Hydro-geotechnical modelling of Como subsidence

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ABSTRACT

The urban area of Como (Italy), due to its subsoil structure and historical evolution, is particularly susceptible to subsidence. Moreover, this phenomenon exposes the lakefront areas to an increasing risk of flooding. Following a procedural scheme including dataset creation and management, 2D and 3D conceptual model and coupled hydrogeological and geotechnical numerical simulations, the most critical zones and scenarios have been analyzed, assessing natural and anthropic groundwater perturbations as the major cause in triggering subsidence phenomenon. The main purpose of this work is to establish an effective tool in supporting groundwater management, forecasting subsidence phenomena and planning mitigation works.

KEY WORDS: Groundwater management, groundwater modelling, urban subsidence, lake flooding.

INTRODUCTION

The subsidence phenomenon can occur in a great variety of geomorphological, stratigraphic and structural contexts following natural processes and anthropic activities, resulting to be one of the major environmental risks that characterize urban, coastal and delta contexts (Carbognin et al., 2004, Cao et al., 2013, Qin et al., 2018). The urban historical area of Como (Fig. 1b), due to the local structure of the subsoil, combined with the anthropic restructuring of the lakeshore lands related to the historical evolution of the area, is particularly susceptible to subsidence. Moreover, this phenomenon exposes the lakefront areas to an increasing risk of flooding (e.g. the ruinous flood of November 2002) with consequent damage to buildings, cultural heritage and infrastructures, such as *Cavour* Square, *Duomo* Cathedral and *San Fedele* Church. The most recent project (still to be completed) to mitigate the problem (Municipality of Como, 2014) includes the construction of fixed and movable bulkheads, detention tanks (Pool A, placed in *Lungo Lario Trieste* and Pool B located in *Lungo Lario Trento*) and barrier interventions through jet grouting (Fig. 1c).

The procedural scheme followed in this work includes: i) dataset creation and management, ii) definition of the 2D and 3D conceptual models, and finally iii) the coupled hydrogeological and geotechnical numerical simulations to recognize the most critical zones and scenarios of subsidence due to natural and anthropic groundwater perturbations.

DATA COLLECTION AND ANALYSIS

A site-specific organized database was first created, within a GIS platform, which includes all the stratigraphic, geotechnical and hydrogeological data, resulting both from in situ and laboratory tests (CPT, CPTU, SPT, Cross Hole, pumping and on-site permeability tests, oedometric, triaxial, uniaxial tests), and from groundwater level and ground elevation monitoring (available from the 70s to 2014).

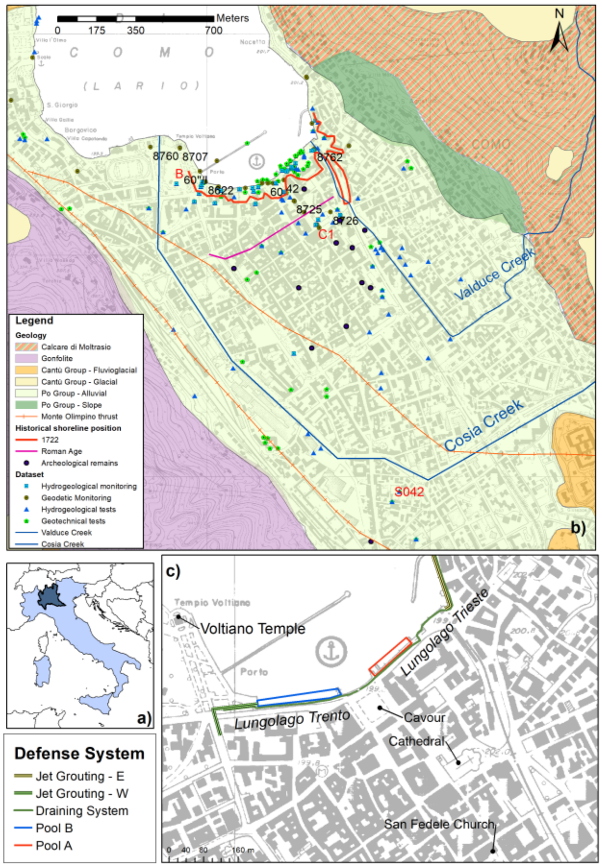

Fig. 1 – a) Location of the study area. b) Geological-geomorphological sketch of the study area and dataset point location (in red, piezometer used for the numerical calibration; in black the geodetic benchmarks) c) Lakefront defense system and of main interest urban points.

Analysis focused on soil geotechnical and hydrogeological properties to which subsidence phenomenon is more sensitive, e.g. volume weights, oedometric modulus, compressibility coefficient and index, and voids index, permeability and storage.

The hydrogeological monitoring has concerned the lake and the piezometric levels, whose comparison reveals a strong groundwater level's dependency on the Lake, which attenuates with the increasing of the distance from the Lake itself.

As regard the ground elevation monitoring, the available geometric levelling and PSInSAR (2003-2012) data were processed and compared to obtain average, relative and absolute strain rates, observing a good agreement between the two techniques.

HYDRO-GEOTECHNICAL CONCEPTUAL MODEL

The stratigraphic, hydrogeological and geotechnical information along each borehole, supported by the surface geological survey, were re-interpreted defining the aquifer system with five homogeneous geotechnical units characterized by uniform behaviour in terms of groundwater flow and subsidence susceptibility.

A 2D and 3D conceptual model was then developed, coherently with the paleo-environmental architecture of the Como basin and with the support of geostatistical analysis.

From the ground level downwards to the depth of about 180 meters, the main units are the following:

(R) *reworked anthropic materials* characterized by an extreme heterogeneity in thickness, spatial distribution and hydro-mechanical behaviour, adequately differentiated (R_C – Cavour sub-unit, R_{LF} – Lakefront sub-unit and R_{UC} – Urban coarse sub-unit) in the parametrization phase (Table 1); (UGS) *upper gravelly sands;* (POS) *palustrine organic silt*; (ICS) inorganic clayey silt, and (LSG) *lower sand and gravel*, constituting three hydrogeological units, continuously detectable within the entire urban area: a surficial unconfined aquifer, locally semi-confined (R and UGS units), a semipermeable-impermeable aquitard horizon (POS and ICS units) separating the first aquifer from the deep aquifer system, place of confined circulation (LSG unit).

Finally, through the joint analysis of stratigraphic interpretation and the geostatistics procedure of *kriging*, the top and bottom surfaces of the identified and parameterized hydro-geotechnical units were reconstructed obtaining the 3D conceptual model, necessary for the successive numerical simulations.

Units thickness and spatial distribution were analysed and bi-dimensional cross sections extrapolated; R unit reach its maximum thickness along the shoreline (10÷15 m) and in *Cavour* Square, while in the rest of the urban area has a constant thickness of 3÷4 m (verified through archaeological remains records). POS and ICS units present a depocenter located in the W edge of the historical city, while UGS unit is characterized by a quite constant thickness of 20÷25 m.

NUMERICAL MODEL

A coupled hydrogeological and subsidence numerical model was implemented, using MODFLOW 2000 (Harbaugh et al. 2000) to recreate groundwater flow, and the modular SUB Package (Hoffmann et al. 2003) to simulate land subsidence. Due to the few data available and the subordinate involvement on the general subsidence process, the second aquifer (i.e SGI unit) was excluded from the modelling. Soil deformation of the first aquifer of thickness b, caused by a level drop (Δh), is computed according to Leake (1990) as:

$$\Delta b = S_{sk} b \Delta h$$

where S_{sk} represents the skeletal component of specific storage and is linked to the expansion or compression of the sediment resulting from a change in effective stress; therefore it could be expressed in terms of the skeletal compressibility m_v (Hoffman et al., 2003) :

$$S_{sk} = \rho_w \mathrm{g} \mathrm{m}_v$$

with ρ_w =water density. Skeletal specific storages (m^{-1}) of the aquitard is defined for two ranges of stress, elastic (S_{ske}) and inelastic (S_{skv}), linked to the relationship between effective stress and pre-consolidation stress. In the context of aquifer systems, the past maximum stress, or pre-consolidation stress, can generally be represented by the previous lowest ground-water level (Sneed, 2001).

The 3D model was meshed into 561 x 524 square cells with 5 m per side, reaching the depth of the bottom of the aquitard. The aquifer system has been vertically discretized by four Layers representing the first four geotechnical units (R, UGS, POS and ICS). The period chosen for the simulation is from 2004 to 2011, as it is the recent period with the most frequent and continuous data recording. The simulation was performed by nine Stress Periods: the first corresponds to a steady state simulation, while the other eight (each representing one "annual scenario" from 2004 to 2011) to a transient simulation. "NO-FLOW" boundary condition was attributed to all the cells of the model that fell in correspondence with the rocky reliefs that is excluded from the simulation of the underground flow. The "CONSTANT HEAD" condition, was used in simulating the hydraulic head of Como Lake, while the "RIVER" boundary condition was introduced to simulate the influence of the natural riverbed of the Valduce creek. The "WELL" condition was used to simulate water withdrawals with maximum total values of about 25 l/s in correspondence with industrial and open loop geothermal enthalpy implants. The aquifer recharge from the bedrock, estimated of about 450 l/s was introduced along the

UNIT	**k(m/s)**	**S(-)**	**S_{ske}(m^{-1})**	**S_{ski} (m^{-1})**
R	$5.3 x 10^{-4}$	0.3	$6 x 10^{-6}$	R_c $1.76 x 10^{-2}$ R_{LF} $1.3 x 10^{-2}$ R_{UC} $3 x 10^{-6}$
UGS	$2.6 x 10^{-3}$	0.2	$3 x 10^{-6}$	$3 x 10^{-6}$
POS	$7 x 10^{-6}$	0.01	$6 x 10^{-6}$	$4.2 x 10^{-3}$
LA	$4.73 x 10^{-9}$	0.006	$6 x 10^{-6}$	$3.77 x 10^{-3}$

Table 1 – Hydro-geotechnical units parameters.

entire perimeter of the active zone by means of fictitious injection wells. The recharge was obtained by combining the Thornthwaite-Mather Model and the Curve Number procedure on rainfall and temperature data of the area, subdivided along the perimeter of the model according to the extent of its features (river basin, geological substrate and quaternary deposits, presence of water streams, and land use).

The representative aquifer-system properties were assumed on the base of the critical analysis of the collected dataset; selected properties (Table 1) and stresses were modified within reasonable limits during model calibration.

Model calibration was carried out through the trial and error method until a RMS normalized value lower than 10% was reached, as reported in Anderson and Woessner (1992), on piezometer B, C1 and S042 for March 2008 and July 2009 and on 9 benchmarks from APAT levelling of 2004 and 2011(Fig. 1b).

The verification of the model was performed by introducing an anthropic perturbation representing the pumping flow rate of 115 l/s, related to the installation of the pool B located in the *Lungolago Trento* area (during the year 2009). The data set used for validation refers to the PZ1 and PZ2 piezometers and to the satellite Permanent Scatters n° 213 and 259, located in the proximity of of the pumping wells.

RESULTS AND DISCUSSION

The simulated surficial aquifer piezometric surface shows a main direction from SE, at 220 m a.s.l. in correspondence of the recharge anomaly of the Respaù creek paleo-channel, to NW at 197 m a.s.l. (lake level).

From the comparison of the annual scenarios (Fig. 2a-b-c) it is clear that the peak of subsidence is reached essentially between 2004 and 2005, in response of the hydro-metric and piezometric minima. The maximum settelment of 2.7 cm is reached in *Cavour* Square; also the area bordering the west side of the historical town (with 1.6 cm), the *Lungolago Trento* (with 1.44 cm), the area of the *Voltiano* Temple (with 1 cm) and the *Duomo* Square (with 0.87 cm) undergo considerable deformations. The southernmost areas of the city record negligible lowering (about $10^{-1} \div 10^{-2}$ mm).

After 2005, the lake level varies with a rises and drops trend, also reflected in an equivalent oscillation of groundwater level (Fig. 2a), particularly evident along the shoreline. However, these oscillations remain above the piezometric minima recorded during the 2004-2005 period, inducing only elastic

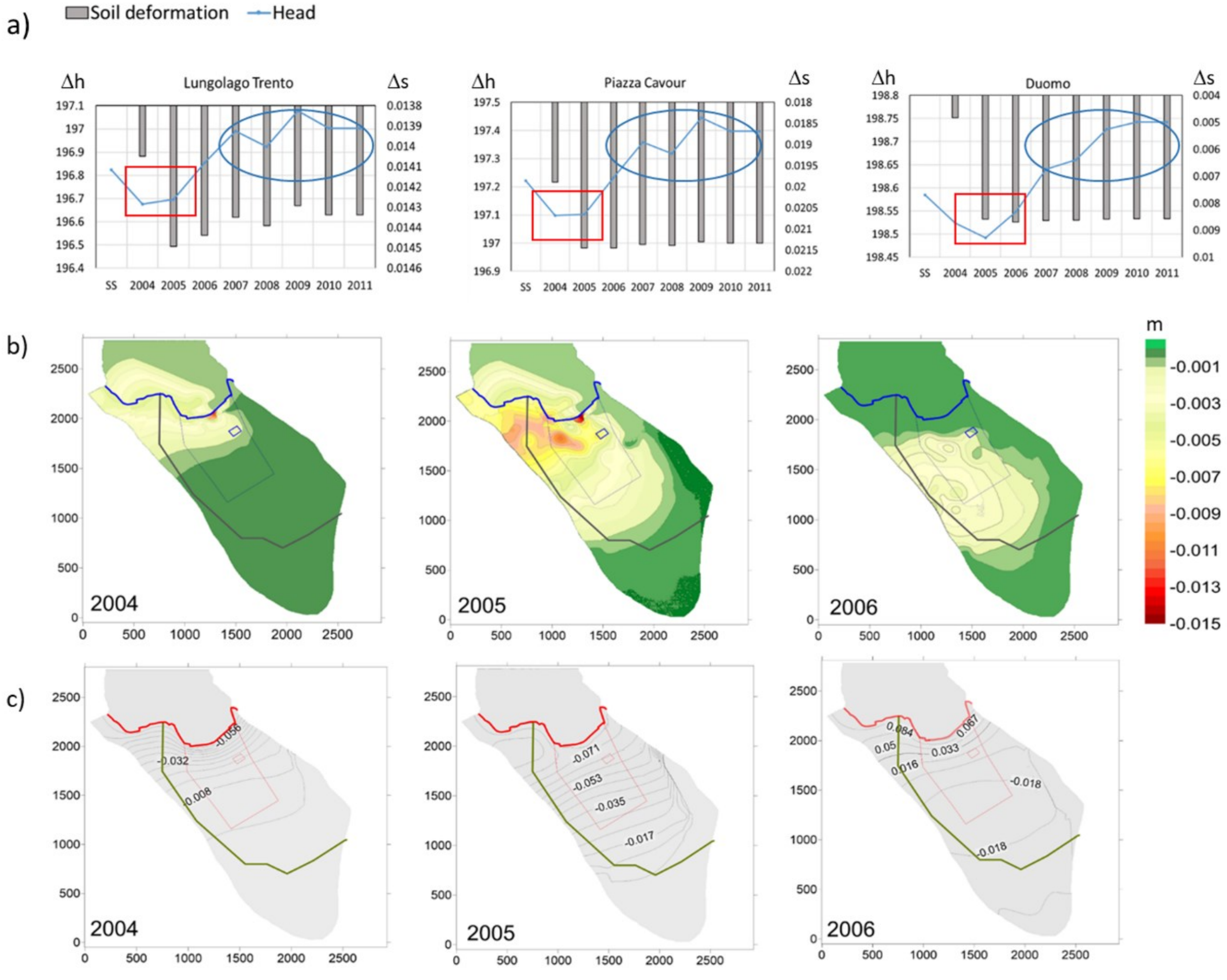

Fig. 2 – a) Annual head (m a.s.l.) and cumulate subsidence (m) the critical areas of Lungolago Trento, Cavour Square and Duomo Square. Piezometric minima marked by red polygon and elastic oscillation by blue ellipses. b) Annual head variation in the study area. c) Annual subsidence variation in the

compaction and swelling cycles of the order of 10^{-1}÷10^{-2} mm. Therefore, the 2004-05 piezometric minima stands as the equivalent reference pre-consolidation stress of the simulation.

Further piezometric lowering, up to a maximum of 40 mm, were recorded at the west side of the historical town during 2006 (Fig. 2b). Considering the low compressibility of the unit R_{uc} present in this area, the compaction (Fig. 2c) is essentially referred to the POS unit, which reached its maximum thickness there.

R_c and R_{lf} and POS units, in accordance with their high compressibility nature, contribute as expected to almost the whole deformation in all the study area. On the contrary ICS unit contributes negligibly to the global subsidence phenomenon; in fact, due to its high depth and low hydraulic conductivity, it is reasonable that the hydraulic variation – and so the effective stress variations - were mainly adsorbed by the shallower units. The moderate elastic recovery of the deformation is to be attribute to the UGS unit, in accordance with the geotechnical nature of the soils.

The anthropic disturbance due to the construction of Pool B, induced a recorded and simulated groundwater drop of 2-2.5 m in the wok site. This perturbation caused a local and almost instantaneous acceleration of subsidence, to a maximum settlement of 6-7 cm in correspondence with the pumping wells (Fig. 3) and which degrades moving away from the recall front. From this scenario it is evident that the units identified in the urban area had not reached the maximum degree of consolidation in the previous subsidence simulation related only to natural variations. It results that soils might undergo significant further lowering in case of external perturbations (natural or artificial) able to drop groundwater level consistently below the recorded minimum of 2004-2005, thus representing a new value of pre-consolidation head for the study area. The built conceptual model and the adopted simulation process could support the evaluation of the deformations pattern related to the construction of any other defence work, in particular the pool A located in the *Lungolago Trieste*, where the unit R_{LF} thickness is consistent (12 m).

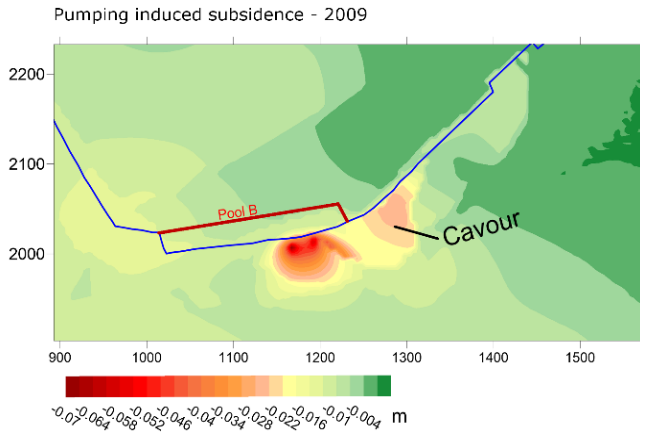

Fig. 3 – Local subsidence maximum developed in 2009 located in the work site of pool B.

CONCLUSIONS

Any natural or anthropogenic perturbation of the groundwater level can induce a deformation of the solid skeleton of soils constituting an aquifer system. Through the case study of Como city, it was developed an effective method for the assessment of the phenomenon of subsidence in urban areas, to be used as a supporting tool in groundwater management, forecasting subsidence phenomena and planning mitigation works.

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