Actual problems in the study of soil dynamics of the Upper Adriatic sea

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RIASSUNTO

Problemi attuali nello studio della dinamica del suolo in Alto Adriatico

Tra i numerosi problemi legati allo studio della simulazione del movimento del suolo nelle zone costiere dell'Alto Adriatico, nel presente lavoro si trattano, in particolare, due aspetti: il primo riguarda l'acquisizione di dati attendibili riguardanti le variazioni altimetriche e planimetriche con applicazione all'area del Delta del Po; il secondo riguarda l'interpretazione di risultati altimetrici osservati per la prima volta sopra giacimenti di gas dismessi, mediante la meccanica dei suoli parzialmente saturi.

Le informazioni sull'evoluzione altimetrica della zona sopra il giacimento Ravenna Terra nel periodo di estrazione e in quello successivo, permette poi di trarre interessanti conclusioni sul proposto innalzamento di Venezia mediante iniezione d'acqua.

Key words: *Aerial photogrammetry, surface movement, reservoir engineering, partially saturated soil mechanics.*

INTRODUCTION

Current problems in the study of the dynamics of soils layers at the surface and in the subsurface of the coastal region in the Upper Adriatic region are: a reliable acquisition of the soil movements in the recent past, their elaboration to obtain useful information for modelling, the acquisition of geotechnical data and data about fluid withdrawal from the underground, and the modelling of the observed behaviour. This is an extremely vast programme and we will address only some solutions recently obtained within the European Programme RAMWASS. In this context we have focussed our attention on the Delta of the Po River and the coastal and neighbouring areas around Ravenna, more to the south.

In particular we have elaborated a procedure to integrate measurements referred to different reference systems and obtained by different methodologies, in order to obtain a coherent map about the evolution of the land movement in the coastal region in the last decades. This has been applied to the Po River Delta.

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The analysis of the altimetric variations of the Po Delta area has been conducted by comparing the orthometric elevations of benchmarks measured in different times. Particularly, two levelling lines measured by IGM have been used: n° 19 measured from 1950 to 2005 (even if not for all benchmarks) and n° 174_D2 measured in 1978, 1984 and 2005. These two lines did not appropriately cover the whole Delta area (32 benchmarks); they have been consequently integrated by other benchmarks to obtain a more uniform distribution throughout the area.

In fact, other benchmarks with known orthometric elevation were those measured for the production of the "Carta Tecnica Regionale (CTR)" (Technical Regional Chart) of 1983. After verifying that the orthometric heights were effectively referring to 1983, in the 1:5000 cartography 43 benchmarks with known elevation in 1983 and homogeneously distributed over the Delta area have been identified. For these benchmarks measurements by means of the GPS methodology have been conducted in 2006: the main problem consisted in the fact that the GPS elevations are ellipsoidic and, consequently, can not be directly compared with the 1983 ones (orthometric).

To this purpose, the ellipsoidic elevations have been transformed into orthometric through the Verto 2 software referring to the determination of the geoid in 2005: in fact, if for the same benchmark the ellipsoid elevation (measured in 2006 by means of the GPS), the orthometric ones (known from the 1983 cartography) and the value of the geoid waviness (known at national level) are known, it is possible to find the vertical settlement of that benchmark.

Another problem was to define a procedure for the validation of the orthometric elevations for the 43 benchmarks of 1983: in fact, in 23 years many benchmarks have been destroyed and substituted by other benchmarks found in the neighbourhood, but often with a not-homogeneous elevation. The consistency analysis for the orthometric elevations of 1983 has been conducted through a second-order surface in the geoid waviness (surface with 9 parameters corresponding to a quadric in space). The correctness of using such a surface has been checked also by using the same second-order surface, determined on an area close to Chioggia (area of 80 km^2), through 20 control points with known double elevations, ellipsoidic and orthometric, temporally homogeneous. In correspondence of 10 check-points (always with known double elevations), differences of 3 mm (average) and standard deviations of 9 mm have been obtained (i.e. much better than those referring to the geoid at national level).

At the end at all the 43 benchmarks the corrected orthometric elevations of 1983 are known; once the orthometric elevations are known for both 1983 and 2006, it is possible to calculate the respective settlements. Then, by linearly interpolating the elevation differences of the two levelling lines of IGM (32 benchmarks), the settlements in the period 1983-2006 of these 32 points have also been obtained. In this way a dataset of 75 points uniformly distributed above the Delta area and temporally homogeneous is obtained.

To produce a deformation map for the area, the 75 benchmarks have been interpolated on a regular grid (size $10\times10m^2$) through the IDW (Inverse Distance Weighting) algorithm: for each grid node the settlement value is determined by weighting more the settlements of the closer benchmarks (figure 1).

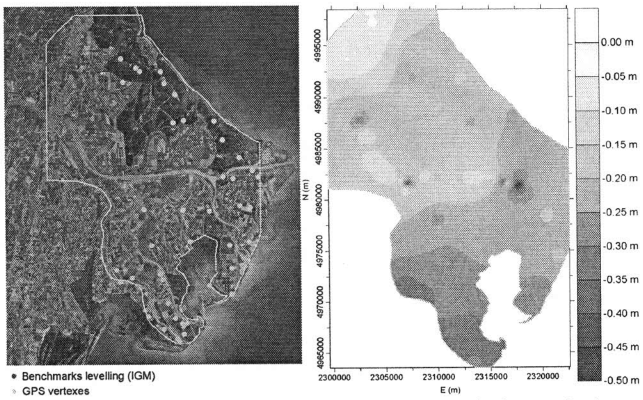

Fig. 1 – Po Delta area and altimetric variations during the period 1983-2006.

The analysis of planimetric deformation was performed by means of archival photogrammetric method (BALDI *et alii*, 2008): three aerial photogrammetric surveys carried out in 1955, 1977 and 1999 were used. The images were processed with the Socet Set software using 49 natural GCP (Ground Control Points) measured with GPS methodology in 2006. The points coordinates, processed by Leica Geo Office software, were transformed in the Gauss Boaga reference system. Finally, the manual restitution of the coastline was performed for each survey: the comparison between the three coastlines show great variations in the order of hundreds of meters (figure 2).

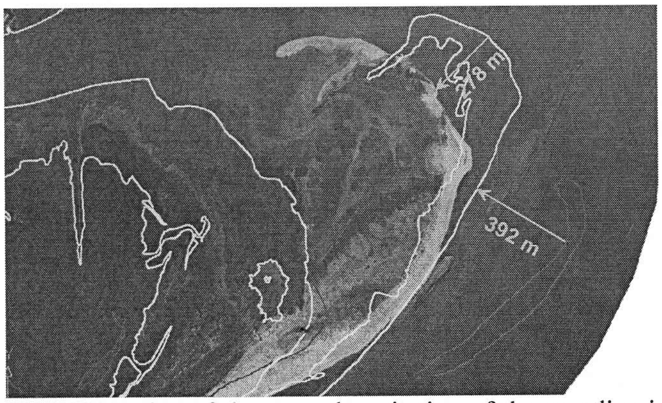

Fig. 2 – Portion of the manual restitution of the coastline in 1955 (red line) and 1977 (yellow line) overlapped on the 1999 orthophoto.

THE RAVENNA REGION

The second area of interest is the region about the city of Ravenna, about 150 km south of Venice, where fluids (water and gas) were extracted. We address here the soil movements after the end of extraction from the gas field Ravenna Terra. To our best knowledge periods after stop of withdrawal from oil or gas reservoirs have received very little attention.
The extraction of gas in the Ravenna Terra field from two main pools located at a depth between 1650 and 2000 m started in 1950, reaching a peak withdrawal of about 7 million Sm^3 per day in 1966 and being practically stopped in 1982. Water has also been heavily extracted from upper aquifers up to a depth of 450 m in the period 1950-1973; afterwards pumping was drastically reduced and finally stopped. Both extractions have contributed to surface settlement, however the one caused by gas extraction decreases rapidly away from the reservoir, while that due to water pumping is spread all over the area. There exist measurements for surface lowering, carried out by Agip for the periods 1982-1998, 1986-1998, and 1992-1998. The data have been first processed by the Department of Structural Engineering, Transportation, Water and Territory Survey of the University of Bologna and successively by the Department of Architecture, Town Planning and Survey of the University of Padua to reach the form shown here (MENIN *et alii*, 2008).

A 3-D rendering of the surface movement in the period 1982-1998 is shown in figure 3. The picture is clearly that of a local behaviour limited to the reservoir itself and to the area close to it: the surface lowers much more close to the reservoir boundary and immediately outside it than over the central part of the reservoir. We observe a reversed settlement bowl. This is the opposite of what is usually observed and obtained numerically during the production period.

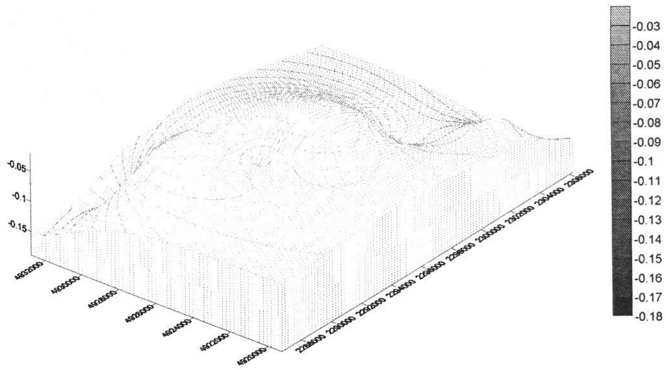

Fig. 3 – 3-D rendering of the settlement above and around the reservoir for the period 1982-1998.

An explanation of this peculiar behaviour may be obtained by applying to reservoir engineering concepts of mechanics of partially saturated soils where capillary effects are of importance. There is direct and indirect evidence that the reservoir sands of this region show the typical features of soils in the presence of capillary forces (MENIN *et alii*, 2008). Of importance is the following test carried out by PAPAMICHOS *et alii*, 1998 on samples from a nearby well. This test tries to reproduce experimentally the water flooding experienced in real cases for "reservoir pressure maintenance" or "due to water influx from surrounding formations" by injecting water into samples at in situ water saturation (ranging from 0.38 to 1), under a constant level of stress, until full saturation is reached. The sample of interest (core 1305), from a depth between 3402.4-3402.5 m, is made of silty sandstone and had a *in situ* water saturation of 0.38-0.45. It has been loaded in oedometer up to geostatic vertical load of 35 MPa and then slowly saturated (during 24 hours of water injection). As shown in figure 4, the vertical strain due to injection is over 0.004, a value far from being negligible when compared to total volumetric strain at reservoir conditions. This is clear evidence that a soil model taking into account capillary effects is applicable to the reservoir sands of the Upper Adriatic basin. The measured behaviour has been reproduced successfully (NUTH *et alii* (submitted)) with an advanced model for partially saturated soil behaviour, see figure 4

Partially saturated soil behaviour allows for a comprehensive description of the observed behaviour above the reservoir. Note that we are in a period of increasing reservoir pressure; hence a Terzaghi-effective stress based model would give a modest rebound while here settlement continues. Inspection of the evolution of the settlement pattern in the observed period shows that the reversed bowl is closing in towards the reservoir centre. This may be explained by the fact that the reservoir rock at the boundary of the reservoir is the first to experience increasing saturation and hence becomes weaker and undergoes structural collapse. The inner part of the reservoir remains partially saturated for long time periods, and maintains its stiffness. In fact, the central part hardly experiences surface movements in the observed period. However, the saturation front is moving inward with time which causes the observed pattern. Simulations carried out (MENIN *et alii*, 2008) confirm this explanation.

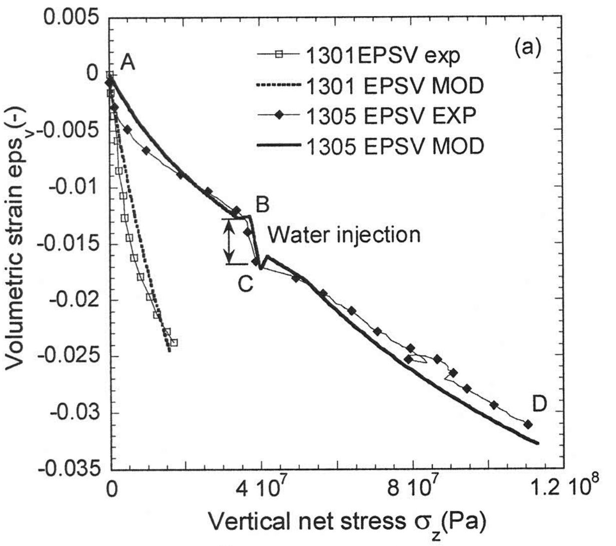

Fig. 4 – Simulation of oedmetric test for material core 1305 inclusive water injection. The prediction of test core 1301 is added for matter of comparison.

Measurements of surface settlements around Ravenna in the past give also a good insight in the feasibility of uplifting Venice through injection of sea water in the underlying aquifers, proposed recently (COMERLATI *et alii*, 2003).

A comparison between the two cities is meaningful because of the similarities in hydro-geological setting and natural environment (SCHREFLER *et alii*, 2009).

The observed settlements in Ravenna for the period 1972–77 are far from being smooth and even a gradient of $1*10^{-4}$ of vertical ground displacement can be found. It does not seem that the observed ground movements are directly affected by the specific location of the pumping wells, but are rather by a local heterogeneity of the involved strata. In addition it must be recalled that the reservoir Ravenna Terra is located at an average depth of about 1800 m below surface so that some smoothing effect of the overburden may be expected. In Venice, where the injection of seawater is foreseen at a depth of 600–800 m, one should expect much less attenuation for differential vertical displacements.

Because of the heterogeneity of the subsoil it seems unrealistic to control with injection from solely 12 wells located on a circle of 10 km in diameter the uplift of the whole area.

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