Numerical Analysis of Land Subsidence at Ravenna Due to Water Withdrawal and Gas Removal

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ABSTRACT Land subsidence at Ravenna has been caused by both groundwater withdrawals from the Quaternary multiaquifer system and gas production from a number of deep prequaternary reservoirs discovered starting from the early fifties and scattered over the area. Water pumpage grew steadily until the middle 70's when consumption was drastically curtailed owing to the economical crisis and the activation of a new aqueduct. Gas removal is currently under way and the search for new fields is still in progress. Geodetic levelling indicates that the overall subsidence, including a natural geologic settlement of perhaps 2 mm/y, achieved a maximum value of 1.30 m from 1950 to 1986 in the industrial zone of Ravenna. In 1980 the Municipality promoted a reconnaissance study with the aim at providing the informative base needed to reconstruct the event, understand correctly the physical behavior and develop a mathematical model relating land sinking to groundwater withdrawal and gas production with an emphasis on the respective influence. The results from the 3-D numerical analyses, performed with the aid of finite differences, finite elements and integral equations, show that the primary responsibility for the regional land sinking is to be placed upon water overdraft. Gas withdrawal exerts a more restricted but nevertheless measurable influence which may be expected to have a high environmental cost if gas production occurs from reservoirs underlying the Adriatic coastline.

INTRODUCTION

An excellent review of the worldwide most famous events of land subsidence caused by groundwater withdrawal can be found in the guidebook published by UNESCO (1984) some years ago. Land settlement due to gas/oil production is also extensively reported in the scientific literature. Ravenna, Italy, is a recent case of particular interest since land sinking that occurred there has been
caused by both postwar groundwater overdraft from Quaternary confined aquifers and gas pumpage from a number of deep Pliocene reservoirs scattered over the area and detected as early as 1952 by AGIP S.p.A., the Italian National Oil Company.

Ravenna is located 60 km south of the Po river Delta and 120 km far from Venice, a city which also experienced an alarming ground sinking in the late 60's, and lies close to the Adriatic coast (Figure la). The settlement process involved a large area and displayed its major effects in the late 70's (Carbognin et al., 1978) when the occurrence started to threaten the industrial zone, the urban districts, the nearby reclaimed marshland and several beautiful historical monuments.

In 1980 the Municipality of Ravenna appointed a Committee with the specific aim at analysing quantitatively the event and providing the informative data base needed for its mathematical simulation with the aid of numerical models. The major objective of the study was the detection of the responsibility for land subsidence to be placed upon water pumping and gas production, respectively. The Committee completed its activity in 1987 and presented his conclusive report to the Municipality in early 1988 (Committee for the Study of the Subsidence of Ravenna, 1988).

The present note summarizes the most significant findings obtained with the numerical simulations of the Ravenna land settlement as it is related to both water and gas withdrawal and gives a short account on the "ad hoc" reconnaissance study promoted by the Committee to properly integrate the existing information about the physical scenario and the history of the event.

GEOLOGICAL SETTING AND HISTORICAL RECORDS

The Ravenna area is part of the south-eatern edge of the wide sedimentary Po river basin (Figure la). The underlying quaternary deposits consist mostly of sandy and silty-clayey layers laid down in different environments, from continental, lagoonal and deltaic in the upper zone to littoral and marine in the lower one. The thickness of the Quaternary soils ranges between 1500 and 3000 m (Figure 2). The basement of the system is characterized by a structure of Pliocene folds and faults which constitute the reservoirs containing gas (chiefly methane).

For what concerns the present study three different environments can be recognized in the Ravenna underground system. These are the upper multi-aquifer system down to the interface between fresh and brackish water, the transition zone where the latter turns progressively into salty water and finally the bedrock saturated with salty water and including several gas reservoirs, mainly made from Pliocene and occasionally Quaternary deposits.

Fluid removal at Ravenna occurs from the 1st and the 3rd environments upon which therefore the present investigation is focused.

The information collected and analyzed by the Committee comes from a number of boreholes, soil drillings and pumping tests unevenly scattered over the Municipality area (Figure 1b). Particularly important are the core samples taken from the deep
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FIG. 1 Map of (a) the eastern end of the Po river basin, and (b) the Ravenna Municipality showing the location of several test holes and four hydro-geologic profiles.

wells BA1, RA1 and ZO1 (Figure 1b) which, together with the geologic profiles reconstructed along the four cross-sectional lines indicated in Figure 1b, have much helped define the multi-aquifer structure summarized in Figure 3 and used in the mathematical groundwater flow model. The in situ test pointed out a horizontal aquifer transmissivity between $2 \times 10^{-6}$ and $7 \times 10^{-5}$ m$^2$/s while the
laboratory analyses performed on the deep holes RA1 and ZO1 and other wells of the Po river basin have provided soil compressibility values $\alpha$ as shown in Figure 4 for both granular and cohesive soils. In the depth 100-4000m $\alpha$ varies between $7 \times 10^{-5}$ and $6 \times 10^{-5}$ cm$^2$/kg, sand being only slightly less compressible than clay (Figure 4).

The settlement after 1950 of the benchmark Porta Adriana in Ravenna is shown in Figure 5a while Figure 5b gives a map of the subsidence bowl over the Municipality area as of 1977, the most critical year in relation to groundwater pumping rate (Figure 6a) which greatly increased during the 50's and 60's and was progressively reduced after 1977 due to both a severe economical crisis and the activation of a new fresh water aqueduct. The behavior in time of the piezometric decline paralleled the consumption rate. Following a drowdown in the deepest aquifer of
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FIG. 4 Vertical soil compressibility vs. depth as measured on core samples taken from the Ravenna area. Two regression straight lines fitted against sand and clay measurements are shown.

more than 40 m recorded in the middle 70's, a recovery of the flow field has been observed (Figure 6b).

Concerning land subsidence due to gas production, the Committee decided to analyse the Ravenna Terra reservoir, which is the oldest field detected and exploited by AGIP, since its production was completed in 1982, 30 years after its discovery, the essential data were made available by AGIP and its location is totally inland where ground leveling was carried out. The Ravenna Terra field consists of two pools A and B situated between 1720 and 1957 m depth. The gas production amounted to 21.77x10^9 Nm^3 and the maximal pressure decline in 1975 achieved the values of 90.5 and 95.5 kg/cm^2 in the upper and lower pool, respectively. The behavior in time of the pressure drawdown in both pools was provided by courtesy of AGIP S.P.A.

NUMERICAL ANALYSES

Land subsidence at Ravenna is simulated with the aid of two separate models. The first model consists of a quasi 3-D hydrologic model of subsurface flow on a regional scale (Gambolati et al., 1986) followed by a 1-D vertical consolidation model applied to the site where an accurate lithostratigraphic column of soil is available down to the depth of the pumped interval. Conceptually this approach is similar to the one applied to predict the subsidence of Venice (Gambolati and Freeze, 1973 and Gambolati et al., 1974) and properly accounts for the hysteretic behavior of silt and clay in rebound.

The second model is a 3-D calculation of the settlement occurred over the Ravenna Terra field from the beginning up to the end of the production life. Due to the shortage of data concerning
the mechanical properties of the rock at the reservoir depth, the use of a more realistic non-linear model is precluded. Hence the simulation has been performed by a linear pro-elastic model (Geertsma, 1973) solved by a boundary element method (Gambolati et al., 1987) over a 3-D heterogeneous layered seminfinite medium. We are aware that the results from a linear model may not be very accurate. However we believe this analysis to be suitable for a useful comparison with the prediction made by the more realistic non linear groundwater model.
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Figure 7a and 7b show a perspective view of the triangular finite element and boundary element (Sartoretto et al., 1990) mesh adopted for the regional flow simulation of the Ravenna multi-aquifer system and the compaction simulation over the Ravenna Terra field, respectively.

Land subsidence at Ravenna due to water pumpage as simulated with the mathematical model is shown in Figure 8a. The largest settlement appears to have occurred in the late 70's with a value of 1.10 m. This prediction is quite consistent with the

FIG. 6 (a) Cumulative groundwater pumping rate vs. time in the Ravenna area, and (b) piezometric level a.m.s.l. vs. time at Ravenna as reconstructed on the basis of available records.
FIG. 7 (a) View of the regional quasi 3-D flow model of the aquifer system underlying the southeastern Po river basin, and (b) of the main pools A and B of the Ravenna Terra gas field.

benchmark record of Figure 5a and the equicontour map of Figure 5b and points out that water pumpage is likely to account almost entirely for the surface lowering observed at Ravenna.

Figure 8b gives the sinking over the major and minor axis of the Ravenna Terra field as simulated in 1975, i.e. when the largest pressure decline occurred. Figure 8b indicates a maximum settlement equal to 0.65 m and shows that the measurable subsidence is practically restricted to the area overlying the gas reservoir and the occurrence in quickly dampened out beyond the boundary of this area.

CONCLUSION

The results from the 3-D numerical analyses show that the primary responsability for the regional land sinking that occurred in the Ravenna area is to be placed upon the subsurface water overdraft recorded until the middle 70's. Gas withdrawal plays a role restricted to the area overlying each reservoir with a
FIG. 8 (a) Land subsidence due to groundwater withdrawal at Ravenna as predicted by the mathematical model, and (b) land settlement due to gas production over the Ravenna Terra field in 1975 as predicted by the linear model along the major and minor axes of the reservoir.

magnitude depending on the depth of burial, thickness of mineralized rocks and gas pressure drawdown. A major environmental impact may be expected where the gas subsidence bowl is intersected by the Adriatic coastline.

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