PRBs construction using high velocity water jet technology: laboratory experimentation

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Abstract

Tailing basins, waste dumps and mineral stockpiles represent potential sources of water contamination. Permeable reactive barriers (PRBs) are one of the most innovative systems for groundwater clean-up: reactive materials are placed in the subsurface forming a sort of filter allowing the incoming plume of contaminated groundwater to flow through, while treated water emerges at the opposite side. PRBs are commonly realized excavating a trench and filling it with an high hydraulic conductivity reactive mix. The research carried out at DIGITA laboratories is aimed at exploring the possibility of using water jet technology for PRBs construction, increasing soil permeability and at the same time injecting active compounds.
In this paper, after an overview of the state of the art of PRBs construction, the principles of the application of the water jet technology to the soil and groundwater remediation are illustrated. Finally the results of the experimental activity are presented and the prospective of the water jet application for PRBs emplacement is discussed.

Keywords: groundwater protection, permeable reactive barriers (PRBs), water jet technology;

1 INTRODUCTION

Several groundwater contamination sources are present in the mining areas. They are mainly represented by waste rock dumps, tailing ponds and acid water drainages. Surface capping and bottom impermeabilization are typically adopted to ensure permanent safety conditions of the major embankments. Nevertheless, the reliability of the interventions on the bottom is often invalidated by difficulties mainly related to the dump thickness and to the geotechnical properties of the basement. Consequently, a residual contamination potential should be considered and complementary actions should be planned for groundwater protection. The most diffused methods for groundwater protection and remediation are based on pump-and-treat systems (P&T). These consist of a series of wells or trenches aimed at capturing the contaminated groundwater that is then pumped above the ground to a treatment plant for the pollution removal. The treated water is discharged in a surface water body (river, lake or sea) or re-injected into the aquifer through injection wells, continuous trenches, drains, or surface application (sprinkler, furrow, or basin infiltration).
Depending on the contaminants, the treatment system is based on chemical-physical precipitation, carbon adsorption, stripping, biological degradation. The pump-and-treat based systems are designed to have a technical life of 30 years. The overall remediation cost can be very high due to the long pumping duration. For instance, in case of NAPL contamination the slow mass transfer of contaminants from these phases to groundwater during P&T prolongs the clean-up process.
The Permeable Reactive Barriers (PRBs), also known as treatment walls, are subsurface vertical permeable screens that contain a reactive medium aimed at the in-situ treatment of the contaminated groundwater [1]. A PRB placed across the flow path of the plume removes the

contaminants by physical, chemical and/or biological processes as the contaminated groundwater moves through it,.

PRBs have some advantages over pump-and-treat systems for groundwater remediation: contaminants are degraded or immobilised in situ without any need of extraction. In addition operation and maintenance costs result to be reduced due to the absence of a pumping system, treatment plant, building heating and so on. Often operation costs concern only the monitoring system while maintenance expenses are related to the periodic replacement or reactivation of the treatment medium, if required. Furthermore, regulatory problems related to ultimate discharge requirements of effluents from pump-and-treat systems are avoided.

2 REACTIVE MATERIALS [1,2,3,4,5,6,7,8,9,10,11]

The selection of the reactive media is based on the type (i.e. organic vs. inorganic) and concentration of contaminants, groundwater flow velocity and water quality parameters.

Treatment design is typically based on the results of both batch reaction tests and laboratory or field-scale experiments.

Batch tests are aimed to obtain information about the reactivity of the media (degradation half-life, sorption kinetics and capacity, etc.). Column tests are typically conducted by passing the contaminated groundwater through a column filled with the reactive material. In these columns flow velocities are adjusted to simulate groundwater velocity and reactor residence time. Through this study the performance of the treatment wall can be predicted.

A variety of treatment media have been tested for PRBs application at the bench scale and at the pilot stage.

Zero-valent iron has been applied for the first time in 1991 by the University of Waterloo. It is presently the most widely used reactive material in the degradation of halogenated organic contaminants, such as TCE and PCE using an abiotic reductive dehalogenation process.

Iron particles are available in sand size particles (2 to 0.3 mm). They are usually mixed with gravel or soil to form the trench filling or used as exclusive component.

Limestone can be used as a treatment media to increase pH aiming at the immobilization of some dissolved metals in groundwater. It has been used to treat acid mine runoff in the mining industry.

Activated carbon has been widely applied for removing various contaminants in above groundwater treatment systems. It adsorbs hydrocarbons and chlorinated compounds in the groundwater. On the other side carbon is friable and light enough to float in water, creating construction problem for trench installations below the groundwater. Injection systems can be used for mixing the carbon with soil to facilitate installation.

The injection of various biological nutrients into an injection well barrier or distribution trench can also be used for the in-situ treatment of groundwater. One such recent application involved the injection of a solution of diluted blackstrap molasses to enhance microbial reduction of dissolved metals into less soluble forms. In this application, hexavalent chrome was reduced to trivalent chrome and then to chromium hydroxide.

Oxygen and hydrogen releasing compounds have been used in injection well barriers in a large number of sites.

3 GEOMETRICAL CONFIGURATIONS [1,2,4,5,7,8,11]

Reactive barrier systems should be in contact with a lower impermeable zone (aquitard) in order to assure that the groundwater flow will go through and not beneath the treatment material. If this condition cannot be accomplished due, for example, to the depth of the aquitard, then the barrier must be constructed much deeper than the contaminant plume.

The thickness of the treatment zone can vary from a tens of centimetres to some meters depending on contaminants mass and residence time (Figure 2).

Permeable Reactive Barrier systems can be divided in:

- Continuous Wall

- Funnel and Gate
- Injection Well Barriers
- Passive Collection with Treatment Reactors Vessels

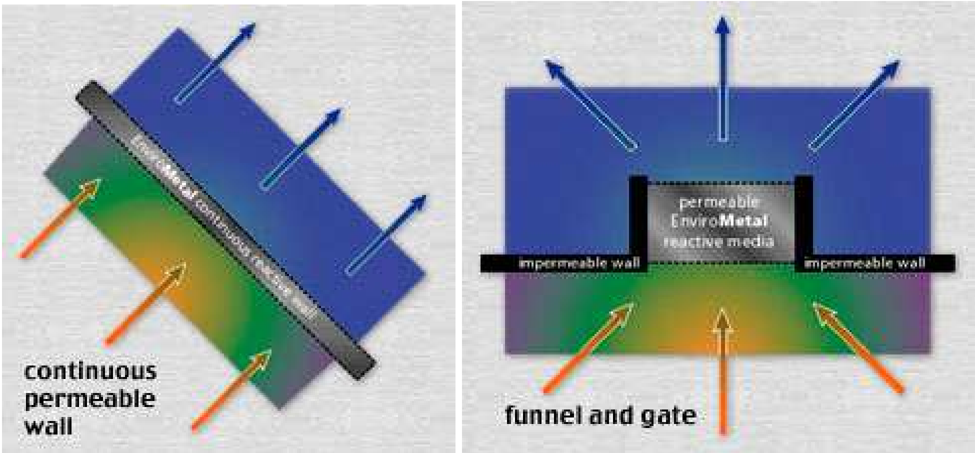

Figure 1 PRB configuration: continuous (left) and funnel and gate (right) [11]

The continuous wall and the funnel and gate configurations are shown in Figure 1. It extends across the width and depth of the plume.
The funnel and gate configuration consists of low hydraulic conductivity (e.g., $1x10^{-6}$ cm/s) cutoff walls (funnel) with gaps filled with the treatment medium (gates). Cutoff walls (the funnel) guide the groundwater to the permeable gates, which contain the reactive materials.
A different strategy consists in the realization of treatment zones in place of treatment walls. In this case the reactive material, in fluid form, is inserted in the soil by injection wells or injection devices and distributed in the treatment volume. Advantages of this strategy are that there is no need to construct a trench and then to handle potentially contaminated soil; furthermore it allows the treatment of aquifer zone at greater depth. On the other hand the level of reliability of the injection wells for creating homogeneous treatment zones appears to be lower than that obtainable in the treatment walls construction.

4 INSTALLATION METHODS

A variety of methods can be used to construct the treatment walls. The choice depends upon the depth and thickness of the treatment zone, safety considerations, the geotechnical site conditions and finally the construction costs.
The following construction methods have been mostly used:

Slurry trench installation

In stable geologic materials and for shallow installations (less than 4 meters) a trench of the appropriate width can be excavated with conventional excavators to intercept the contaminated plume and backfilled with the reactive material.
For deeper installations or for instable ground the use of slurry is usually required to stabilize the excavation. In this case, unlike impermeable walls construction methods that utilize bentonite slurry, the emplacement of permeable barriers requires the use of biodegradable polymers to avoid the problems of reducing the soil permeability with residual slurry material. In fact, after treating, the slurry polymer decays allowing the groundwater to pass through the reactive zone.
The bio polymer trenching method has been used to realize trenches for civil applications up to 25 meters deep and from 0,5 to 1,5 meters wide and, because of the continuity and the excavation rate, it proved to be cost effective. Furthermore the presence of boulders or rocks strata do not constitute a limit for the method because they can be easily removed from the

trench. On the other hand, it implies the handling of potentially polluted material, introducing possible hazards for the exposed workers.

Sheet piling excavation

In this method, steel sheet piles are driven around the perimeter of the PRB to the desired depth using vibrating devices and the soil within the sheet pile is excavated. After the excavation has been completed, the empty volume is filled with the treatment material; the sheet piling is then removed and groundwater allowed to flow through the treatment zone.
The construction process includes several distinguished operations (sheet piling, excavation, backfilling) resulting discontinuous, time consuming and costly. One of the main problems with sheet pile installations consists in penetrating hard layers, rock or boulders. Other difficulties concern the reduction of the soil permeability due to the pile-driving vibrations, the production of toxic fumes during installation and the pumping and treatment of dewatering fluids. Finally the reachable depth is limited to 8-10 meters.

Continuous Trenching Machine Installations

Continuous trenching machines have been developed to install horizontal underground utilities and constructing trench drains and interceptor trenches. These machines allow simultaneous excavation and backfilling without separate shoring. Excavation is made by a cutting chain disposed in front of an attached trench-box to temporarily shore the trench. As the machine moves forward removing the soil, reactive material is added to the trench-box, backfilling the trench and creating a continuous treatment zone. Available utility trenching machines have depth capability of less than 7 m, while some specialized machines used for interceptor wall construction can excavate up to 8-10 m. The continuous construction process results in a reduction of time and cost of installation.

Soil mixing installation

Soil mixing processes are commercially used in the consolidation and stabilization of soils. The construction process consists in drilling a small diameter hole to the needed depth, inserting the injection tool to the bottom and injecting the reactive material in form of slurry while the device is raised to the surface. Soil is then mixed with the reactive slurry forming a vertical treated column. The vertical barrier is created by driving a pattern of overlapping columns.
The diameter of the column depends on the soil properties and varies from 5 to 2 meters while the reachable depth ranges from 20 to 40 meters.
With this method the reactive material is added to the original soil without excavation and the amount of reactive media injected must be limited or else more soil must be removed.

5 OUTLINE OF PRB'S STATE OF ART [1,2,3,4,5,6,7,8,9,10,11]

In the following figures the values of the characteristic parameters of 68 PRB constructions (64 installed in North America and 4 in Europe) are summarized. Figure 2 represents the frequency of the depth and thickness values while in Figure 3 the geometrical configuration and the type of reactive material and contaminant are depicted.

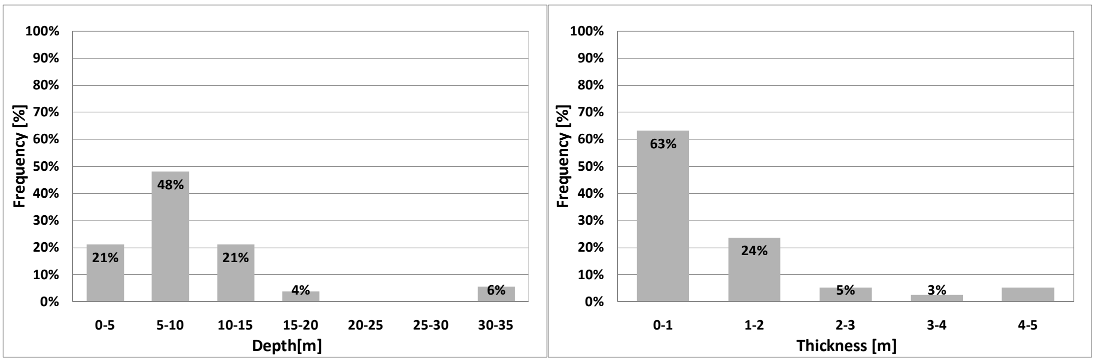

Figure 2 PRBs by Depth (left) and Thickness (right)

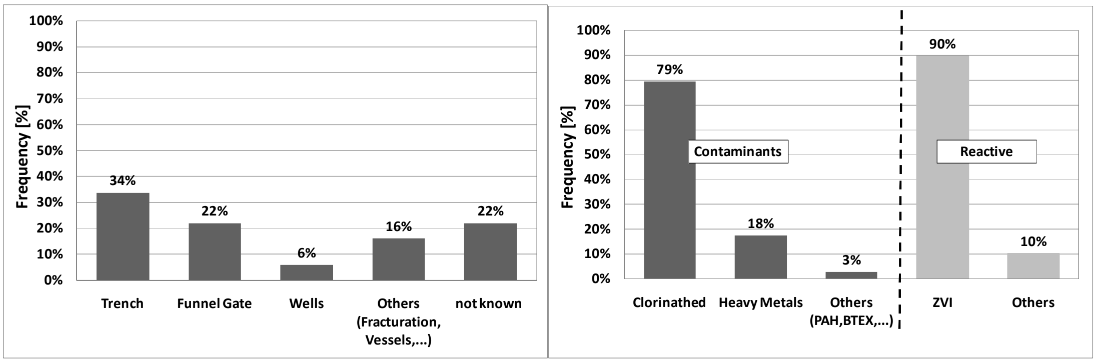

Figure 3 PRBs by types (left) and by contaminant and reactive compound(right)

Figure 2 (left) highlights that the most part of the emplacements (69% =21%+48%) has been realized at depth smaller than 10m while just the 6% reaches 35 meters. Furthermore, around the 60% of them has thickness in the range 0 - 1 m, while in few cases the thickness is between 4-5 m.

Figure 3 (left) shows that the most diffused PRB types are treatment walls (34%) and funnel and gate (22%) while injection wells and others types represent only the 20% of the applications. The chart of Figure 3 (right) is divided in two parts: the diagram on the left represents the frequency of the treated contaminant while the one on the right concerns the frequency of the reactive materials. As can be seen, the 80% of the applications has been aimed at treating chlorinate organic compounds while only 20% of them concerns heavy metals treatment. Finally, Figure 3 (right) highlights that zero valent iron (ZVI) is used in the 90% of the reviewed installations.

6 EXPERIMENTAL ACTIVITY

The research carried out at the DIGITA and here summarized is aimed at verifying the applicability of water jet technology for the injection of reactive materials and the realization of treatment zones. This technology appears to be suitable for the emplacement of treatment volumes at considerable depth (more than 10 meters) and only in the strata that require to be treated. Soil in fact do not need to be excavated so the intervention can be concentrated only in the volume crossed by the contaminated groundwater. Various experiments have been performed mainly focused on determining the relations between the penetration of the jet into the soil, the operational parameters of the jet (pressure, flowrate) and of the driving lance (nozzle trajectory and velocity) and the soil properties [12,13,14,15,16,17,18]. The distance of

penetration, in fact, is the parameter that mostly influences the time and the overall cost of the reactive volume realization.
The experimental activity has been developed in different directions. A first series of tests was aimed to measure the velocity of the water jet while penetrating into the soil (Figure 4a). A second series concerned the realization of vertical treatment columns and was aimed at studying the relations between the jet operational parameters and the resulting column radius (Figure 4b). A third series dealt with the construction of vertical curtains of reactive material and focused on the study of the value of the curtain length and thickness that can be reached with the application of the jet technology (Figure 4c).
In all the experiments the high pressure generation system was a three piston pump Hammelmann HDP 334, driven by a diesel engine Caterpillar CAT 3406B with 354 kW, capable of supplying a flow from 10 l/min to 50 l/min at a pressure from 10 to 250 MPa.

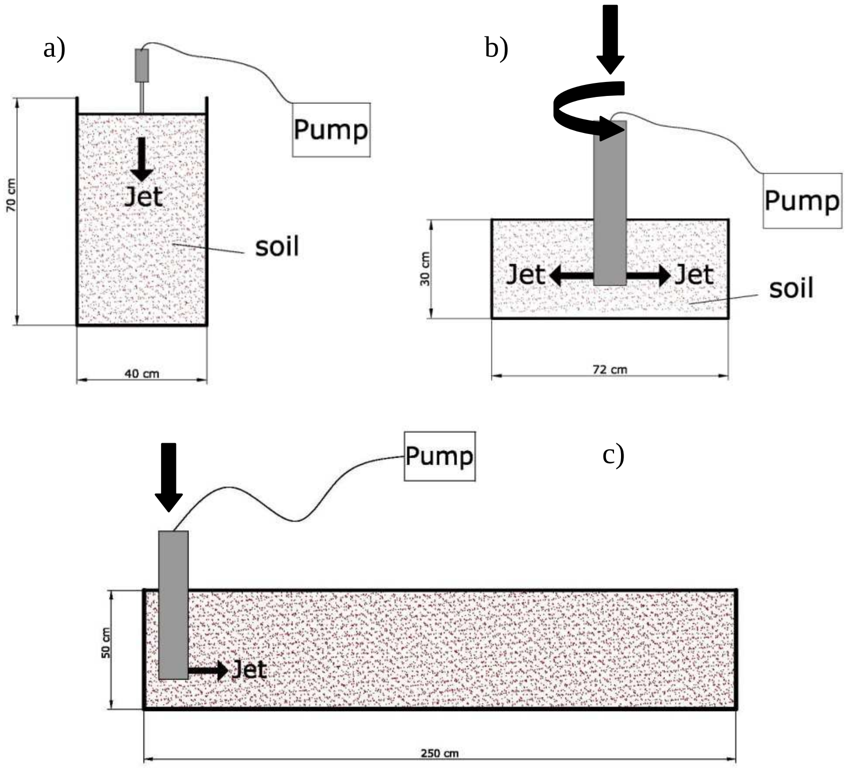

Figure 4 Sketch of the three experimental apparatus

6.1 Measurement of the velocity of a waterjet penetrating a soil

The first aim of the experimental research was measuring the velocity of a continuous jet while penetrating in a sandy soil. In this study the jet nozzle was steady while the jet operational parameters (generating pressure and flowrate) were varied to investigate their influence on the penetration velocity. The soil was placed in a thin transparent container 75cm high, 30cm wide and 4cm thick and injected by the steady water jet from the top (Figure 5 - left). The geotechnical properties of the samples were the following:

- Particle size distribution
- Density
- Saturation degree

Because of the extreme rapidity of the phenomena, a high frequency shooting and recording camera was used to capture the images of the jet position at each time step.
The camera was set to record at a frequency of 500 fps (one frame every 2 ms), with a resolution of 1280 x 512 pixels, for a total time of 6.5 s. The result is a sequence of 3500 .jpg images.

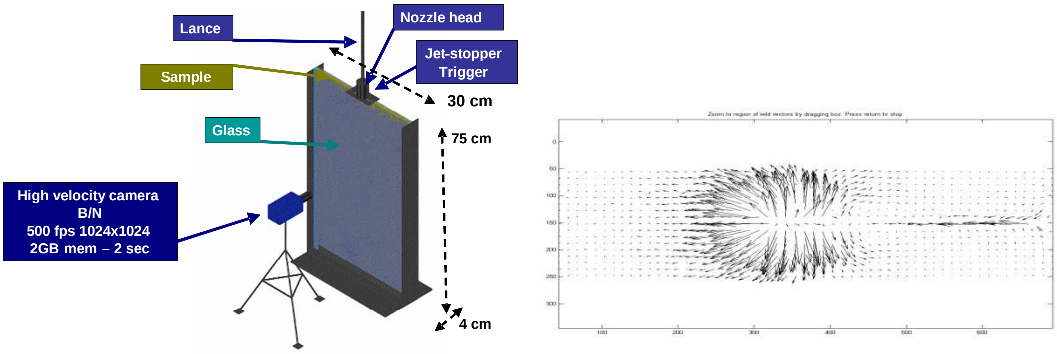

Figure 5 Experimental apparatus (left) - Example of PIV analysis result (right)

Images were then analysed with PIV technique [18,19] to obtain the jet penetration velocity and the movements of the soil particles [20] (Figure 5 -right)

Three series of tests were carried out, using different nozzle diameters. Each series was made up of three tests (see Table 1). The selected nozzle diameters were 1.0, 1.2 and 1.4 mm. A further test with a nozzle of 0.8 mm and power equal to the lowest value of the three series was carried out. Table 1 shows the sequence of tests and the values of the setting parameters.

Table 1: Tests

	Test #	P [MPa]	ϕ_{nozzle} [mm]	V [m/s]	Q [l/min]	W [kW]
I	1	60	1	338.3	10	36
	2	100	1	434.2	13	77
	3	130	1	495	15	115
II	4	50	1.2	307	13	39
	5	80	1.2	395.9	17	79
	6	100	1.2	434.2	19	112
III	7	40	1.4	274.8	16	39
	8	65	1.4	356.8	21	80
	9	80	1.4	395.9	23	110
IV	10	75-80	0.8	395.9	7.5	36

P: generation pressure; Φ_{nozzle}: nozzle diameters; v: jet velocity at the nozzle's section; Q: flow rate; W: generation power.

The results are depicted in figure 6 which shows the values of the penetration velocity along the jet path for the different test conditions.

The graph Figure 6 highlights that the penetration velocity and therefore the jet's kinetic energy, declines as an exponential function of the jet's leading edge advance through the sample. It can also be seen that the jet velocity at the sample impact point is about one half the one at the nozzle's outlet and that it halves again after only 200 mm, reaching a value in the range (20-50 m/s). At the bottom of the sample, after penetrating for 700 mm, the velocity results to be around 1-5 m/s.

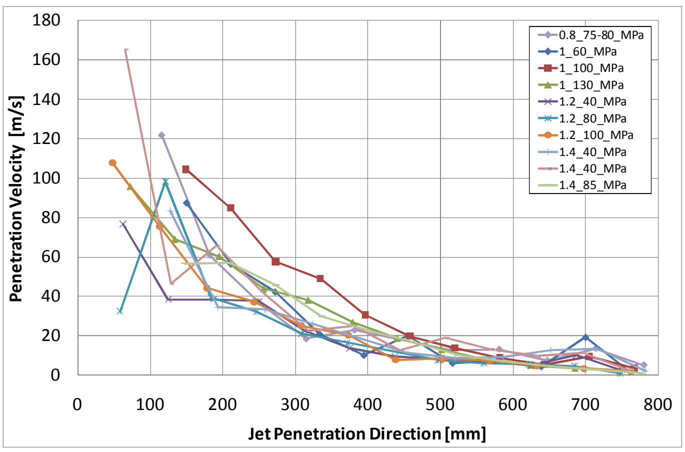

Figure 6 Penetration velocity along sample axes.

6.2 Measurement of the radius of a treated column

This stage of the experimentation deals with the realization of PRBs by columnar treatments. In this case both a rotation and an lifting motion are applied to the jet lance. The rotary motion ensures that the jet of water reaches the points arranged over an arc of 360°C, while the upward linear motion ensures that at each nozzle rotation overlapping slices of soil are treated.
The radius of influence (or the depth of penetration) of the jet in the soil depends on the jet's generation parameters: pressure (P), flow rate (Q) and hydraulic power (W=P·Q), but also on the lance velocity (rotation around its vertical axis and vertical translation) and on the soil characteristics.
Aimed at assessing the relation between total velocity of the nozzle and the radius of the soil column treated by the water jet [14,15,16,17] an experimental apparatus has been appositely constructed. It consists of a vertical lance driven by two electric motors which generate the vertical uplift and rotation motions. The lance is connected to the pressure pump and it is equipped with a nozzle head in which two nozzles, 1 mm in diameter, are positioned opposite to each other and perpendicular to the lance's rotation axis.
Each soil sample, having mass of about 150 kg, is compacted in layers inside a cylindrical container 76 cm in diameter and 30 cm high.
Two series of tests were carried out on sandy soil samples with dry specific gravity between 1.7 and 1.8 kg/dm^3. In the first series dry soil samples were used while in the second one the soil samples were saturated. Tests were carried out keeping operational parameters unchanged except for the total velocity of the nozzles varied in the ranged from 1.5 to 5 cm/s. The water jet generation pressure was set at 40 MPa.

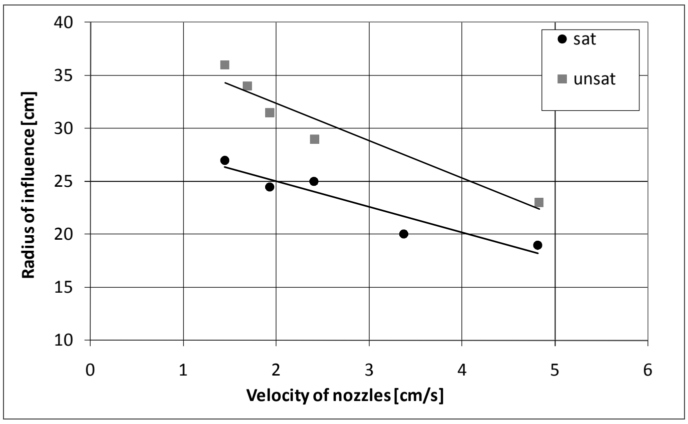

Figure 7 Radius of influence vs velocity of nozzle

The graph in Figure 7 highlights the influence of the nozzles total velocity on the column radius. As expected, the radius decreases with increasing speed ranging from 23 to 36 cm in dry soil and from 19 to 27 cm in saturated soil. It comes out that performance in dry material is twice that achieved in saturated material.

6.3 Curtains formation

The third experimental phase was aimed at assessing the potential of water jet technology for the creation of permeable reactive curtains i.e thin treatment walls. For this purpose the jet was directed horizontally in the soil while the nozzle holding lance was moved upward along the axis of a borehole without rotation. In this case the apparatus was able to inject a mix of water and solid particles by premixing them inside a pressurized bottle.
The specific goal of the experiments was to assess the relation between the upward velocity of the lance and the dimensions (length and thickness) and composition (original soil - injected particles) of the obtained curtain.

The samples were realized by compacting about 650 kg of sandy soil (particle size below 2mm) inside a box 2.5 m long 0.4 m high and 0.4 m wide.
The soil was injected by a slurry of water and copper slag particles having a size distribution in the range 0.05 mm - 0.7 mm. Copper slag contains more than 45% of ZVI and its unit weight is 3.66.
The lance was connected to the water-solid mixing device (Dia-Jet) and driven by a movement system which allows the vertical velocity to be set in the range 18 - 90 cm/min. The jet was generated at 20 MPa by a 1.8 mm diameter nozzle. The resulting total, liquid and solid flow rates are reported in Table 2.

Table 2 Waterjet system flowrate

	Total	**Water**	**Solid**
Volumetric Flowrate [dm^3/min]	29.5	19.5	10
Mass Flowrate [kg/min]	56	19.5	36.5

Four injection tests were conducted on saturated soil samples. At the end of each test the obtained curtains were measured with the support of image analysis. The copper slag concentration in the injected volume was measured by magnetic separation of the copper slag particles from the soil.
The penetration length and thickness have been evaluated as the length and thickness of the solid having copper slag concentration greater than 45%; the external soil, in which the cooper slag concentration was lower than 45%, has been considered not injected.
Table 3 summarizes the setting values of the test (generating pressure, vertical velocity and duration) and the results obtained (curtain dimensions).

Table 3 Injection tests results

Saturation State	**Pressure**	**Vertical Velocity**	**Test Duration**	**Curtain Height**	**Curtain Length**	**Curtain Thickness**
	MPa	**[cm/min]**	**[sec]**	**[cm]**	**[cm]**	**[cm]**
Saturated	20	90	6,6	19	-	11
Saturated	20	60	10	15	35	11
Saturated	20	30	20	17	45	14
Saturated	20	18	33	26	49	16

As expected, the resolts odf the tests highlight that both curtain length (jet penetration depth) and curtain thickness decrease with the lance vertical velocity. The depth of penetration almost reaches 0.49 m while thickness varies from 11 cm to 16 cm.
Figure 8 shows the relations between curtain length and thickness and vertical velocity.

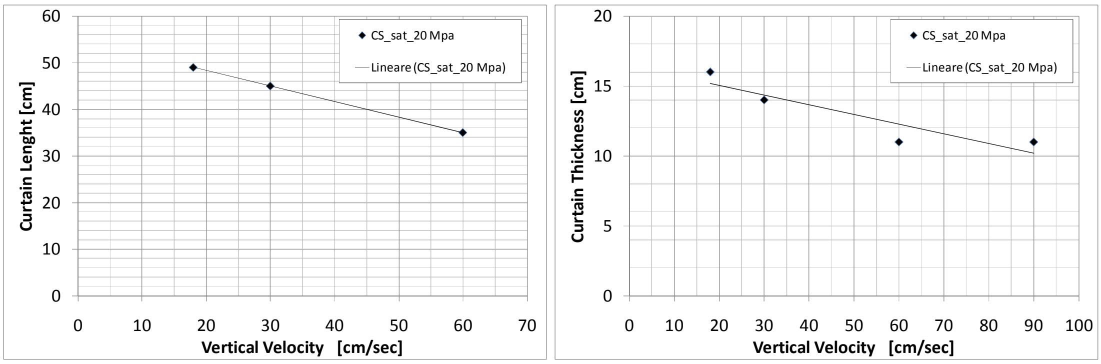

Figure 8 Curtain lenght (left) and thickness (right) vs lance vertical traverse velocity

7 CONCLUSIONS

The research on the penetration of a water jet in a sandy soil demonstrates that the jet velocity decreases as an exponential function of the jet advance in the sample and after 80 cm it drops down to 1 – 5% of the initial value.

A coherent result has been obtained operating with a water jet generated by a nozzle driven along an helicoidal path with velocity in the range 1.5 – 5 cm/s. The radius of the treated columns resulted in the range 25 – 35 cm when the generating pressure was 40 MPa. The study highlighted also the important role of the saturation degree of the soil: the penetration radius reaches 25 cm in saturated conditions and 35 cm in dry ones.

The realization of vertical treatment walls using a rotating water jet lance entails the emplacement of one or more rows of columns driven to the wanted depth. On the base of the experimental results a distance between columns of 60 – 80 cm can be planned for realising one row columns wall.

As alternative application, thin curtains can be realised by using a vertically traversing nozzle. The experimental study carried out on this subject demonstrates that vertical panels about 40 – 50 cm large, 10 – 15 cm thick and with more than 45% of reactive material in the panel's volume, can be obtained with a traverse velocity of 20 cm/s. This means that a continuous curtain can be formed by consecutive panels driven from vertical holes 80 – 100 cm apart. If a thickness larger than 10 – 15 cm is required for the treatment, more than one curtain can be realised along the flow direction.

The length of the paned can be substantially increased by generating the two opposite jets at higher pressures.

The use of water jet as PRBs construction technology presents some important advantages that, depending on the site conditions, can result decisive. The first aspect concerns the cost of realization of the treatment wall. It has been estimated around 300 $/m^2 for the columns geometrical configuration and in 200 $/m^2 for the 15 cm thick curtains, on the base of the experimental results. Both values result to be lower than those linked to slurry trench, sheet piling and continuous trench installations that typically range from 1000 to 2000 $/m^2 .

A further economical advantage is introduced when the treatment has to be applied in a selective form i.e. selecting strata at various depth. In these cases, both techniques (columns or curtains) allow the emplacement of the treatment material just in the strata in which it is required, avoiding any operation (excavation – wall shoring and trench filling) on the others.

It has also to be considered that injection techniques do not require any excavation of potentially polluted material resulting in safer working conditions.

Moreover the replacement of the spent reactive material with new one is easier through the same injection holes.

The major deficiency of injection methods is related to the difficulty of controlling both the wall's thickness and the treatment material concentration during construction. Under this aspect they result to be less reliable than traditional emplacement methods. Nevertheless, it must be underlined that, low construction cost and adaptability of the methods allow adjustments, improvement and, if needed, replications where the first intervention has failed or proved to be not fully reliable.

8 ACKNOWLEDGEMENTS

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