An experimental field plant for water flow monitoring and modelling in a vineyard terraced area (Lamole, Greve in Chianti, Italy)

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Abstract

In many hilly and mountainous area of Italy, terraces are extensively diffuse. It is a common opinion that terraces do not respond to the actual needs of modern agriculture owing to the high maintenance costs, difficulty in employing machines, reduced field dimensions etc. Today, beyond the role of the terraces in preventing hydrogeological instability and landslide risks, one has to take into consideration their importance from a historical and traditional point of view.

At Lamole ("Fattoria di Lamole", Greve in Chianti, Firenze, Italy), an experimental field plant was set-up in order to study and model the water circulation in a terraced slope together with the influence soil and water exerts on the stability of the dry-stone retaining walls. The terraces are intensively cultivated for high quality wine production. The dry-stone walls are ancient, some in original condition, some restored and others needing to be completely rebuilt, but deformations and collapses are occasionally present.

A preliminary survey was carried out in order to estimate the hydraulic and mechanical soil characteristics. Field saturated hydraulic conductivity measurements, infiltrometer tests and soil texture determinations (fine particle-size and skeleton fraction) were performed.

In a second phase of the experimental work, water run-off directions and drainage area were derived using a terrestrial laser scanner and a high-resolution digital terrain model. The Relative Path Impact Index was calculated (Tarolli *et al.*, 2013). A geo-electrical and geo-seismic survey was also carried out in order to reconstruct the stratigraphic profile of the slope and to identify the depth of the bedrock. Another electrical analysis was performed on a small area to determine the water flow paths into the soil.

A representative dry-stone wall was and is still being monitored. Throughout two pressure cells, the earth pressures at the retaining soil-wall interface is being measured. Volumetric water content and ground-water levels are also being monitored using a capacitance probe and piezometers which reach different depths.

By coupling the hydrological, hydraulic and geotechnical parameters, a simple dry-wall stability model was used and tested. The model takes into account the pressures derived from the uphill water infiltration, the stone friction and the buoyancy to simulate the wall deformations.

Keywords: ERT, field saturated soil hydraulic conductivity, RPII, stability, terraces, water circulation

Introduction

Agricultural terraces are extensively diffuse in many hilly and mountainous areas around the world (Spain, Italy, Germany, Greece, Israel, Peru, Nepal, China, Taiwan, Indonesia, Kenya etc.). They permit different crop cultivation (olive, vine, mango, rice, etc.) on flat fields of varying size created generally behind stone walls. Beyond the agricultural aspects, terraces are considered very effective for soil conservation (decreasing runoff and sediment production) and for the reduction of hydrogeological instability as well as landslide risks. We present here the design and set-up of an experimental field plant whose aim is the study and modelling of water circulation in a terraced slope together with its influence on the stability of the retaining dry-stone walls.

The pilot plant is located at “Fattoria di Lamole” (Greve in Chianti, Firenze, Italy) where both ancient and recently restored or rebuilt dry-stone retaining walls are present. The intense vineyard cultivation makes it very representative in terms of range of external stresses that affect both hillslopes and walls. The research is being developed within a bigger framework of landscape preservation as a way to prevent hydrogeological instabilities and landslide risks.

Materials and methods

Study area

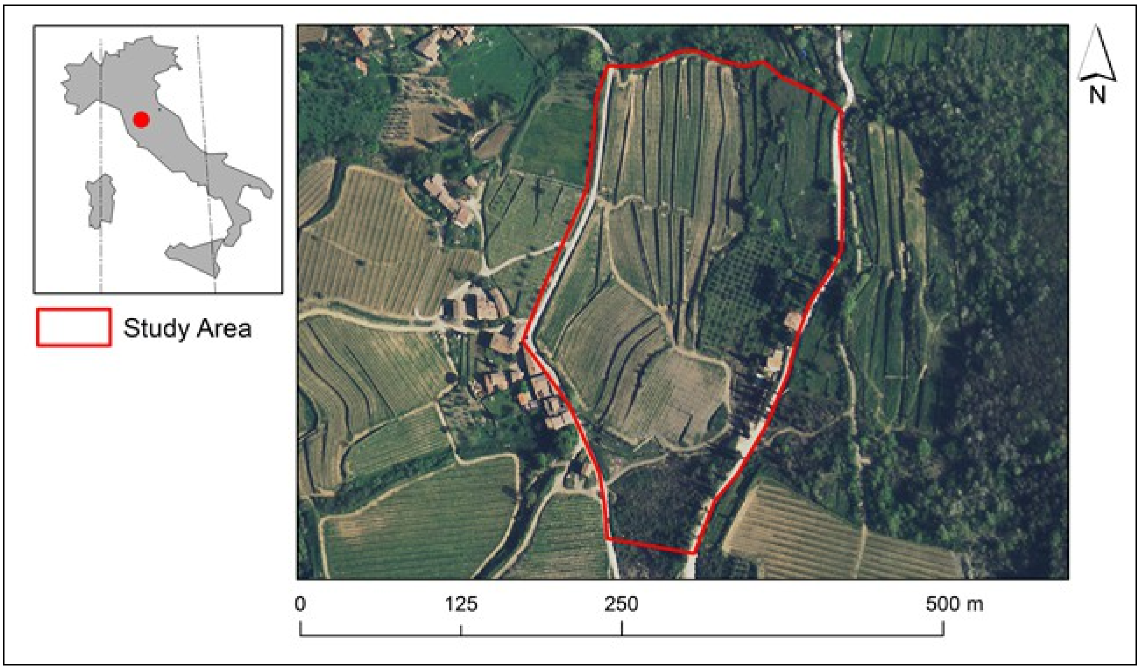

figure 1: location of the study area: "Fattoria di Lamole", Greve in Chianti, Firenze, Italy

The study area is in the "Chianti Classico" wine area, in the center of Tuscany, and it is located in the small village of Lamole within the municipality of Greve in Chianti (province of Florence). The study area is a typical hilly environment (515 e 579 m a.s.l.), along a slope facing North-North West, on soils that have been developed from sedimentary rocks such as sandstones and marls (Figure 1). Vineyards here are growth on terraces made only of dry-stones, that represent a typical landscape element of this region. The terraces have been restored since 2003 in order to maintain their original role of soil erosion prevention, and to realize the production of high quality wine. Few months after the restoration, one of the terraces displayed deformations and slumps (Figure 2). This particular wall was therefore considered as an interesting element for the analysis described in the following chapters.

figure 2: example of dry-stone wall collapsed after intense rainfall

Experimentations

First, every point in the retaining walls that showed some weakness (from bulging to collapsing) have been marked with GPS and then the whole vineyard area underwent to a survey through a terrestrial laser scanner and a high-resolution digital terrain model derived in order to identify water run-off directions and drainage area. The Relative Path Impact Index (RPII) and superficial flow accumulation was calculated (Tarolli *et al.*, 2013) and this parameter shows itself to be coherent with the critical spots observed in situ and marked with GPS. Since the RPII seems to be correlated with the critical spots on the walls, hydraulic and mechanical soil characteristics were studied in order to find how water gathering could affect the walls stability.

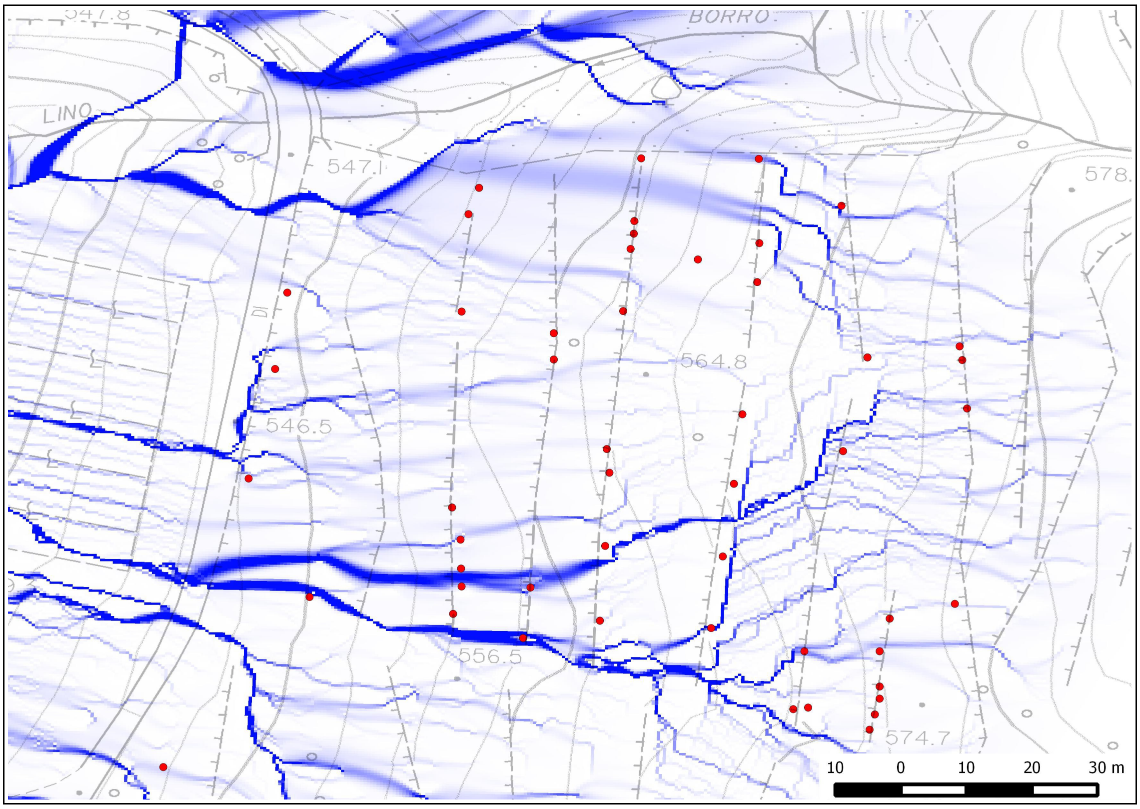

figure 3: red points indicate GPS location of critical spots (from bulging to collapsing), in graduated blue, water flow accumulation (from 1 to 800 contributing cells) on c.t.r. Regione Toscana-Map

The soil texture (fine particle-size and skeleton fractions) was determined according to USDA prescriptions by means of sieving and sedimentation on 0.1-0.3-0.45 m deep samples, and presence of water-stable/instable aggregates have been determined by a revised method derived from the one originally proposed by Burri *et al.* (2009). Direct shear tests on undisturbed and reconstituted soil samples were also performed in order to obtain the Mohr-Coulomb failure envelope parameters (internal friction angle and cohesion).

Field saturated soil hydraulic conductivity has been measured *in situ* by the Simplified Falling Head (SFH) technique (Bagarello *et al.*, 2004), partially modified due to the soil high stone and gravel fractions that prevented to drive the steel cylinders deep in the vineyard soil; Infiltration rate measurements have been also performed using a double ring infiltrometer.

Geo-electrical and geo-seismic surveys were also carried out in order to reconstruct the stratigraphic profile of the slope and to identify the depth of the bedrock.

A representative dry-stone wall has been monitored near one of the weakened points: through two pressure cells placed 90 cm and 180 cm deep (fig. 4), the earth pressures at the soil-wall interface has been measured and recorded both in saturated and unsaturated states. Load tests have been undertaken filling a tank up to 1 m^3 of water placed on the soil just behind the wall in order to validate pressure measures from pressure cells.

figure 4: earth pressure cells installed behind the monitored dry-stone wall to monitor the total soil-wall pressure

figure 5: piezometers installed on the monitored dry-stone wall to measure the water level behind the wall itself

Soil humidity and pressure data have been collected for the last two years during rainfall events: the volumetric water content and ground-water levels have been monitored through a capacitance probe (Sentek EnviroSMART®; 0.10, 0.20, 0.30, 0.50 e 0.70 m deep) and three vertical piezometers which reach different depths in the vineyard behind the dry-stone wall, while three supplemental horizontal piezometers were installed through the wall itself; atmospheric pressure data have been collected both from the SIR (Regional Hydrologic Service of Tuscany) data-base and by an electronic barometer placed on the wall.

figure 6: field water expansion test on 4th march 2015; capital letters points to the water leakages through the retain wall in order of appearance

After all the preliminary surveys an infiltration test has been conducted on 3th march 2015 close to the location of the monitored section of the wall: a centrifugal pump through a galvanize-steel pipe system and flexible hoses, brings water from an old mill basin to a 1000 liters polyethylene tank used as a reservoir. From the tank the water flows (0,03 l/s) by gravity to a rectangular infiltrometer (about 1 square meter) placed close upstream to the location of the wall collapse. Two ERT lines (A, close to the wall, and B, next to the infiltration area) have been disposed a few meters apart, parallel to the wall, in order to record the resistivity variations throughout the test duration (till 11:40 AM to 5:30 PM).

A field water expansion test has been performed on the following day (4th march 2015) through brimming over the infitrometer edge: flooded area expanded chiefly towards the main ditch, affecting the area upline the load cells. The maximum extension of the area has been reached in roughly 5 minutes, remaining quite stable until the end of the test.

Results

The soil is classified mainly as sandy gravel with little silt (fig. 7); the fine fraction is classified by USDA nomenclature as loamy sand in the tilled part and as sandy loam under the plow profile (40-50 cm deep).

11 SFH tests have been carried out, and the field saturated soil hydraulic conductivity (K_{fs}) have been calculated considering both the not corrected bulk density and, taking into account the skeleton fraction, the corrected bulk density. The K_{fs} cover a wide range of values, from 122 mm/h to 2389 mm/h, although the value higher than 800 mm/h seems to be excessive (tab. 1).

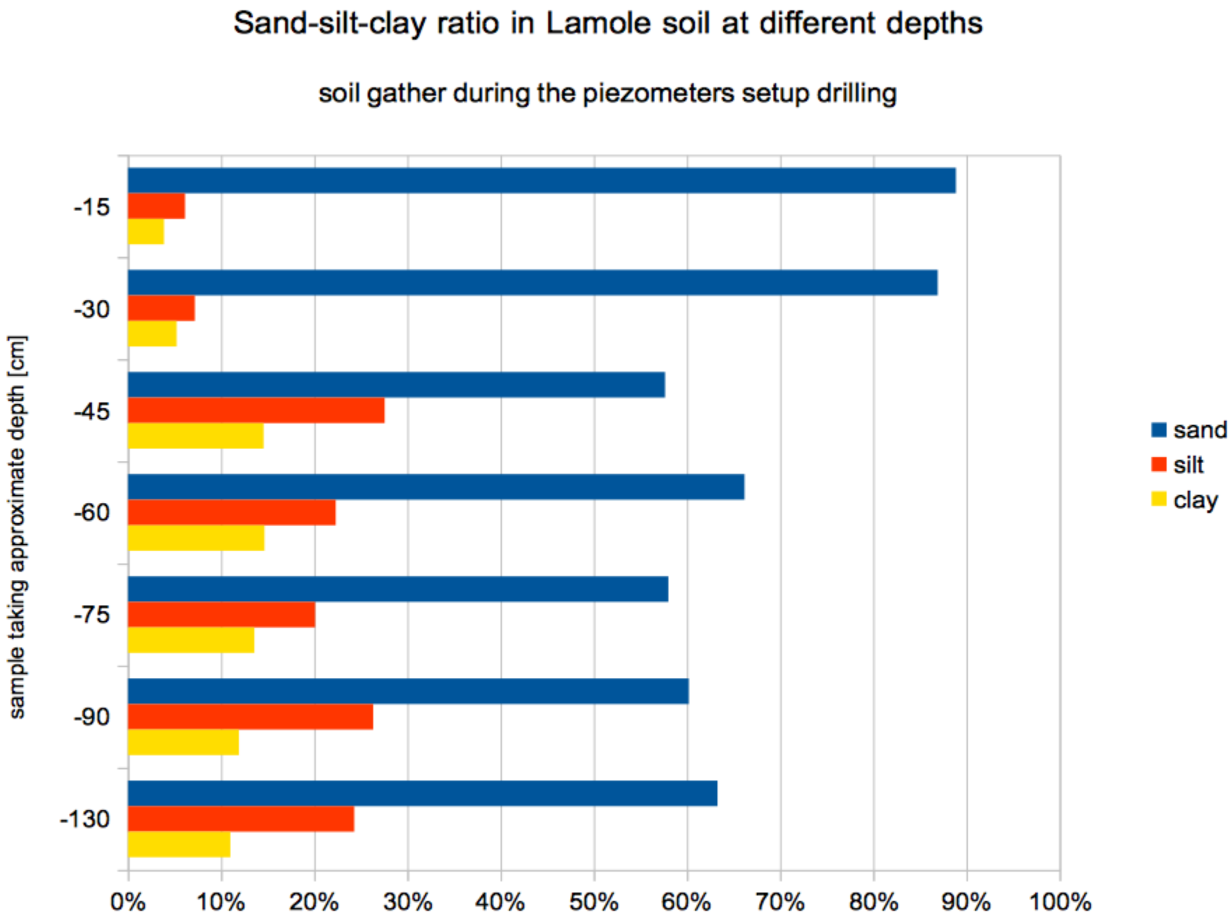

figure 7: soil texture obtained from specifically gathered samples (until 45 cm depth) and from drillings made in order to set three vertical piezometers between the vine rows; due to the different kind of sample the lithoid fraction valuation is misrepresented and thus it has not been reported in the graph

Prova	1	2	3	4	5	6	7	8	9	10
K_{fs} (mm/h)	756.9	952.1	132	257	114	1128	2276	1877	1462	13

table 1: field saturated soil hydraulic conductivity (Kfs) values as obtained through the SFH tests in the vineyard

Also the 5 infiltrometric tests gave high variable infiltration rates (form 10 mm/h to 80 mm/h), even though the soil doesn't appear to be different; as first conclusion the coarse material in the soil could have influenced the tests.

The geo-electrical data suggest the presence of high resistivity zones interspersed with the saturated sand, as if it was dry soil; the further GPR surveys (both at 200 Mhz and 600 MHz) show that this area is characterized by chaotic reflections and diffractions, testifying the presence of a fairly shallow high presence of rocks where water can accumulate in larger quantities during precipitation events.

The infiltration from the plot shows itself quickly after irrigation start, and changes in resistivity are evident also at depth, well under the discontinuity identified by the background ERT image (above). This results corroborates the idea that water infiltration takes place at depth and water can easily accumulate, thus changing the state of stress.

The geo-seismic survey shows three different kind of soil, with a mid-conductive layer from substratum alteration lays under 2-3 m of landfill, in turn divided in a deeper one and a superficial one (mainly the latter modelled by terraces). The lesser detail of this kind of survey doesn't allow to appreciate the 0,5 m deep discontinuity identified with others kind of analysis.

The pressures measured by the two load cells appear to be not immediately related with rainfall. Instead, the trend of atmospheric pressure is in direct relation with the load cells values trend. The variability effect due to atmospheric conditions has been purged from load cells data, obtaining a better correspondence between the pressure data and the rainfall. Instant pressure variability in the data registered by the load cells is related also with temperature variability, although on the long run the effect of rainfall is predominant in respect to the temperature effect; the load cells data have been corrected also in this aspect. Finally it has been possible to identificate different behaviour for the two cells, the deepest one responding clearly for more intense events while the upper one shows better correspondence with low rainfalls.

The trend of the pressure measured by the cells is related with the soil water content, usually showing and increase until the water content peak end. Sometimes is possible to note sudden decreases in correspondence to rainfalls that caused noticeable pressure increase: this can be explained with micro movements of some wall elements, probably responsible on the long run to the bulging (fig. 9).

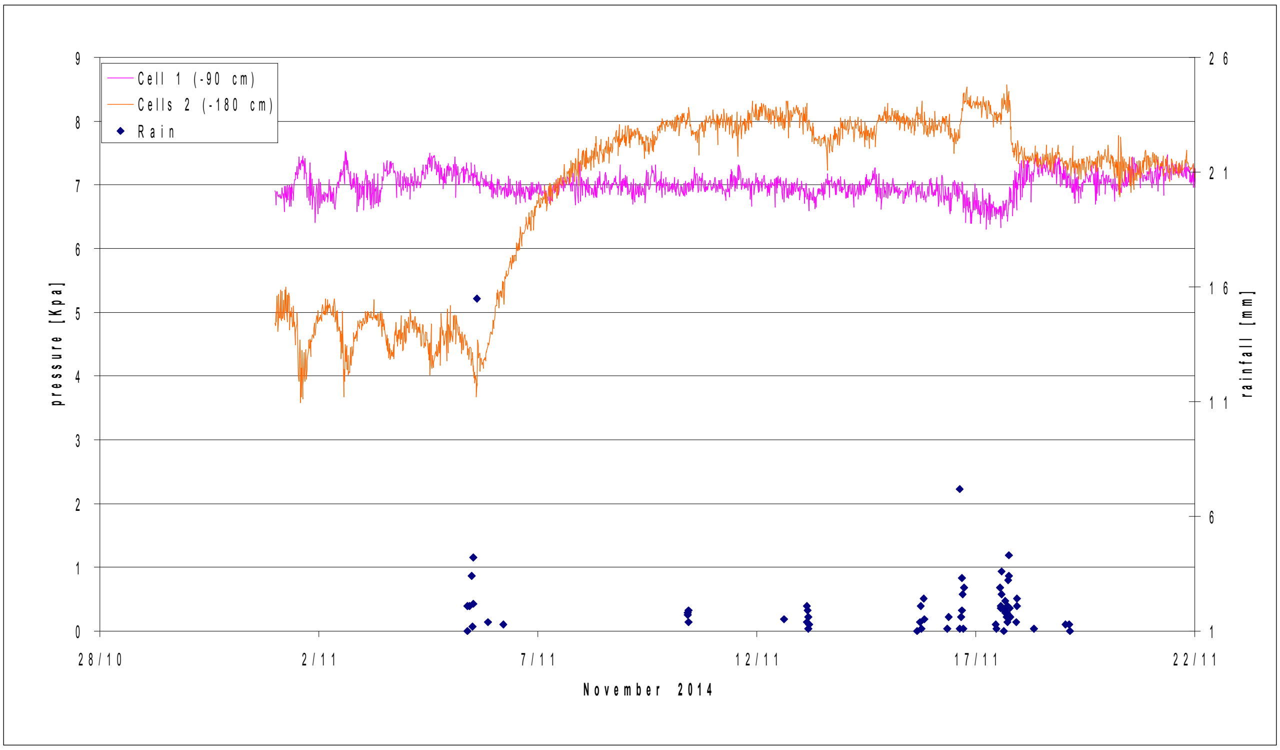

figure 8: pressure variation measured at two depths vs rainfall (november 2014), the blue points represent the rain related to the quarter hour

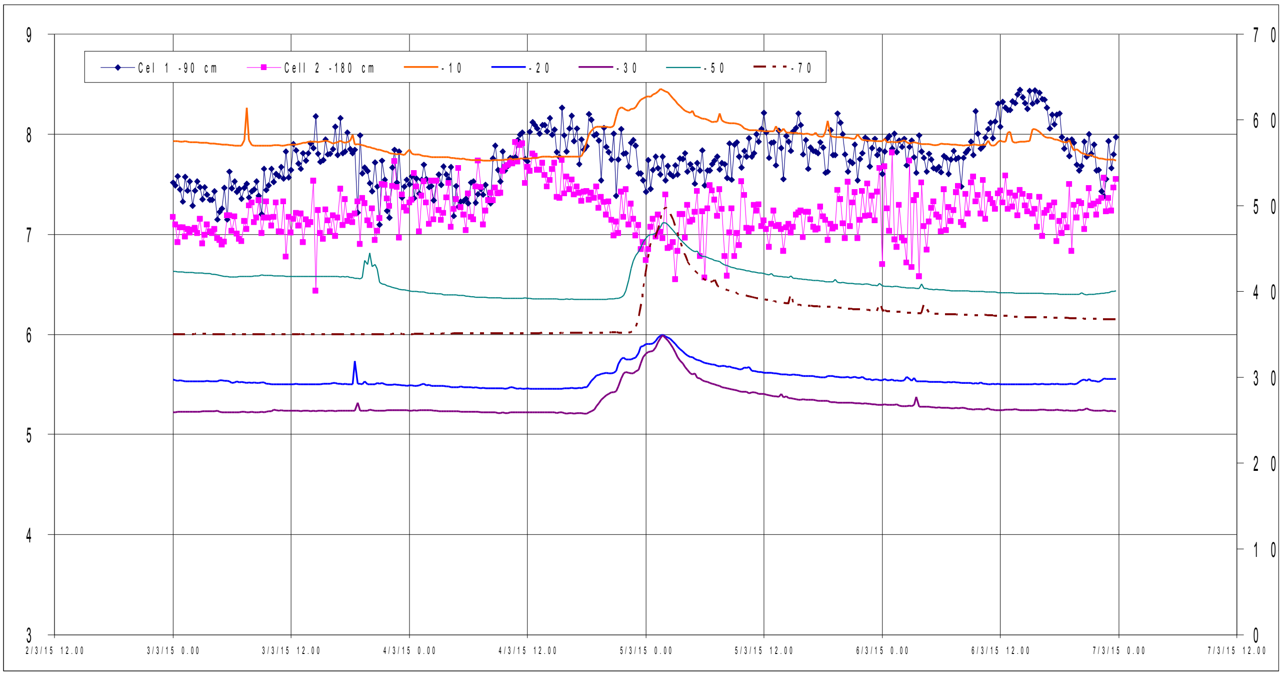

figure 9: pressure variation measured by the load cells and soil water content in percentage by volume recorded through the capacitance probe (-10,-20,-30,-50,-70 cm)

The pressure increase on the two cells behind the wall for an applied load of 1000 kg have been estimated with the Boussinesq approach: the presumed values are 1,207 kPa for the 90 cm deep cell and 0.15 kPa for the 1,8 m deep one. The measured value during the real load test confirm the hypothesis only for the upper load cell, being respectively 1,2 kPa and 1 kPa, probably because the Boussinesq postulates are ideal while in real conditions the soil is not homogeneous and the wall is not perfectly smooth and micro movements can happen.

The collected soil moisture data highlight as water contents vary with depths; in the details high water levels are founded around 0,5 m deep, in correspondence with the plow profile, and in the 0,7 m deep layer, while the layers at 0,2 and 0,3 m lack in water storage. The upper layer is usually the most humid, collecting even the lightest rain and the dew.

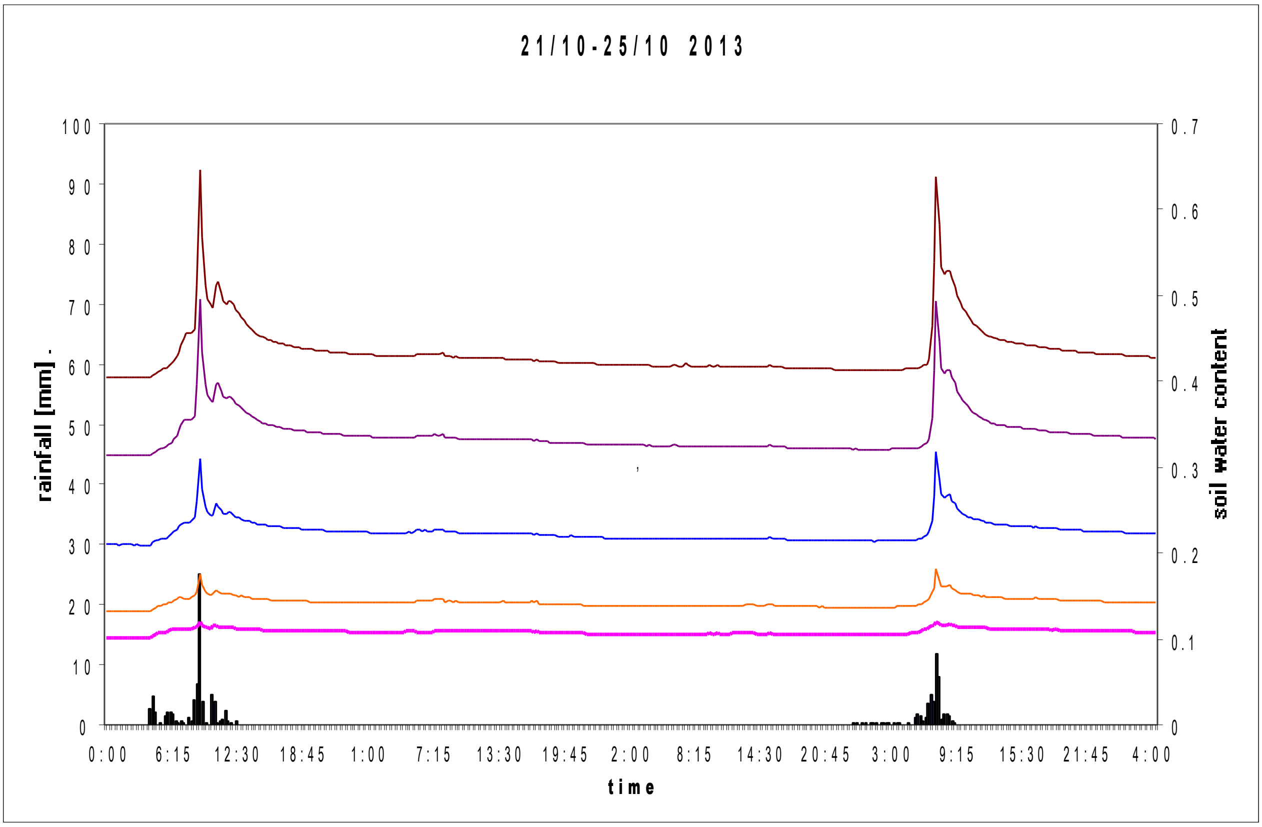

figure 10: variation of soil water content by volume, measured at different depths, vs rainfall

During the infiltration test an infiltration rate of about 100 mm/h has been estimated; in the final part of the test water started to flow out from the delimited area starting to flood the soil around the infiltrometer. No relevant humidity increase at any depth have been registered by the diviner during this test.

The first minor water expansion test shows an almost immediate increase of water content in soil registered by the capacitive probe, higher and more stable in the 0,1 m deep layer (effect probably due also to the faint rainfall in the evening), lower in the deepest layers and having the minimum for the 0,3 m deep layer. In the vertical piezometer 1 (1,33 m deep from ground level) the water reaches 35 mm, lowering very soon; in the piezometer 2 (0,66 m deep from ground level) water reaches a higher height (75 mm) and a more gradual emptying. During the second minor water expansion test the increase in water content is more gradual and shows a maximum value for the 0,5 m deep level, while the 0,1 and 0,3 m deep layers have lower contents; the 0,2 deep layer shows the lowest level in water content. The registered variancies could be due to the discontinuity previously hypothesized.

During the large expansion test water disappeared due to natural piping and flowed through the valley-facing side of the wall: the water appeared first at the base of the wall and successively rose towards the top of the wall (this is particularly evident for points H-I and C-D), while in none of the piezometers located near the piping there were traces of water.

In the diagram comparing registered pressures from load cells (90 and 180 cm deep) with humidity values measured by the diviner (10, 20, 30, 50 and 70 cm deep), the only interesting variation is the increase of pressure for the lower load cell after the water expansion test, fitting with the water apparition on the valley facing side of the wall.

In the diagram about humidity values recorded by the diviner, minor peaks incompatible with the infiltration and the water expansion tests can be seen. The recorded humidity increases in soil at growing depths between 5:45 PM and 10:45 PM is evident after the 4 PM rain on 4th march. In the diagram showing the load cells response, the 4 PM rain on 4th march seems to have effects in the mean increase of pressures, although delayed in time and around 0.2-0.5 kPa.

From the last 3 different processes in the same area distributed in time (prolonged infiltration, subsequent flood and final natural rain) it’s possible to deduce that load cells react only if water comes from piping, while the diviner quickly respond to the meteoric inflows up to 70 cm deep under the surface, and the 2 m deep layers are reached in the long run (20 hours and more). Analisys of data collected from the monitoring system since 2013 can be understood only having in mind the previous observations.

From the last experiences (3 different processes in the same area distributed in time: prolonged infiltration, subsequent flood and final natural rain) it's possible to deduce that load cells react only if water comes from piping, while the diviner quickly respond to the meteoric inflows up to 0,7 m deep under the surface, and the 2 m deep layers are reached in the long run (20 hours and more). Analisys of data collected from the monitoring system since 2013 can be understood only having in mind the previous observations.

The RPII index, as a concentration factor, could explain the piping alimentation (and maybe piping formation) and then the critical points localization for the walls' instability (and the reduction for the critical rain return period).

It's important to remind that the runoff pathways develop in areas weakened by fractures and fault systems (very evident through GPR measures perpendicular to the slope): water enters in the soil and gather in those fractured zones.

Conclusions

In order to discovery the subterranean outflow ways that have no direct correspondence with natural long-term run-off pathways or with passing preferential surface downflow ways, it is possible to imagine one last experience for the future: flood an extended area for a prolonged period using a drip or a micro-sprinkler irrigation system to connect with the pumping system already installed.

The collapsed wall near the observed zone could be modelized with our finite elements scheme (including hydrostatic pressure and friction reduction): a simple dry-stone wall stability model has been carried out; this model analyses the wall stability with finite elements method, evaluating pressures derived from uphill water infiltration, stone friction and buoyancy in retaining wall layers: simulated deformation are suitable with the observed ones.

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