Injection of liquids into the soil with a high-pressure jet

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Abstract: With regard to injection fertilizing, the more general topic of liquid injection into the soil with the aid of a high-pressure jet is of great importance. Injection fertilizing means that liquid fertilizer is injected into the soil near the plant roots. This provides many agronomical advantages. However, currently available mechanical injection fertilizing techniques in the field use have some disadvantages, such as very heavy wear on individual components. Therefore, research on the direct, contactless injection of liquids into the soil with the aid of a high-pressure jet is being carried out at the Institute of Agricultural Machinery and Fluid Power of the Technische Universitaet of Braunschweig. The potential and the possibilities of injection by a high-pressure jet are being examined in trials on a stationary test rig. In these trials, different soils were used under different conditions (soil moisture, and soil density), and the possibilities of injecting pure water in the form of a high-pressure water jet were studied. It was shown that the variation of different parameters of the high-pressure jet, such as water pressure, volume flow, etc., allow different injection depths in the soil to be realized. Especially soil moisture has a very great influence on injection. In dry soils, for example, the binding forces of the soil bodies (solid body bridges, van-der-Waals forces, etc.) are very strong so that only small injection depths can be reached. The higher the degree of soil moisture is, the larger the injection depth becomes. Depending on the soil type, average soil moisture, water pressure of 40 MPa, and speed of the nozzle over the ground of 2 m/s provide injection depths of 70 – 90 mm. In addition to application in the area of injection fertilizing, the considered injection of liquids into the soil also shows great potential in plant protection, irrigation, as well as the injection of decontamination agents into contaminated soils.

Keywords: injection of liquids, soil, fertilisation, high pressure, contactless, frictionless

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1 Introduction

Due to the very significant increase in fertilizer prices in recent years, fertilizer application techniques are showing a trend away from the conventional distribution technique towards injection, which means that, in contrast the conventional spreading technique, the fertilizer is injected into the soil instead of being distributed on a large surface area. This so-called injection fertilizing is a technique in which ammonium fertilizer rich in nitrogen is deposited in the soil near the plant roots instead of nitrate fertilizer. In order to reach an optimal fertilizing effect, deposition in highly concentrated depots in the soil has proven an efficient solution. As compared with other fertilizers rich in nitrogen, it is one of the advantages of the ammonium fertilizer used that it cannot be washed out by rain and remains in the soil as a stable source of nitrogen. In the literature, injection fertilizing according to this technique is termed CULTAN (Controlled Uptake Long Term Ammonium Nutrition) (Sommer, 2005; Matoka, 2008).

In the current technical applications of this technique, the fertilizer is deposited mechanically. Spokes inject fertilizer into the soil in the form of depots at a depth of 50 – 90 mm. The spokes are arranged like stars on spoke wheels which can roll on the ground. A

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hub-controlled valve in the spoke wheels controls fertilizer application (N. N., 2008). The disadvantage of this technical realization is the high cost of the injection equipment. In addition, the spokes are in direct contact with the soil, which may lead to nozzle clogging and causes wear on the spokes due to continuous penetration into the soil. Moreover, the spokes may break if they hit foreign bodies.

Given the disadvantages of this technique, research on the direct, contactless, and therefore wear-free injection of liquids into the soil with the aid of a high-pressure jet were carried out as a part of the research project promoted by the German Research Foundation (DFG) in order to show the possibilities and the potential of this method. The main advantage of this method is the non-existing of a special injecting tool. The high pressure jet functions as the injecting tool. The fundamental examinations are not carried out in the field use, but on a stationary test rig for water cutting. During these trials, exclusively pure water is used. Some examples of the results of the research project are given in the following chapters

2 Theoretical fundamentals of the injection of liquids into the soil with the aid of a high-pressure jet

The interpretation of injection and the behaviour of the high-pressure jet during injection first require a theoretical consideration of injection. Therefore, some general theoretical fundamentals concerning of the structure of a high-pressure jet and its abrasion of a general material are discussed, followed by a theoretical consideration of the binding mechanisms of the soil grains in the soils used which must be broken up by the high-pressure jet. Based on these two considerations, a theoretical study of injection into the soil by a high-pressure jet is presented.

2.1 Structure and abrasion behaviour of a high-pressure jet

The high-pressure jet (with pressure >30 MPa) is formed in a jet nozzle. After the jet leaves the nozzle, it develops into a free jet. The properties of the free jet change with its distance from the nozzle. Figure 1 shows the schematic structure of the free jet. Depending on its distance from the nozzle, the free jet can be divided into a starting zone, a main zone, and an end zone.

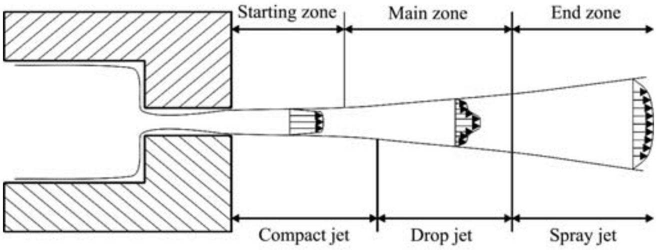

Figure 1 Structure of the free jet

In the starting zone, the jet is still compact and has a speed of more than 850 m/s (Susuzlu, 2008, Wulf, 1986), which depends on the pressure and the volume flow. However, the jet core, whose density and speed remain the same after it leaves the nozzle, tapers off. In the boundary layer area of the jet, speed abruptly drops to 0 m/s. In the main zone, the jet continues to fan out due to an impulse exchange with the surrounding air. Speed distribution in the jet changes constantly. Initial droplets form at the edge of the jet. In the end zone, the previously compact jet has completely dissolved. An uncountable number of atomized droplets has formed, which have mixed with the air. The dimension of the starting zone and the main zone depends on the pressure and the volume flow and is normally less than 50 mm each. In order to be able to use the high-pressure jet, it is necessary to avoid the end zone because the jet has lost its high energy concentrated in one point (Mohamed, 2004; Werner, 1991; Wulf, 1986).

After the distance between the nozzle and the surface of the material has been covered, the formed free jet hits the material. When the water, which is flowing with a very strong velocity, suddenly hits the surface, an impact force acts on the material. If the distance between the nozzle and the material used as a target for the high-pressure jet is small (10 – 40 mm), one can assume that the cross sectional area of the high-pressure jet is virtually constant, which can be seen in the common waterjet-technology with a pressure of 100 – 400 MPa and a flowrate of 3 – 10 L/min (Krismann, 1994). The impact force which acts on the surface causes material abrasion. In order to be able to explain the reasons for this material abrasion in detail, firstly a single droplet is considered, whose effect is described using a general material as an example.

2.1.1 Impact and impact pressure phase

As is shown in Figure 2, an impact pressure phase occurs after the single droplet hits the surface.

The impact force causes a shock wave in the material which spreads spherically in the direction of the jet around the place of impact in the material (Kroos, 1995). This shock wave leads to plastic deformation of the material. In brittle materials, the very high pressure gradient causes tensile stress in the material in the edge area of the place of impact, which results in crack formation. In addition, the sudden redirection of the flow leads to a speed increase. This may cause pressure reduction in the water, which leads to the formation of steam bubbles if the pressure falls below the steam pressure. If the pressure rises again, the collapse of the steam bubbles causes cavitation phenomena which do an abrasion to the material (Schubert, 2003; Weiss, 2001).

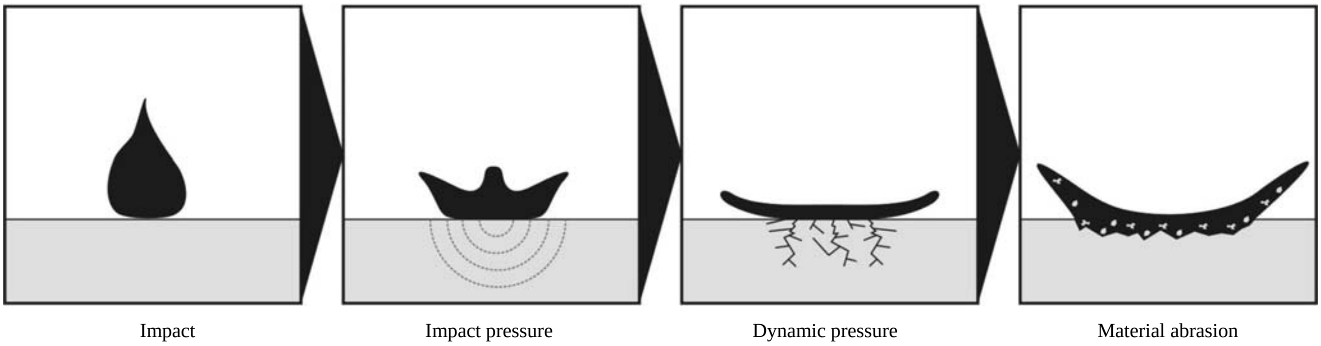

Figure 2 Load on the material due to the impact of a single droplet on the material surface (according to Brueser (2008))

2.1.2 Dynamic pressure phase

The length of the impact pressure phase is in the millisecond range (Wulf, 1986). This phase is followed by the dynamic pressure phase (cf. Figure 2). During the dynamic pressure phase, the remaining water of the single droplet follows, and a quasi-static pressure establishes itself. Generally, the following three phenomena occur during this process:

1) Due to the quasi-static pressure, crack formation which began in the impact pressure phase continues, supported by a hydrodynamic and hydrostatic pressure increase in notches and gaps.

2) Crack formation is supported by a reduction of the internal binding forces of the material caused by the entry of additional moisture.

3) Moreover, lateral water flow-off and high pressure lead to very heavy shear stress, which generates shear forces in the material and has a strong erosive effect (Mohamed, 2004; Momber, 1992; Wulf, 1986)

2.1.3 Material abrasion

Swelling pressure is the pressure which must be exceeded by impact and dynamic pressure for material abrasion to take place. Swelling pressure is a variable parameter which is independent of the material. If impact and dynamic pressure are lower than swelling pressure, no material abrasion occurs. If the swelling pressure is exceeded, this leads to crack formation in the material as described above. When the cracks grow afterwards, they may merge and run together, which cause individual particles to be removed. This removal of individual particles is supported by the above-mentioned lateral water flow-off as well as the resulting shear forces and cavitation phenomena (Wulf, 1986). In reality, a high-pressure jet is not a single droplet, but a continuously acting jet. In order to be able to apply the considerations about single droplets described above to the jet, the continuously acting jet must be assumed to be a multiple droplet which consists of a series of numerous single droplets (cf. Figure 3).

Since the individual droplets of a multiple droplet hit the surface of the material very briefly after the previous droplet, the remaining time is not sufficient to allow the water of previous droplet to flow off. Thus, the water cushion forms on the surface of the material which decreases the kinetic energy of the individual droplet, thereby reducing impact pressure (Mohamed, 2004). In addition, material abrasion results in the formation of a crater in the material. This prevents the entire water from flowing off, and the suspension of residual water and abraded material which remains in the crater reducing the kinetic energy of the high-pressure jet. In addition, friction between the high-pressure jet and the crater walls has a cushioning effect. When the crater reaches a certain depth, the cushioning effect of the suspension and the walls is so strong that the pressure falls below the swelling pressure, and material abrasion stops (Krismann, 1994).

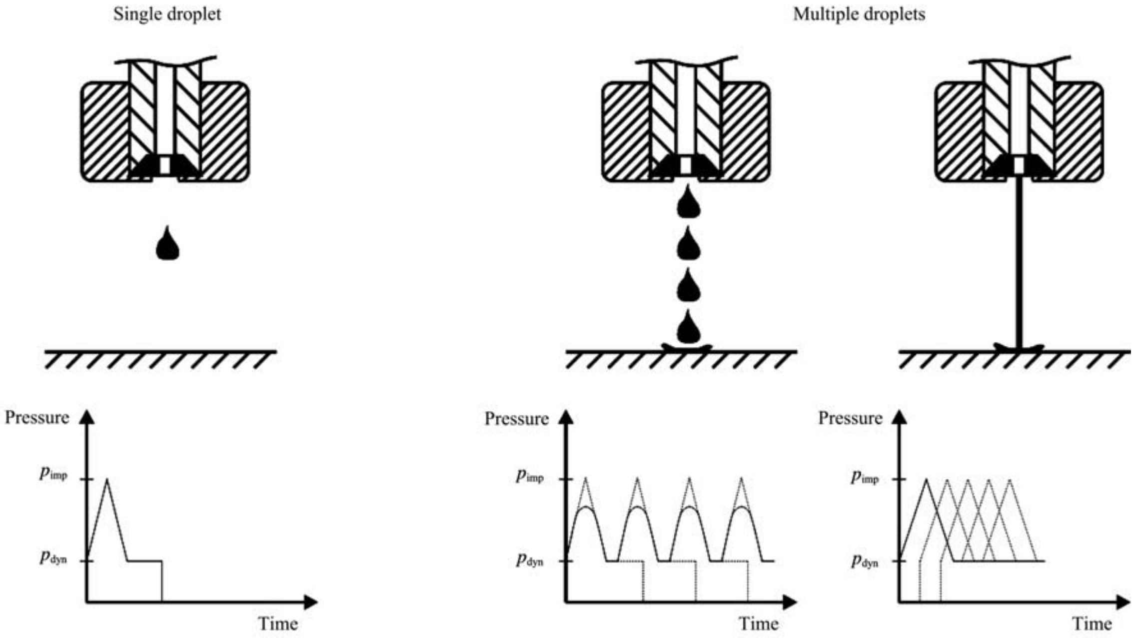

Figure 3 Single and multiple droplets

2.2 Binding mechanisms of soil grains in the soils used

In the literature, different binding mechanisms are described which exert a more or less significant influence on the binding intensity of two soil grains depending on the kind and the structure of the soil. According to references (Das, 2010; Schubert, 2003) the following four binding mechanisms can be distinguished which are relevant for soil mechanics:

1) Bonds due to adhesion forces
2) Bonds due to liquid bridges
3) Bonds due to solid body bridges
4) Interlocking bonds

These binding mechanisms are briefly explained below. In general, the shape of the soil grains is assumed to be ideally round. Non-circular soil grains and grains with a rough surface are not considered here. In addition, the fact that real soil is a disperse system with a percentage of foreign substances which cannot be neglected is considered only rudimentarily here given its complexity. Thus, the following considerations must be regarded as theoretical approaches, whose tendencies are reflected by real soil.

2.2.1 Bonds due to adhesion forces

If the molecules of two different soil grains interact, this is termed adhesion according to reference (Kwade, 2008). In this case, three different adhesion forces may occur:

- Van-der-Waals adhesion forces
- Electrostatic adhesion forces

- Magnetic adhesion forces

Van-der-Waals adhesion forces are caused by electric dipole moments, which are present in the atoms and molecules of the soil grains. They influence each other and lead to adhesion forces between the grains (Morgeneyer, 2004). Van-der-Waals adhesion forces exert a relevant effect only over a very short distance of less than 100 nm (Weiss, 2001). If distances exceed this value, the adhesion force diminishes very quickly. Electrostatic adhesion forces are present if the soil grains show antipolar charges, which lead to the formation of Coulomb adhesion forces. Magnetic adhesion forces act if the soil grains are charged magnetically and therefore attract each other (Momber, 1992). Since both electrostatic and magnetic adhesion forces are unusual in soil mechanics, they are not discussed in more detail here (Jury, 2004).

2.2.2 Bonds due to liquid bridges

In general, the soil under consideration contains moisture which is present as freely mobile water in the interior of the soil. If the soil moisture content is low to medium (maximum 8%-35% depending on the soil type), this water collects in the form of liquid bridges between the soil grains (Weiss, 2001). Depending on the kind and the characteristics of the soil, the binding forces caused by liquid bridges are generally far stronger than the van-der-Waals forces (Tomas, 1983). As a result of the surface tension of the water, the soil grains are attracted. In addition, a capillary pressure develops in the water. If this pressure is lower than the ambient pressure, an additional capillary force is generated (Kroos, 1995).

2.2.3 Bonds due to solid body bridges

In contrast to liquid bridges, this binding mechanism is characterized by a bridge of solid substances, which form fixed bonds between the grains. In general, these bridges can be formed by different sintering mechanisms, hardening binding agents, or the crystallization of substances solved in liquid bridges (Kroos, 1995; Rumpf, 1975). In the soil, bridge formation by sintering mechanisms and hardening binding agents plays a subordinate role. The crystallization of salts, however, is particularly relevant in soil mechanics. Salts in the soil are generally termed nutrients. If soil moisture is sufficient, salt is generally solved in the soil water so that it can be absorbed by plant roots. If soil water evaporates from the soil due to heat and solar radiation, the salts crystallize and form solid substance bridges between the soil grains. The adhesion forces of solid substance bridges can be many times stronger than liquid bridges. Therefore, solid substance bridges are decisive for the firmness of a soil (Kroos, 1995; Schlick, 1989; Schulze, 2006).

2.2.4 Interlocking bonds

So far, soil grains have been assumed to be ideally round. In reality, soil grains have various forms. As shown in Figure 4 (point A), these forms may cause individual soil grains to interlock and to form interlocking bonds.

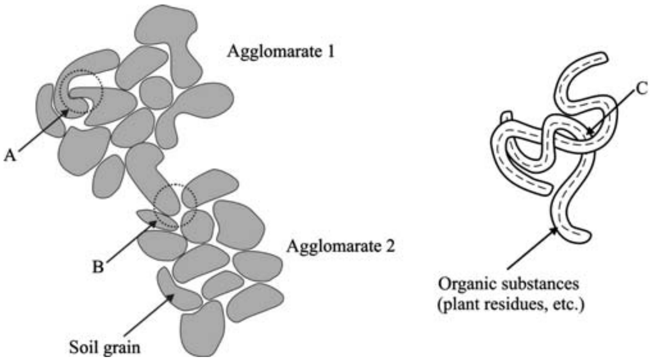

Figure 4 Interlocking bonds in a soil

Soil grains tend to form agglomerates. The different forms of several agglomerates can also lead to interlocking (cf. Figure 4, point B). In addition, soil also consists of organic substances, such as plant residues and microorganisms (cf. Figure 4, point C). They can intertwist and thus form an interlocking bond.

2.3 Physical conceptual explanation of high-pressure jet interaction with soil

Based on the general theoretical consideration of a high-pressure jet and the binding mechanisms between the soil grains described above, this section provides a theoretical study of injection into the soil by a high-pressure jet.

The impact of a high-pressure jet on the soil has not yet been considered in theoretical studies so far.

However, theoretical approaches for the description of soil erosion due to the impact of rain drops can be found in the literature in references Henk (1989) and Luetke Entrup (2006). These theoretical descriptions of the impact of a single rain drop and the resulting erosive processes in the soil can very well be applied to the impact of a high-pressure jet on the soil. In addition, the soil under consideration can be regarded as a very porous medium. Therefore, the theoretical consideration of the behaviour of very porous concrete under the load of a high-pressure jet (according to reference Brueser, 2008) can be applied to the theoretical consideration of the impact of a high-pressure jet on the soil. Based on these studies, a theoretical analysis of the impact of a high-pressure jet on the soil will be developed below. In contrast to the damaging behaviour of the high-pressure jet in currently described high-pressure jet technology (with pressure >30 MPa), three factors are mainly responsible for damage to the soil caused by the impact of a high-pressure jet.

1) Impact effect of the jet

Like in conventional high-pressure jet technology, the impact of the high-pressure jet on the soil has a damaging effect. When considering the impact of a single droplet, it is also possible to distinguish an impact pressure phase and a dynamic pressure phase. In the impact pressure phase, the impact force causes a shock wave in the soil which spreads spherically in the direction of the jet around the place of impact in the material. In the edge area of the place of impact, the very high pressure gradient causes tensile stress in the soil, which results in crack formation. The impact pressure phase is followed by the dynamic pressure phase. During the dynamic pressure phase, the remaining water of the single droplet follows, and a quasi-static pressure establishes itself.

Directly after their formation, the cracks are filled with air. When a water droplet hits the crack opening, the air included in the crack is compressed, and pressure increases. As a result, the crack is opened wider, which is termed as air cracking. Another form of air cracking occurs when the soil grains are compressed by the impact effect of the high-pressure jet, a rearrangement of the grains takes place and the resulting reduction of the soil air space. This also leads to excess pressure and soil cracking (Brueser, 2008; Jury, 2004; Pi, 2008; Tomas, 1983).

2) Moistening effect of the water

In contrast to conventional high-pressure jet technology, the moistening effect of the water has a very significant influence on the damaging behaviour. The application of water onto the soil only causes a local increase in soil moisture. More soil moisture leads to lower firmness of the soil. Due to the water input, the intensity of the binding mechanisms between the soil grains diminishes (Miyazaki, 2006). Solid body bridges between the soil grains, for example, can be broken up by the added water which dissolves crystallized soil salts. In addition, the soil begins to swell due to the water input. Moreover, the heterogeneity of the soil can result in uneven swelling. This leads to additional stress and cracks in the soil (Brueser, 2008; Jury, 2004; Pi, 2008; Tomas, 1983).

3) Porosity of the soil

Soil is a highly porous medium. Except soil mineral grains of different sizes, it consists of an organic part as well as water and air. Especially the air leads to the formation of air-filled cavities in the soil. However, the application of a high-pressure jet exerts local pressure on the soil. Due to the above-described impact effect of the jet and the moistening effect of the water, soil grains are removed from soil aggregates. The impact of the first droplets of the high pressure jet may result in the soil grains being ejected to the side and onto the soil surface. This leads to the formation of a crater in the soil. When other droplets of the high-pressure jet hit the crater, the next soil grains removed from the soil agglomerate cannot escape to the side because the droplets apply pressure from above and the crater walls form a lateral obstacle. Due to the pressure, the soil grains are shifted and compressed. The distances between the soil grains in the side walls and in the bottom of the crater are reduced. In addition, the air-filled cavities formed by the air in the soil become smaller, and the soil grains removed from the soil agglomerate are embedded. For this reason, soil grains are ejected from the forming crater only in the first short phase during the impact of the high-pressure jet. In the following phases, no soil grains are ejected from the crater (Brueser, 2008; Jury, 2004; Pi, 2008; Tomas, 1983).

The above-described processes during the impact of the high-pressure jet on the soil are summarized in four process steps in the following Figure 5.

In the first process step, the high-pressure jet hits the soil surface. Impact and dynamic pressure introduce a shock wave into the soil, which results in crack formation. In the second process step, air cracking occurs in the cracks and the cavities filled with soil air. In the third process step, water input reduces the intensity of the binding mechanisms, which causes crack formation to progress further. The first soil grains are removed from the soil agglomerate and ejected to the side so that a crater develops. In the fourth process step, shifting and compression processes take place in the edge layers of the crater. The deepening of the crater is progressing, while the reduction of the binding mechanisms due to water input and crack formation caused by impact and dynamic pressure (first and second process step) continue. Since the crater is filling with water, which reduces the effect of impact and dynamic pressure. The reduction of the binding mechanisms due to water input is the primary reason for the deepening of the crater.

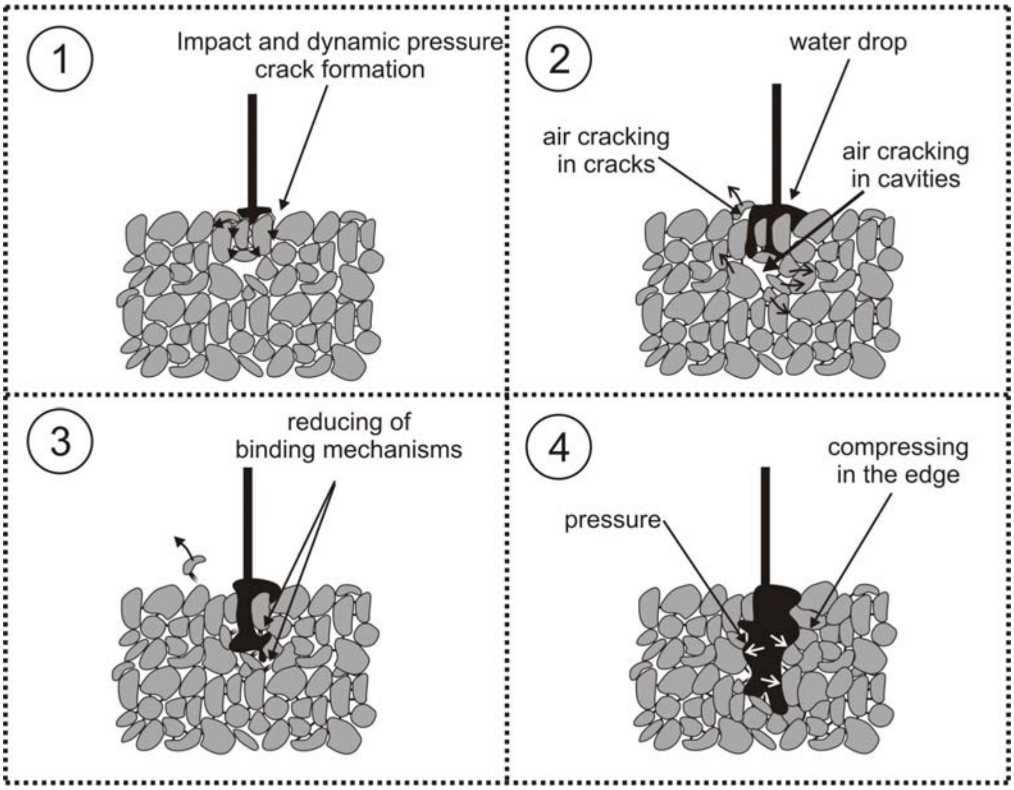

Figure 5 Abrasion and injection behaviour during the impact of a high-pressure jet on the soil

3 Materials and methods

3.1 Design of the test rig

The trials were carried out with the aid of a stationary test rig for high-pressure jet cutting. Figure 6 shows a schematic overview of the test rig.

In the test rig shown in Figure 6, water was injected into the soil. For this purpose, an injection box (150 mm×150 mm 1000 mm) filled with soil was placed inside the test rig. The injection box was driven over by a jib boom installed on a linear axle. The linear axle was driven by an electric motor with a frequency converter operated with speed and position control. The speed of the linear axle can be adjusted steplessly between 0 m/s and 6 m/s. Several cutting heads can be attached to the jib boom and carried by it. The cutting heads produced a high-pressure jet which acted vertically downwards. A pressure sensor installed in front of the cutting head measured water pressure directly in front of the nozzle. The cutting heads used were supplied with pressure by a pipe system which received water pressure from a high-pressure pump in the dry area.

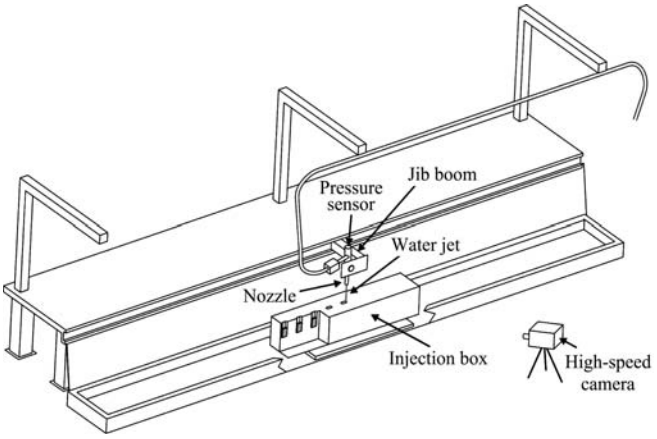

Figure 6 Design of the test rig

3.2 Realization of the trials

As shown in Table 1, the parameters which can be varied with the aid of the test rig can be categorized into soil-specific, water-specific, and plant-specific parameters. During the trials, each individual parameter could be varied in its specific range, which led to a large number of trials. For reasons of clarity and work facilitation, a reference trial with a basic setting for each parameter was carried out. Based on this reference trial, one parameter each was varied in five steps in the trial series, while the other parameters kept their basic settings. However, the parameter "soil type" was an exception because the soil type had been shown to exert a significant influence on the results. In addition, a wide variety of soil types occured in agricultural practice so that it was impossible to determine a soil type for reference. For this reason, the trials were carried out with a variation of the listed parameters for all three soil types. The analysed soil types were.

- a silty sand (80% sand, 13% silt, 7% clay)
- a sandy silt (55% sand, 36% silt, 9% clay)
- and a silty clay (9% sand, 23% silt, 67% clay)

Both the range of the parameters and the basic settings of the reference trials are also listed in Table 1.

Table 1 Varied parameters and basic settings

Parameter	Range			Basic settings
Soil-specific parameters				
Soil type	Sand	Silt	Clay	Any soil type
Soil moisture – Mass-%	5, 25, 40			25
Soil density – kg/mPP^3	1000, 1500, 2000			1500
Frozen soil	yes		no	No
Water-specific parameters				
Water pressure – MPa	5, 25, 40, 60, 80, 100, 110			40
Water volume flow – l/min	0.5, 2.2, 3.3, 4.8, 5.6, 7.5, 11			7,5
Plant-specific parameters				
Advance speed – m/s	0.5, 1, 1.5, 2, 2.5, 3, 3.5			2
Nozzle distance – mm	20, 60, 100, 140, 180			20

The course of the trials included preparation, realization, and the processing of the results. These phases comprised the following steps:

3.2.1 Trial preparation

If necessary, the desired soil moisture is adjusted by watering or drying of the soil. Afterwards, the injection box is filled with a soil sample having the desired density. This is controlled by means of a scale. The weight and the volume of the box allow density to be deduced. Then, the filled injection box is positioned in the stationary test rig. Afterwards, nozzle distance, injection angle, pressure, volume flow (selection of the jet nozzle), and advance speed are adjusted.

In all trials only one nozzle with a diameter of 0.9 mm was used. Using one nozzle leads in case of changing the pressure to an increasing volume flow, if the pressure increases. Only in the case of varying the volume flow several nozzles with diameters between 0.3 mm and 1.1 mm were used.

3.2.2 Realization of the trial

During the realization of the trial, the pilot valve is opened, and the linear axle drives over the injection box at the desired advance speed. During this process, the high-pressure jet produced by the nozzle is injected into the soil. After the box has been passed, the pilot valve closes, and the linear axle drives back into its initial position.

3.2.3 Processing of the results

After the end of the trial, the data collected during the realization of the trial are stored. During later trial evaluation, these data are used to determine specific injection energy. It is calculated by the energy needed for the injection process (calculated by pressure, volume flow and time), divided by the injection depth (depth of the slot) and the injection length (length of the slot in soil formed by the water jet). Injection depth is measured manually with the aid of a ruler, which is lowered into the slit from above down to the bottom of the slit. Afterwards, the injection box is emptied.

In order to obtain more reliable results and to exclude potential measurement errors, the trials were carried out three times in a row for each individual setting.

3.3 Evaluation of the trials

The trials were evaluated both quantitatively and qualitatively.

During quantitative evaluation, the trials were evaluated based on injection depth in the soil and the specific energy expended for injection.

Injection depth was measured manually with the aid of a ruler. The torque of the pump and the rotational speed of the pump drive, the pressure and the volume flow of injection, as well as the position and the speed of the linear axle were recorded by the sensors installed in the test rig while the trials were being carried out.

Based on these measurement values, the mechanical drive power of the pump, the water volume injected into the soil, and the water-hydraulic power of the injected high-pressure jet could be calculated. For an energetic comparison of the results, it had proved sensible to use the specific energy required for injection instead of water-hydraulic power. The required energy was related to the horizontal length of injection and injection depth so that specific injection energy was determined.

The qualitative evaluation of the trials was carried out with the aid of a high-speed camera. Its goal was the determination of the behaviour of the high-pressure jet in the soil and the location of the water. In detail, the trials focus on the following three aspects:

First, the spraying of water from the injection slit is analyzed optically from outside using the high-speed camera.

Second, the analysis of the course of the high-pressure jet within the soil is interesting for the studies. Here, the use of dyed sand has proved useful. During trial preparation, the dyed sand was poured into an injection box in the form of layers. For each layer, a different type of sand with a different colour was used so that the layer filling in the injection box was multicoloured after the box has been filled. When the trial was carried out, the high-pressure jet was used to inject the water into the injection box. After the trial had been completed, the soil sample was taken out of the injection box in one piece, and the individual layers were removed along the slit direction and at right angles to the slit. The face cut allowed qualitatively conclusions about the course of the high-pressure jet in the soil to be drawn.

Third, additional studies focus on the location of the injected water in the soil. In order to determine the location of the injected water, black-light liquid was added to the high-pressure jet. After the trial had been completed, the soil sample was also taken out of the injection box in one piece, and the individual layers were removed along the slit direction. The face cuts were illuminated with black light. This caused the black light liquid which had infiltrated into the soil to shine and thus enabled qualitatively conclusions about the location of the injected water to be drawn. The face cuts were photographed individually.

4 Results and discussion

4.1 Results of the quantitative examinations

The results of the quantitative examinations, during which sensors were used to collect measurement data such as the pressure or the volume flow, are described in Figures 7, 8 and 9. As explained above, the trials were carried out three times in a row for each individual setting, by making 3 measurements each row. Since all results described below measurements deviate only minimally (<10%) and a tendency can always be discerned, the following description of the trial results will be limited to the trend lines for reasons of clarity. For the sake of better comparability, the trend line for the three examined soil types (sand, silt, and clay) will be included in each diagram.

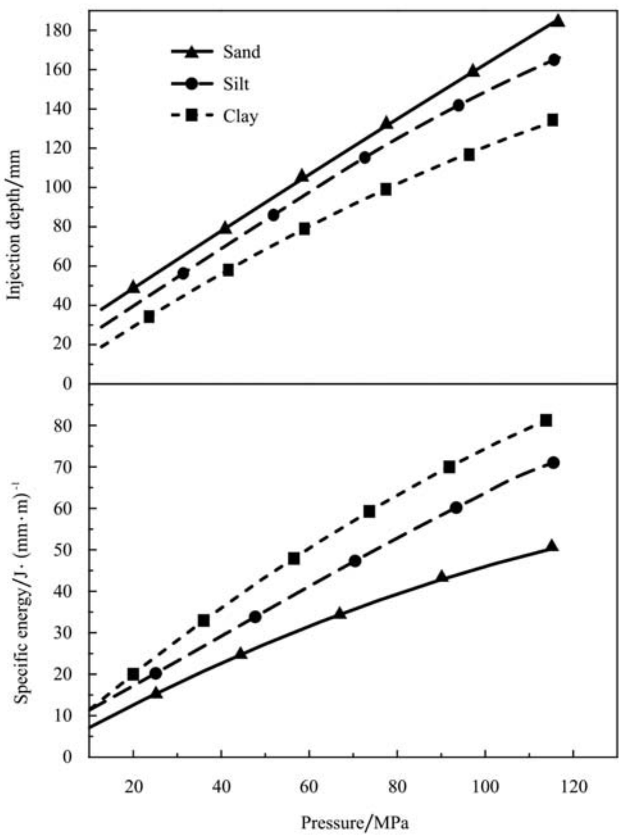

Figure 7 Injection depth and specific energy at different water pressure

Figure 7 shows the injection depths measured for the three different soil types when water pressure is varied. In all trials the same nozzle was used, so by increasing the pressure, the volume flow increases also. The structure of the jet in all trials looked the same. In Figure 7 (top), injection depth under the conditions of varying water pressure is shown. Growing injection depth at higher water pressure can be distinguished in all soil types. On lighter soil (sand soil), maximum injection depth proves to be larger than in heavy soil (clay soil). The reason for these differences lies in the different soil grains of the soil types, which results in a different intensity of the binding mechanisms between the soil grains and, hence, different firmness of the soil. Due to more intensive binding forces, heavier soils (clay soils) have a far more stable soil structure. This soil structure must be broken up by the high-pressure jet, which requires more energy in these soils than in lighter soils.

The course shown in Figure 7 (top) flattens at higher pressure. This has two reasons: First, friction occurs in the soil between the high-pressure jet and the sides of the slit in the soil. This friction increases as injection depth grows. As a result, the energy of the high-pressure jet diminishes, which is reflected by a slightly reduced injection depth increase. Moreover, higher water pressure leads to a greater water volume flow. This water forms a water cushion in the soil. When the high-pressure jet penetrates the water cushion, friction occurs between the high-pressure jet and the water cushion, which results in a reduction of the energy of the high-pressure jet. As the volume flow increases, the water cushion grows which causes increased friction and is also the reason for the slightly reduced injection depth increase. Figure 7 (bottom) shows the specific energy to be expended when water pressure is varied. At high pressure, an increase in specific energy can be discerned. Since specific energy is composed of the quotient of energy input and injection depth, the growth in energy input is far bigger than injection depth increase. Under energetic aspects, lower pressure is therefore preferable.

As another example of measurement-technical examinations, injection depth and specific energy at different percentage of soil moisture are shown in Figure 8.

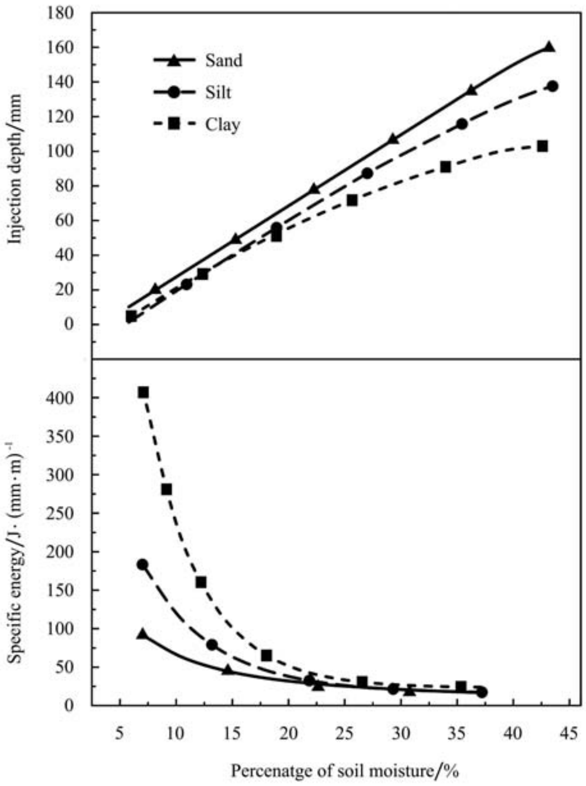

Figure 8 Injection depth and specific energy at different mass-percentages of soil moisture

As soil moisture increases, injection depth proves to grow very significantly (Figure 8 (top)). Water pressure and volume flow were identical in all trials. At lower percentage of soil moisture, maximum injection depth is very small. At high percentages of moisture, very great injection depth is possible given otherwise identical settings. The reason for this phenomenon can be seen in the interaction of the individual soil grains (in particular via solid body bridges). In dry soils, this interaction is very significant, which leads to the formation of a stable soil structure. The moister the soil is, the smaller this interaction becomes. Therefore, far less energy is required to reach great injection depth in moister soils. This behaviour is also shown in Figure 8 (bottom). Especially in heavy clay soil, the specific energy to be expended at very low percentages of soil moisture is many times greater than under the conditions of high soil moisture.

In Figure 9 injection depth and specific energy are plotted over the volume flow.

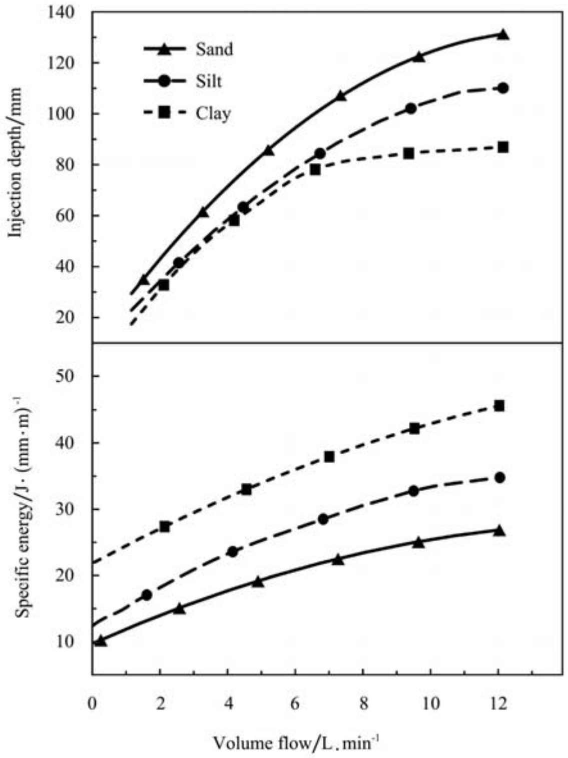

Figure 9 Injection depth and specific energy at different volume flow

Figure 9 (top) shows that injection depth grows at larger volume flows. Under the conditions of larger volume flows (>7 L/min), the curve flattens significantly. This course of the curve is comparable with the course in Figure 7 (top) and can also be explained as a result of friction between the high pressure jet and the soil as well as the water cushion which forms in the slit. Since the height of the water cushion grows as the volume flow increases, friction occurs between the high-pressure jet and the water cushion, which also explains the flattening course in Figure 9 (top). In Figure 9 (bottom), specific energy is plotted over the volume flow. Even though injection depth grows at larger volume flows, specific energy increases significantly. However, the increase in specific energy is far lower than in Figure 7 (bottom).

4.2 Results of the qualitative examinations

In addition to the quantitative examinations, the studies also focus on the qualitative analysis of the injection process. Figure 10 shows four details of a picture taken by a high-speed camera. The goal of the examination is the analysis of the jet structure and the injection behaviour of the high-pressure jet into the soil.

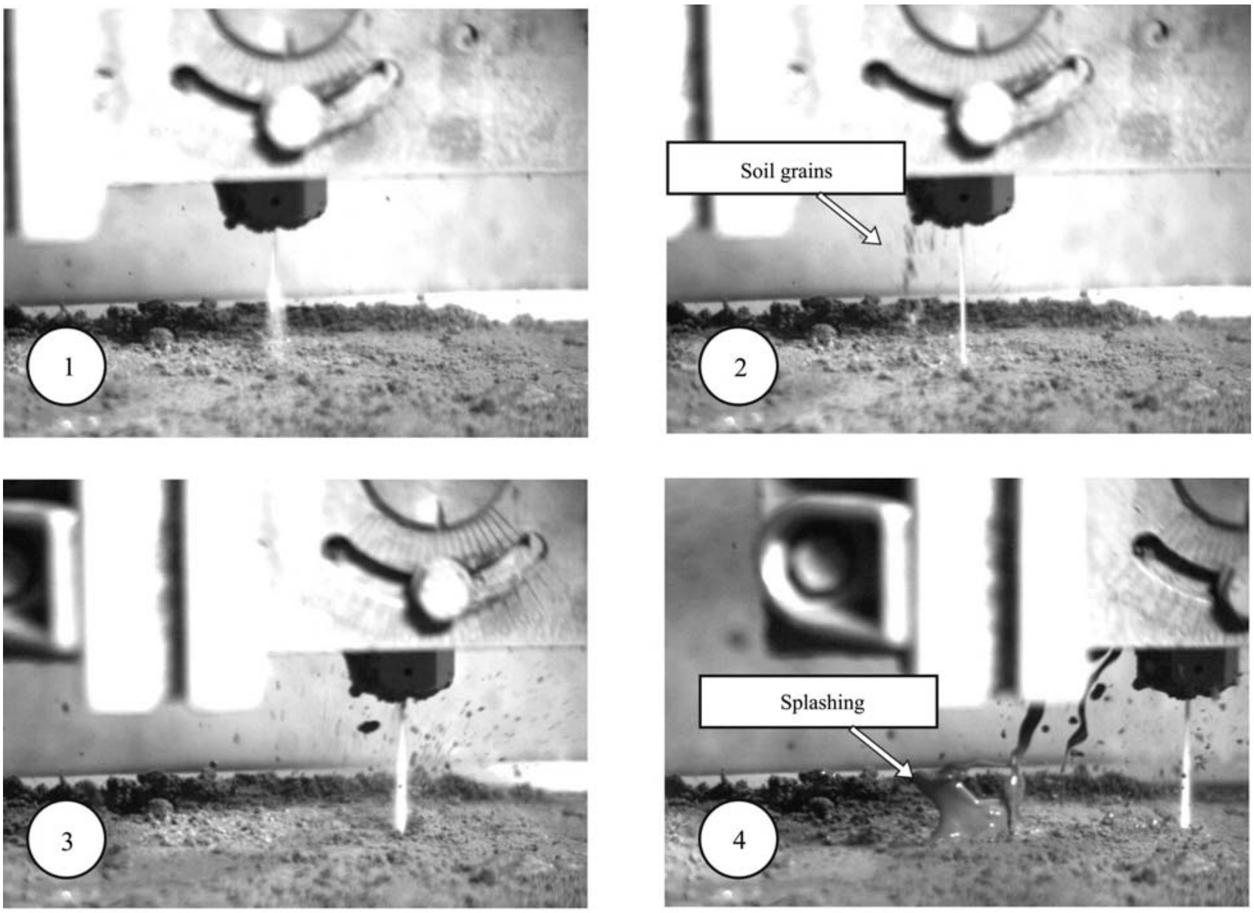

Figure 10 Examination of the jet structure and injection behaviour

For this purpose, the pilot valve is opened suddenly while the nozzle is moving over the soil sample. As shown in detail 1, the high-pressure jet forms after the sudden opening of the valve and hits the soil surface. Detail 2 shows how the high-pressure jet penetrates into the soil without water splashing. Only the ejection of a few soil grains can be discerned. This process continues while the linear axle is moving on, as shown in detail 3. Meanwhile, the slit which is forming in the soil is filling with injected water. This causes heavy turbulence in the injected water so that briefly water splashing out of the slit can be observed, as shown in detail 4. As the linear axle moves on, the slit in the soil becomes longer, and the resulting growing cushioning effect of both the injected water and the slit walls reduces the turbulence in the slit. Therefore, the splashing shown in detail 4 subsides, and a quasi-static condition comparable with detail 3 establishes itself.

If coloured sand poured layerwise into the box is used, the turbulence in the water can be discerned very well. Figure 11 shows a cross-section of such a soil sample.

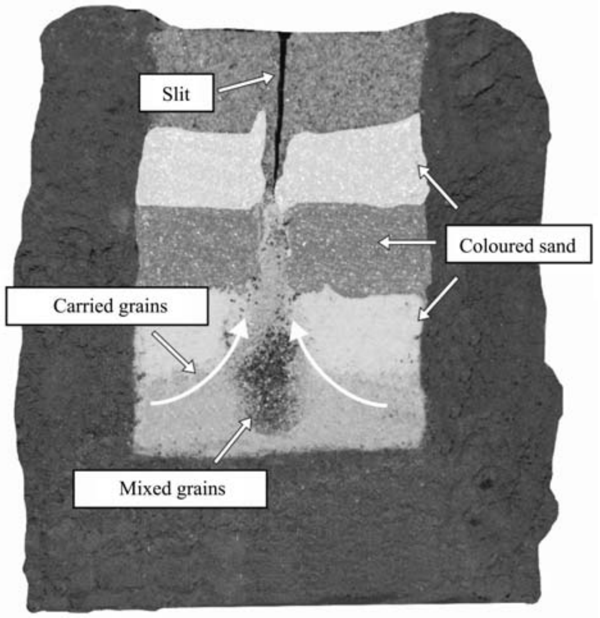

Figure 11 Cross-section of a soil sample with coloured sand poured layerwise into the box

The coloured sand layers and the slit formed in the soil can be distinguished very well. At the bottom of the slit, an area can be seen where grains of all coloured sand layers are found in a mixed form. This mixing of the soil indicates heavy turbulence in the water at this place. Soil mixing cushions the high-pressure jet so that the water does not splash out of the slit. One also sees that the grains of the lower sand layer cannot only be found in the lower sand layer, but also in the area of the slit above the mixed soil and, hence, up to two layers above the lower sand layer. This indicates that in particular the water in the area of the lower sand layer has the tendency to flow upwards out of the slit. The soil grains carried along by the water settle in the upper layers. However, one can assume that the motion of the water flowing upwards is reduced very strongly because no water splashing out of the slit was observed during the trials.

Other qualitative trials focus on the determination of the location of the water in the soil. For this purpose, black-light liquid is added to the high-pressure jet, as is described above. Figure 12 shows a cross section of a soil sample illuminated by black light.

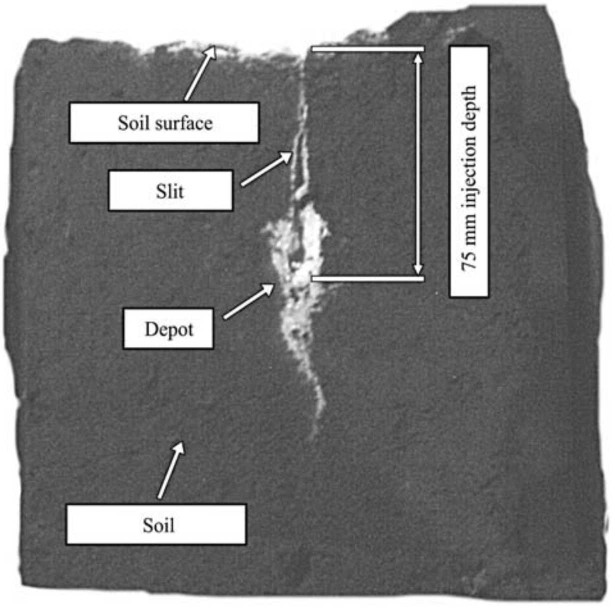

Figure 12 Cross section of a soil sample illuminated by black light into which water with added black-light liquid was injected

Here, the slit which is forming in the soil can also be distinguished very clearly. In addition, the black-light liquid shows that the injected water remains at the bottom of the slit. The injection depth measured here is about 75 mm. There, the injected water forms a depot, and some water seeps into deeper soil layers.

4.3 Summary and discussion of the trial results

The trial results show that it is possible to inject liquids into the soil with the aid of a high-pressure jet. Soil moisture was proven to exert a very great influence on this technique. Especially when soils are dry (moisture <10%), the binding mechanisms between the soil grains are so strong that they cannot be broken up by the high-pressure jet. As a result, injection depths are small (<20 mm). In moist soils (moisture >30%), however, low pressure (40 MPa) is sufficient for large injection depths (>100 mm).

Increasing the volume flow in order to reach greater injection depth is only useful in the low volume flow range (0–7 L/min). In the large volume flow range (>9 L/min), the dampening effect of the water cushion in the slit is so strong that an additional volume flow increase only results in slightly greater injection depth. In addition, the results show that higher pressure (>40 MPa) allows injection depth to be varied in contrast to a larger volume flow.

In addition to these quantitative results, the qualitative results allow the conclusion to be drawn that it is possible in principle to inject liquids into the soil with the aid of a high-pressure jet without water splashing. Only during a very short period of time (<1 s) after the opening of the pilot valve does water splash above the surface. During injection, turbulence occurs in the injected water in the soil slit, which also results in soil mixing in the area of turbulence in the soil. Immediately after injection, a water depot forms in the soil.

Studies which were not described above show that injection into frozen soil enables only very small injection depths of less than 20 mm to be reached. Even if pressure is increased to far more than 100 MPa, this does not result in significantly larger injection depth. For this reason, these studies will not be pursued.

In general, the results show that the examined technique is very suitable for the planned application in the area of injection fertilizing. The injection depths required for this purpose, which range between 50 mm and 90 mm, can be reached at an average degree of soil moisture of about 25%, a water pressure of 40 MPa, a volume flow of 7.5 L/min, and an advance speed of 2 m/s. The results show that this technique also has great potential for the application for example in the area of the fertilizer-injection. In addition to application in the area of injection fertilizing, the injection of liquids into the soil, which was studied here, also shows great potential in plant protection, irrigation, as well as the injection of decontamination agents into contaminated soils.

5 Summary

In the research project presented here, research on the injection of liquids into the soil with the aid of a high-pressure jet was carried out. In this publication, first the theoretical fundamentals of the injection process were explained. After these theoretical studies, the stationary test rig used for the trials as well as the goals and the course of the trials were described. In the following discussion of the trial results, quantitative and qualitative results were distinguished. In the quantitative evaluation of the results, the trials were assessed with regard to injection depth into the soil and the specific energy to be expended. Here, a water pressure of 40 MPa, a volume flow of 7.5 L/min, and an advance speed of 2 m/s proved appropriate in soils having an average moisture content of about 25 %. The injection depths of 70 – 90 mm reached during these trials meet the requirements which result from potential application in the area of injection fertilizing. The results also showed that dry and frozen soils do not allow injection depths in the required range to be reached. The goal of the qualitative examinations was the qualitative consideration of the behaviour of the high-pressure jet. These examinations showed that turbulence occurs in the injected water in the slit which develops in the soil. Nevertheless, water splashing out of the slit was observed only for a short time. In addition, it was shown that a depot forms in the soil after the injection process.

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