# A WATER INJECTION EXPERIMENT IN THE VADOSE ZONE: THE USE AND VALUE OF NON INVASIVE CROSS-HOLE DATA FOR MODEL CALIBRATION

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## ABSTRACT

The characterization of the deep vadose zone is traditionally a difficult task, since access without disturbance of samples or modification of in-situ conditions is practically impossible. On the other hand, the presence and flow of water in the vadose zone controls a number of phenomena of great environmental interests, such as contamination of water resources, catchment hydrology, floods and slope stability. As a consequence, non invasive – geophysical - techniques, such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR), are being increasingly used to investigate the vadose zone. The use of cross-hole methods is particularly effective and increasingly applied. The dependence of the geophysical response on changes in soil moisture content, e.g. via changes in electrical resistivity or dielectric properties, is the key mechanism that permits the use of non-invasive techniques to monitor the vadose zone in time-lapse mode, i.e. via repeated measurements over time. The data from non-invasive techniques can be subsequently used to calibrate physical-mathematical models of water flow in the unsaturated zone. In this paper, we present the results of a forced infiltration experiment conducted at the research site in Gorgonzola, close to Milan, Italy. The site geology is typical of the alluvial quaternary sediments of the Po river plain, characterized by a fairly coarse sandy-gravel grain size distribution. Four 20 m deep boreholes were drilled at the site; three of them are permanently equipped with stainless steel borehole electrodes for ERT imaging. Each borehole has a set of 24 electrodes, spaced 0.8 m vertically. The same boreholes are also being used for cross-hole GPR tomography. Both MOG (multiple offset gathers) and ZOP (zero offset profiles) have been adopted as configurations for GPR surveys. Monitoring of natural infiltration processes started in January 2005. In July 2005 a first artificial water injection experiment was performed using a 2 m deep, 2.60 m long trench. A total of 3 $m^3$ of tap water infiltrated in about 2 hour time. A number of ERT and GPR MOG datasets were acquired from July 5 (date of water injection) to July 11, 2005. The data were used to calibrate a 1D unsaturated flow model [*Simunek et al.*, 1998]. In a second infiltration experiment, conducted in January 2006, more than 20 $m^3$ of water were injected, thus helping the characterization of the deeper part of the soil profile. A 3D unsaturated flow model [*Lin et al.*, 1997] was calibrated on the results of the second experiment. Strengths and limitations of the methodology are analysed and discussed.

## 1. INTRODUCTION

Water presence and flow in the vadose zone controls a number of phenomena of great environmental interests, such as contamination of water resources, catchment hydrology,

floods, slope stability. The vadose zone is characterized by a complex, non-linear behavior. In addition, this zone is difficult to access without causing major disturbance to the natural in-situ conditions. Hydrologic characterization of the vadose zone is challenging, particularly when the investigation extends deeper than one or two meters below ground. Direct measurement of water content requires the recovery of soil samples for laboratory analyses. All direct measurements are invasive, based on drilling. As a consequence, non invasive – geophysical - techniques, such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR), are being increasingly used to investigate the vadose zone.
From a practical standpoint, two compartments can be identified in the subsurface that require different approaches for indirect monitoring. The *shallow* vadose zone, no deeper than a few meters below ground, can be successfully imaged, with extensive spatial coverage, by taking measurements from the ground surface. In contrast, the *deep* vadose zone, requires measurements in single-boreholes, between boreholes, or from the surface to boreholes to achieve sufficient resolution for quantitative hydrologic interpretation.
The development of geophysical techniques for the characterization of the subsurface has been very rapid over the past couple of decades. Ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) have seen the most widespread use to date. Of particular importance to hydrologic characterization and monitoring are the abilities of geophysical methods to describe two aspects of the subsurface:

a. *static* aspects, which *do not* change over time, principally related to physical and chemical properties of the geological medium;
b. and *dynamic* aspects, which *do* change over time in response to changes in fluid saturations and water chemistry.

This successful use of geophysical data for hydrologic investigations requires:

- that the collected geophysical data have a clear, identifiable and quantitative petrophysical relationship to environmental variables of interest;
- that the resolution and sensitivity of geophysical methods in space and time is fully understood and is appropriate to constrain the hydrologic process of interest;
- that indirect measurements be incorporated into hydrologic models in the most effective way, (i.e. accounting for resolution, sensitivity and scale effects).

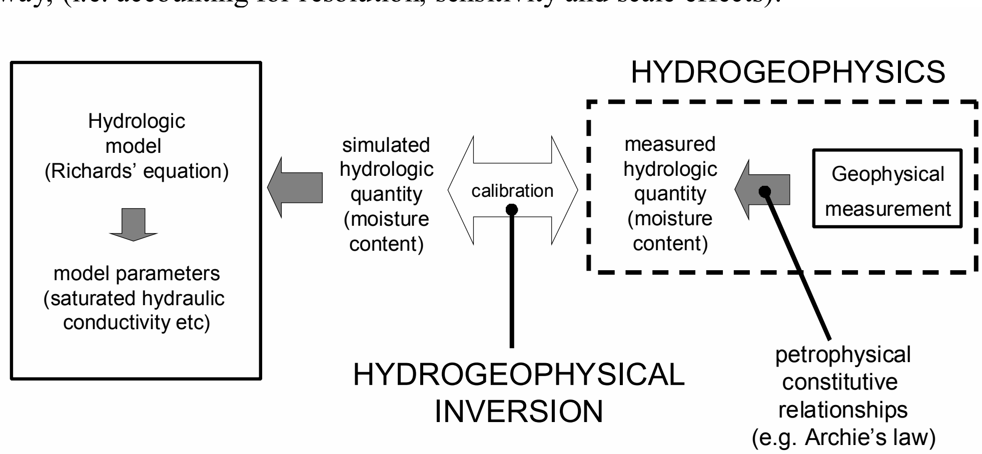


FIGURE 1. a conceptual scheme for the use of geophysical data to calibrate unsaturated water flow models.

The use of cross-hole methods is particularly effective and increasingly applied. The dependence of the geophysical response on changes in soil moisture content, e.g. via changes in electrical resistivity or dielectric properties, is the key mechanism that permits the use of non-invasive techniques to monitor the vadose zone in time-lapse mode, i.e. via repeated measurements over time. These techniques are used in different configurations in the shallow and deep vadose zones, due to practical access issues. Both natural infiltration processes and specifically designed tracer tests can be monitored over periods of time that can last from a few hours to several years. The data from non-invasive techniques can be subsequently used to calibrate physical-mathematical models of water flow in the unsaturated zone (Figure 1).

## 2. WATER INJECTION EXPERIMENTS

Time-lapse cross-hole geophysical measurements have been used to monitor two water injection experiments at the Gorgonzola experimental site, close to Milan, NE Italy. The site has been equipped to monitor the unsaturated flow dynamics in the local alluvial quaternary sediments of the Po river plain, characterized by a fairly coarse sandy-gravel grain size distribution. Four 20 m deep boreholes were drilled at the site; three of them are permanently equipped with stainless steel borehole electrodes for ERT imaging.

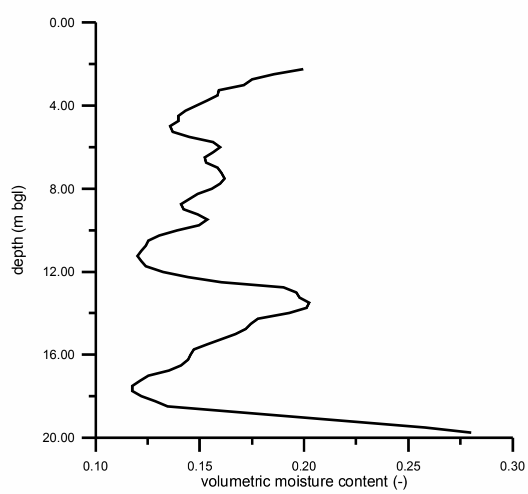


FIGURE 2: moisture content profile on January 17 at the Gorgonzola site (before the second water injection experiment) as derived from GPR ZOP data on boreholes A-B. The conditions before the first experiment (July 2005) were practically identical.

Each borehole has a set of 24 electrodes, spaced 0.8 m vertically. ERT data are acquired using am IRIS Syscal Pro system. The same boreholes can also be used for cross-hole GPR tomography, as demonstrated by field evidence, in spite of the existence of electrodes and cables in each borehole. Both MOG (multiple offset gathers) and ZOP (zero offset profiles) have been adopted as configurations for GPR surveys. A PulseEkko 100 system has been used with 100 MHz borehole antennas. Conversion from GPR traveltimes to moisture content values has been provisionally performed using the relationship by *Topp et al.* [1980], but site specific calibration of dielectric properties is planned in the near future. ERT has been used so far only to provide qualitative images of changes in resistivity due to water saturation changes. Inversion of ERT data has been performed using the CRTomo 2D code [*Kemna*, 2000], while the code Migratom [*Jackson and Tweeton*, 1994] was used for the inversion of GRP MOG data. ZOP profiles have been analyzed under the assumption of straight ray horizontal propagation. Monitoring of natural infiltration processes started in January 2005.

In July 2005 a first artificial water injection experiment was performed using a 2 m deep, 2.60 m long trench dug perpendicular to the plane described by boreholes A and B, located 6.65 m apart. A total of 3 $m^3$ of tap water infiltrated in about 2 hour time. 8 surface electrodes were positioned to supplement the borehole electrode configuration. A number of ERT, GPR ZOP and GPR MOG datasets were acquired from July 5, 2005 (date of water injection) to July 11. In January 2006 a second experiment was conducted injecting a much larger water volume (22 $m^3$) in the same trench over a period of 11 hours. The same data acquisition setup was adopted, but the frequency of acquisition was much higher (hourly) than in the July 2006 experiment.

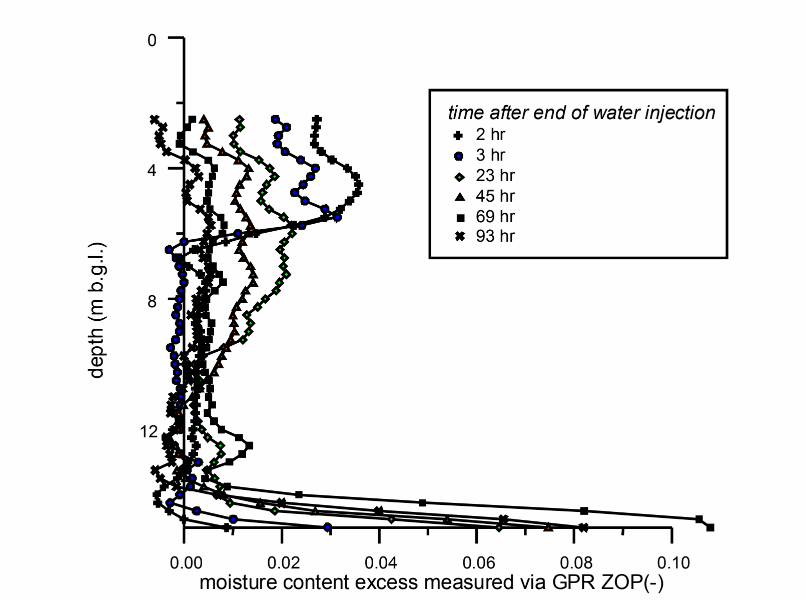


FIGURE 3: Excess of moisture content with respect to background (i.e. before water injection) derived from GPR ZOP data during the first water injection experiment. Note the water table rise in the deeper part of the profile, as a consequence of regional irrigation.

## 3. RESULTS

ERT, GPR ZOP and GPR MOG images show very clearly the structure of the site subsurface (Figure 2 and Figure 5) where finer (wetter) sediments are present deeper than 12 m b.g.l. Resistivity and water content differences with respect to background both show with clarity the infiltrating front that can also be tracked effectively by using the simple ZOP procedure (e.g, Figure 3), even though the latter cannot identify the lateral spreading occurring at the early stages of infiltration. Note that, as expected, the resolution characteristics of ERT and GPR MOG surveys impact substantially the image characteristics [*Cassiani et al.*, 1998; *Day-Lewis et al.*, 2004 and 2005].

In order to quantify the results of the experiment in terms of hydraulic parameters of the subsoil, model calibration is needed (Figure 1). A first attempt was made to simulate the first water infiltration experiment using a 1D transient unsaturated flow code [*Simunek et al.*, 1998]. Only the ZOP data (Figure 3) were used for calibration. Even though the geometry of the experiment is highly simplified by the 1D simulator, and consequently the absolute value of measured excess water content cannot be expected to be matched exactly, the vertical movement of the water slug centre of mass can be accurately reproduced using, in the model, hydraulic conductivity values very close to the only available in-situ measurement result. As previously shown [*Binley et al.*, 2002], the motion of the centre of mass is very sensitive to the value of saturated hydraulic conductivity, that can be calibrated very precisely. Note that the late time estimates of the centre of mass are subjected to much larger errors than the early time values, because in the first injection experiment the utilized water volume was too small to investigate with reliability the deeper vadose zone, at longer times after the end of injection.

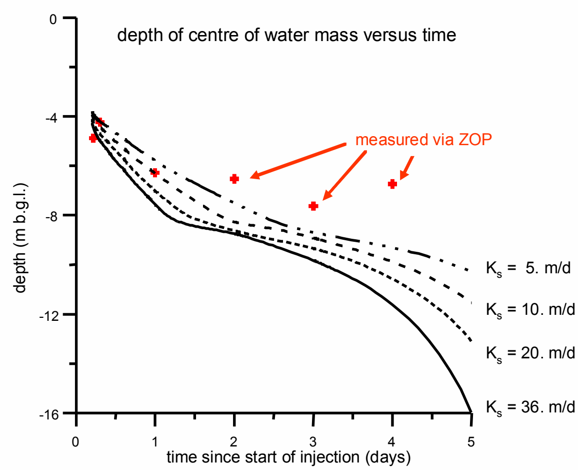


FIGURE 4: Centre of mass vertical motion as computed by 1D infiltration flow simulations compared against the centre of mass motion derived from ZOP data for the first experiment (Figure 3). Four values of saturated hydraulic conductivity ($K_s$) of the subsoil were used and provide different results.

The second water injection experiment proved much more informative of the deeper vadose zone. Three distinct phases can be identified: during water injection (Figure 6A) the excess moisture content invades the first 8 to 9 m below ground; in the following phase (Figure 6B) the water migrates in the fine sediment layer at about 12 m; finally water is progressively and slowly released from this fine layer into the underlying deeper sediments (Figure 6C).

A 3D finite element model was used to simulate the second water injection experiment (Figure 7) based on laboratory data of hydraulic conductivity on core samples. Similar to the first experiment, the comparison between simulation results and field (GPR ZOP) data helped at least bracket the actual in situ hydraulic conductivity values, here analyzed layer by layer (Figure 8).

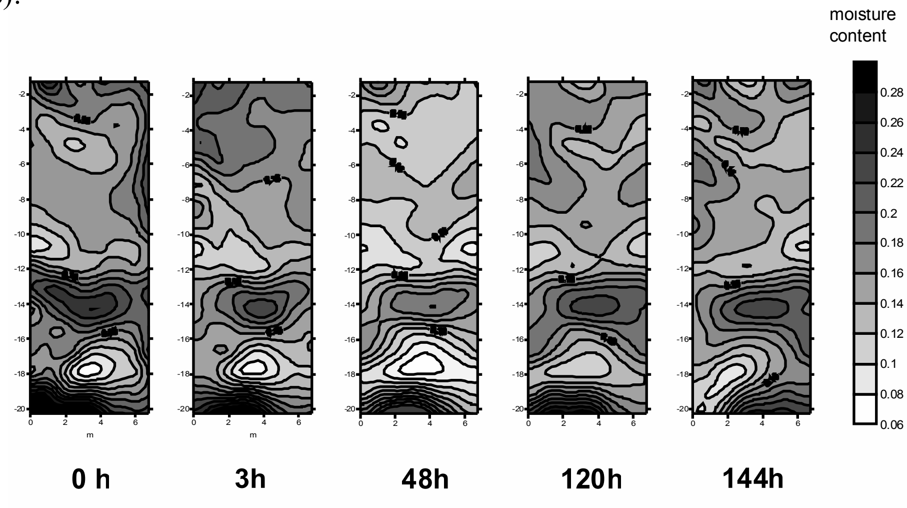


FIGURE 5: GPR MOG images of the A-B borehole plane at the Gorgonzola test site before and during the second water injection experiment (January 2006).

## 4. CONCLUSIONS

The water injection experiments conducted at the Gorgonzola test site proves that fast infiltration in permeable quaternary sediments of the Po river plain can be monitored accurately by both borehole ERT and GPR in time-lapse mode. Use of these data to calibrate unsaturated flow models proves to be an invaluable tool to derive unsaturated hydraulic parameters under in situ conditions.

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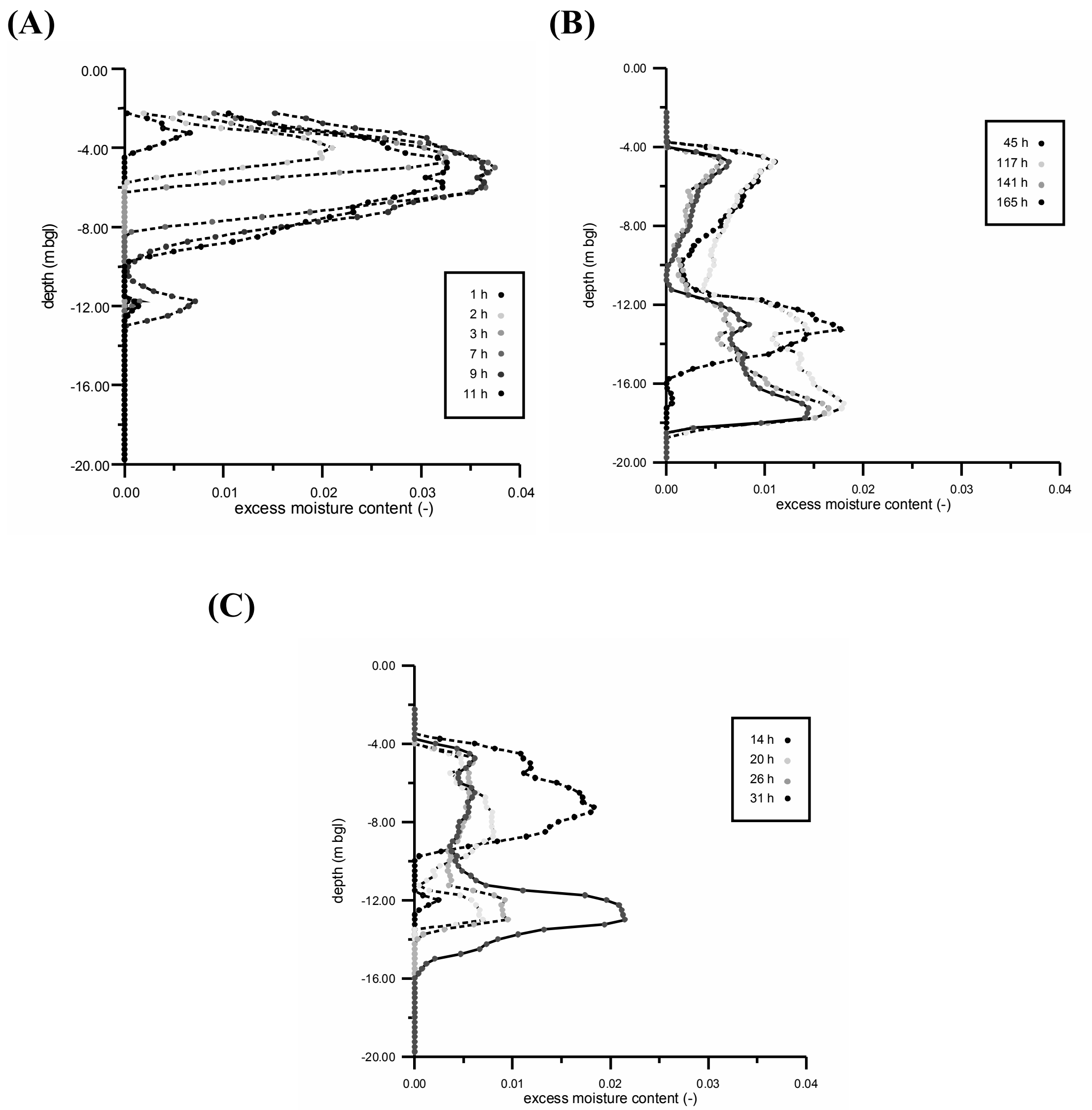


FIGURE 6: excess moisture content during the second water injection experiment as measured by GPR ZOP: (A)during the first 11 hours (i.e., until the end of injection); (B) during the 17 hours following the end of injection; (C) 45 to165 hours after start of injection.

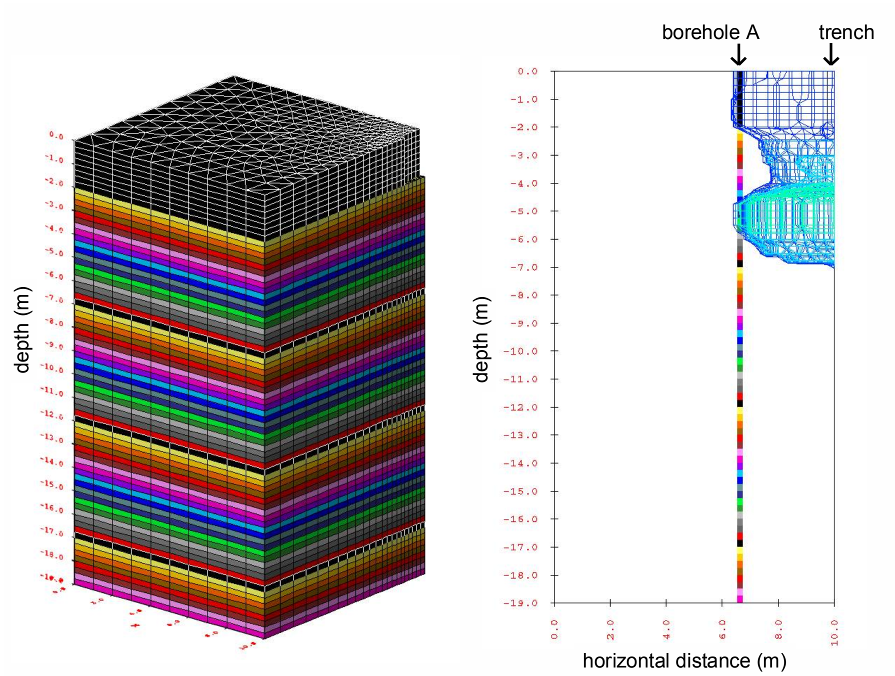


FIGURE 7: 3D finite element mesh and moisture content simulated at the end of second water injection experiment (11 hours).

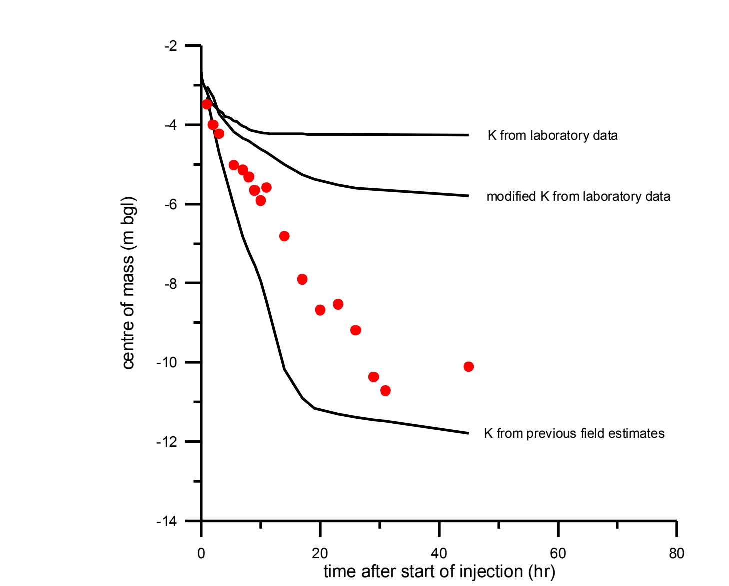


FIGURE 8: Centre of mass vertical motion as computed by 3D infiltration flow simulations compared against the centre of mass motion derived from ZOP data (Figures 6-8).