Using water jet for increasing reactive barriers efficiency in contaminated soil: a preliminary evaluation

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The water jet is a widely used technology in the dimensional stones industry, for cutting metals, glass, etc. This technique has been recently considered for soil disgregation/fracturation and, in general, for increasing soil permeability. A waterjet equipment consists of a pressurising unit connected with a lance which has a block at its free end in which two or more nozzles are inserted. The lance is inserted in the soil and a high-velocity water jet is produced that is able to destroy soil structure and/or to fracture/displace highly-compacted impermeable soils. One possibility is to increase the area of influence of reactive barriers.

In this work, we present preliminary modeling results on the effects of water jet on the area of influence of wells. Our study is conducted through a set of numerical simulations. The evaluation is performed on the basis of variations produced from soil modifications on water injectable rate, area of influence of the chemical species that are transported and on the amount of contaminant released in the soil. Finally, we discuss future developments in our study in terms of both modeling and laboratory experiments.

1. Introduction

Reactive barriers are one of the most popular and long-term intervention techniques for soil restoration/remediation. When properly implemented, they are capable to intercept the contaminant flow and degraded it as a sort of large size reactive filter. These barriers are practically implemented by excavating a trench and filling it with a suitably treated soil and/or a row of wells in which chemically active compounds are injected. In both cases, the barrier releases of compounds that promote contaminant degradation and filters the incoming polluted water. The implementation of standard reactive barriers may be costly and time consuming. The use of waterjet technology is seen as a viable alternative to reduce both costs and realization time. The waterjet technology [1] consists in the

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production of high velocity water jets by special pumps or pressure intensifiers. They are currently used for cutting stones, metals and many other materials. Portable versions of these machines are constructed for waterjet kerfing in dimensional stones quarrying (marble, granite), in industrial surface cleaning, in the demolition of building or industrial structures. Furthermore this technology is used for military operations such as warhead defusing and in the medical field. In the later application it allows the selective cutting of tissues with different strength. As documented later, when inserted in a soil, the waterjet lance can cause soil fracturing and disgregation and locally increase soil permeability [2]. Thus, this device is regarded as potentially capable to conjugate the creation of a large area of influence around the injection point with a quite small excavation cost. As one may expect, this is to be confirmed both from the modeling and, above all, from laboratory and field measurements.

In this work, we present some preliminary results on modeling waterjet applications for implementing reactive barriers filtering contaminated water driven by groundwater flow. The outline of this paper is as follows. In section 2 a general description of the waterjet equipment is given. Then, in section 3, the main processes that we accounted for are described and the governing equations are listed. Section 4 focuses on the modeling of permeability variations caused by the water jet and on the definition of area of influence. In sections 5 we present simulation results and we discuss them in terms of efficiency and implementation costs. Finally, conclusion and future developments are discussed in section 6.

2. The waterjet equipment

A waterjet device consists essentially of two main parts: the pumping device and the nozzle for the generation of the jet. The pumping device is usually a plunge pumps drawn by a diesel or electrical engine. The nozzle can be obtained in a sapphire stone mounted on a carbide support with a conical entrance or can consist in a cylindrical hole realized in a hard steel support. A general scheme of the waterjet lance is shown in figure 1 where the different stages of the water jet action are displayed. The lance, as shown in figure 1, consists of a pipe connecting the pressure generation unit at the nozzles head, as shown in figure 2-left. It is disposed with its axis in vertical direction and it is animated by two contemporaneous movements: a translation parallel at its axis and a rotation around the same axis. As a consequence the jets flowing from the nozzles describe spiral trajectories with vertical axis. This equipment is carried by a metallic structure under which there is the vessel containing the soil to be treated, see figure 2-right. The multiple nozzles head, see figure 2-left, has been designed to meet the following goals: 1) generation of four high-velocity water jets: two with direction normal to the lance axis and the others at 15^o with respect to it; 2) air injection; 3) introduction of fine grained solids; 4) water extraction. The specimens to be tested will be prepared in cylindrical vessels of 80 cm in diameter and 100 cm in height. Their physical properties will be obtained through a consolidation process induced by the application of vertical loads.

The pressure used for generating the jets spans from 100 to 300 MPa and the flow rate varies from 10 and 120 liter per minute. In table 1 the value of the operative parameters of the water jet are depicted for typical uses. The experimental equipment to be used

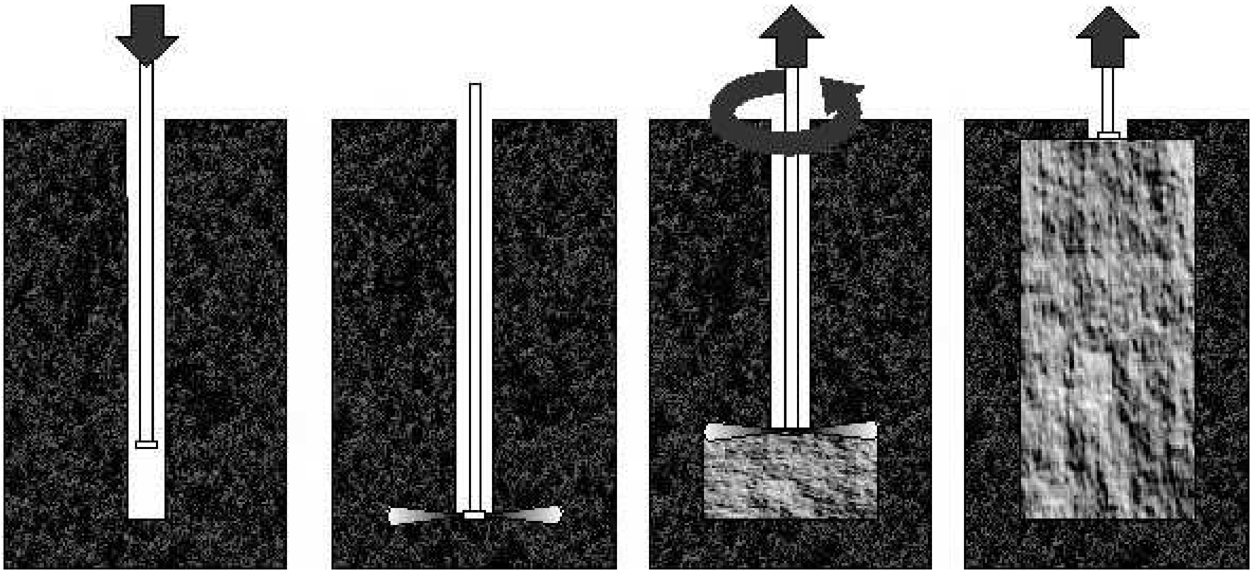

Figure 1. Sketch of the lance of a vertical section of soil in which the water jet is inserted. The four images schematize the different steps of the technology. From left to right: 1) insertion of the lance in the soil; 2) jet start; 3) rotation of the lance and vertical translation; 4) end of the process when the lance reaches the top layer of the soil.

Table 1
Technical characteristics of the waterjet technology.

Test number	1	2	3	4	5	6
Nozzle diameter [mm]	1.5	1.5	1.5	0.9	0.9	0.9
Generation pressure [MPa]	15.0	30.0	60.0	15.0	30.0	60.0
Flow rate [l/min]	11.3	16.1	22.9	4.1	5.8	8.2
Penetration [cm]	38.0	63.0	77.0	20.0	27.0	43.0

for contaminated soil treatment is composed by the pressure generation unit that is hydraulically connected with a lance that is provided, at its free end, with a multiple nozzles head.

The current modeling work was suggested from our previous laboratory experiences. The study of the effect of the water jet on soil hydraulic conductivity began performing some tests in which the jet operated on a column of compacted soil for a fixed time interval (1.00 second). The objective was to study the dependence of the penetration from the operative parameters of the jet (generation pressure and flow rate). The results are presented in table 1. In another cycle of tests the effect of the relative motion between the nozzle and the soil was studied. The nozzle had a linear movement with the respect of the soil. Also in this case the penetration was measured for various values of relative velocity and different operative water jet parameters. The results obtained are plotted in

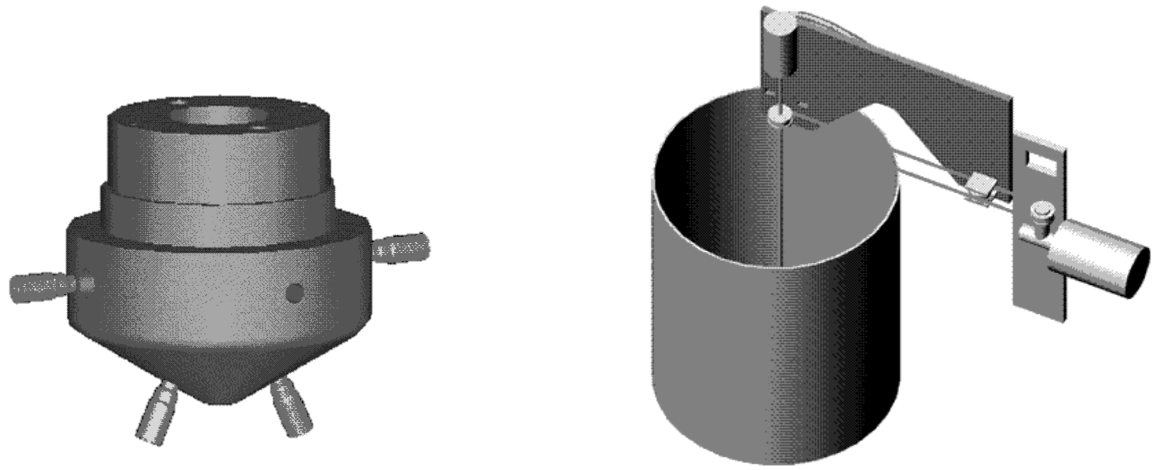

Figure 2. Head of the lance (nozzles are also visible in the CAD-image) (left) and laboratory device for the laboratory experiment (right). The diameter of the vessel used shown is approximately 80 cm while the height is about 1 m.

figure 3.

3. The modeling approach

The modelling of the WJ application for the case of reactive barriers in groundwater relies on three major processes, that is, saturated flow, multispecies transport and biodegradation. The governing equation for two-dimensional horizontal flow is the following [4]:

$$S_s \frac{\partial h}{\partial t} = \nabla \cdot (\mathbf{T} \cdot \nabla h) \tag{1}$$

where h is hydraulic head, $\mathbf{T}$ soil transmissivity, and S_s is the soil storativity coefficient. The governing equation for multispecies transport reads as follows [5]:

$$\phi \frac{\partial C_i}{\partial t} + \nabla \cdot (\mathbf{v} C_i) = \nabla \cdot (\phi \mathbf{D_h} \cdot \nabla C_i) - \phi B_i, \quad i = S, O \tag{2}$$

where ϕ is the porosity of the medium, C_i is concentration of the i-th species, $\mathbf{D_h}$ is the hydro-dynamic dispersion, $\mathbf{v}$ is Darcy's velocity, and B is the source/sink term. Subscripts S and O stands for organic substrate and dissolved oxygen, respectively. Biodegradation was modeled accounting for a rather simple model of aerobic degradation including an organic substrate (the contaminant), and electron acceptor (oxygen) and a bacteria population. The governing equations for the biodegradation model selected read as [3]:

$$\begin{aligned} B_S &= C_X \mu_0 Y_S \frac{C_S}{K_S + C_S} \frac{C_O}{K_O + C_O} \\ B_O &= C_X \mu_0 Y_O \frac{C_S}{K_S + C_S} \frac{C_O}{K_O + C_O} \end{aligned} \tag{3}$$

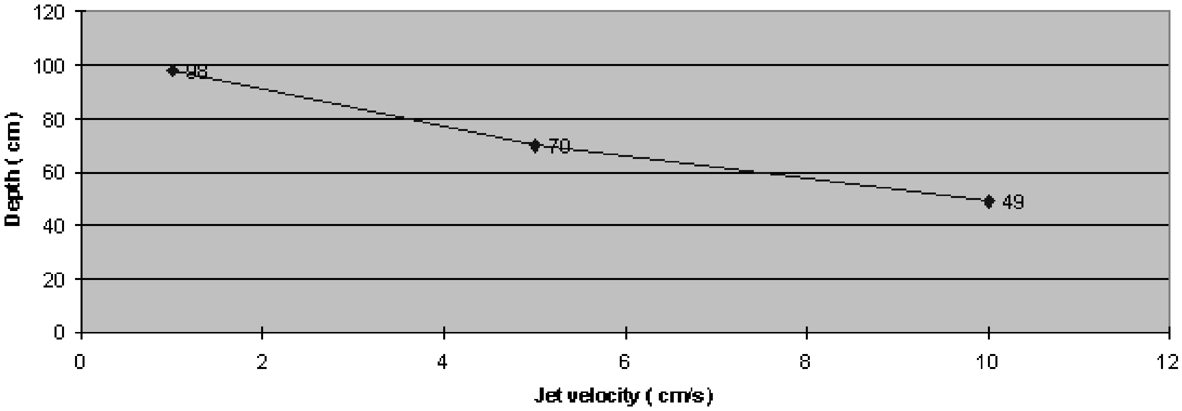

Figure 3. Relation between water jet tranverse velocity and depth of penetration.

$$\frac{\partial C_X}{\partial t} = -C_X \left(\mu_0 \frac{C_S}{K_S + C_S} \frac{C_O}{K_O + C_O} - k_d \right)$$

where μ_0 is the maximum degradation rate, K_S and K_O are the half-saturation constant for organic substrate and oxygen, respectively, Y_S and Y_O are yield coefficients, k_d the bacteria decay coefficient, and C_X is the mass of bacteria per unit volume.

The numerical solution of the system of equations presented so far was computed using standard linear finite elements for spatial discretization, and finite differences for time discretization. Biodegradation equations were coupled with advection-diffusion using a standard operation-splitting approach. At each timestep, the transport equation was solved and, then, for each node, the concentration were corrected by the biodegradation term. The timestep was kept small in order to ensure an sufficient accuracy in the solution (more details can be found in references [6,3]).

4. Permeability and area of influence

The water jet causes soil grains fracturation, clay melting in a sort of mud, sand displacement. In some cases, the jet may be simply deviated by pebbles or small rocks. As one can understand, the effect of the rotating jet is generally not homogeneous but can produce local heterogeneities that modify soil texture. The way of modeling these modifications is not unique. As a first approach, we have considered the global effect on variations as the product of two independent components, one that accounts for a radial effect, and another simulating local, randomly-distributed heterogeneities:

$$T(x, y) = T_0(x, y) \exp\left(-r(x, y)/R^*\right) \left(-0.5 + A \cdot rand()\right) \tag{4}$$

where we indicated with T_0 the initial distribution of the transmissivity, R^* is an attenuation constant, r is the distance from the waterjet injection point, A is scaling correction factor and rand is a generic random-number generation function.

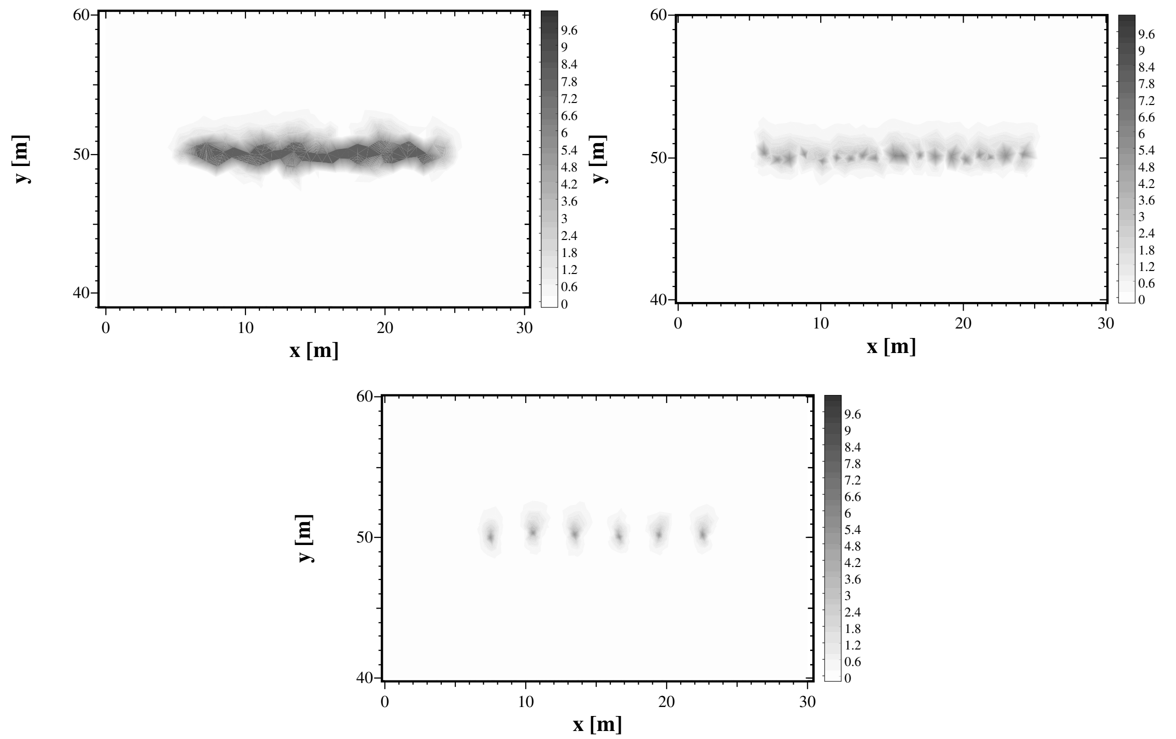

Figure 4. Initial conditions for oxygen for the continuous trench (left), wells case (center) and the waterjet case (right).

In this work we refer quite often to the *area of influence* of a species. This is defined as the area (we work in two dimensions) of the domain in which the concentration of the species under study is higher than a user specified threshold value:

$$A_{influence} = \int_{\Omega} F(C) d\Omega \tag{5}$$

where Ω is the area of the domain and $F = 1$ where $c \geq \bar{c}$ and $F = 0$ where $c < \bar{c}$. This definition allows us to quantify the effect of the reactive barrier on the whole domain.

5. Results and discussion

The potential applications of the waterjet device are manifold. In this paper we focus on a preliminary evaluation of the water jet in the setup of a reactive barrier intercepting a plume of organic contaminant transported by groundwater flow (more details on the results presented here can be found in reference [6]). Our objective was to investigate how the water jet can be applied to build a reactive barrier with a lower effort and at a lower costs compared to other commonly used techniques. To do this, we considered the case of a rectangular domain that is contaminated by a spill occurred at one end of the boundary. It is assumed that field sampling allowed to identify the source location and the direction of the flow, and, as a consequence, a possible location of the intercepting

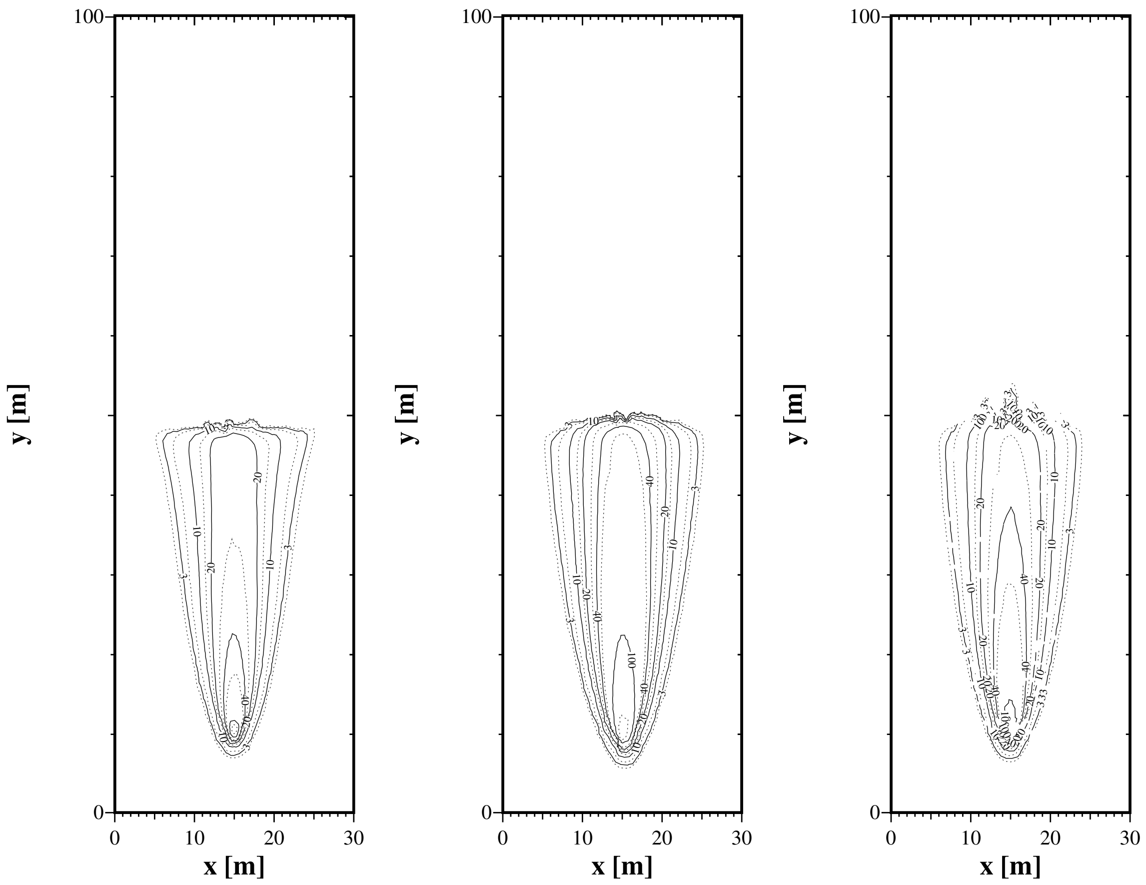

Figure 5. Substrate plume at t=80 days for the continuous trench (left), line of wells (center) and water jet (right).

barrier. The domain, 100 m long and 30 m wide, was discretized using and unstructured mesh of approximately 9800 triangular elements and 5000 nodes. At t=0 we assumed a uniform concentration of both oxygen and bacteria, while no contaminant was present in the domain. The total simulation time was 80 days. Three cases of reactive barrier were simulated: a) a line of wells; b) a continuous trench; c) and a line of wells in which the water jet was applied. For all the cases, the empty space created with either the continuous trench or the wells are filled with a special oxygen-releasing matter in order to promote biodegradation. In table 2 details are given on the alternative reactive barriers. In Figure 5 the plume of contaminant is shown for the three cases at t=80 days. One should notice that the three plumes are somewhat between the source of contamination and the reactive barrier. This is due to the differences of permeability caused by the presence of the trench, the wells, and the wells treated with the water jet. The volume of perturbed soil increased when passing from simple wells, waterjet wells and to the continuous trench, respectively. As a consequence, this caused a proportional increase of hydraulic conductivity in the domain. This induced an increase of flow velocity and,

Table 2
Mass balances and costs of the three interventions.

	Mass of O_2 [g]	Mass of S [g]	$A_{influence}$ of O_2 [m^2]	$A_{influence}$ of S [m^2]
Water jet	1277	13539	656	655
Trench	4577	9650	1016	605
Wells	4172	22721	1300	691

thus, an increase of dilution of the contaminant. The comparison of the three techniques was made in terms of area of influence, amount of oxygen present in the soil and cost of the three interventions. In figure 6-left the area of influence of both oxygen and substrate are shown as a function of time. These indicate that the water jet is able to contain the area of influence of the contaminant with a area of influence of the oxygen. In the right part of figure 6 the mass of oxygen and contaminant present in the domain are shown as a function of time. We note that the amount of oxygen present in the domain for degrading the contaminant is lowest one for the case of the water jet. This indicated a good efficiency of the water jet in delivery dissolved oxygen for promoting the degradation. Table 2 summarizes the results obtained for the three cases at $t = 80$ days. The mass of dissolved oxygen present in the domain, the mass of contaminant, the area of influence of dissolved oxygen and of the contaminant. The relevant information, that can be derived from this table, is that the use of the water jet increases biodegradation efficiency for the same degradation of organic substrate. Our evaluation was based on the area-of-influence concept on which some arbitrary threshold of the chemical species are set by the user. Further investigation is needed on this issue.

When considering the analysis of the costs of the warious intervention, the water jet compared well with respect to the line of wells and the continuous trench. The cost evaluation was made taking into account mainly the excavation costs (operational costs have been neglected at this stage). As shown in table 3, our evaluation indicates that waterjet intervention is the most convenient among the three solutions examined. We remark that this evaluation is not conclusive at all, but it is considered an interesting indication that needs to be investigated in more detail.

6. Conclusions and future developments

In this work we presented a preliminary modeling evaluation of the waterjet technology applied to polluted soils. This technology is seen to be useful for improving the efficiency of reactive barriers and for reducing both realization and operational costs. Being the use of this technology brand new in soil contamination scenarios, we considered a simplified scenario for reducing the complexity of the problem to be modelled. We identified saturated flow, multispecies transport and contaminant degradation as the main processes taking place in the system considered. Furthermore, the variations of permeability caused by the jet were modeled multiplying the initial value by a negative exponential term accounting for the distance from the injecting lance and a stochastic term including possible heterogeneities created by the jet.

Table 3
Summary of costs.

Reactive-barrier type	Global costs [Euro]	Details
Continuous trench	22000	depth=20 m, width=80 cm
Line of wells	30000	depth=20 m, diameter=10 cm
Water jet	15000	depth=20 m, diameter=10 cm

In order to test our model, we considered an hypothetical contamination scenario at field scale. An aquifer was assumed to be contaminated by an inflow of dissolved organic substrate invading the domain. Three biological reactive barriers setup were considered for intercepting and filtering the contaminated water: a set of wells, a continuous trench and a set of wells to which the water jet was applied. In all cases, we assumed that the oxygen-releasing matter was filling the empty space produced by soil removal (wells and trench) or soil removal/fracturing (water jet). The evaluation was made in terms of contamination removal efficiency, amount of oxygen released in the soil and in terms of installation costs.

Our analysis indicated that the application of the waterjet technology can be effective in promoting dissolved-oxygen delivery. The efficiency of each well is increased by soil fracturing and a smaller number of perforations was required compared to other techniques. This implied also that a smaller amount of supplied oxygen was needed for biodegrading similar amounts of contaminant. This effect was inferred from a small area of influence of oxygen and the small area of influence of organic contaminant. This would indicate also lower operational costs compared to the other two cases. An approximate estimate of installation costs indicated that the use of waterjet equipment is more convenient than the other two alternatives presented in this work, that is, the line of wells and the continuous trench, at least for the depth of 20 m we considered. We remark that our estimated costs did not go into a deep detail, but this result was encouraging. Actually, we are aware that our evaluation is currently based only on modeling results that will have to be verified against laboratory and field measurements. This work, however, has given us a number of indications regarding what future work should focus and questions to be answered, some of which are listed below:

- what is the impact on unsaturated porous media? In our study we considered only the saturated case, but we do expect that the water jet may be used more effectively in unsaturated porous media, when the air-filled porous media is more sensitive to waterjet action;

- how and how much does the area of influence change when injecting a viscous fluid containing oxygen-releasing matter? We considered that the water jet made some "free-space" in the porous medium and that this empty space was filled with oxygen-releasing matter. However, this stuffing matter is probably a kind of non-newtonian mud, whose characteristics are similar to those of concrete injected in soils in jet-grouting applications for consolidation practice in civil engineering. When considering the non-ideality of the oxygen-releasing matter, the real area of oxygen delivery is expected to be smaller than that hypothesized here;

- the injection of oxygen releasing matter is performed for enhancing bacterial efficiency. Increasing biomass growth may cause pore clogging and this may affect the global efficiency of the installation;
- the area of influence considered in this work relies on the hypothesis that all the space wiped with the waterjet "beam" undergoes a significant increase of permeability. This is not necessarily true, since the modification may be transient (the soil structure may collapse on itself) and an increase of permeability close to the injection point may cause a decrease of permeability far from the injection point (a sort of hard coating shell may be created around the jet due to compaction of soil grains).

These are some of the issues on which we are going to work in the near future.

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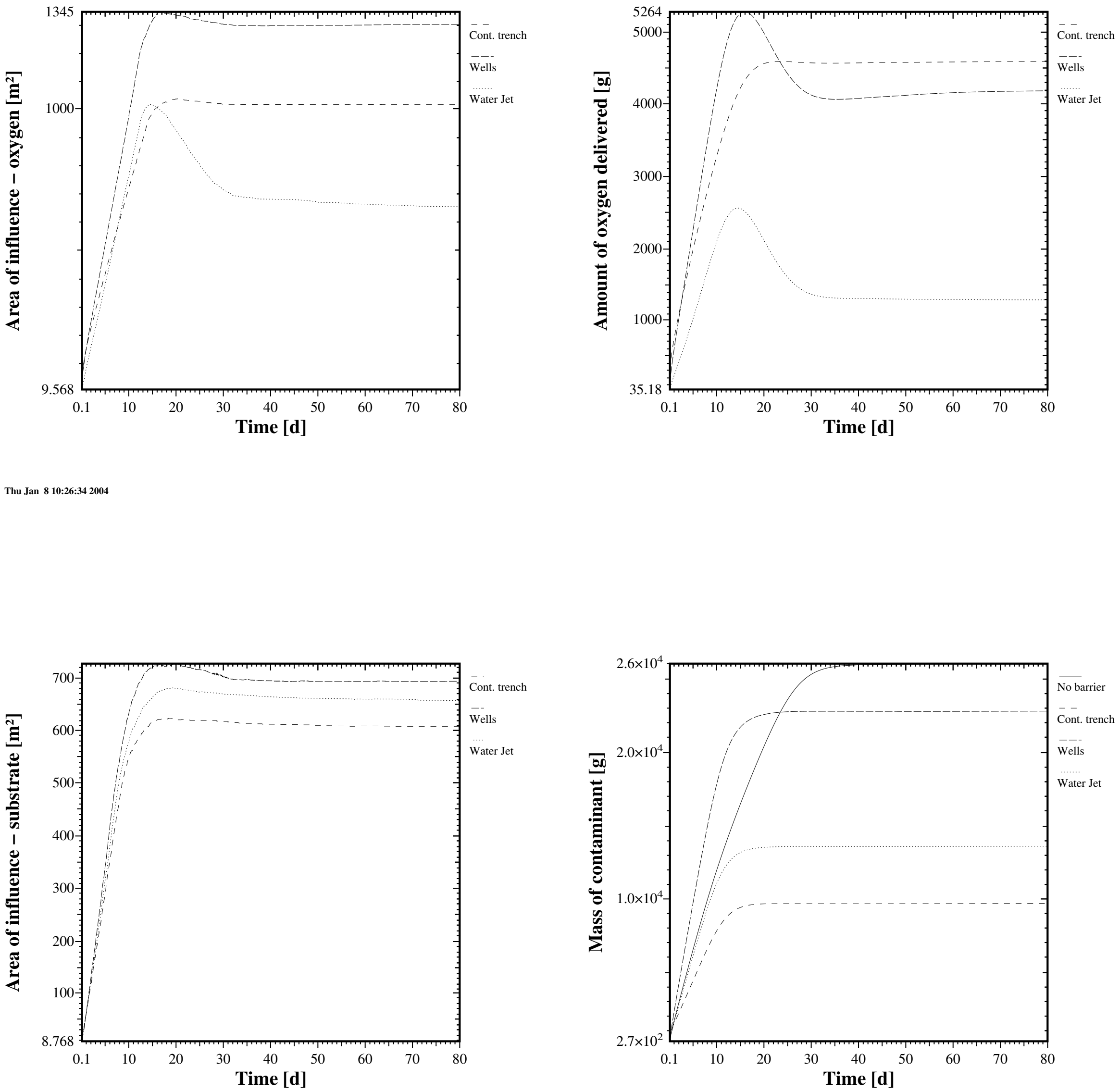

Figure 6. Area of influence for the oxygen (left-top) and substrate (left-bottom), and amount of oxygen (right-top) and substrate (right-bottom) present in the domain (right) as a function of time.