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The selection of sealing technologies of the subsoil and hydrotechnical structures and quality assurance

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Abstract: Various types of trenchless methods are extensively used to create engineering barriers for the purpose of achieving relatively low hydraulic conductivity of the subsoil and hydrotechnical structures. The most commonly used technologies of the grouting curtain creating are the DSM (Deep Soil Mixing), WIPS (Vibro Injected Thin Wall), low-pressure injection and jet-grouting. Vertical barriers are widely used in environmental control systems to restrict the lateral spreading of liquid or gaseous contaminants and for seepage control through and beneath a levees. The barrier walls are constructed in a single or two phases using a slurry composed mainly of bentonite, cementitious materials and water. Often to solve complex geotechnical problems the technologies are combined (e.g. combining DSM and jet grouting). In the paper some examples of practical application of chosen types of technology dedicated different problems solving are presented. The results of geotechnical investigations of hydraulic permeability, shear strength and depth control of cut-off wall are given. The tests were carried out using BAT system, Cone Penetration Tests (CPT) and drillings. The presented test results should help define the technical and financial criteria that should be used to compare grouting based methods and other techniques applicable to the same geotechnical special works. These recommendations should permit an adequate application of grouting techniques and contribute to finding solutions for the delicate problem of ground sealing, notably when proceeding with hydrotechnical or environmental structures placed below water table.

Keywords: antifiltration barrier, cut-off wall, deep soil mixing, jet-grouting, bentonite, slurry trench, permeability test

1 Introduction

Antifiltration barriers are usually made in the subsoil of hydrotechnical structures, in the dam bodies or flood embankments and foundation excavations [1–3]. They are also used in the areas of waste landfills, where they act as barriers preventing the penetration of contaminants into the ground and groundwater [2]. The basic form of anti-filtration protection are horizontal or vertical waterproofing screens, which, depending on their purpose, are made as complete screens - deepened to the natural impermeable layer, or incomplete - suspended, extending the groundwater filtration path. In addition, the use of antifiltration screens in the ground and the body of embankments and dams improves their stability, which is particularly important in the case of flood protection facilities. Another aim of the sealing works is to prevent unfavorable filtration phenomena, such as suffosion or hydraulic piping, which arise as a result of many years of operation of the objects [5]. Depending on the function and possibility of making the curtain can be made of hardening slurries, ensuring high anti-filtration and strength parameters. The scheme of the antifiltration barrier in hydrotechnical structure is shown in Fig. 1.

2 Requirements for waterproofing barriers

Depending on local conditions, the barriers are made in different technologies and to various depths [3, 5]. The requirements for the curtains depend on the function it is

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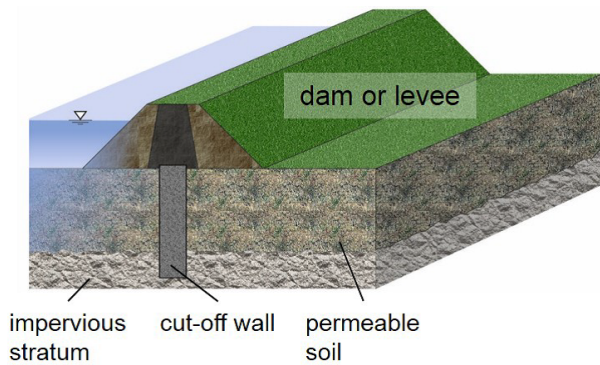


Figure 1: Schematic of an earth dam with cut-off wall [1]

supposed to fulfill, the technology of construction and the type of material it is made of. The most important parameter of the curtain is its tightness. It is determined by the saturated filtration coefficient (k), and its value should be in the range from 10^{-6} to 10^{-9} m/s, depending on the requirements [6]. Another important parameter determining the safety of an anti-filtration diaphragm, which is taken into account both in the design calculations and in the assessment of the condition of already constructed structures, is the unconfined compressive strength [7]. Usually, the strength for the such type of curtain should be in the range of 300÷500 kPa, however, it is stressed that apart from the mechanical strength of the curtain, another very important feature is its cooperation with the surrounding ground. This means that the strength should be adjusted at the design stage so that the curtain cooperates flexibly with the surrounding soil [7, 8]. This is particularly important in the case of maximum loads, e.g. during extreme water conditions. In such a case, a curtain made of a rigid material after exceeding the limit stress will be destroyed and lose its tightness, while a curtain made of a material with elastic-plastic properties will be deformed without losing its tightness. The other type includes, for example, diaphragm made with the use of appropriately modified adhesives based on natural clay [9]. An important feature of the barriers is also their durability, especially the lack of loss of tightness and strength associated with the influence of changing humidity and temperature conditions [10]. This property is strongly dependent on the type of binder, which should be characterized by homogeneous composition and lack of sedimentation, which is the main reason for the lack of resistance to freezing in the case of the construction of screens in the form of walls and ditches filled with hardening slurry, as well as in the case of technology where part of the soil is removed and replaced with a binder. Generally the basic expectations for waterproof barriers can be determined as follows: high in-

ulating properties, long-term functionality, resistance to hydrostatic pressure, resistance to deformation, high resistance to corrosion caused, no impact on the environment.

3 The most widely used sealing technologies and methods

3.1 Low-pressure injection

One of the oldest methods of soil sealing is low-pressure injection (LPI) [11, 12]. Contrary to the more widely used jet grouting method, it is based on the introduction of a hardening binder into the ground through a specially made borehole. Depending on the ground conditions (system of layers and type of soil), the injection is carried out with a specified momentary binder output and working pressure not exceeding not more than 5 MPa. The momentary output and injection pressure are selected in order to achieve the maximum range of injection. In the case of non-cohesive soils in a loose state, the range of soil sealing reaches over 100 m. In this technology both horizontal and vertical waterproofing curtains are made by making in rows a series of injection holes with spacing ensuring continuous filling of the soil with a binder. The limitation of this method is the type of binder, which in the liquid state should be characterized by specific rheological parameters, and above all, the content of at least 80% of fractions below 5 μm .

3.2 Slurry walls

Cut-off walls are vertical slurry walls (SL) with very low water permeability to minimize the ground water flow [13]. In contrast to the known load-bearing, impermeable retaining walls the slurry walls are intended to act as cut-off walls without any load bearing function, a mixture of water, bentonite, cement and maybe filler can be used [14]. This slurry remains in the excavated panel and hydrates. It also remains as a plastic seal, so that the wall can follow small displacements in the soil without cracking. Since the slurry remains in the panel, this is called the single-phase technique. Using this technique, panel depth is limited due to the relatively short time from placing and setting of the suspension. In deeper panels, the two-phase technique is used to construct a slurry wall. Construction is similar to the cast in-situ diaphragm wall installation (Fig. 2).



Figure 2: A view of cut-off wall construction.

After completion of the panel's excavation, the actual sealant slurry will replace the stabilizing bentonite fluid. This sealant has to be placed using the slurry-displacement or tremie method and needs to have a 0.75 t/m^3 higher unit weight than the bentonite slurry to replace it. To improve permeability and contaminant resistance, combination cut-off walls can be installed using the single-phase system. Sheet piles or plastic liner sheets can be installed within a bentonite-cement-slurry wall.

3.3 Deep soil mixing

The deep soil mixing (DSM) method does not require excavation of the soil to the surface, it is used both for sealing and strengthening the ground [15, 16]. Depth mixing is carried out by means of special single or tandem augers. The main purpose of this method is to improve the properties of soils deposited in the subsoil, especially their strength and impermeability, by mixing them with binders and sealing materials. In order to achieve better uniformity of the anti-filtration shutter, the mixing process can be repeated several times in the vertical direction. Both the agitator rotational speed and the agitator pulling up speed are selected according to the type of soil. The basic advantages of the deep mixing method include relatively high partition thickness, small amount of excavated material produced during partition execution, elimination of the possibility of slurry sedimentation and clamping a thin anti-vibration partition (which reduces the risk of partition leakage) and lack of vibrations that may limit the workmanship in some locations, e.g. in the case of close proximity of buildings. Moreover, this method ensures good interlocking of the partition in the ground (Fig. 3).



Figure 3: DSM technology.

The disadvantages of the DSM method include difficulties in obtaining a homogeneous mixture in very cohesive soils and the necessity of very precise delineation of subsequent columns and keeping the mixer vertically in order to ensure the tightness of the barrier.

3.4 WIPS technology

WIPS diaphragm - vibratory injected bentonite diaphragm, usually made of cement bentonite grout with filler, its thickness is 15-20 cm [17]. Slots are made continuously with a device called a trencher, which is a section equipped with a set of nozzles through which the binder is injected (Fig. 4). The hardening slurry is pumped both in the penetration phase and during the pulling out of the vibrator. In the immersion phase the suspension acts as a slurry - it facilitates profile penetration into the ground and stabilizes the gap walls. When the vibrator is pulled out, the whole space of the gap is filled with an appropriate hardening slurry. A continuous diaphragm in this technology is created by making subsequent overlapping layers.



Figure 4: WIPS technology (<https://www.keller.com.pl/>).

The thickness of the partition is influenced not only by the cross-sectional dimensions of the element penetrating the ground, but also by the type of soil in the place where the barrier is made. In practice, a wall made with the WIPS method can be made up to the depth of several meters. The WIPS method is characterized by high efficiency and as-

sociated low costs of making a protective screen. It also allows for additional compaction of the ground in sandy soils locally. The disadvantages include the small thickness of the barrier, which additionally depends on the type and condition of the ground, as well as the existence of a threat to its tightness and the possibility of the appearance of filter "windows" as a result of uncontrolled tightening of a thin barrier in unfavorable ground and water conditions. Moreover, the WIPS method requires very precise delineation of the next places where the vibrator is immersed, which must be maintained vertically in order to maintain the tightness of the aperture.

3.5 Jet grouting

The jet grouting technology is based on the high-velocity injection of one or more fluids (grout, air, water) into the subsoil [18, 19]. The fluids are injected through small-diameter nozzles placed on a pipe that, in its usual application, is first drilled into the soil and is then raised towards the ground surface during jetting (Fig. 5). The injected water-cement grout cures underground, eventually producing a body made of cemented soil. Most of the time, the treated volume has a quasi-cylindrical shape and is thus named 'jet-grouted column' or simply 'jet column'. There is, however, the possibility to make cemented bodies of different shapes, either by changing the treatment procedure or by joining several partly overlapped columns.

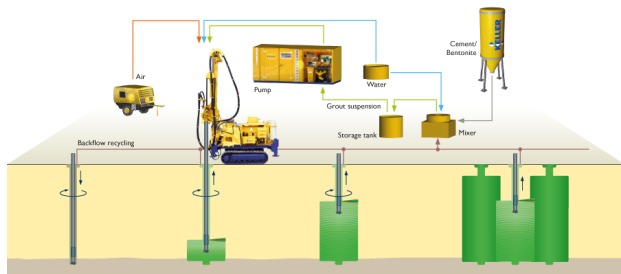


Figure 5: The jet grouting process (<http://www.kellerholding.com/soilcrete-jet-grouting.html>).

From the early stages of jet grouting, a variety of technical solutions has been proposed to increase the dimensions of the jet-grouted elements and to obtain columns as regular and homogeneous as possible. In fact, nowadays, there are several different ways to perform jet grouting, and new alternative procedures are frequently proposed. The main technological features of the different procedures are, however, described in this chapter, consid-

ering the various treatment procedures, the most relevant equipment and the materials needed for jet grouting.

4 The quality control tests of barriers

The quality control tests of barriers generally consist of supervision during construction, field investigations and/or laboratory tests of samples collected from the barrier [20]. Depending on the type of barrier, the function it is to perform and the technology of its execution, the scope and type of control tests are selected individually for each case. In the case of some technologies, it is possible to prepare samples from the diaphragm material and perform laboratory tests. However, field investigations under actual conditions of stress, compaction and humidity of the surrounding soil seem to be a more reliable approach. The type of test and the controlled properties depend on the function the diaphragm should perform. Single-phase diaphragm walls usually consists of a mixture of bentonite (mainly Na), cement, water and sometimes special additives too. Their most important properties, strength and low permeability, depend on the proportion of ingredients, hardening time, thickness of the wall (hydraulic gradient). The diaphragm wall must be firm enough to retain the water pressure and the lateral earth pressure including surcharges and must be safe not be too rigid so that it can deform without joints under loads. Desirable is a plastic wall with a strength and a deformability like the adjacent ground. In general, the unconfined compressive strength should be at least 300 kPa after 28 days. The dominant parameter of a diaphragm wall is its permeability, which is measured by the coefficient of permeability k (m/s) after Darcy's law. The value of k is given in the design and the specification and has to be accomplished after the construction. The minimum value of k is 10^{-8} m/s for slurry trench walls sealing waste disposal [21]. In literature there are many near-surface in-situ hydraulic conductivity testing methods which can be applied for covers and liners but for direct measurements of permeability of deep vertical barriers or fine-grained soils the BAT probe is considered to be the most appropriate [22]. The BAT probe has the advantage over other in-situ testing equipment like DMT [23] or CPTU [24, 25] because it can directly measure the in-situ hydraulic conductivity.

The first example of a study of the quality of anti-filtration barriers based on the results of geotechnical investigations are a control tests of permeability, wall strength and depth (range) of barriers in flood embank-

ments being modernized. Objects for which control tests were carried out are selected sections of flood embankments of the rivers Narew and Vistula, which were modernized several years ago. The modernization of selected sections of dykes consisted in making a diaphragm, which, depending on the object, was carried out using the low-pressure injection technology, WIPS or DSM. Field investigations of permeability were carried out with the use of BAT probe, while the strength, homogeneity and range of the diaphragm were tested with the use of CPT probe. The methodology of these tests is described in detail in the literature [22, 24, 26]. CPT tests were performed with a Van den Berg probe type HYSON 200 kN with a Mechanical Friction Jacket Cone (Begemann type) (Fig. 6). Examples of CPT results in the form of graphs, where the distribution of basic probing parameters q_c and R_f can be used to assess its strength and the actual depth of the diaphragm. The graphs also show the results of field permeability tests of the barrier with the BAT probe, as well as the results of permeability tests performed in the laboratory (Fig. 7, 8, 9 and Tab. 1).



Figure 6: A view of CPT and BAT test execution.

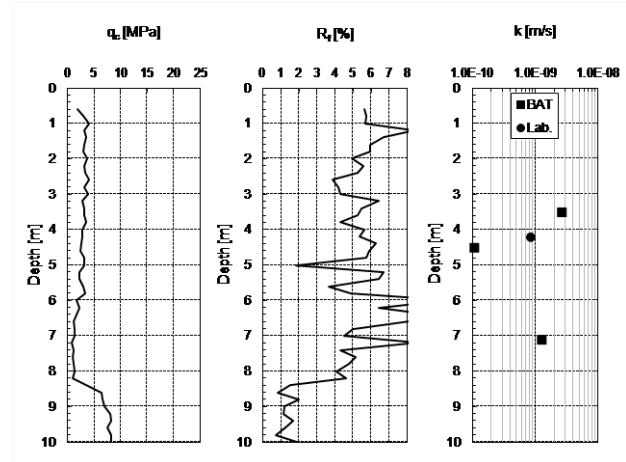


Figure 7: Results of CPT and BAT tests of waterproofing vertical sealing of flood embankment performed in a low-pressure injection (LPI) technology.

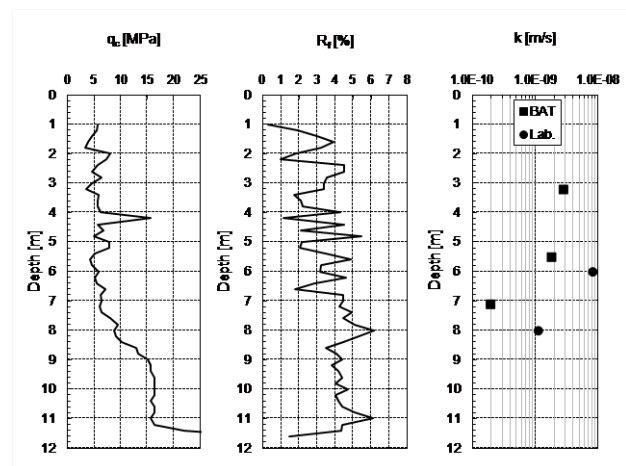


Figure 8: Results of CPT and BAT tests of waterproofing vertical sealing of flood embankment performed in WIPS technology.

The next example of the quality control tests of barriers are permeability and strength tests of a single-phase slurry wall diaphragm. The BAT and CPT tests were carried out on the section of the Vistula embankment being modernized [2, 8]. The method of modernization is presented schematically in Figure 10.

Particular properties of the fluid slurry (density, viscosity and 24h water settling) and slurry hardened after 28 days (ρ_c - density, R_c - compression strength and k - hydraulic conductivity) were determined in the laboratory. Next control in situ tests of the cut-off wall were carried out after 30 days of its construction. Permeability tests for estimation of hydraulic conductivity were performed with BAT probe [22]. The barrier depth, homogeneity and strength were determined by CPT soundings. Selected results of the conducted research [2, 8] are presented in Ta-

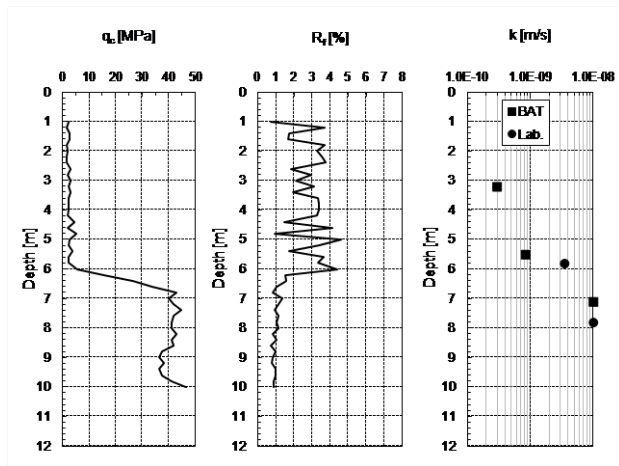


Figure 9: Results of CPT and BAT tests of waterproofing vertical sealing of flood embankment performed in DSM technology.

Table 1: Values of hydraulic conductivity k of from in situ and laboratory tests of barriers performed with different technology.

Object/ Techno- logy	In situ BAT permeability tests		Laboratory permeability tests	
	Depth [m]	k [m/s]	Depth [m]	k [m/s]
A/WIPS	3.2	$2.77 \cdot 10^{-9}$		
	5.5	$1.79 \cdot 10^{-9}$	5.5-6.0	$8.10 \cdot 10^{-9}$
	7.1	$1.9 \cdot 10^{-9}$	7.5-8.0	$1.10 \cdot 10^{-8}$
A/DSM	3.2	$2.90 \cdot 10^{-10}$		
	5.6	$8.30 \cdot 10^{-10}$	5.5-6.0	$3.47 \cdot 10^{-9}$
	7.1	$>1.00 \cdot 10^{-6}$	7.5-8.0	$9.53 \cdot 10^{-8}$
B/LPI	3.0	$3.17 \cdot 10^{-9}$	1.0-1.5	$7.09 \cdot 10^{-11}$
	4.5	$9.73 \cdot 10^{-9}$		
	5.5	$1.86 \cdot 10^{-9}$	6.5-7.0	$3.49 \cdot 10^{-9}$
B/LPI	3.0	$2.66 \cdot 10^{-9}$		
	4.5	$6.53 \cdot 10^{-9}$	4.0-4.5	$1.72 \cdot 10^{-8}$
	7.1	$7.40 \cdot 10^{-8}$	6.5-7.0	$1.25 \cdot 10^{-8}$
C/LPI	3.0	$2.61 \cdot 10^{-9}$		
	4.5	$1.05 \cdot 10^{-8}$	4.0-4.5	$8.31 \cdot 10^{-10}$
	7.1	$6.00 \cdot 10^{-9}$		
C/DSM	3.0	$>1.00 \cdot 10^{-6}$		
	4.5	$>1.00 \cdot 10^{-6}$	5.5-6.0	$1.1 \cdot 10^{-9}$
	7.1	$>1.00 \cdot 10^{-6}$		

ble 2. The comparison of results of the hydraulic conductivity obtained in the laboratory and in situ indicates their high convergence. The in situ tests are faster and are carried out in natural conditions of forming and maturing and this is the main reason why they are more reliable. In Figure 10 a view of BAT piezometer before installation into a cut-of wall is presented.

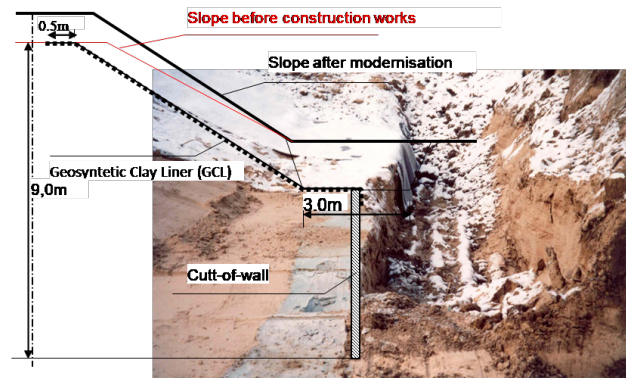


Figure 10: A view of the flood embankment modernization. Connection of Geosynthetic Clay Liner (GCL) with the cut-off-wall.

Table 2: Properties of hardened slurry from laboratory and in situ tests.

Laboratory tests			In situ BAT tests	
ρ_c [g/cm ³]	R_c [MPa]	k [m/s]	Depth [m]	k [m/s]
1.532	1.27	$1.84 \cdot 10^{-8}$	1.5	$2.5 \cdot 10^{-9}$
1.656	2.25	$3.18 \cdot 10^{-9}$	3.0	$1.9 \cdot 10^{-9}$
1.194	0.53	$0.53 \cdot 10^{-8}$	4.2	$1.5 \cdot 10^{-9}$



Figure 11: A view of BAT piezometer before installation into a cut-of wall.

The third example relates to the use of DSM technology to reduce the water inflow to the excavation. Increasingly in order to reduce the inflow of ground water to the foundation excavations in the event that it is not possible to make a "tight bathtub". (deep lying of the low permeable soils), partial antifiltration barriers are used. Sometimes, due to difficult geotechnical conditions (e.g. the presence of pebbled soils), it is not always possible to make a steel sheet wall (e.g. Larsen type), hence the technologies with which a barrier that reduces the water inflow to the excava-

tion is sought. One of such solutions is a diaphragm made in DSM technology with the use of cement-bentonite and polymineral clay solutions, which, apart from other solutions is being used more and more often. The curtain made in one of the newly built housing estates in Warsaw, in addition to limiting the inflow of water to the excavation, was also designed to support the walls of the excavation [27]. The tests were carried out using BAT system (Fig. 12), Cone Penetration Tests and drillings. The main purpose of performed investigations was post construction quality control of diaphragm wall made in DSM technology. The test results are given in Table 3.



Figure 12: A view of BAT test execution in DSM wall.

Table 3: BAT permeability test results of barrier performed in the DSM technology using a slurry composed of bentonite, cementitious materials and water as well as polymineral clays.

Depth	Soil type	Degree of compaction - I_D	Hydraulic conductivity
[m]	[-]	[m/s]	[m/s]
3.2	Fine sand	0,25	3.6×10^{-9}
4.0	Medium sand	0,25	1.21×10^{-8}
4.2	Fine sand/ Medium sand	0,40	7.1×10^{-9}
4.3	Medium sand	0,25	2.4×10^{-7}
5.1	Fine sand	0,45	1.9×10^{-9}
5.2	Fine sand	0,37	6.4×10^{-9}
5.2	Medium sand/ Coarse sand	0,41	2.07×10^{-7}

5 Conclusions

Based on the conducted research, it can be stated that the BAT probe and CPT can be successfully used to assess the permeability and strength of the barriers performed in LPI, slurry walls or DSM technology. Depending on the hardness of the screen, the most suitable way of inserting the BAT piezometer into the barrier should be chosen. If the diaphragm hardness is high, in order not to damage the filter tip, it is necessary to drill a hole and then install the filter by driving. The results of CPT and BAT probing confirmed the usefulness of these devices for the assessment of the technical condition of flood embankments modernized. In each case it was possible to quantitatively assess the quality of the seal and its range and homogeneity. An unquestionable advantage of these tests is the fact that they are carried out in situ. The tests carried out on the quality of waterproofing membranes modernized several years ago showed that regardless of the applied technology of making the membrane, the structures are durable and meet the basic requirement concerning the filtration coefficient $>1 \times 10^{-9}$ m/s. The permeability of the DSM diaphragm depends mainly on the soil of the subsoil in which the diaphragm is made. In case of very permeable soils, in order to achieve the required permeability of the diaphragm it is necessary to change the recipe or pressure of the injector.

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