An innovative way for the construction of PRBs

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Abstract

The concept of permeable reactive barriers (PRB) is being considered with increasing interest for polluted groundwater remediation, as an alternative to conventional physical barriers. The construction of a PRB using the excavation/backfill concept is generally difficult and expensive. A new approach to the problem examines the application of high-pressure water jets for the creation of this kind of barriers.

The papers deals with the research activity being carried out at DIGITA's Waterjet Laboratories and the results obtained during a study aimed at evaluating the volumes of soil involved in the process as a function of the operating parameters. Then the envisaged technology for the construction of reactive barriers or curtains is described.

In conclusion some considerations concerning the industrial application and the economic feasibility of the method are reported.

Keywords: Soil containment, reactive barriers, waterjet,

1. Introduction

For any remediation project a preliminary decision must be made between the two alternative options of cleanup or containment. The choice should be made on both technical and economic grounds, taking also into account the fact that possible environmental risks may be associated to any action inducing the rupture of a balance naturally established between soil matrix, water and pollutants.

Actually, in the case of cleanup with in situ or ex situ technologies, environmental risks with possible effects on public health, are likely to arise. They include wrong management of surface and groundwater drainage and incomplete treatment process. Unless properly managed, leachates and pollutants can migrate, thus contaminating subsoil, groundwater, and nearby surface streams and even the air in case of release of volatile components.

Considerations for utilizing a treatment method include energy consumption, maintenance costs, requirements for excavation, adequate treatment performance, installation and management of a monitoring system.

The task of physical barriers is that of containing contaminated groundwater, divert uncontaminated flow, and/or provide a barrier for the application of a treatment process.

If containment actions are chosen, groundwater pumping may be necessary in order to remove the contaminants from the encircled area and to prevent migration of contaminants.

Therefore, the site must be investigated for a wide range of conditions, including groundwater levels, surface drainage and subsurface ground conditions. The study must be extended to include the diffusion and spreading of contaminated plumes in three dimensions.

Reactive barriers have the advantage of performing a cleanup process without the risk connected with soil removal, incurred in the case of off-site treatments.

Compared with physical barriers, the benefit of PRBs consists in overcoming the drawback of contaminant accumulation, while avoiding the problem of interfering with the groundwater flow.

However the capability of PRBs to remove or transform the contaminants into harmless products is time dependent, since the filling material used in the barriers will undergo a progressive "saturation" and it may need periodical replacement or reconditioning.

Conversely, since a certain residence time is necessary for a satisfactory removal of the contaminants, the thickness of the barrier must be adequate as a function of its permeability characteristics compared with those of the surrounding soil.

2. Physical Barriers

2.1. Slurry walls

Subsurface physical barriers, often designated as “slurry walls”, consist of vertically excavated trenches filled with a slurry. The slurry hydraulically supports the trench walls to prevent collapse as well as to retard and control groundwater inflow.

Slurry walls are often used where the mass of waste is too large for treatment and where soluble and mobile constituents pose a pending threat to a source of clean water. They are often used in conjunction with capping.

The technology proved effective in many cases. However, specific contaminant types may degrade the slurry wall components and reduce its effectiveness in the long-term, thus eventually requiring further remediation in the future.

Most slurry walls are constructed of a soil and bentonite (S-B) or cement and bentonite (C-B) mixture with water. The bentonite slurry is used primarily for wall stabilization during trench excavation. The backfill material is then placed into the trench (displacing the slurry) to create the cut-off wall that provides a barrier with low permeability and chemical resistance. Alternative filling materials can be used if greater structural strength is required or if chemical incompatibility between bentonite and site contaminants exists, like in the case of strongly acidic or saline waters. Slurry walls are typically made using clam shell bucket excavators.

The most effective application of the slurry wall for site remediation or pollution control with minimum leakage potential is to found it into a low permeability bottom layer such as clay or bedrock. The "hanging" wall configuration in which the wall projects into the ground water table can be adopted to block the movement of lower density or floating contaminants such as oils, fuels, or gases.

An important limitation of the technology is that slurry walls only contain contaminants; accumulation phenomena can even occur due to effluents generated by a plant within the delimited area.

Costs likely to be incurred in the design and installation of a standard soil-bentonite wall in soft to medium soil range from 500 to 750 Euros per square meter, not including variable costs required for chemical analyses, feasibility or compatibility studies, monitoring and testing.

2.2. Grout curtains:

Grout curtains are constructed by injecting grout under pressure. The type of grout most commonly used is Portland cement. Grout curtains reduce the permeability and increase the mechanical strength of the soil but they can be three times more expensive than slurry walls.

Due to economic reasons, grouting is best suited to seal weak and fractured rocks and for situations where other barrier walls are impractical. In addition to cost considerations some grouts, phenolic, acrylamide and polyester are not often used because their toxicity requires special care in handling and safeguards after implementation.

2.3. Sheet piling

Sheet piling consists of a series of shielding screens with interlocking connections driven into the ground with impact or vibratory hammers, resulting in a low permeability cut-off wall for subsurface groundwater containment and control. Screens can be made from a variety of materials such as steel, vinyl, plastic, wood, concrete and fibreglass or other composites.

Sheet piling has been a proven technology within the construction industry for years and for many applications to depths up to 30 m except in rocky or very dense soils.

Joints that can be sealed mechanically or with clay-based, cementitious, polymeric matter after the screens have been driven into the ground.

Advantages of the system compared to slurry walls and geomembranes include: minimal disturbance of the site during construction, rapid installation, adaptability for irregular layouts, easy installation in areas with high water tables and surface water, easy inspection and monitoring during construction, predictable hydraulic performance, and contaminant removal potential.

The barrier can form a key element in the implementation of a “funnel-and-gate” treatment system.

Potential uses of pile barriers include enclosures of hazardous wastes, municipal landfills and industrial sites. Sometimes they are temporarily installed to facilitate in-situ remediation, as well as pilot scale testing of remediation processes. They can be used for isolating accidental spills, preventing seepage of contaminated groundwater into waterways, and reduce the spreading of contaminant plumes to enhance the efficiency of “pump-and-treat” techniques.

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2.4. Geomembrane barrier walls

Accorsing to this recent proposal, a continuous sheet of high density polyethylene is vertically installed, forming a membrane barrier wall. Special equipment cuts through the ground, installs the HDPE sheet from a roll and backfills the space.
Joints are minimized by the technique but when needed a special pair of interlocking profiles are used to connect the sheets. The method minimizes site disturbance and removal or handling of contaminated waste. It would be cost effective selection in certain cases over slurry walls but would depend on the subsurface ground conditions, especially in rocky soils.

2.5. Jet Grouting
Jet grouting is a general term describing various construction techniques in which high-pressure fluids or binders are injected into the soil at high velocities (250 to 350 metres per second). Jet grouting breaks up the soil structure completely and mixes the soil particles in-situ with a binder to create a homogeneous mass, which in time solidifies.
Major advances include increased depth capabilities, more homogeneous mixing, and the ability to capture harmful vapours in environmental remediation projects.

3. Permeable Reactive Barrier:

PRB are constructed underground with the aim of passively intercepting a contaminated groundwater forcing it to flow through a wall of reactive material.

3.1. Basic concept
As groundwater flows through the wall, contaminants are captured and fixed or transformed into harmless by-products as a result of chemical, biological or physical processes. They can be constructed by excavation and backfill methods or as in most cases by trenching.
Sand, zero-valent metals, chelating agents, sorbents biopolymers or microbes are mixed at the proper ratios and introduced into the excavation. Reactive materials can also be placed by jet grouting or mechanical soil mixing techniques.
Overlapping the rows drilled by a suitable equipment creates a treatment zone. The advantages include the fact that no spoiling or disposal of materials is needed, it is much faster and less working room is required.

3.2. Types of PRB
Permeable reactive barriers or zones are an attractive and competitive option for the in-situ remediation of contaminated sites also in view of the many benefits to be gained from their use (EPA 2002):
- ease of installation, low maintenance and running costs;
- cost effective;
- can be used to treat numerous diffuse contaminant sources, often difficult to identify;

There are a number of different types of PRBs:

<u>Continuous reactive barrier.</u> The reactive material is placed perpendicular to the contaminant plume direction (flow lines). The reagent is introduced into a continuous trench filled with material having higher hydraulic conductivity than the terrain to be treated, so as to avoid any significant alterations in groundwater flow.

<u>Funnel-and-gate barriers.</u> This type of PRB consists of a central portion (*gate*) through which the contaminant plume flows, and similarly to the continuous barrier, is filled with a highly permeable material mixed with the reagent. Two impermeable walls are installed at the sides of the gate that direct the groundwater towards the reactive zone. This system offers greater process control but is disadvantaged by the fact that a reduction in cross-section may uncontrollably increase flowrate through the reactive zone, thereby reducing residence times of the contaminated water therein..

<u>Reactive columns.</u> These systems are fairly similar to the tunnel-and-gate barriers. The contaminant plume is directed, by installing impermeable funnels, trenches or embankments towards the reactive zones, generally of cylindrical shape.

PRBs can be installed as permanent or semi-permanent units.

4. potential of waterjet technology

4.1. Application to soils

High-pressure water jet technology was developed primarily for cutting hard materials like stone, glass and metals, because of its ability to concentrate high energy onto small surfaces (Summers, 1994; Ciccu et al., 1998).

To date little research has been conducted and few applications have been tested on granular materials and these are essentially concerned with:

- soil consolidation (*jet grouting*, *soil mixing*)
- excavation or excavation aid
- remediation of contaminated soils

4.2. Experimental results

Little has been published on waterjet action on soils. The most comprehensive studies are those conducted by Yoshida, et al. (1989) who investigated the effect of waterjet generation parameters on a single soil type and by Atmatzidis & Ferrin (1987) who explored the effect of the same generation parameters on different soils under varying conditions. Recent research efforts have focused on the potential use of this technology for cleaning up contaminated sites (Ciccu et al., 2006; Cable et al., 2006).

The techniques traditionally used for soil remediation such as *vapour extraction, soil flushing, steam stripping, bioremediation, bioventing, and air sparging*, (EPA, Annual status report-Treatment technologies for site cleanup: 2001) are difficult to apply to slowly permeable soils. High pressure water jets can be used for increasing the hydraulic conductivity of these soils via displacement and removal of the fine fraction.

The use of high pressure water jets for the selective removal of soil fines onto which contaminants have adsorbed (*upflow washing)* has already yielded promising results in the treatment of NAPL and heavy metal contaminated soils (Niven & Khalili, 1998).

While for compacted fine-grained soils this technique aims to enhance permeability, in moderately permeable soils the water jets can also be used for introducing and distributing substances in the soil (in solution or suspension) that are capable of reducing or minimizing the effects of contamination..

The combination of increasing hydraulic conductivity and introducing reagents makes the HP waterjet technique particularly suited to on-site remediation and specifically for creating permeable reactive barriers (PRBs) or reactive zones (RZs), now recognized as effective technologies for contaminated site clean-up (EPA, 2002). PRB, which are installed to intercept the contaminant plume, act as a kind of large filter.

The results of research conducted to date on the use of waterjet technology for cleaning contaminated soils can be summarised as follows:

- The time required for the water jet to achieve maximum penetration in the soil is in the order of a few seconds, even less in non-cohesive granular material. An exponential relationship exists between penetration depth and action time.
- The relationship between penetration depth and traverse velocity of the nozzle is also exponential and as speed increases so the zone of influence diminishes.
- The volume of soil affected by the action of the waterjet is in any case much greater than the hole bored: this “zone of influence” (zone permeated by water under action of the jet) increases with increasing soil particle size.
- For the same water content, the greater bulk density reduces jet penetration depth; this can be explained by the corresponding increase in resistance and/or reduction in soil permeability. This effect is negligible for sands but very marked for fine-grained soils.
- The degree of saturation influences jet penetration depth into the soil; for soil finer than sand, maximum penetration depth is achieved at complete saturation, while minimum penetration is attained for a degree of saturation of 40-50%.
- Penetration depth increases linearly with hydraulic conductivity of the soil.
- Penetration depth decreases with increasing uniaxial compressive strength.

4.3. Achievements

The experimental results have shown that in sand with a specific gravity of 1.7 kN/m^3, the water jets generated by the 1mm nozzles at a pressure of 40 MPa, form columns with varying radius depending on lance rotation/translation speed.

Tests were carried out on a single soil type keeping operating parameters unchanged except for lance rotation/ translation speed. Further studies are currently under way to investigate the effect of increasing water jet pressure and flowrate. Obviously, an increase in water jet energy will produce a larger radius of influence and result in a more energetic treatment of the soil but also in increased costs. Thus the right balance needs to be struck to maximize effectiveness with the resources employed. A series of tests is planned operating at high rotation speed and low translation speed so as to investigate the effects of helix step covered by the nozzles during motion.
The experimental results highlighted a number of limitations due to:

- Large sample size
- Difficulty in sampling muddy material (mixing)
- Difficulty in understanding and determining particle flow

3.3. Waterjet lance

The drive system for the lance (Figure 1, left), which has two diametrically opposed jets, comprises three motors that impart three different kinds of:

- Horizontal translation
- Vertical traverse motion
- Rotation

Movement and speed are regulated by an electronic control panel. Pressure energy of the water is converted into kinetic energy through the nozzles, made of very hard and wear resistant materials such as tungsten carbide, corundum, diamond or sapphire with diameter ranging from 0.1 to 1.5 mm.
Good nozzle design is paramount to achieving efficient cutting and obviously depends on the use actually made of it: for example, for cleaning operations, the nozzle should be designed such that the stream diverges at the orifice exit, whereas for waterjet cutting the stream needs to remain coherent over as great a distance as possible.
The nozzles are the only waterjet components that are subject to wear by the solid particles suspended in the water. To increase wear resistance, the water needs to be treated beforehand to reduce hardness and the solid matter removed using a multi-stage filter.
Two 1 mm diameter nozzles were used in the tests, positioned perpendicular to the lance rotation axis (Figure 1, right).

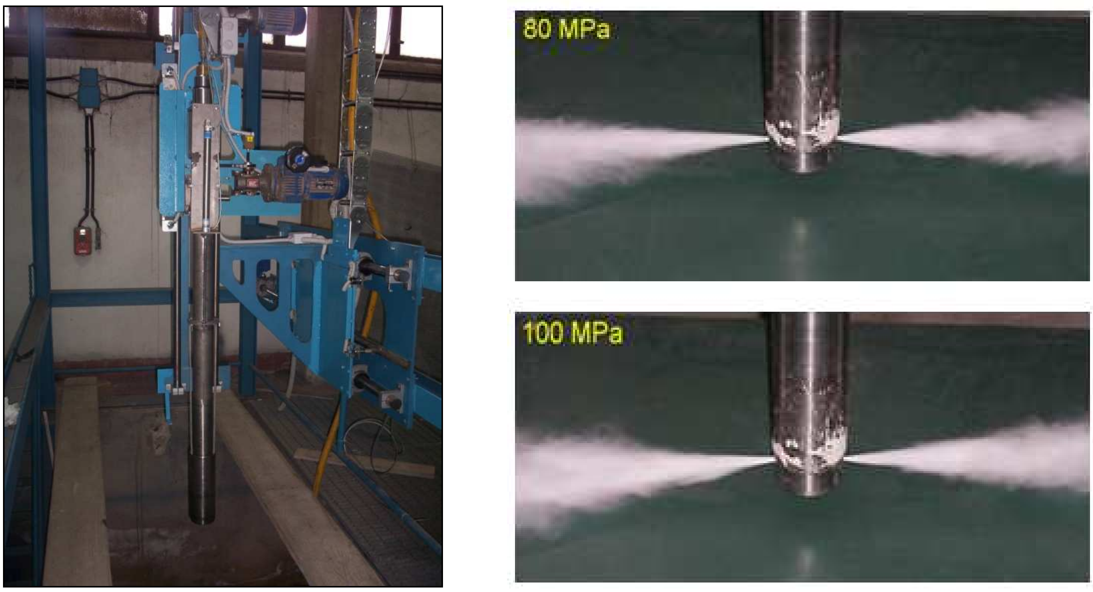

Figure 1. Lance support structure and features of the water jets

5. Waterjet technology for installing reactive barriers

5.1. Vertical columns
The use of waterjet technology for installing reactive barriers consists in creating an aligned series of vertical columns of highly permeable soil into which the decontamination reagents can be injected

(Ciccu et al., 2007). The columns are designed similarly to the jet grouting columns used for soil consolidation, i.e. by introducing a lance into a hole down to the desired depth. One or two horizontal waterjets are then introduced and the lance which rotates around its own axis, is then withdrawn (Figure 2). This produces a vertical column of highly permeable soil

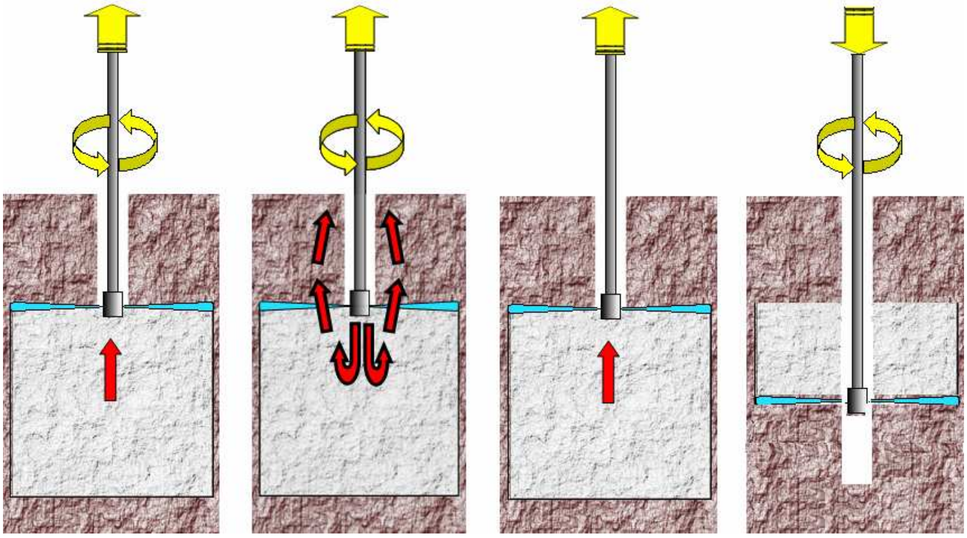

Figure from which the fines, containing most of the contaminants, are then removed.

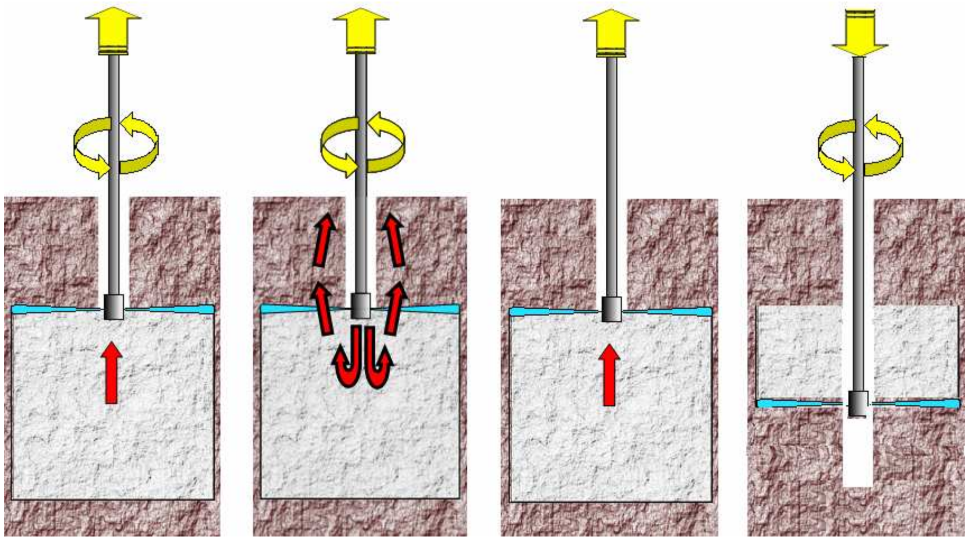

Figure 2. Operating set up of waterjet lance in a vertical cross-section of the soil in different configurations.

The simulations, performed using conventional mathematical models, showed the contaminant to be captured by the barrier in all three cases once stationary conditions had been reached (80 days). The different techniques were then compared in terms of barrier installation costs, amount of contaminant and oxygen consumed by the barrier (Gallo et al., 2009).
Table 1 shows the cost analysis for three techniques from which it clearly emerges that waterjet technology competes well with the traditional techniques, having roughly the same cost as the continuous trench and lower costs than a single line of injection wells. The analysis only took installation costs into account, disregarding the cost of oxygen supply which were it considered would only strengthen the conclusions drawn. .

Table 1 - – Summary of costs for 20 m deep, 18 m long PRB. (US-EPA, 2002)

	PRB width [cm]	Size, Number	Unit cost	Total cost [€]
Continuous trench	80	18 m	1500 €/m	27000
Injection wells	10	21	1500 € each	31500
Waterjet	100	10	2500 € each	25000

Summing up, the barrier created with a line of soil columns treated with the waterjet has lower installation costs, enhances oxygen mobility while maintaining optimum levels of organic substrate degradation.

5.2. Vertical or horizontal curtains

The construction of the columns would require a relatively long time with direct consequences on cost. Since a series of columns will not form a continuous barrier, the reliability of the cleanup process depends on their capability of draining the flow. For this to occur, the permeability of the material in the column (either the treated soil deprived of fines or the filler substance introduced for the purpose of fixing/transforming the contaminants) should be considerably higher than that of the surrounding soil. With the goal of further increasing the permeability sand can be injected together with the reactive substance.

A curtain is obtained by traversing the waterjet lance along its axis with no rotation of the two diametrically opposed nozzles.

The thickness of the curtains should be calculated for allowing enough residence time to the flow until attaining satisfactory cleanup results, depending on the type of contaminant and its concentration. If the case, the problem can be solved by installing a number of curtains suitably placed in order to improve the efficiency of the barrier. The study of the best spatial arrangement of the curtains can be made through computer simulation.

A periodic replacement of the filler material may be necessary for the restoration of the barrier efficiency that underwent saturation. Or else new curtains can be placed in the soil. This option can be preferable owing to the relatively low cost of the curtains.

As for the filler material, the clay-size waste issued from the aluminium production, known as “red mud” can be used to neutralise acid tailings and waste rocks. Red mud has been also investigated in relation to heavy metal fixation in different scenarios (Fytas et al. 2007).

5.3. Injection methods

One of the advantages of waterjet is the capability of carrying a variety of substances, either solid or fluid, that can be injected to form the PRB.

These substances include:

- Chemical additives, generally long-chain polymers, for improving the coherence of the jet
- Inert sand for the formation of the framework of a high permeability wall or curtain
- Reactive material capable of fixing/transforming the contaminants
- Compressed air for enhancing the penetration of the jet
- Chemical or biologic agents for the development of the cleanup process

The task can be accomplished using both concepts of “suspension” and “injection” suitable for the generation of abrasive jets known with the acronyms ASJ and AWJ, respectively. According to the ASJ method, the slurry of water, chemicals and solid particles is premixed into a pressure vessel and delivered to the target through a nozzle at a pressure of the order of 30-60 MPa and a relatively high flowrate (up to 100 l/min) in most applications.

In the case of AWJ, solid particles and air are sucked into a mixing chamber where a Venturi vacuum is produced and are incorporated in a water jet issued through a primary nozzle forming a stream of air, water droplets and solid particles flowing through a focussing tube. Working pressure is typically around 400 MPa and water flowrate few litres per minute.

The choice depends on site conditions.

6. Conclusions

Waterjet technology can be used for creating highly permeable soil columns. Column diameter will depend on soil properties and on waterjet generation parameters and operational conditions. Reagents

can be introduced into the soil columns treated in this way, creating reactive barriers able to intercept and remediate contaminant plumes.
The effectiveness of such a barrier has been evaluated using a mathematical model for simulating contaminant transport and biodegradation phenomena. The analysis showed that the barrier consisting of soil columns treated with the waterjet is equally effective in intercepting the contaminant plume as continuous trenches and injection wells.
Furthermore, the cost of installing a barrier of this type is lower compared to injection wells while it compares favourably with the continuous trench technique, offering the advantage that the contaminated material does not need to be removed.
The barrier can also consist of a series of curtains in a suitable arrangement in order to maximise the contaminants capture ability.

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For the general description of the barriers resort has been made to information available in the internet system.

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