# In situ soil remediation with HP waterjet

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## Abstract

Water jet technology is can be potentially used in a variety of soil remediation processes. A new approach to the problem examines the application of high-pressure water jets for the creation of reactive barriers. In this case, one of the advantages is the increase in soil permeability as the result of a process induced by the jets consisting of fracturing and disintegration of the material and in the removal of the finer particles contained therein.

The papers deals with the research activity carried out at DIGITA's Waterjet Laboratories and the results obtained during a study conducted to evaluate the volumes of soil involved in the process as a function of the operating parameters and the physical modifications induced by jet action. In conclusion some considerations concerning the industrial application and the economic feasibility of the method are reported.

**Keywords**: Soil remediation; waterjet, reactive barriers

## 1. Introduction

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 (*jetgrouting*, *soil mixing*)
- excavation or excavation aid
- remediation of contaminated soils

Likewise, 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 monoaxial compressive strength.

## 2. Study Of Waterjet Action

### 2.1. ***Experimental***

Prior to conducting laboratory and field tests, a preliminary investigation was carried out to evaluate the feasibility of waterjet technology for in situ remediation, determining penetration rate of a continuous waterjet through a granular medium and the displacement and velocity ranges of the soil particles.
The main difficulty associated with this type of measurement and analysis is that the phenomenon occurs extremely rapidly, but this was overcome by using a high speed video technique. Tests were carried out on samples of quartz sand with a particle size of 1-2 mm, placed between two closely spaced parallel crystal slabs. The phenomenon was filmed through the transparent windows with a camcorder and the frames then processed using the *Particle Image Velocimetry* technique- PIV (Raffel & Willert C., 1998), so as to measure particle displacement over time and penetration rate of the water jet through the soil sample. Tests were carried out in the laboratories of the Department of GeoEngineering and Environmental Technologies (DIGITA) at the Cagliari University’s Faculty of Engineering.

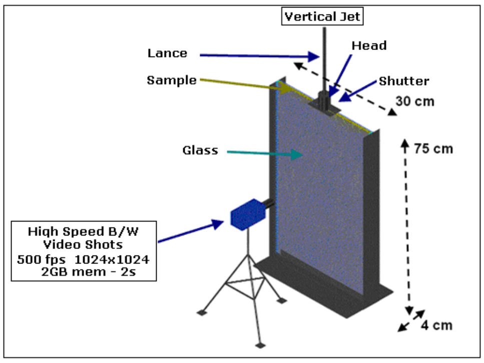

Figure 1.Dynamic image acquisition system

The image acquisition system comprises a high speed camcorder connected to a PC. The camcorder used (MemView 2GB della SouthernVision Inc.) acquires black and white images at a frequency of 500 fps at full resolution of 1280x1024 pixels. Maximum recording time is 2 seconds. It is possible to record for longer times at lower resolution and/or at lower frequencies.

The images were shot under adequate lighting to ensure sufficiently good quality images for subsequent processing.
After a preliminary investigation using a fixed lance, a second series of tests was conducted to study the influence of the traverse velocity in a orthogonal direction on penetration depth.
The choice of soil particle size was dictated by the need to simplify analysis of the video images recorded. Prior to the test, the sample was saturated with water to impart a uniform colour and to ensure that measurement of particle velocity through image analysis was not hindered by the presence of water flowing over the sample surface.
As can be observed from Figure 2, concerning a test conducted on a dry soil sample, two distinct zones can be recognised: the central area is the path of the water jet itself, whereas the outer zone represents the slow permeation of the water introduced by the jet. The presence of this second zone precludes proper analysis of particle velocity.

Figure 2. Image acquired during tests on dry soil sample

Water content of the tested soil was thus set at around 5-7 %, in that as the material is extremely permeable and the bottom of the container perforated, the water actually retained by the soil is only a fraction of the total amount introduced.

## 2.2. ***Particle Image Velocimetry (PIV)***

The optical technique known as Particle Image Velcometry (*PIV*) makes it possibile to measure the displacements and hence velocity of particle fields from a series of images. The pictures stored in the computer are divided up into square meshes that are searched, using statistical techniques, in the subsequent frames. Particle displacement is determined by PIV processing.
The plethora of data to be processed requires the use of sophisticated post-processing techniques also for displaying and summarising the results. The numerical result contained in a series of files can be displayed in the form of displacement vectors between two user-defined time instants $t_1$ e $t_2$ .

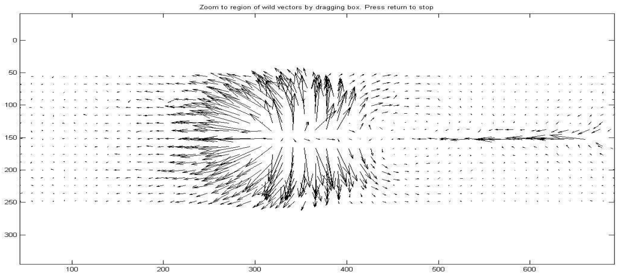

Figure 3. Example of vector representation of the results of geoPIV8 analysis

## *2.3. Results*

Examination of the sample at the end of the test and of the video images, showed that the lateral radius of influence of the waterjet is not constant but gradually increases with the distance of the examined point from the nozzle and hence with penetration of the jet through the soil. A sort of conical kerf can be observed which is caused by the increasingly ragged edge cut by the waterjet.
Examination of the video images also makes it possible to estimate the total time taken by the waterjet to completely penetrate the soil sample. However only a rough estimate can be provided and no other evaluation is possibile apart from that at lower speeds penetration time is longer..
Measurements of penetration rate, its variation (deceleration) and the displacements induced in single portions of soil versus time are obtained with the PIV technique.
PIV data processing generates a penetration rate profile. This is obtained by determining the position of the waterjet at a given instant considering the maximum displacement gradients and dividing the value of the displacement vector by time. The results in terms of penetration rate are shown in the graph of Figure 4 for the different experimental conditions.

A second series of tests was carried out to evaluate the infuence of the translatory movement of the nozzle in a direction orthogonal to the waterjet on penetration rate. The lance was mounted on a support arm connected to an electrically driven displacement device.
The results are shown in Figure 4.

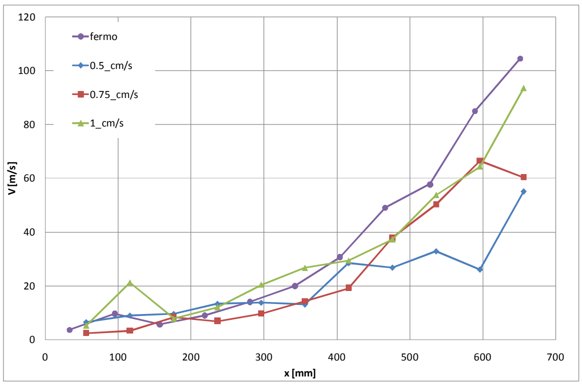

Figure 4 – Penetration rate for translatory velocities of 0, 0.5, 0.75, 1 m/s

As in the previous case, the penetration rate is obtained by determining the time instant in which displacement gradients are greatest and dividing the displacement by time.

## 3. Experimental study of waterjet action on soil

The technique consists of introducing a lance into a vertical hole, drilled using a mechanical device or with the waterjet itself, to the end of which a nozzle holder head is attached, a jet of water exiting from each nozzle. Combining rotary and axial translatory movement, helical movement is imparted to each nozzle. The rotary motion ensures that the jet of water reaches the points arranged over an arc of 360°C, while the translatory motion ensures that at each nozzle rotation overlapping slices of soil are treated. In this way the soil volume involved can be represented by a cylinder with vertical axis. The treatment of a given volume of soil is obtained constructing a vertical grid. The grid side length, in terms of distance between adjacent columns, is one of the most important parameters for this technique and is related to the distance at which the treatment is still effective.

Thus the experimental study focused on the laws relating the radius of the soil column treated to the waterjet parameters, namely:

- jet pressure;
- number and diameter of nozzles;
- flowrate of each jet and combined flowrate (function of pressure and nozzle diameter);
- stand-off distance;
- lance rotation-translation speed;
- helix step (defined by the above parameters);
- jet direction.

The optimum combination of these parameters for obtaining high column radius of the treated material and for achieving high ultimate permeability (index of treatment effectiveness) depends on the soil properties, especially particle size, density, mechanical strength, mineral composition, porosity and water content (Yoshida, Shibazaki, Kubo, Jimbo, & Sakakibara, 1989). Laboratory studies were carried out to investigate these properties.

### *3.1. Experimental set-up*

A continuous waterjet system was used for the experimental tests, neglecting pressure fluctuations of the piston pump, kept to within the limit of 2%. The system essentially comprises a moveable lance connected to a pressure pump and to a support frame which contains the soil sample to be tested. Pressure energy is converted into kinetic energy by means of two opposed nozzles with a roughly 1 mm diameter sapphire orifice, perpendicular to the lance rotation.

The lance is connected to an electric two-motor drive system, that actuates vertical translation and rotation. Rotation speed is regulated by means of frequency converters mounted on the control panel . The pressure system consists of a piston pump that delivers a flowrate exceeding 50 l/min at a maximum pressure of 250 MPa.

### *3.2. Preparation of test sample*

Experimental tests were carried out on samples of sand mixed with clay previously characterized by means of grain size analysis (Figure 5), edometric tests and permeability tests.

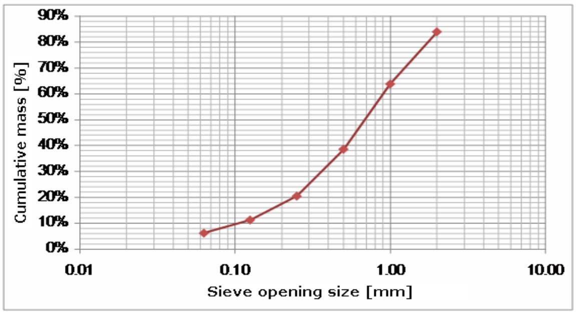

Figure 5. Grain size curve of the sand sample

Each sample, weighing a total of around 75 kg was compacted layer by layer in 80 cm diameter by 30 cm high cylindrical containers. Operating procedure was as follows:

1. Material selection and weighing
2. Addition of water where necessary and homogeneization in a cement mixer
3. Material loaded into container
4. Material compacted with a hydraulic piston
5. Cores drilled for creating hole for inserting lance.

The material has a coefficient of consolidation of $8 \cdot 10^{-3}$ $cm^2/s$, a coefficient of volume compressibility of $4 \cdot 10^{-3}$ $cm^2/kg$ and hydraulic of $3 \cdot 10^{-3}$ cm/s.

### *3.3. Waterjet lance*

The drive system for the lance (Figure 6, left), which has two diametrically opposed jets, comprises three motors that impart three different kinds of:

- Horizontal translation

- Vertical translation
- 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 6, right).

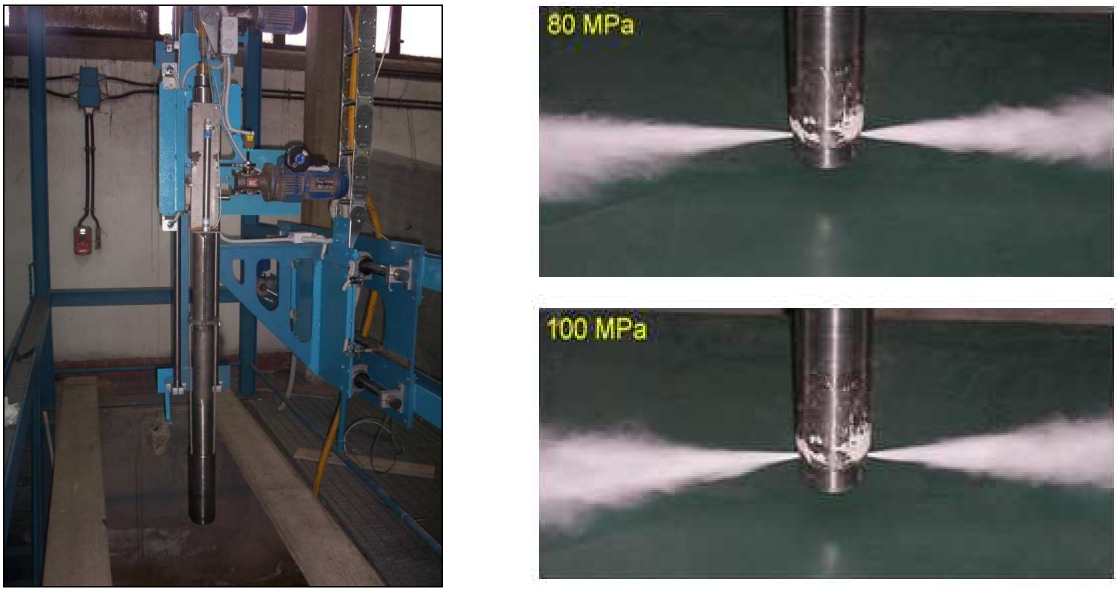

Figure 6. Lance support structure and features of the water jets

### *3.4. Experimental results*

The radius of action of the waterjet, and hence of the treated soil volume, versus lance rotation/translation speed is shown in Figure 7. As anticipated, the radius of influence decreases with increasing speed and was found to range from 23 to 36 cm in dry soil and from 19 to 27 cm in saturated soil . Thus operating on dry soil results in a twofold increase in performance.

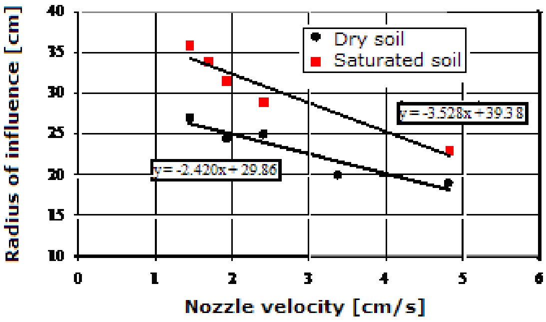

Figure 7. Radius of influence versus absolute nozzle velocity

### *3.5. Discussion*

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

## 4. Field tests

A full scale in situ experimental investigation was conducted using a commercial waterjet system to assess the reliability of the laboratory results, in particular execution times versus operating variables. A jet grouting system was used consisting of a water/cement mixer, a mixing pump and a lance fitted with a nozzle holder (Figure 8).

The 65 mm lance, mounted on a tracked vehicle, is fitted with drivers for rotary and translatory motion. It is also equipped with a 70 mm cutter head for boring the hole for water injection and is connected to the pump by means of a 40 m long 40mm diameter tube..

For the in-situ investigation this system was tested using plain water.

Figure 8. Water injection system: tracked vehicle with lance, pump and control panel

The pump generates pressures of up to 37 Mpa, relatively low compared to those used in the laboratory tests, though hydraulic power is substantially comparable in the two cases considering the greater flowrate produced by the larger diameter nozzles.

## 5. Permeable reactive barriers (prb)

### *5.1. 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:

**Continuous reactive barrier**. 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.

**Funnel-and-gate barriers.** 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..

**Reactive columns.** 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.

### *5.2. Waterjet technology for installing reactive barriers*

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. 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 9). This produces a vertical column of highly permeable soil Figure from which the fines, containing most of the contaminants, are then removed.

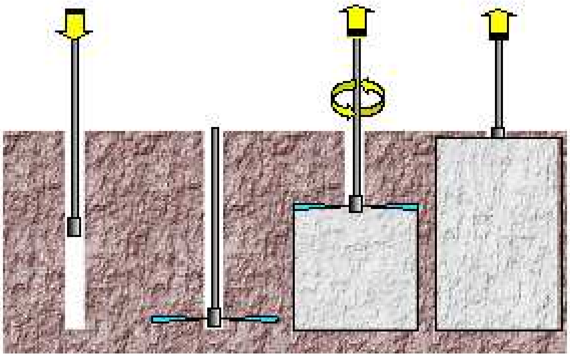

Figure 9. Operating set up of waterjet lance in a vertical cross-section of the soil. Simulation results

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 | Size, Number | Unit cost | Cost [€] |
|---|---|---|---|---|
| **Continuous trench** | 80 cm | 18 m | 1500 €/m | 27000 |
| **Injection wells** | 10 cm | 21 | 1500 € each | 31500 |
| **Waterjet** | 100 cm | 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. Conclusions

Waterjet technology can be used for creating highly permeable soil columns. Column diameter will depend on soil properties and on waterjet generator operating parameters. 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..

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