Time-lapse surface-to-surface GPR measurements to monitor a controlled infiltration experiment

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ABSTRACT The knowledge of moisture content changes in shallow soil layers has important environmental implications and is fundamental in fields of application such as soil science. In fact, the exchange of energy and water with the atmosphere, the mechanisms of flood generation as well as the infiltration of water and contaminant into the subsurface are primarily controlled by the presence of water in the pores of shallow soils. At the same time, the estimation of moisture content in the shallow subsurface is a difficult task. Direct measurements of water content require the recovery of soil samples for laboratory analyses: sampling is invasive and often destructive. In addition, these data are generally insufficient to yield a good spatial coverage for basin-scale investigations. In-situ assessment of soil-moisture contents, possibly at the scale of interest for distributed catchment-scale models, is therefore necessary. The goal of this paper is to assess the information contained in surface-to-surface GPR surveys for moisture content estimation under dynamic conditions. GPR data are compared against and integrated with TDR (Time Domain Reflectometry) data. TDR and surface-to-surface GPR data act at different spatial scales and two different frequency ranges. TDR, in particular, is widely used to estimate soil water content, e.g. converting bulk dielectric constant into volumetric water content values. GPR used in surface-to-surface configuration has been used increasingly to quickly image soil moisture content over large areas. Direct GPR wave velocity is measured in the ground. However, in the presence of shallow and thin low-velocity soil layers, such as the one generated by an infiltrating water front, dispersive, guided GPR waves are generated and the direct ground wave is not identifiable as a simple arrival. Under such conditions, the dispersion relation of guided waves can be estimated from field data and then inverted to obtain the properties of the guiding layers. In this paper, we analyze the GPR and TDR data collected at an experimental site of the University of Turin, during a controlled infiltration experiment.

1. Introduction

The vadose/unsaturated zone, i.e. the part of the subsurface above the water table, is characterized by many, non–linear, complex key processes that control the mass and energy exchanges between the subsurface and the atmosphere. In fact, the vadose zone acts as a boundary for atmospheric processes, including micro-meteorology and climate change, and subsurface water migration, with strong implications in water resources management and subsurface contaminant hydrology. Generally, unsaturated processes also control the availability of water for agriculture, and are the driving mechanisms in slope stability, floods and a number of other issues in engineering geology.

In agricultural sciences, the problem of transport in the shallow soil is fundamental for the study of movement of fertilizers or pesticides and to understand preferential flow of water and solutes moving faster in certain parts of the soil profile than in others (Simunek *et al.*, 2003). From both the theoretical and the practical points of view, the distribution and the movement of water in the unsaturated zone is largely documented in recent literature at a wide range of scales (Wood, 1997; Merz and Bardossy, 1998; Yu, 2000; Western *et al.*, 2001). In most cases, the impact of the vadose zone on hydrologic problems is often treated using highly simplified approximations; in addition, invasive techniques, based on sampling and weighing, are fraught with practical difficulties and can only provide scattered information on the state of the system in space and time. In fact, direct sampling disturbs the soil, restricting the capacity to monitor transient processes and it is difficult to use small-scale samples to describe representative field-scale properties, since heterogeneity of the subsurface occurs over much larger scales.

Consequently, the estimation of water content space and time variations in shallow soil layers using in-situ non invasive techniques has been the focus of intensive research over the past three decades, with particular attention to techniques that measure the dielectric constant κ (-) of the porous media (e.g. Topp and Davis, 1985; Roth *et al.*, 1990; van Overmeeren *et al.*, 1997; Robinson and Friedman, 2003; Cassiani *et al.*, 2006a, 2006b; Strobbia and Cassiani, 2007), that is strongly affected by the presence of water in the soil pores. Among other techniques, two methods have gained popularity for the in-situ estimation of soil moisture content: these are Time Domain Reflectometry (TDR) and surface-to-surface Ground-Penetrating Radar (GPR), both based on electromagnetic (EM) wave propagation albeit at different ranges of frequency. For both methods the determination of soil water content is based upon various relationships between water content and the dielectric constant (e.g. Topp *et al.*, 1980; Topp and Ferré, 2002; Brovelli and Cassiani, 2008).

TDR measures are able to determine the apparent dielectric permittivity of a medium, based on the measured velocity of an EM wave guided by two or three parallel metal rods, inserted into the medium of interest (i.e. into the soil). An attached non-metallic probe handle is connected to a fast rise time pulse generator and an oscilloscope through a coaxial cable. The two-way travel time of the EM wave along the rods is measured. Generally, TDR measurements require dedicated, high-frequency, electronic instrumentation, however, the broad use of this method has led to the availability of commercial TDR systems, for laboratory and field use, completed with automated monitoring and multiplexing. In this mode, TDR is well suited to very rapid monitoring of the volumetric water content distribution, but it is limited by the small measurement volume within the waveguide. GPR used in surface-to-surface configuration has increasingly been proposed as a means to obtain fast and inexpensive images of soil moisture content over large areas at shallow depth (Chanzy *et al.*, 1996; van Overmeeren *et al.*, 1997; Weiler *et al.*, 1998; Parkin *et al.*, 2000; Redman *et al.*, 2000; Huisman *et al.*, 2001; Davis and

Annan, 2002; Galagedara *et al.*, 2003a, 2003b; Grote *et al.*, 2003; Huisman and Bouten, 2002) and to detect wetting front depths (Vellidis *et al.*, 1990). In surface-to-surface GPR measurements, the velocity of direct ground waves that travel from the transmitting antenna to the receiving antenna just below the soil surface (Du and Rummel, 1994; Huisman *et al.*, 2003; Cassiani *et al.*, 2006a) can be used to estimate the soil water content at shallow depths over relatively large areas, at a scale of interest for hydrological models. Generally, three different survey types [i.e. (1) Wide Angle Reflection and Refraction (WARR), (2) Common Mid Point (CMP), and (3) Single Offset (SO) methods] can be used to estimate the direct ground wave velocity and infer the water content. The success of the method relies on the assumption that identifying such direct arrival is straightforward and cannot be confused with other events. This condition is not always met, e.g., in the presence of critically refracted radar waves (Bohidar and Hermance, 2002) or guided waves (Arcone *et al.*, 1984, 2003; van der Kruk *et al.*, 2006; Strobbia and Cassiani, 2007). Generally, a water front of infiltration from the surface can produce such problems. To avoid ambiguous identification and consequently to obtain a correct interpretation of these events it is strictly necessary to perform a GPR WARR or CMP measurements, where the nature of the energy arrivals is more easily identified than in a SO survey.

The goal of this paper is to assess the information contained in surface-to-surface GPR surveys for moisture content estimation under dynamic conditions. In this paper, we show the results of a controlled infiltration experiment, monitored via TDR and time-lapse surface-to–surface GPR measurements. GPR data are compared against and integrated with TDR data. The results of both methods and direct trench observations are used to constrain a 1D infiltration model to yield estimates of the soil hydraulic properties.

2. Methodology

2.1. GPR

Hydrological uses of GPR are directly linked to its ability to measure dielectric properties of the variably saturated soil, which in turn are strongly controlled by water content. For instance, the identification of the water table using GPR has been a goal frequently pursued with varying degrees of success (e.g. Nakashima *et al.*, 2001). However, GPR is probably more useful as a means to identify temporal changes of volumetric water content above the capillary fringe. In shallow investigations, the volumetric water content can be estimated from GPR velocity measurements using both transmitter and receiver antennas deployed at the ground surface (see Huisman *et al.*, 2003). The energy transmitted through the ground follows multiple pathways simultaneously (Fig.1a). The determination of the propagation velocity is key to estimates of volumetric water content. While other techniques have been proposed [e.g. full-wave electromagnetic inversion*:* Lambot *et al.* (2006), Weihermueller *et al.* (2007)] the general approach is to identify distinct arrivals on the radargram (e.g. Fig. 1b) and pick traveltimes for such events, to be used for velocity calculation.

The data acquisition procedure largely dictates the GPR arrivals that can be used for velocity analysis. Running a single-offset profile (both antennas are moved simultaneously with the same minimal mutual distance) allows for velocity determination only from reflections, if they come from a horizon or a body at a known depth (Davis and Annan, 1989; Lunt *et al.*, 2005).

Alternatively, a number of Common Mid-Point (CMP) gathers can be collected (Fisher *et al.*, 1992; Greaves *et al.*, 1996), similar to seismic reflection processing, and velocity analysis can be performed on reflection events.

The event most obviously useful for velocity determination is the direct wave through the ground (Du and Rummel, 1994; Chanzy *et al.*, 1996; van Overmeeren *et al.*, 1997; Weiler *et al.*, 1998; Huisman *et al.*, 2001, 2002a, 2002b; Hubbard *et al.*, 2002; Grote *et al.*, 2003). Either a WARR mode (e.g. van Overmeeren *et al*, 1997), where one antenna is kept fixed while the other is moved, or a CMP mode (Fisher *et al.*, 1992), where both antennas are moved simultaneously to keep the same mid-point, can be adopted. Both WARR and CMP allow generally for a good identification of direct waves through the air and the ground (see for example Fig.1c). An alternative approach, proposed by Huisman *et al*. (2001) consists in single-offset profiling with a sufficiently large offset (a few meters) in order to clearly distinguish the ground wave arrival from the tail of the faster air wave. The very simple velocity analysis based on the direct arrival through the ground is very appealing and increasingly used. However, this procedure relies on the assumption that such a direct wave is clearly identifiable on the radargrams and cannot be confused with other events (Fig. 1). These conditions are not always met, for instance in presence of guided waves (Arcone *et al.*, 2003, Liu and Arcone, 2006; Cassiani *et al.*, 2006a, 2006b; van der Kruk *et al.*, 2006; Strobbia and Cassiani, 2007). Little attention has been given in the literature to such different situations, and to the potential pitfalls they can introduce in a simplified interpretation of the data.

A low velocity layer of variable thickness, lying on top of a faster (drier) subsoil, potentially gives rise to a critically refracted wave that can overtake the slow direct wave through the soil and manifest itself as the first arrival (Bohidar and Hermance, 2002). In addition, the low velocity topsoil layer may act as a waveguide, sandwiched between the air above and the fast velocity bedrock below.

2.2. TDR

The TDR method gained wide acceptance in the hydrological community when it was demonstrated that: (a) TDR can make rapid, non-destructive, minimally invasive measurements of volumetric water content; and (b) the method can be applied in a wide range of soils without the need for medium-specific calibration. The method advanced further, due to its ability to measure both volumetric water content and bulk electrical conductivity in the same sample volume. Finally, the method has seen broad use both in the field and in the laboratory because users can design probes to have sample volumes and spatial sensitivities to satisfy specific monitoring needs. Several recent reviews provide a comprehensive overview of the theory and application of the method (e.g. Robinson and Friedman, 2003). The method is most commonly applied by inserting two or three parallel metal rods directly into the soil. The rods can be inserted vertically or sub-vertically, from the ground surface, or horizontally in excavated trenches. The rods can be inserted and removed immediately after measurement when conducting areal surveys. Alternatively, many probes can be connected to a common TDR instrument through a multiplexer to allow for automated sampling. Because TDR measurements are rapid, generally requiring only a few seconds once the rods are installed, very high, temporal resolution of dynamic hydrological processes is possible. A fast

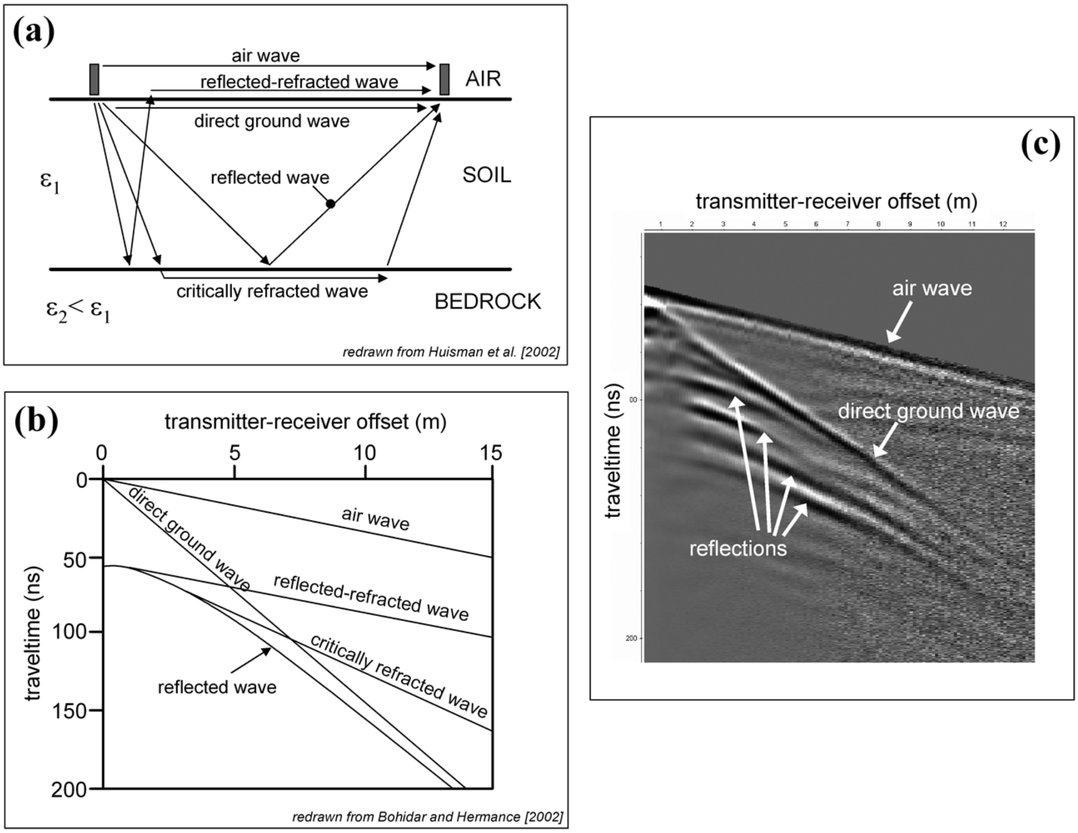

Fig. 1 - (a) expected GPR wave propagation pathways in surface-to-surface configuration; (b) corresponding time-offset relationships; (c) example field data under natural conditions from the Grugliasco site (March 2004).

rise-time voltage step is applied to the rods through connecting (coaxial) cables. The difference in two-way travel times of the step to the top and bottom of the rods, together with the known length of the probes, is used to determine the propagation velocity. This is used to infer the dielectric permittivity, and thereby the water content, via the use of suitable constitutive laws (see section 2.3). The accuracy of travel time determinations relies on the preservation of sufficient high frequency energy in the travelling wave to reliably identify the reflection from the end of the probe. Therefore, like GPR, the primary limitation on the depth of investigation of TDR from the ground surface is signal loss. For electrically conductive soils, the maximum depth of investigation may be only a few centimetres; for dry sand, measurements can be made down to several meters depth. Typically, TDR probes range from 10 cm to 2 m in length. Electrically resistive coatings have been used to propagate signal through lossy media, but these coatings have deleterious effects on the calibration of the TDR probes. A final advantage of TDR is that it allows for a combination of travel-time and signal-attenuation measurements to infer the complex dielectric permittivity (e.g. Heimovaara *et al.*, 1995).

2.3. Dielectric constant constitutive models

Many studies have been carried out to investigate the relationship between the bulk relative dielectric permittivity κ of a porous medium and its volumetric water content. The Maxwell-Garnett mixing model is based on the effective medium approach (EMA) and is not generally valid (i.e. it can only be applied to high porosity systems), but it provides the upper/lower bound for the bulk dielectric permittivity (Robinson and Friedman, 2003). Modifications of the EMA leads to the self-consistent and self similar consistent models or Hanai-Bruggeman theory; for a review see Chelidze and Guéguen (1999).

Two empirical approaches have gained popularity in practical applications: one is the complex refractive index method (CRIM), which is a volume-averaging relationship and explicitly incorporates porosity ϕ, volumetric water content θ, and the dielectric constant of solid matrix (κ_s), air (κ_a) and water phase (κ_w) (Roth *et al.*, 1990):

$$\kappa^{\alpha} = (1-\phi)\kappa_s^{\alpha} + \theta\kappa_w^{\alpha} + (\phi-\theta)\kappa_a^{\alpha} \tag{1}$$

where α is an exponent generally taken equal to 1/2. If time-lapse measurements of bulk dielectric constant are collected, CRIM provides a convenient means of estimating changes in soil-volumetric water content with no need to account for the dielectric permittivity of the solid phase.

The second empirical approach was developed for the interpretation of TDR data. Topp *et al.* (1980), using a wide range of different soils, developed an empirical relationship to relate the effective permittivity to the volumetric water content, which takes no explicit account of variations in the properties of the solid matrix (e.g. permittivity, porosity, connectivity, etc.):

$$\theta = -5.3\times10^{-2} + 2.92\times10^{-2}\kappa - 5.5\times10^{-4}\kappa^2 + 4.3\times10^{-6}\kappa^3. \tag{2}$$

The Topp model is generally applied unless the medium has properties (e.g. porosity, magnetic susceptibility, high clay content) that differ from typical agricultural soils. Unusual soils require calibration and are better served by the CRIM model. In the case of mineral soils the Topp *et al.* (1980) relationship provides an adequate description of the water content range lower than 50%. According to the literature, the accuracy of the Topp *et al.* (1980) formula in an application like ours is around 2-3 %.

3. Field application

3.1. Site description

The experimental site is adjacent to the campus of the Agricultural Faculty of the University of Turin, Italy, in Grugliasco, about 10 km from the city center of Turin (45° 03' 52'' N, 7° 35' 34'' E, 290 m a.s.l.). The soil is sandy, mixed (calcareous), mesic Arenic Eutrudepts and the sediments in this area are largely eolic sands. Vegetation in this area used to be rain-fed barley crop. No previous evident spatial patterns of root uptake were present because of the narrow distance

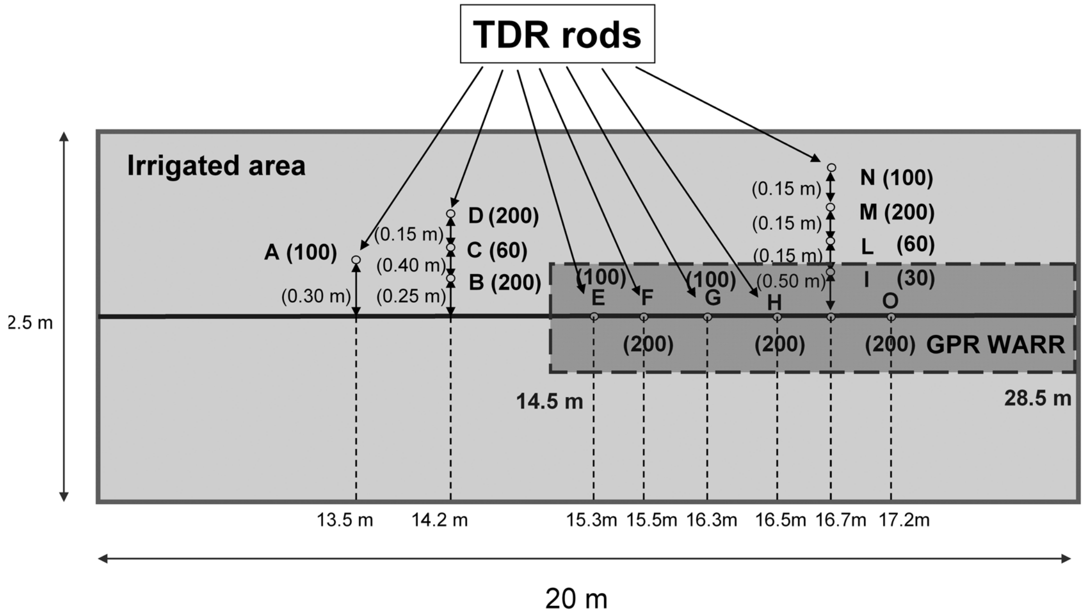

Fig. 2 - Grugliasco site: sketch of the measurement area with TDR locations (the numbers indicate the rod lengths in cm), GPR survey area (dark grey) and irrigated area (light grey).

between rows (0.1 m). Now vegetation is composed of natural grass.

We focused our attention on an area of 20×20 m^2, permanently equipped with TDR bars of different lengths down to 2 m depth, placed in the middle of this area, along two perpendicular transects as is shown schematically in Fig. 2. The site is characterized by a regular stratigraphic sequence of sandy soil; the unsaturated zone has a porosity ranging between 0.35 and 0.4, high vertical permeability and low organic content; therefore, the area represents an ideal test site for percolation studies. The water table is at about 20-meter depth and therefore no influence of the saturated zone must be taken into account in the experiment interpretation. According to the Comprehensive Soil Classification System, two primary horizons are recognised: up to about 1-1.5 meter in depth the A-horizon of mineral matter (80% sand, 14% silt and 6% clay, d_{50} = 200 microns, saturated hydraulic conductivity ~ 10^{-6} cm/s) with average porosity of 0.4, and cationic exchange capacity of 4 meq/100 g; below this, lies the C-horizon of partially altered material (95% sand, 3% silt and 2% clay) with porosity of 0.35 and CEC=0 meq/100 g.

A 200 MHz GPR minimum offset profile was acquired on site before irrigation to confirm the site stratigraphy (Fig. 3). The relatively low frequency adopted is suitable to illuminate the subsurface to a depth of about 8 m, but its limited resolution does not allow an accurate imaging of the first few meters that are the objective of the irrigation experiment. An older GPR reflection survey conducted in 2003 using 450 MHz antennas (Fig. 4 - courtesy A. Godio, Polytechnic of Turin) was used to discriminate the first few meters. The overall interpretation of the two GPR surveys confirms the presence of an interface at around 1.5 m depth between the two soil horizons (A and C), the latter extending in depth to roughly 3 m. Another interface is present at 5 m depth, probably separating the upper sand layers from deeper gravels.

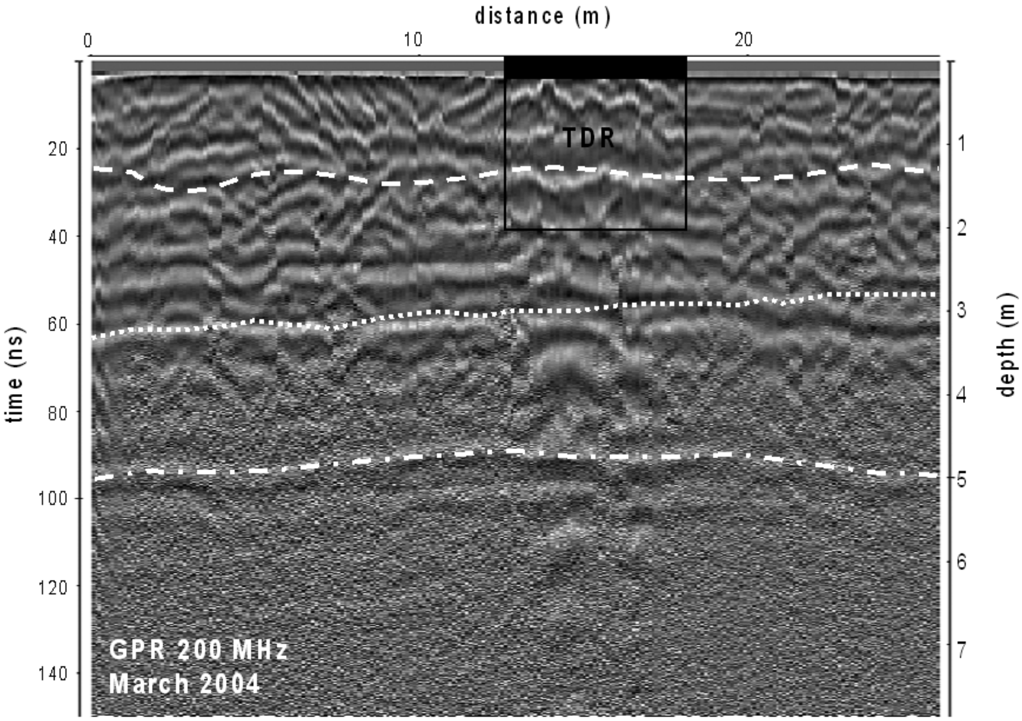

Fig. - 3: Minimum offset GPR reflection survey (200 MHz) collected under natural conditions at the Grugliasco site. Note the location of the TDR probes relative to the overall survey line.

3.2. Design of the infiltration experiment

An irrigation experiment was performed at the site on September 28, 2004 by means of a line of sprayers, placed in the middle of the experimental area so as to wet completely an area of about 3 m by 20 m (Fig. 2). The irrigation lasted for 6 hours. TDR bars and GPR measurements were performed over the irrigated area. The soil was initially extremely dry as a consequence of an exceptionally dry summer period. The irrigation intensity was always lower than the infiltration capacity of the soil, so no ponding was observed on the soil surface.

3.3. GPR data

Soil water content was monitored by means of surface-to-surface GPR using a PulseEkko 100 radar system with 200 MHz antennas. The sampling interval was 0.2 ns, 64-fold vertical stacking was used, and WARR offset increments equal to 10 cm over a 14 m line were sampled. A GPR WARR survey was acquired before the start of irrigation, and roughly every two hours thereafter over the six-hour irrigation period (during short intervals in irrigation).

3.4. TDR data and direct evidence

TDR rods ranging in length between 0.15 m and 2 m, spread along the irrigated line (Fig. 2), were monitored using a Tektronix 1502 B. One-meter and two-meter-long couples of vertically

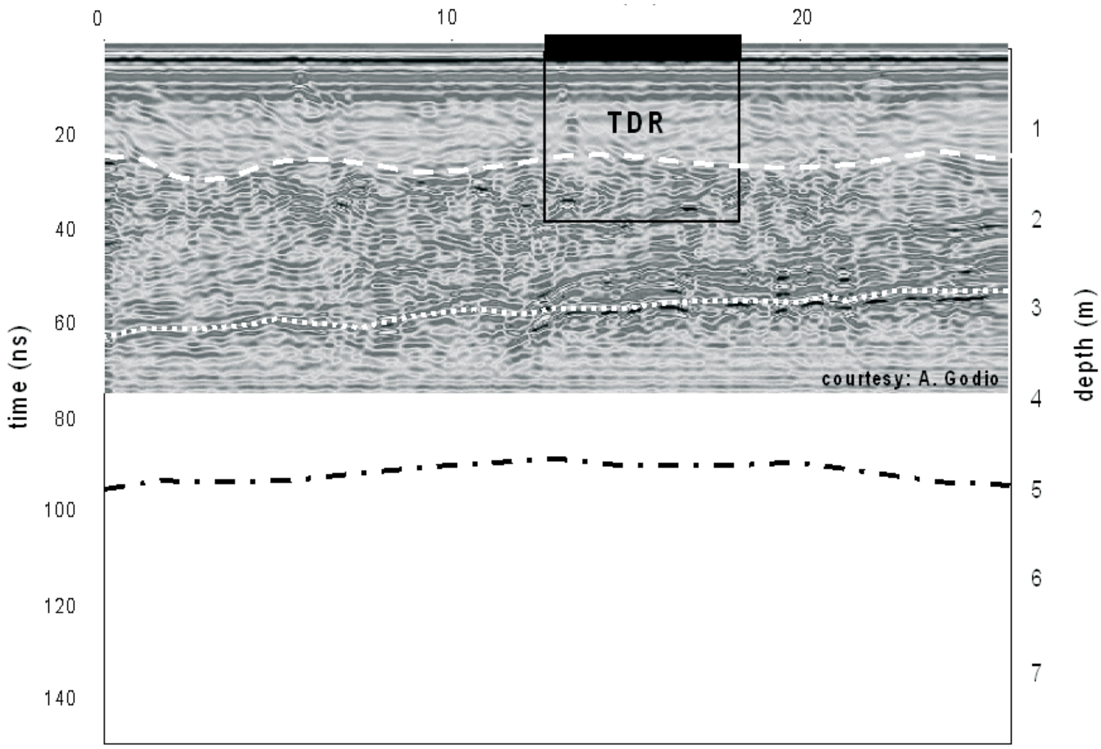

Fig. 4 - Minimum offset GPR reflection survey (450 MHz) collected under natural conditions at the Grugliasco site (courtesy Alberto Godio, Polytechnic of Turin).

inserted TDR stainless steel rods (6 mm diameter) were located at 1 m horizontal intervals along the same transect of the GPR measurements, starting from coordinate 12.5 m up to 16.5 m of this transect, namely just outside the longer boundary of the pond. Other 8 pairs of vertical TDR probes ranging in length between 0.15 m and 2 m were infixed just aside at about 500 mm distance. A transect of 16 150 mm-long vertical TDR probes was also placed before the irrigation trial. TDR data acquisition was performed during the same intervals as those used for the GPR acquisition, i.e. before the irrigation start and every two hours from then an. A pit, about 1.5 m deep, was dug in the irrigated plot, and visual inspection was made to support indirect evidence of the contact between the wet and the dry soils.

4. Discussion of field data and modelling results

The very homogenous structure of the soil at the Grugliasco site is ideal to identify a sharp infiltration front on a WARR radargram. As the front infiltrates, a low-velocity layer develops sandwiched between the air above, with the fastest possible GPR velocity c = 0.3 m/ns, and a fast half-space below, having the GPR velocity of the dry soil. Fig. 5 shows the evolution of WARR surveys over time, clearly showing that the presence of a low-velocity layer between the surface and the infiltration front changes the nature of the GPR data. At a first glance, the data can be interpreted as showing a critically refracted GPR wave, coming from the interface between the

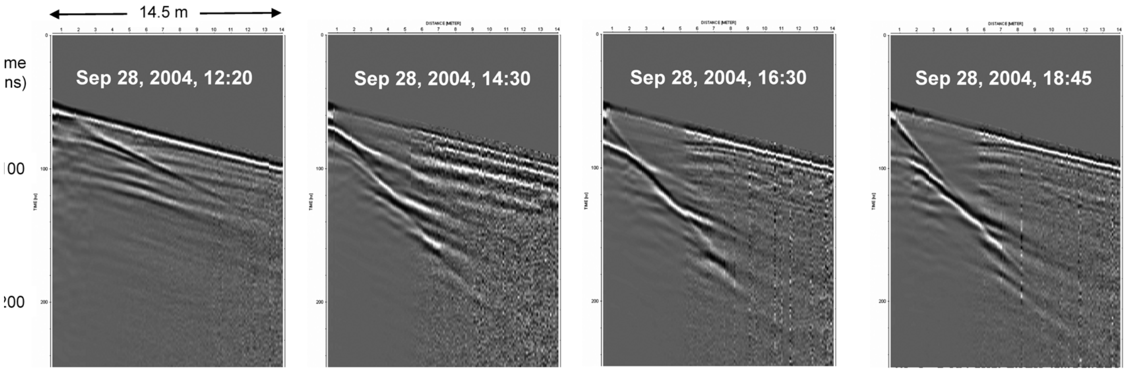

Fig. 5 - 200 MHz GPR time-lapse WARR acquisition at the Grugliasco site during the controlled irrigation experiment at the ground surface. Total time is 250 ns and maximum offset is 15 m in each panel.

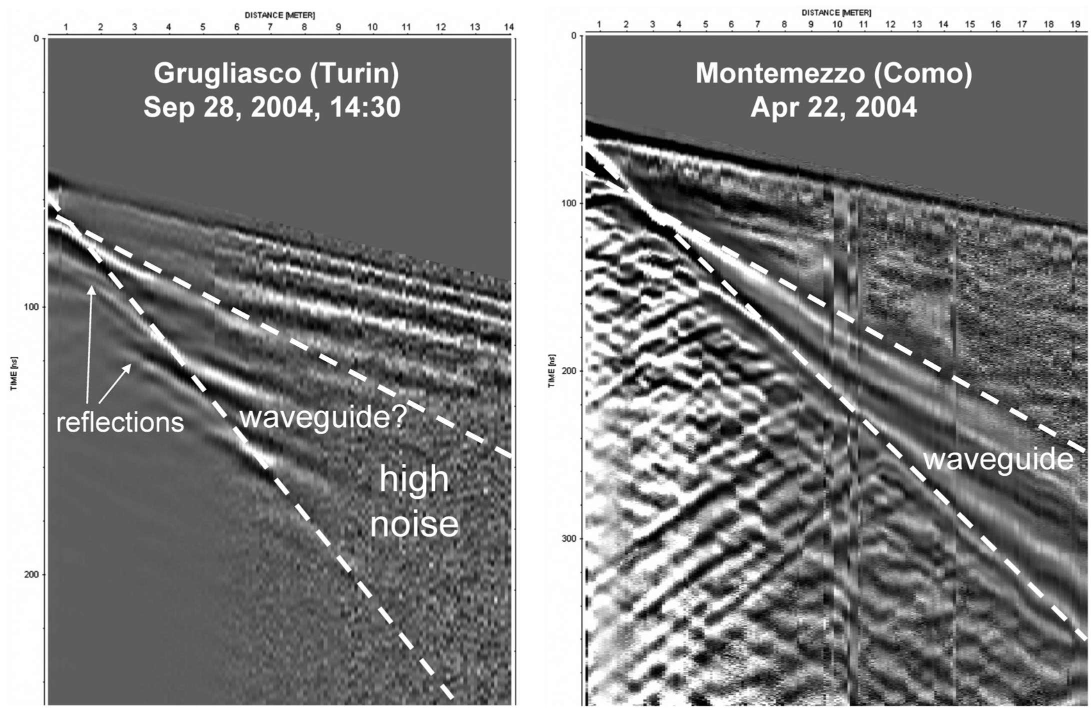

Fig. 6 - Comparison between GPR WARR data collected at Grugliasco 2 hours after the start of irrigation (left panel) and the data collected at the Montemezzo site (Como) in April 2004. In the Montemezzo data, the events to the right of the waveguide energy are interpreted as energy travelling horizontally and reflected back by discontinuities in the bedrock.

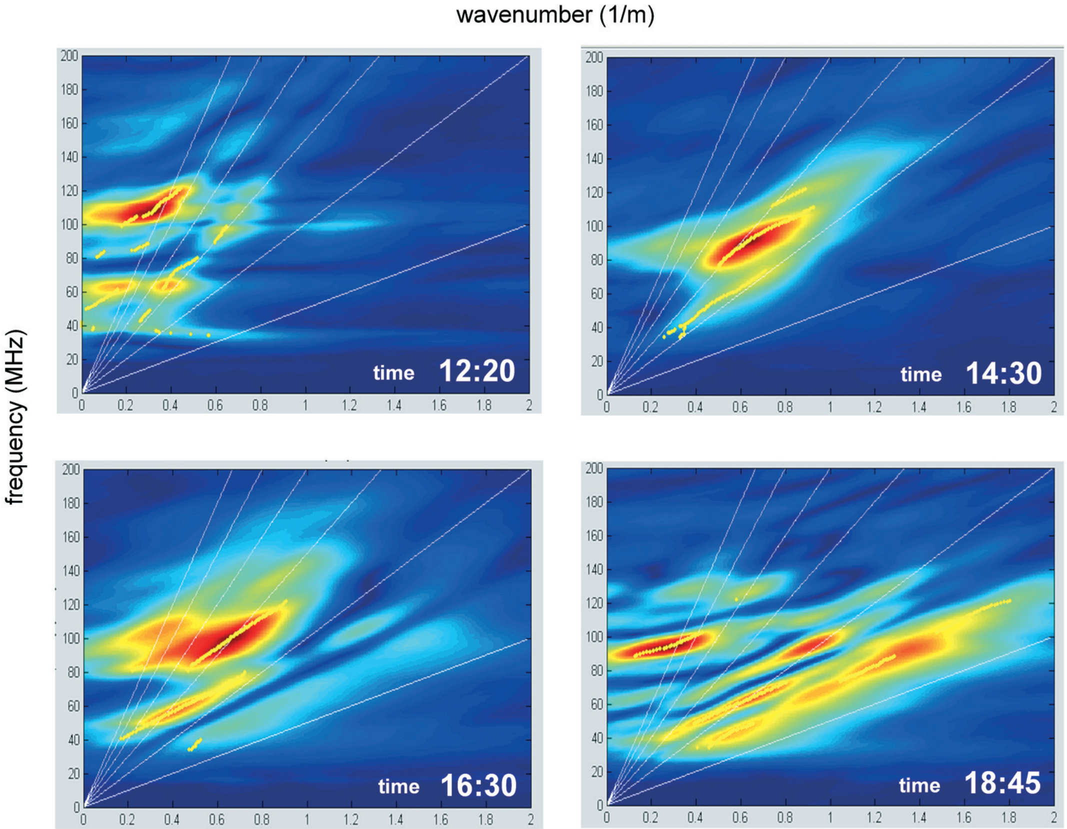

Fig. 7 - *f-k* spectra corresponding to the four radargrams in Fig. 5. The absolute maxima at each frequency are marked with a yellow dot. The white lines indicate different apparent velocity values and are displayed for reference.

wet layer and the dry layer below. This refracted energy is recorded at earlier arrival times than the direct GPR wave, through the low-velocity wet layer. As time progresses, and the thickness of the wet layer increases as irrigation progresses, the intercept time (at zero offset) of a such critically refracted event increases, according to simple considerations (Bohidar and Hermance, 2002).

However, with a more in-depth analysis, the data seem to show a more complex behaviour, similar to a series of multiple reflected-refracted events. The presence of multiples is in fact a transition towards a waveguide phenomenon. In presence of a slow layer, with thickness comparable to the wavelength, a waveguide phenomenon can take place, as shown also in other situations (Arcone *et al.*, 2003; van der Kruk *et al.*, 2006; Strobbia and Cassiani, 2007). The wet layer between the ground surface and the infiltration front is precisely a slow layer of this type, as its thickness is likely to be in the meter range. In Fig. 6 a comparison is made between the data at Grugliasco after 2 hours of irrigation, and the data collected at Montemezzo (Como, Italy) over a mountain slope with soil layer about 1 m thick, and discussed in detail by Cassiani *et al.* (2006b) and Strobbia and Cassiani (2007). At the Montemezzo site, the thin soil layer resting on top of a fractured metamorphic bedrock acts as a waveguide for GPR energy. There is some clear similarity between the two data sets, even though in the Grugliasco case high noise at large offsets prevents from a clear identification of the bulk of

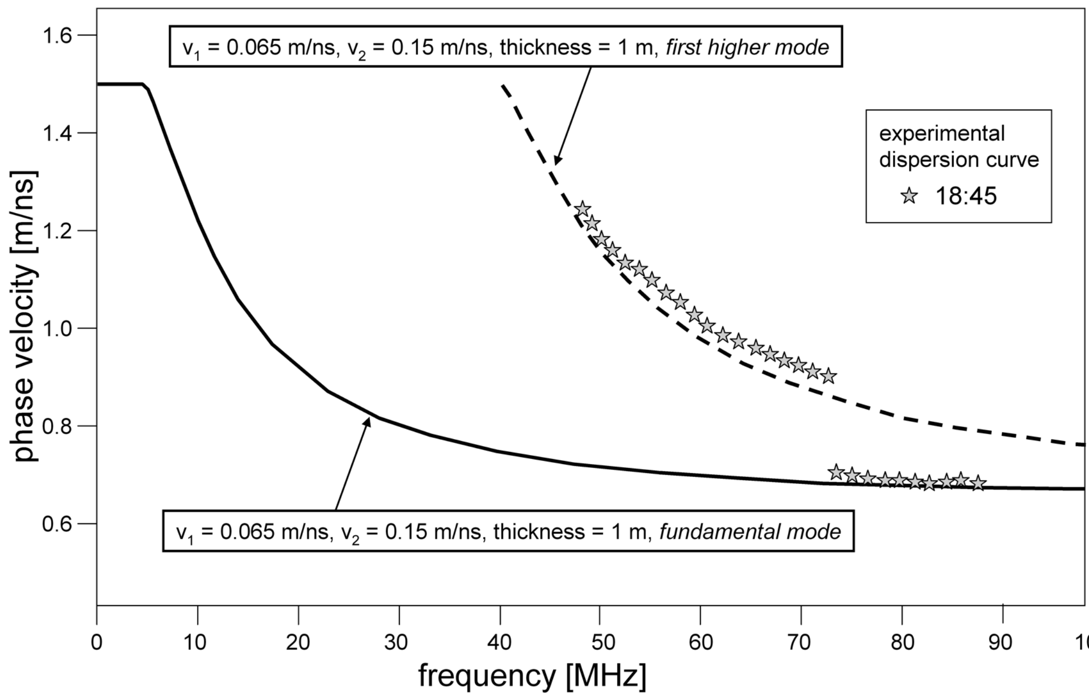

Fig. 8 - Experimental dispersion curves corresponding to the radargram at 18:45 in Fig.5, compared with an expected simulated dispersion curve produced with parameters similar to the observed velocities and thickness during the Grugliasco irrigation experiment. Note the strong discrepancy (except at high frequencies) between experimental and modelled data for the fundamental mode, while the simulation of the first higher mode may match the lower frequency part of the curve.

the guided wave-energy arrival.

Consequently, we attempted a waveguide analysis of the 4 recorded radargrams in Fig. 5 according to the procedure described in Strobbia and Cassiani (2007), based on the *f-k* spectrum analysis, for the simplified case of one, single-guiding low-velocity layer. The data contain (Fig. 5) energy other than the guided waves: primarily the direct air wave and some reflections (see also Fig. 1c): in particular, the air wave contains enough energy, and shall be muted in order to obtain meaningful *f-k* spectra. These are shown for the 4 radargrams in Fig. 7. The peaks of the energy spectrum, corresponding to the global maxima for each frequency, are also shown in Fig. 7. These maxima correspond each to an *f-k* pair, that can be converted into a phase velocity-frequency pair. The ensemble of such pairs will constitute the relevant dispersion curve for each radargram. The dispersion curves for the latest radargram are shown in Fig. 8.

Following the Strobbia and Cassiani (2007) approach, the next step is to find a suitable distribution of dielectric properties of the subsurface that gives rise to the observed dispersion curve. The subsurface is in this case schematized as a one-layer system confined by a semi-infinite half-space, so that only three parameters are needed to represent the system: the velocity of the wet layer v_1, the velocity of the dry layer v_2 and the thickness of the wet layer (note that the velocity of the upper cladding layer-air-is known to be 0.3 m/ns).

Fig. 8 also shows a trial dispersion curve (fundamental mode, solid line) built using typical

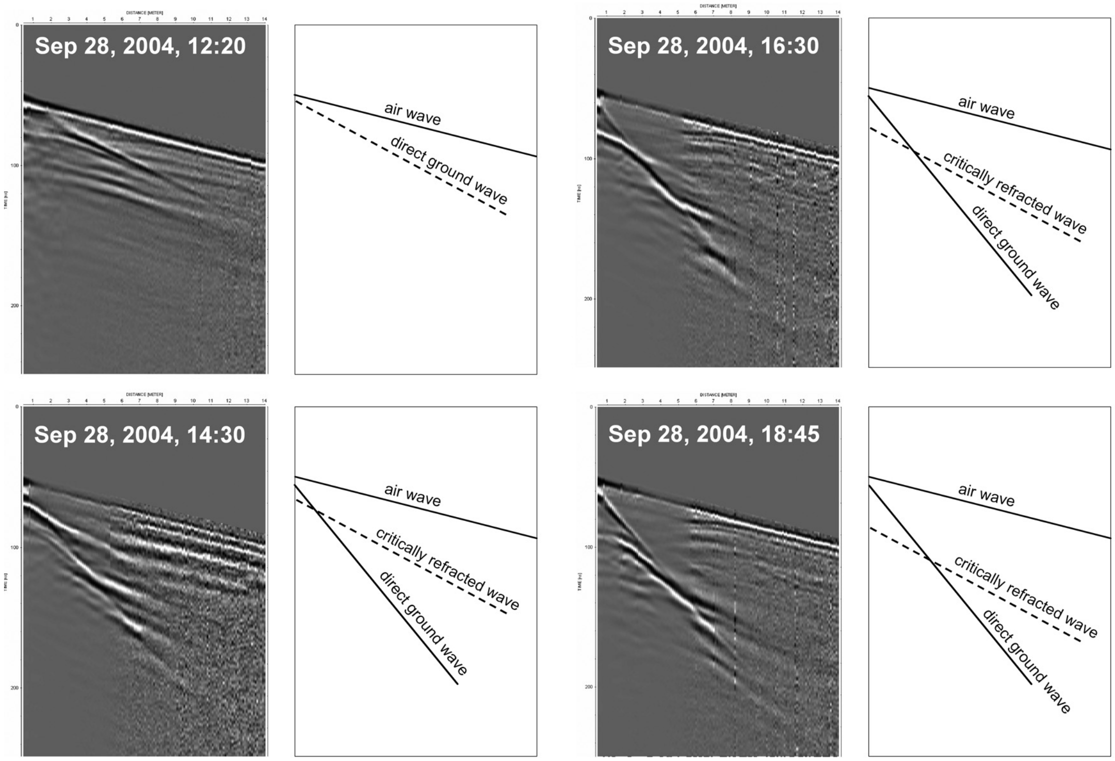

Fig. 9 - Interpretation of the four radargrams acquired during irrigation using a simplified approach that assimilates the data to critically refracted events.

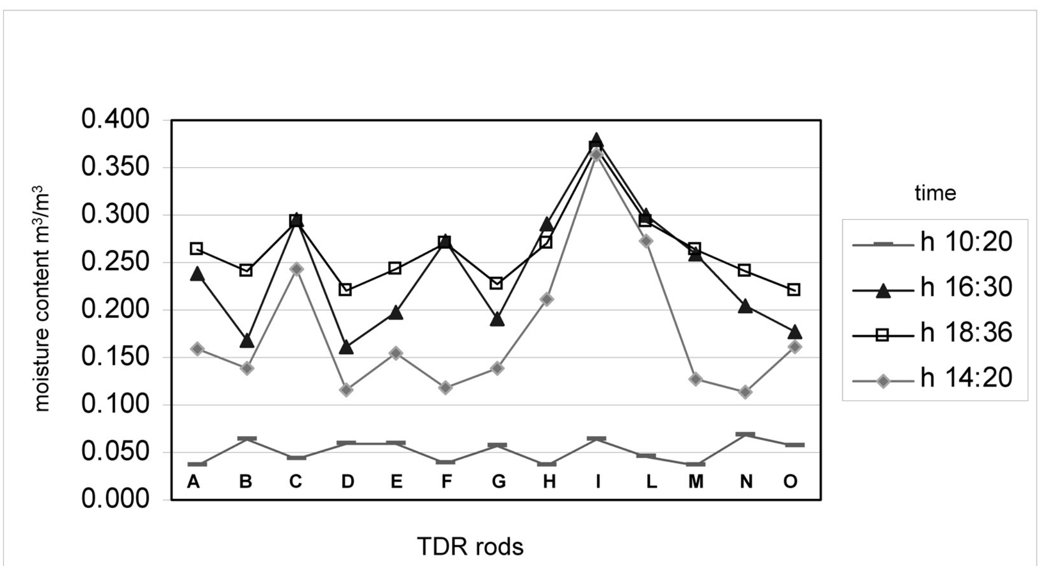

Fig. 10 - Soil water content values from TDR measurements at the four instants in time during irrigation at the Grugliasco site; for the location of each probe, see Fig. 2.

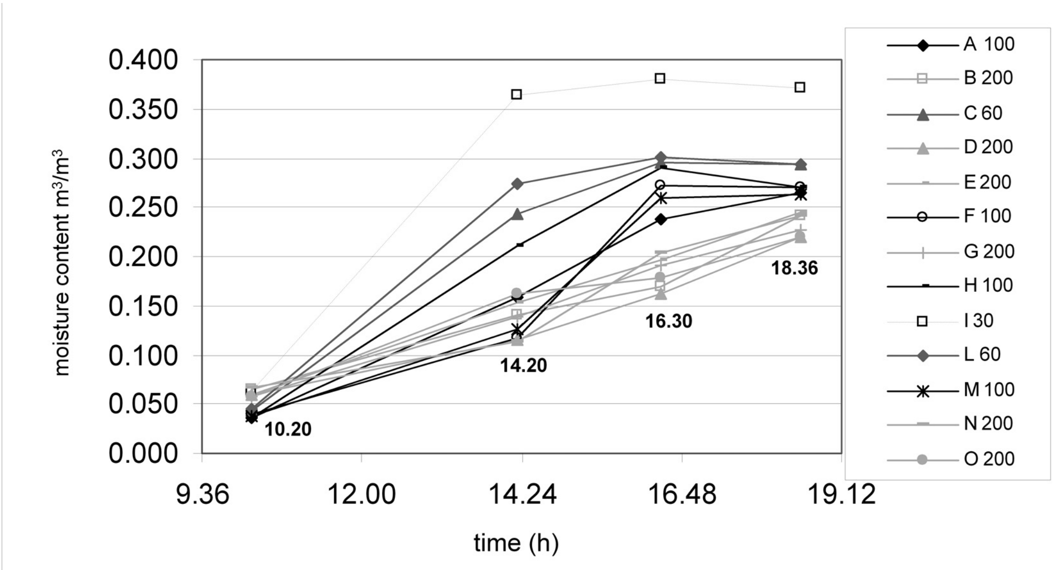

Fig. 11 - Soil water content values from TDR measurements at the four instants in time during irrigation at the Grugliasco site; for the location of each probe, see Fig. 2.

velocities and thickness given the situation at hand: it is noteworthy how far this expected dispersion curve is from the experimental ones. In fact, the experimental dispersion curve (here at 18:45) is too steep and defined in a range of frequency too high to represent a waveguide in the range of 0.5-2 m thickness, as expected.

The experimental dispersion curve is most likely correspondent to a higher mode. In Fig. 8 the first higher mode is plotted as well (dashed line). The fact that a higher mode is dominant can be associated to the larger attenuation of the fundamental mode, which is characterized by shorter wavelengths, and by the excitability of different modes for the dielectric and geometric properties of the waveguide. Moreover, the quality of the dispersion image is affected by artefacts generated by a mixture of energy arrivals, including important reflection events (see Fig. 5), while the waveguide energy does not, for the most part, emerge above the high electromagnetic noise level. The presence of noise and reflections, is therefore, preventing us from using, in this case, a standard waveguide analysis based on the fundamental mode to infer the dielectric properties - and hence the moisture content - of the near surface. After a proper event identification, a higher mode inversion could be done: this is, from a methodological viewpoint, identical to a fundamental mode inversion.

For the purpose of the study presented here, we attempted, instead, a simplified interpretation of the Grugliasco data, that may prove to be general enough to be used also in other cases. As discussed above, the situation that gives rise to GPR guided waves is a particular case of the situation that gives rise to critically refracted waves: a slow layer, sandwiched between two high-velocity cladding layers. When the GPR wavelength is much smaller than the slow-layer thickness, the energy travels according to Snell's law and gives rise to direct and critically refracted events while if the wavelength is comparable in size to the layer thickness, a waveguide develops. Of course, there is a continuous transition between the two cases. In fact, the guided waves appear as a wedge of energy, comprised between maximum and minimum phase velocities (see straight lines in Fig. 6) that can be interpreted

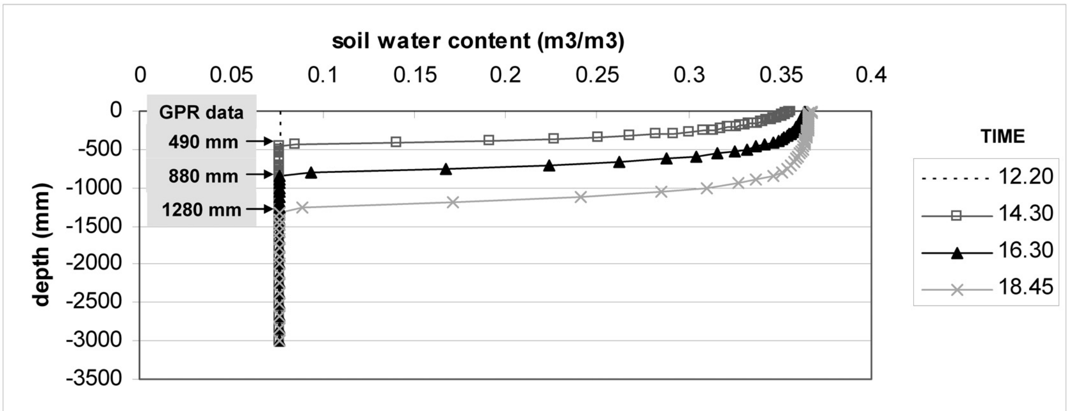

Fig. 12 - Soil water content profiles simulated using a 1D infiltration model calibrated on the location of the infiltration front as indicated by GPR measurements (see Table 1) using the unsaturated flow parameters in Table 2.

respectively, as the velocity of the bedrock and the velocity of the slow layer. This means that, to some degree of approximation, it is conceivable to interpret the data on the sole basis of such maximum and minimum velocities, obtained by a visual fitting of two straight lines on the radargram, using a critical-refraction interpretation approach (Bohidar and Hermance, 2002). Note that this simplified approach is, indeed, being used already in the literature, albeit as a consequence of not recognizing fully the waveguide character of the data (van Overmeeren *et al.*, 1997).

We used this simplified approach to interpret the data collected at Grugliasco (Fig. 9), obtaining the estimates of the velocity of both the dry and wet soil layers, and of the thickness of the wet layer (Table 1). Using the Topp *et al.* (1980) relationship (Eq. 3), the estimated volumetric water contents of the dry and wet soils are respectively 5% and 38% - the latter still below full saturation as the soil porosity is larger (40%). These values are fully supported by the TDR data (Figs. 10 and 11). The depth of the infiltration front estimated by GPR refraction analysis is also confirmed by direct inspection, even though some discrepancy is observed at the beginning of infiltration (after 2 hours; see Table 1): this is probably a consequence of using an approximation to interpret data that have the

Table 1 - Grugliasco site: estimates of GPR velocities and infiltration front depth during the irrigation experiment of September 28, 2004.

Time	Velocity into wet level v_1 (m/ns)	Estimated water content in wet level	Velocity into dry level v_2 (m/ns)	Estimated water content in dry level	Depth of water front by GPR data analysis (m)	Depth of water front by direct trench analysis (m)
12:20	-	-	0.156	5%	-	-
14:30	0.063	38 %	0.154	5 %	0.49	0.35
16:30	0.062	38 %	0.154	5 %	0.88	0.8
18:45	0.064	38 %	0.151	5%	1.28	1.25

Table 2 - Van Genuchten-Brooks-Corey parameters adopted for the calibrated 1D infiltration model.

h_g [mm]	n	porosity	residual water content θ_r	Brooks-Corey exponent	saturated hydraulic conductivity K_s [mm/h]
220	2.5	40%	0.	7.3	16.8

characteristics of guided waves more than at later times when the thickness of the slow layer is larger.

The GPR and TDR data have been used to calibrate a one-dimensional infiltration model based on the code developed by Manzini and Ferraris (2004). The key parameters for calibration are the saturated hydraulic conductivity K_s, and the pressure scale parameter h_g, while the other parameters of the unsaturated soil are derived from laboratory measurements. The parameters used are shown in Table 2, while the modelled infiltration process is shown in Fig. 12.

5. Conclusions

The results of this study confirm the effectiveness of GPR measurements to delineate the variation of soil/water content during an infiltration experiment. This type of non-invasive in-situ monitoring can provide in-situ estimates of moisture content under undisturbed conditions and at the metre scale, as required for the to understanding of soil hydrology and the soil-atmosphere interaction in terms of mass and energy exchange processes.

Our analysis shows, however, that care must be paid to interpret this type of GPR data, as the infiltration process gives rise to a wet, low-velocity layer, having thickness increasing with time: this layer acts as a waveguide for GPR energy. In principle, such data shall be interpreted using an inversion of the GPR wave-dispersion curve (variation of velocity with frequency). However, we showed that it is possible to apply also a simplified interpretation approach, based on a critical-refraction theory, that provides estimates of velocities and wet-soil thickness in excellent accord with TDR soil-moisture measurements and direct inspection. A 1D infiltration model could be effectively calibrated on the GPR-derived infiltration data, leading to estimates of the governing parameters of the unsaturated flow at the site of interest.

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