.0 to 18.5% (in cases of soils containing peat inserts), which might explain the fact that the injects had not fully hardened. Such a high content of organic particles can be considered as unusual even for soils obtained from the inter-embankment zone.

The aim of the tests on samples collected from different types of cut-off walls was to determine the changes in the characteristics related to permeability and strength in the zones subjected to injections. The comparison of the permeability coefficients of the non-cohesive soils constituting the body of the bank with the permeability coefficients of the cut-off walls shows a significant decrease in their value. Sands constituting the body of the bank are characterised by permeability coefficients ranging from 2.90E-03 to 3.75E-03 cm/s, whereas the permeability coefficients for the cut-off walls fall into the range from 6.84E-06 to 6.00E-07 cm/s. As a result, the parameter decreased by at least two orders of magnitude. Thus, a very significant decrease in the permeability of the soils inside the bank was achieved, which could be compared to the situation, where a core from cohesive soils, i.e. clays or sandy clays, would have been constructed inside the bank.

Another important parameter essential for the effectiveness of the constructed cut-off wall are its strength related characteristics. The angles of internal friction for soils taken from the embankment fell into the range $38.94 \leq \Phi \leq 43.56°$ and cohesion $0.0 \leq c \leq 13.05$ kPa, whereas the results obtained for the cut-off walls ranged from $31.92 \leq \Phi \leq 42.41°$ and cohesion $10.35 \leq c \leq 26.18$ kPa (Garlikowski et al 2010). The comparison of the strength related parameters of the soils of the embankment and of the cut-off walls, collected in the same area, leads to the conclusion that the value of the angle of internal friction have decreased by approx. 15% in the top zone, but have remained practically unchanged in the lower areas, while the value of cohesion significantly increased, in most cases by over 100%.

The bearing capacity of the soils in the bench and the crown of the flood bank, as well as in the upper zone of the constructed cut-off walls, was determined with use of CBRd plunge. Photo 24 shows the mark of the CBRd plunge on the surface of the cut-off wall constructed with use of vibration injection technology from inject based on clay Bełchatów. The conducted tests have shown that the bearing capacity of the subsoil from medium sand in the crown of the bench, at natural moisture content, falls into the CBRd range from 29 to 52%. The bearing capacity of the subsoil from clayey sands in the crown of the embankment falls into the CBRd range from 9 to 19%, whereas the bearing capacity on the surface of cut-off walls constructed with use of all technologies has fallen to zero.

CBRd determined on the sample of clayey sand, prepared according to the procedure specified in BN-70/893105 and PN-S-06102, i.e. on a compacted sample, soaked in water for 4 days, at $I_s = 0.985$ ($\gamma/\gamma$ d), reached only 9%. It should be emphasised here, that the state of compaction of clayey sands in the crown corresponds to the coefficient of compaction $I_s$ from 0.69 to 0.90, which means that the CBRd of these soils after soaking during a flood freshet can reach the levels of CBRd 1 – 3%. In case of the sands inside the bench, tested according to the above specified procedure at the state of compaction corresponding to density index $I_D = 1{,}0$, CBRd reached the value of 11%, while the state of compaction of these soils inside the embankment corresponds to $I_D$ from 0.709 to 1.040. The soaking of the soils, especially those of the density corresponding to density index $I_D < 1.0$ will cause the CBRd values to fall below 11%. The determined CBRd values of the soils on the crown and bench of the flood bank have shown that during periods without freshets these subsoils can be accessible even for heavy vehicles. Unfortunately, after having soaked during a spate of flood waters their bearing capacity will evidently decrease and they will be not accessible even for light vehicles.

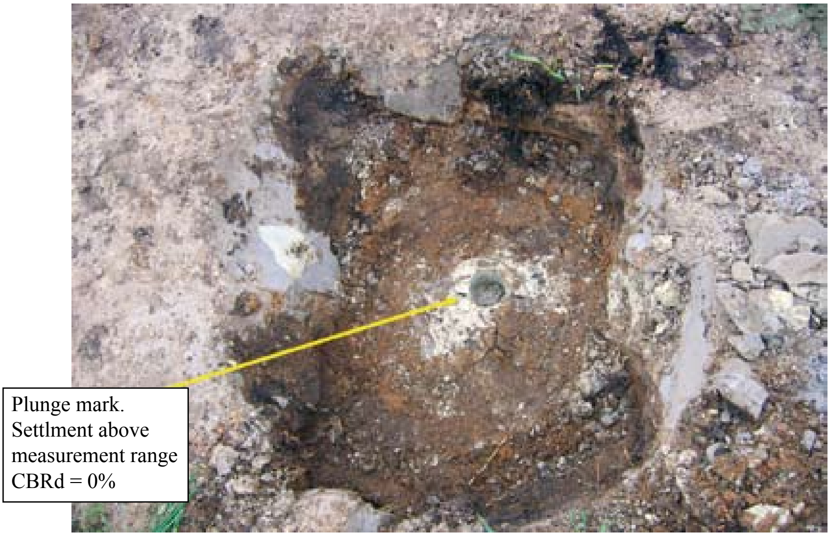


Photo 24. Mark of the CBRd plunge on the surface of the cut-off wall constructed with use of vibration injection technology from inject based on clay Bełchatów

# 5. DSM CUT-OFF WALL CONSTRUCTED ON THE FLOOD BANK ON VISTULA IN SAMOCICE NEAR TARNOW

After the research in Kostrzyn had been completed, an opportunity emerged to test the hydraulic cut-off wall constructed in 2007, by the same company – Przedsiębiorstwo Robót Geologiczno-Wiertniczych. As exposures of this type are very rarely made and made available for research, we decided to use this possibility as an opportunity to extend the research conducted on real objects in a realistic scale. This type of research allows us to confirm or deny the usability of such cut-off walls for the sealing of flood banks. The cut-off wall was constructed in the right-side flood bank on Vistula, in the section parallel to the town Samocice. It was exposed by an excavation in the crown of the bank. The upper part of the cut-off wall was constructed with use of DSM technology, with inject based on clay Bełchatów. In the open-pit, samples were collected from the exposed walls of the soil embedded in the cut-off wall,to determinate of physical and mechanical parameters.

Clayey alluvial clays of dusty clays granulation, which form the body of the embankment, are characterised by a low degree of compaction. In the exposed part of the bank the soil inside the body, down to the depth of 1.40 m, has the consistency of "yeast dough". In the transverse section macro pores have emerged, 0.5 to 3.0 mm width, in form of flattened, horizontal voids. Part of these macro pores, even as far as 0.6 m from the edge of the cut-off wall, had been filled with grout. The grout, injected and then mixed in the zone of the cut-off wall, was pressed into larger voids outside the zone of the cut-off wall, in the direction of the downstream slope. Filled-in voids of the diameter up to several centimetres cut through by the excavation are shown on the exposed wall of the transverse section of the bank (Photos 25–27). Sample collected in such places are different then others, due to much higher moisture content and significantly lower dry density $\rho_d$.

Photo 25. Exposed wall of the soil in the body of the bank. Places, where inject filled the macro pores of soil outside of the zone of the cut-off wall are marked

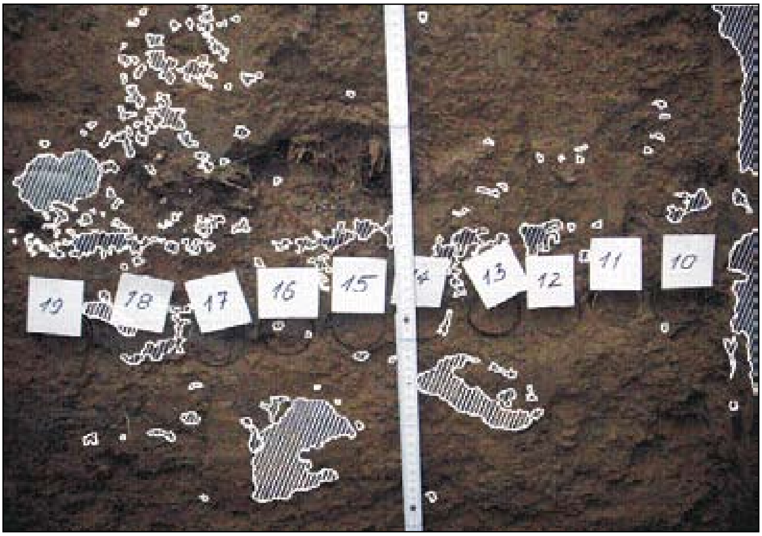


Photo 26. Level 0.80 m below the crown of the bank – marked locations where macro pores were filled with inject

Photo 27. Level 1.25 m below the crown of the bank – marked locations where macro pores were filled with inject

The granulation of the soils in the body of the bank, determined at 3 levels, shows that they are highly homogenous. With the content of clay fraction at 14 ÷ 15% they differ by several per cent in the content of dust and sand fractions. Figure 15 shows the granulation of alluvial clay from the valley of Odra, of loam granulation, as compared with the granulation of these soils. These clays are characteristic for the middle section of the river Odra, and their properties had been well evaluated during the realisation of the research program CPBR 10.8 [Orzeszyna 1990]. In order to complement the analysis of the results obtained from the tests of the cut-off walls, the results obtained for loam $4\text{-}G_z$ will be referred to and compared in the later sections of this work.

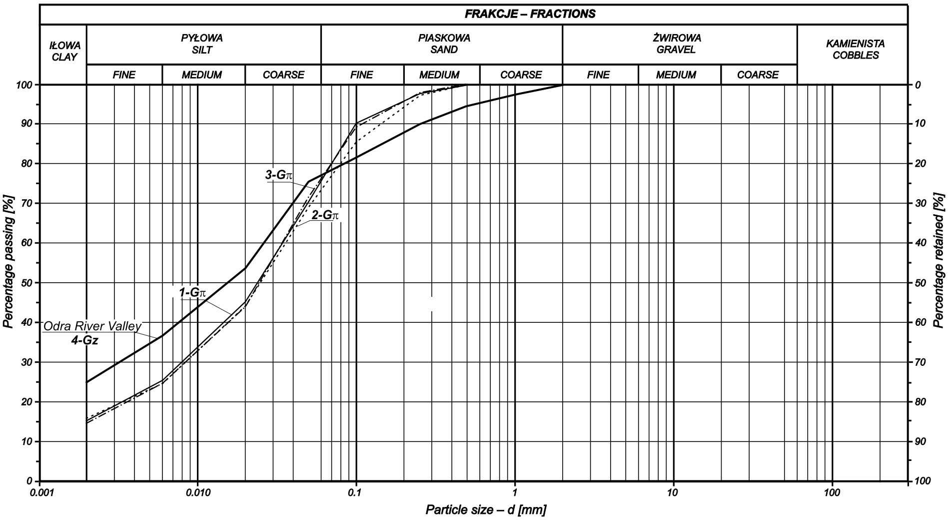


Fig. 15. Granulation of fluvial alluvial clays, whose characteristics will be subject to comparison

Samples were collected from the wall of the exposed body of the bank in Samocice, in three horizontal rows, in order to determine possible changes in density caused by the construction of the cut-off wall. Low variability of the density shows, that there is no such tendency. This is probably a result of the high cohesion of the soils constituting the bank.

The moisture content of samples of silty clay ranges from $19.43 < w < 25.71\%$, whereas the moisture content of samples of silty clay containing some amount of inject fall into the range $24.45 < w < 50.10\%$. Such significant change in moisture content shows the areas, where inject filled existing macro pores. It also proves that the moisture content of injected soils is significantly higher than that of the soils constituting the body of the bank, even several months after the construction of the cut-off wall. The respective dry densities $\rho_d$, are characterised by the following variability: silty clays $1.405 < \rho_d <$

1.593 g/cm$^3$, and silty clays containing inject $1.216 < \rho_d < 1.481$ g/cm$^3$. Natural moisture of clays is higher or similar to the optimum moisture content $w_{opt.} = 19.30\%$, hence their range falls on the so-called "wet side" of the compactibility curve. The permeability coefficient $k_{10} = 2.5 \times 10^{-5}$ cm/s was determined for dusty clay embedded in the bank at $\rho_d = 1.450$ g/cm$^3$, $w = 21.53\%$.

Changes in moisture content that are important from the point of view of shrinkage, can occur down to the depth of approx. 1.5 m below the crown of the embankment. Due to that, the shrinkage values of soils embedded in the bank and of the soils of the cut-off wall in this zone of the embankment were determined. The course of the shrinkage isoline Gz presented in Figure 16 shows, that in the case of moisture contents higher than $w_{opt.}$ ("wet side" of the compactibility curve) the highest values of shrinkage should be expected. Shrinkage of Gπ (dusty clay) as compared to Gz (loam) is significantly lower, mainly due to the content of clay fraction, and its values fall into the range $1.8 < S_k < 5.4\%$, where the largest shrinkage was determined in sample No. 22 of very low density $\rho_d = 1.369$ g/cm$^3$ and relatively high moisture content $w = 24.06\%$.

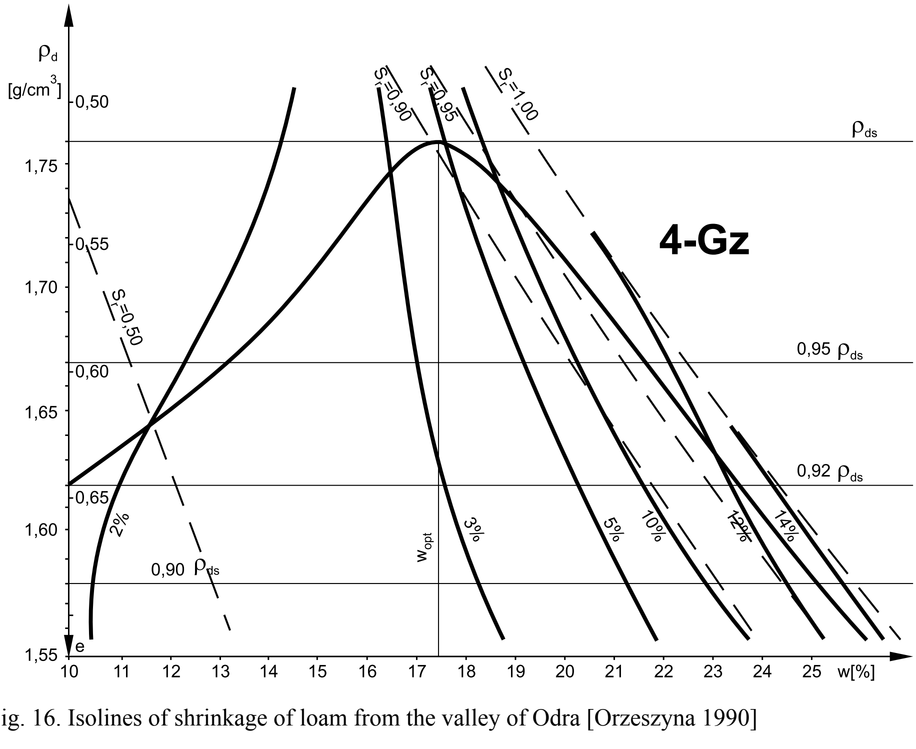


Fig. 16. Isolines of shrinkage of loam from the valley of Odra [Orzeszyna 1990]

The way in which the soils behave in contact with water, which happens during the spates of freshet waters by the flood bank, reflects the durability of structural bonds created after the embedding of the soils. It can be described by the time, which after the sample loses its original shape. Soaking collapsibility tests carried out by numerous researchers quoted in [Grabowska-Olszewska 1980, Keil 1954, Sowers & Sowers 1970, Śliwa 1960] prove that:

- soaking resistance increases with the increase of clay fraction content and with compaction,
- The resistance depends on the presence of clayey minerals and of the initial moisture content of the soaked soil.

Soaking resistance of soils to can be determined by the comparison of the collapse time of 50% of the samples mass. Figure 17 presents the isochrones of soaking for clay Gz from the valley of Odra [Orzeszyna 1990]. First of all, one should emphasise a very significant shortening of the soaking time of the samples after they had been dried to air dry state – for $w_z = w_{sps}$. A very short collapse time of 50% of the mass is also characteristic for those samples, whose moisture content falls on the "dry side" of the compactibility curve. As for the silty clay taken from the body of the bank, 50% of the sample mass of the density $\rho_d = 1.390$ g/cm$^3$ and $w_r = 27.70\%$ collapsed after 13 min., and 50% of the sample mass of the same density after having dried to $w_{sps}$ collapsed already after 5.2 min. These times of collapse are shorter than those of clay Gz from the valley of Odra. The Times of collapse of Gπ were significantly longer, up to 2226 min., when the initial moisture content of soaking was close to the full saturation moisture content $w_{sr}$. A similar tendency is visible in the case of Gz shown in Figure 17. Nearly full saturation of the soil, achieved during the process of compaction prior to the beginning of soaking, guarantees high resistance to soaking. Unfortunately, in natural conditions, such state is characteristic for soils in the deeper parts of ground structures, below the 1.5 m zone prone to drying. It means, as short soaking times obtained for Gπ of the bank show (13 min. for sample of natural moisture content and 5.2 min. for sample dried to air dry state), that the resistance to soaking of soils in the external zones of the bank is low.

Apart from the decrease in the angle of internal friction by approx. 10°, also a radical fall in cohesion was observed, for low density samples, practically down to c = 0 kPa. Basing on this tendency of changes in cohesion, confirmed in the research on other cohesive soils [Janiak, Kowalski, Orzeszyna 1992], the stability of the embankment was analyzed for the assumption, that in the zone located above the depression curve the strength parameters correspond to the determined parameters, and below the curve of depression the value of cohesion was reduced to zero.

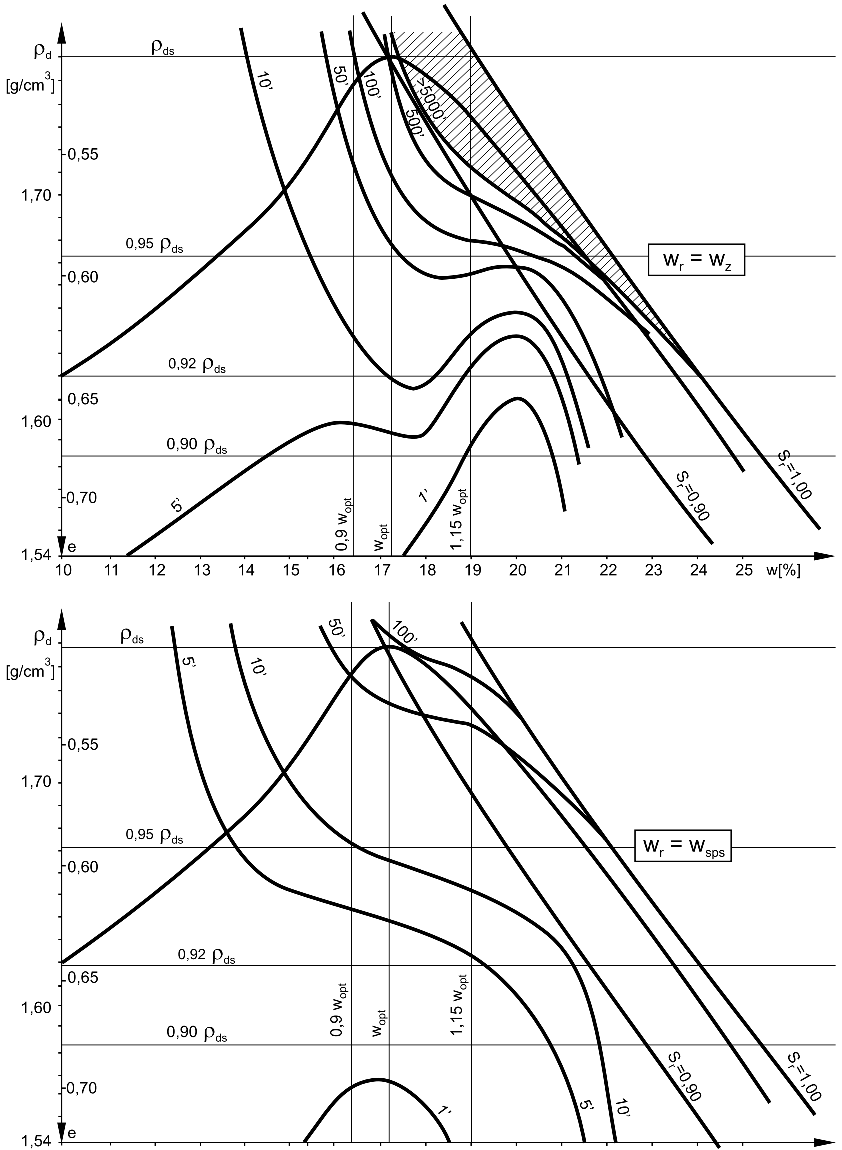


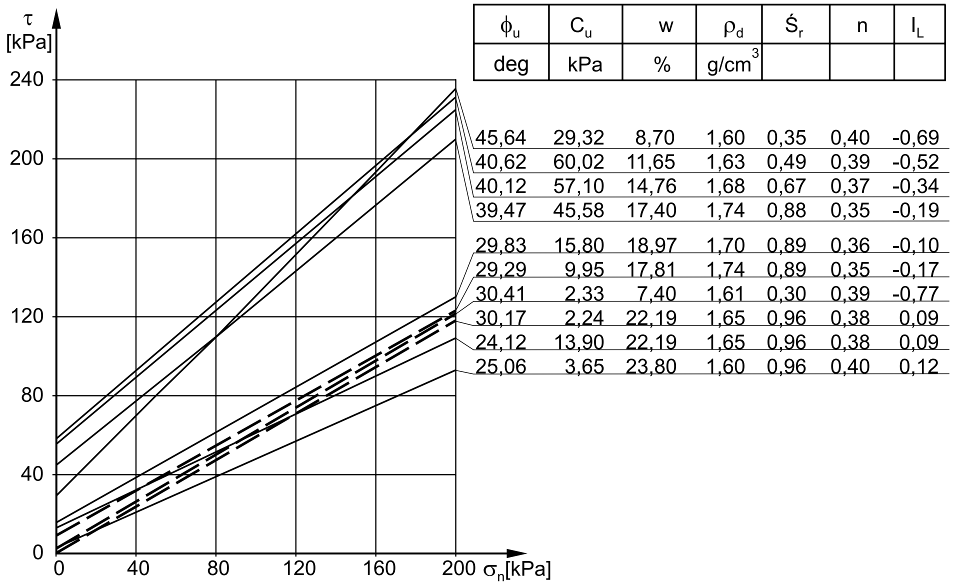
Fig. 17. Isochrones of soaking for loam 4-Gz from the valley of Odra [Orzeszyna 1990]

The estimated values of bearing capacity of soil σ, determined with use of hand penetrometer PW-1, in case of silty clay Gπ embedded in the bank fall into the range from 29 kPa (sample No. 22 – at density $\rho_d$ = 1.369 g/cm$^3$ and w = 24.06%) to 147 kPa (sample No. 2 – at density $\rho_d$ = 1.551 g/cm$^3$ and w = 16,69%). Similarly the values of shearing resistance τ determined with use of rotating probe SO-1 for silty clay Gπ embedded in the bank range from 10 kPa (sample No. 22) to 28 kPa.

In the case of the soil of the cut-off wall, the estimated values of the soil's bearing capacity fall into the range from 79 kPa (sample No. 41 – at density $\rho_d$ = 1.060 g/cm$^3$ and w = 57.57%) to 491 kPa (sample No. 36 – at density $\rho_d$ = 1.267 g/cm$^3$ and w = 39.56%), values of shearing resistance τ range from 14 kPa (sample No. 41) to 59 kPa (sample No. 62 at density $\rho_d$ = 1.047 g/cm$^3$ and w = 54.12%).

The bearing capacity σ and shearing resistance τ values determined in the soil of the cut-off wall are 3 to 4 times higher than those of Gπ embedded in the body of the flood bank.

The strength parameters, determined for silty clay in direct shear apparatus, are as follows: at density $\rho_d$ = 1.370 g/cm$^3$ and w = 25.24%, internal friction angle Φ = 23.6°, cohesion c = 14.0 kPa. As a result of long-term soaking of cohesive soils, their strength parameters significantly decrease. Figure 18 shows the change in the characteristics of cohesive clay as a result of soaking. The internal friction angle determined for the soil of the cut-off wall, in direct shear apparatus equals Φ = 42.77° and cohesion c = 31.69 kPa.



| $\phi_u$ | $C_u$ | w | $\rho_d$ | $Ś_r$ | n | $I_L$ |
|---|---|---|---|---|---|---|
| deg | kPa | % | g/cm$^3$ | | | |
| 45,64 | 29,32 | 8,70 | 1,60 | 0,35 | 0,40 | -0,69 |
| 40,62 | 60,02 | 11,65 | 1,63 | 0,49 | 0,39 | -0,52 |
| 40,12 | 57,10 | 14,76 | 1,68 | 0,67 | 0,37 | -0,34 |
| 39,47 | 45,58 | 17,40 | 1,74 | 0,88 | 0,35 | -0,19 |
| 29,83 | 15,80 | 18,97 | 1,70 | 0,89 | 0,36 | -0,10 |
| 29,29 | 9,95 | 17,81 | 1,74 | 0,89 | 0,35 | -0,17 |
| 30,41 | 2,33 | 7,40 | 1,61 | 0,30 | 0,39 | -0,77 |
| 30,17 | 2,24 | 22,19 | 1,65 | 0,96 | 0,38 | 0,09 |
| 24,12 | 13,90 | 22,19 | 1,65 | 0,96 | 0,38 | 0,09 |
| 25,06 | 3,65 | 23,80 | 1,60 | 0,96 | 0,40 | 0,12 |

Fig. 18. Graphs of shearing resistance of loam 4-Gz from the valley of Odra. The dashed line shows the Coulomb's failure lines for samples after 14-day soaking [Janiak et al. 1992]

Figure 19 presents circular slip curves of the lowest stability factors, calculated with use of the Swedish method $F_F = 1.172$ and the Bishop method $F_B = 1.186$. In situations, when there is a zone of lower strength parameters inside the body of the flood bank, the stability of the bank may be threatened.

Figure 20 shows circular slip curves of the lowest stability factors ($F_F = 2.552$ and $F_B = 2.638$) determined in the cross section with the hydraulic cut-off wall. In the area outside the cut-off wall, on the downstream slope of the embankment, due to the elimination of the possibility of soaking of the soil, the safety factors of the area increased respectively to $F_F = 2.622$ and $F_B = 2.763$. Thus the introduction of the hydraulic cut-off wall increased the values of the safety factors by over 100%.

On the cross-sections of samples 44, 46 and 61 the changes in colour indicate various degrees of mixing of the soil with inject. The areas of a darker shade contain the largest amount of inject. This is also manifested in the granulation curves of 5 samples taken from different locations in the cross-section of the sample WP-44.

Mixing of native soil with inject, particularly in the case of cohesive soils, results also in remaining, unmixed nodules of native soil, which are visible in the cross-section of the constructed cut-off wall (Photo 28).

The edge of the cut-off wall constructed with use of DSM technology does not create a flat surface. The mixing of the soil with inject has formed a surface tightly connected with the embedded soil, irregular and filling all voids.

Samples were taken from the edge of the cut-off wall in two vertical rows. Various degrees of mixing of Gπ with inject has led to a quite significant variability both of the moisture content and of the density of the soils of the cut-off wall. The moisture content values of the soil in the cut-off wall fall into the range $39.56 < w < 57.57\%$, and the dry density $\rho_d$ values vary in the range $1.047 < \rho_d < 1.267$ g/cm$^3$.

The coefficient of permeability determined for the soil in the cut-off wall (sample No. 62) at $\rho_d = 1.047$ g/cm$^3$ and $w = 54.12\%$, $k_{10} = 7.83 \times 10^{-7}$ cm/s.

The determined values of shrinkage of the soils in the cut-off wall fall within the range $0.0 < S_k < 6.6$ %. Part of the samples presented a slight shrinkage or zero shrinkage. These are samples that contained nearly only soil, with only slight amounts of inject.

The time of soaking collapsibility of the soil in the cut-off wall was determined on samples of the moisture content $w_r$ as in the moment of figure and after they had dried to air dry state $w_{sps}$. The times of soaking collapsibility $t_{50\%}$ of all samples, and, what should be noted, of air dry samples, exceed 7200 min. This means that Gπ mixed with inject is not subject to collapse, and the constructed cut-off wall is resistant to soaking.

Another significant problem of cohesive soils embedded in the surface-near areas of earth structures is their susceptibility to temperatures below zero, manifesting in form of frost heave. According to the criterion of frost heave specified in PN-S-02205 dusty clays forming the embankment are very susceptible to frost heave. Collected samples No. WP 45 and WP 47 (samples taken from the cut-off wall) were tested for frost heave in a cooling chamber. Figure 21 shows the course of frost heave of the samples over time. Maximum increases in height of the samples reached 6 and 7 mm. The obtained results of the frost heave tests qualify the mixture constituting the cut-off wall as frost resistant – insusceptible to frost heave.

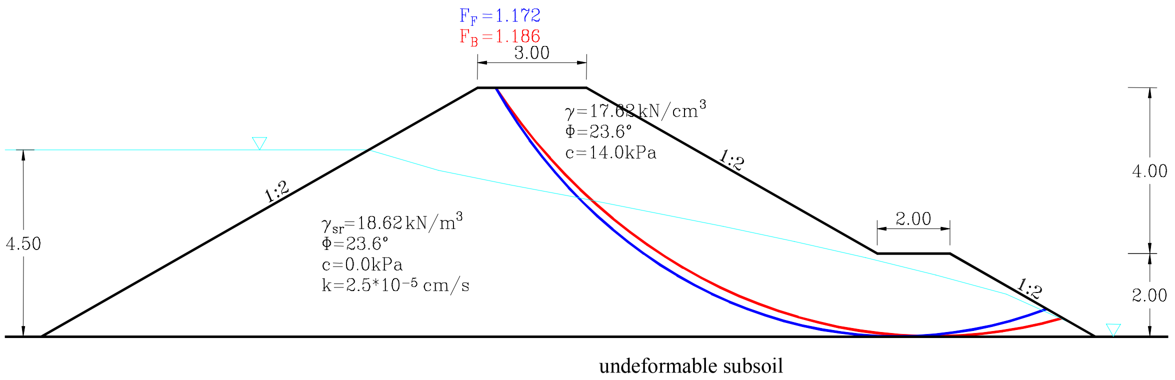


Fig. 19. Stability analysis of the flood bank on Wisła in Samocice. Circular slip curves of lowest stability factors determined by the Swedish (Fellenius)method $F_F$ and Bishop Method $F_B$.

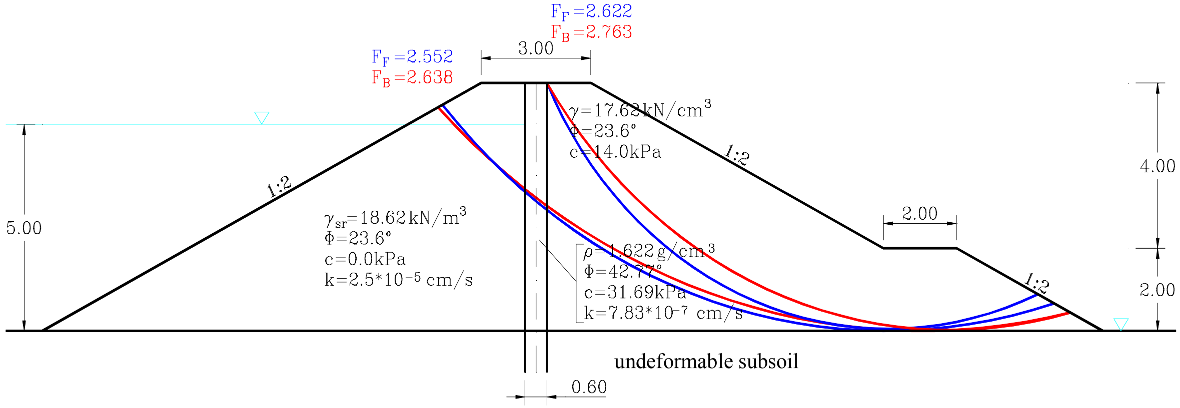


Fig. 20. Stability analysis of the flood bank on Wisła in Samocice after the introduction of the hydraulic cut-off wall. Circular slip curves of lowest stability factors ($F_F = 2.552$ i $F_B = 2.638$) determined in the transverse section with the hydraulic cut-off wall and on the downstream slope, in the area outside the cut-off wall ($F_F = 2.622$ and $F_B = 2.763$)

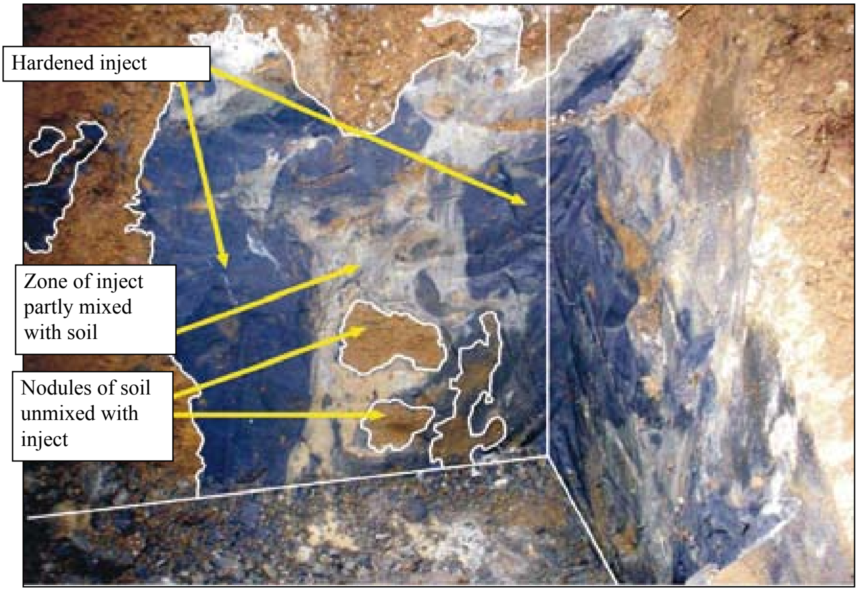


Photo 28. Cross-section through the cut-off wall

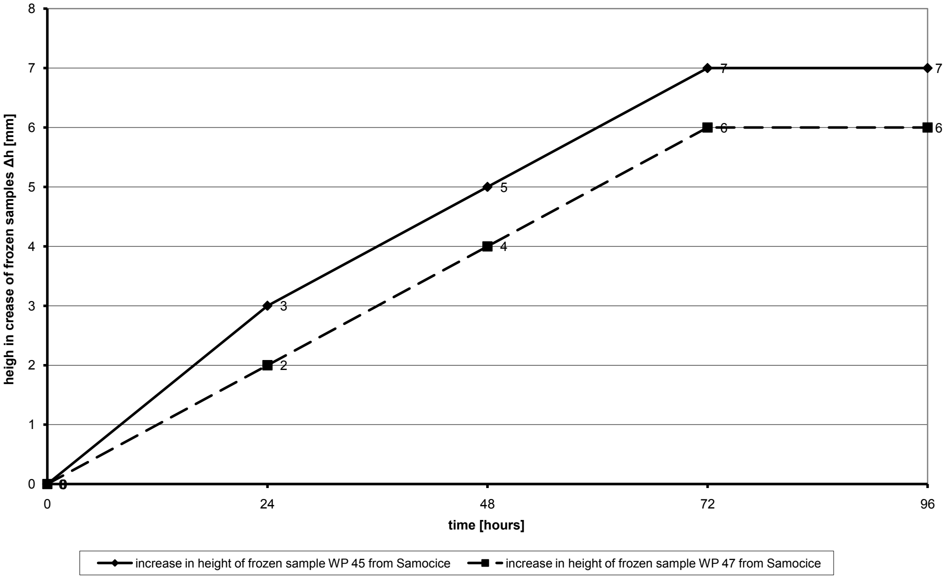


Fig. 21. Frost heave test of samples collected from the hydraulic cut-off wall in the flood bank on Wisła in Samocice

# 6. CONCLUSION

Observations, investigation results and experiences gathered for many years, have proven to the technical Staff dealing with flood protection, that the main problem of most existing flood embankments is the low state of compaction of the soils embedded therein and the lack of means to prevent filtration. For decades, the occurring flood freshets damaged the flood protection infrastructure, yet the scale of the damages was far from alarming. Only the disastrous flood in 1997, the duration of that disaster and the resulting hundreds of damages forced the administration to reconstruct and modernise destroyed flood protection infrastructure. The selection of modernisation solutions depended on local conditions and on the necessity to maintain the required transverse section of the inter-embankment zone. The solutions accepted for realisation are mainly screens and cut-off walls sealing the embankments, as well as elaborate systems of buttresses and drainage on the downstream slopes. Solutions based only on the capturing of filtrating waters by drainage, apart from the necessity to occupy an additional stripe of land for construction, also require some solutions for the system of outflow of the captured waters in the embankment adjacent area. Actions taken after the flood have resulted in periodical comprehensive technical reviews, which showed that a significant part of the embankments was in a poor state of repair. Due to the fact, that it was necessary to conduct modernisation works on an enormous scale, the authorities started to see vibration injection, DSM and low pressure injection technologies in a more favourable light, and so they started to be applied inside the flood banks, as vertical anti-filtration cores, often of large width. These technologies offer a realistic possibility to conduct large-scale, linear works in a relatively short time, at relatively low costs, and moreover, they penetrate the flood bank and the subsoil from the inside, filling in and eliminating voids, caverns and other structurally discontinuous areas that are difficult to locate during evaluation.

Neither of the presented technologies could be distinguished as better than the others when it comes to the construction of cut-off walls inside flood banks, as the applicability of any given technology depends on the conditions, in which the cut-off wall is to be constructed.

It should also be stressed, that all the above specified technologies enable the correct construction of vertical hydraulic cut-off walls in flood banks. However, there are specific geotechnical conditions, in which the application of a particular technology will lead to better results. The following cases can be taken into consideration:

- Body of the bank and subsoil consist of relatively homogenous non-cohesive soils – all variants of soil mixing technology;
- Subsoils of cohesive soils interbedded with soils of coarse granulation; subsoils containing remains of trees – soil mixing technologies with use of cutting mills;
- Embankments consisting of low compacted soils with numerous interbeddings, also containing inserts and laminations of organic soils – vibration injection technologies;
- Subsoils consisting of low compacted soils, loosened by suffosion, with numerous voids and caverns; subsoils consisting of cohesive soils of soft-plastic and plastic consistency; subsoils contain wide organic interbeddings – vibration injection and low pressure injection technologies;
- When there is a need to caulk the zones of contact of structures and subsoil – low pressure injection or jet grouting technologies.

Considering the facts listed above, it can be said that the introduction of inject can cause, apart from the zonal displacement of loose soils and the filling of the voids, also the mixing and thus the completion of permeable pores in non-cohesive soils with the inject grout. Mixing the native soil with the inject which will then harden, can also result in the stabilisation of the soil, which is a desired result from the point of view of the bearing capacity of the soil. In order to determine the efficiency of the constructed cut-off walls, a series of field tests was conducted on two objects that were insulated with use of vertical hydraulic cut-off walls. The research confirmed the proper functioning of the created cores as hydraulic cut-off walls, and allowed us to evaluate the possibility to use injections in order to strengthen the crowns of flood banks to an extent sufficient for the purposes of transport. The conducted field research enabled a deep analysis of the actual conditions in which a cut-off wall is created and operates, and allowed us to precisely determine its parameters basing on laboratory tests. As in field tests it is difficult to evaluate the degree of saturation of soil with inject, laboratory tests on the other hand allow to control the composition of mixtures and to evaluate the influence of various factor on the effects of injection more precisely. The results of these tests and analyses will be presented in a publication devoted only to this topic (Garlikowski, Lejcuś, Orzeszyna, Pawłowski 2010). Basing on the presented results and analyses, the following general conclusions can be drawn:

1) Conducted comprehensive field tests prove, that ultrafine binders can be applied for the purpose of construction of hydraulic cut-off walls.
2) The conducted analysis show that both the type of inject and the type of soil are essential for the characteristics of the created cut-off wall.
3) The research shows that inject based on clay from Bełchatów is more suitable for the purpose of construction of hydraulic cut-off walls.

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# FLOOD EMBANKMENTS MODERNISATION WITH USE OF VERTICAL HYDRAULIC CUT-OFF WALLS – FIELD RESEARCH RESULTS

## Summary

The embankments on most Polish rivers were designed and constructed in the beginning of the 19th century, and later modernized and expanded when necessary. Such activities were not based on a detailed evaluation of the subsoil, or on the selection of appropriate types of soil, and the transverse section of banks was determined without taking into account any hydraulic calculations. When the crowns of banks were raised above the level of water recorded during subsequent catastrophic floods, the effects of increased filtration in the body of the banks were not considered at all. Uniform technological and construction solutions consisting in the zoning of the transverse section of the bank, e.g. by means of the construction of cores or screens that would limit filtration, were not applied. The analysis of a large sample of damages to the embankments (approx. 450 recorded cases of damages to flood banks in Poland, study conducted in 1980 by CBSiPWM) has shown, that over 50% of such damages were caused by filtration through the body and subsoil of the banks. The basic activity conducted in order to modernize the embankments is making them more tight. When the banks are set on a layer of alluvial clays of a large depth, only the body of the bank requires tightening, so that it can be performed in form of a screen or a cut-off wall in the axis of the bank. Equipment enabling the construction of vertical cut-off walls in soils in form of poles, slabs, walls and hydraulic cut-off walls, has been available for several years in Poland and for several decades abroad. Such walls can be constructed with use of various methods, developed through a series of technologies designed by various companies. The basic technologies used for the construction of cut-off walls are: dry or wet mixing of soil with binders (soil mixing), the construction of uniform walls (vibration injection), and injecting the soil with grout under low (low pressure injection) or high pressure (jet-grouting). This monograph presents the results of field research, whose objective was to evaluate the usability of hydraulic cut-off walls constructed with use of vibration injection, DSM and low pressure injection, from injection grouts prepared using clay from Bełchatów and sludge from Bolesławiec. The investigation was conducted on the right-side embankment on the Warta river, near Kostrzyn. The study also contains the results of tests conducted on a cut-off wall constructed with use of DSM technology, on the embankment on Wisła in Samocice near Tarnow. Samples were collected from the constructed cut-off walls. Then they were tested in order to determine basic geotechnical parameters. The analysis of the obtained results has not enabled us to clearly distinguish one of the presented technologies as outstanding for the purpose of the construction of cut-off walls inside flood banks, as the factor that decides about the usability of any given technology are the conditions in which the cut-off wall is to be constructed. It should also be noted, that all of the technologies specified above enable the correct construction of vertical cut-off walls in flood banks, but as far as the applied material is concerned, better results were obtained when inject based on clay from Bełchatów was used.

**Key words:** flood ambankment, hydraulic cut-off wall, injection grout

# MODERNIZACJA WAŁÓW PRZECIWPOWODZIOWYCH Z WYKORZYSTANIEM PIONOWYCH PRZESŁON PRZECIWFILTRACYJNYCH – WYNIKI BADAŃ TERENOWYCH

## Streszczenie

Projektowanie i wykonawstwo obwałowań większości Polskich rzek realizowano na początku XIX wieku, z biegiem czasu modernizując i rozbudowując je w miarę potrzeb. Zabiegi te nie opierały się na szczegółowym rozpoznaniu podłoża i doborze odpowiednich rodzajów gruntów, a przekroju poprzecznego wału nie ustalano na podstawie obliczeń hydraulicznych. Podwyższając koronę modernizowanych obwałowań ponad poziom wód występujących w kolejnych katastrofalnych powodziach, nie brano pod uwagę efektów wzmożonej filtracji w korpusie wału. Przy budowie nowych obwałowań i kolejnych pracach modernizacyjnych nie stosowano jednolitej technologii i rozwiązań konstrukcyjnych polegających na strefowaniu przekroju poprzecznego wału np. przez wykonanie jądra lub ekranu ograniczającego filtrację. Analiza dużej próby uszkodzeń obwałowań (ok. 450 zarejestrowanych przypadków zniszczeń wałów przeciwpowodziowych w Polsce wykonana w 1980 r., przez CBSiPWM) wskazała, że przyczyną ponad 50% zniszczeń były uszkodzenia filtracyjne przez korpus i podłoże wału. Podstawową operacją realizowaną w ramach modernizacji obwałowań jest ich doszczelnianie. Gdy wały posadowione są na warstwie mad gliniastych o dużej miąższości, doszczelnienie dotyczy samego korpusu wału i można je zrealizować w postaci ekranu lub przesłony w osi wału. Od kilkudziesięciu lat za granicą, a od kilkunastu w Polsce, dostępne są urządzenia pozwalające na wykonywanie w gruntach przesłon pionowych w postaci pali, bloków, ścian i przesłon hydroizolacyjnych. Mogą one być realizowane różnymi metodami, które zostały rozwinięte poprzez szereg technologii opracowanych przez poszczególne firmy. Podstawowymi metodami wykonywania przesłon jest mieszanie gruntu ze spoiwem na sucho lub mokro (soil mixing), wykonanie jednolitej przesłony (wibracyjnie iniekowana przesłona szczelinowa), wprowadzenie do gruntu zaczynu pod niskim (iniekcja niskociśnieniowa) lub wysokim ciśnieniem (jet-grounting). Niniejsza monografia przedstawia wyniki badań terenowych mających stwierdzić przydatność przesłon hydroizolacyjnych wykonywanych w technologiach WIPS, DSM i IN z zaczynów iniekcyjnych przygotowanych na bazie iłu Bełchatów i szlamu Bolesławiec. Badania prowadzono na prawostronnym obwałowaniu rzeki Warty k. Kostrzyna. W pracy zawarto również wyniki badań przeprowadzonych na przesłonie wykonanej w technologii DSM na wale wiślańskim w Samocicach k. Tarnowa. Z przesłon tych pobrano próbki, które poddano badaniom w celu oznaczenia ich podstawowych właściwości geotechnicznych. Analiza uzyskanych wyników nie pozwoliła wskazać na którąkolwiek z przedstawionych technologii, jako wyróżniającej się przy wykonywaniu przesłon w wałach. O przydatności danej technologii decydują bowiem warunki, w jakich ma być wykonana przesłona. Należy również stwierdzić, że wszystkie ww. technologie pozwalają na prawidłowe wykonanie pionowych przesłon hydroizolacyjnych w wałach przeciwpowodziowych, ale gdy chodzi o zastosowany materiał, to lepsze rezultaty uzyskiwano, stosując iniekt na bazie iłu z Bełchatowa.

**Słowa kluczowe:** wały przeciwpowodziowe, przesłony przeciwfiltracyjne, zaczyn iniekcyjny