THE GEOTHERMAL EUGANEAN FIELD. A SUBSIDENCE MODELLING APPROACH

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Abstract
Multidisciplinary researches have been carried out from many years in the Euganean hydrothermal fields (Veneto, North Eastern Italy). Subsidence modelling of the Abano field is a new research program for the same area. The geological studies perfonned by means of new wells, produced new knowledge about the hydrothermal structure. It was possible to draw a better definition of the geometries of the productive basin obtaining more data about the hydrodynamic structure and the thermal situation of the reservoir. The geophysical researches examined the micro variations of the gravity versus the time in comparison with the high precision levelling-net. A borehole with a depth beyond 400 m, allowed to core samples of the sands, silts and clays of the alluvial quaternary sequence. They were submitted to laboratory tests to find the main geotechnical parameters. Finally a finite element modelling technique was used to perform the subsidence simulation. This model adequately calibrated can be used for a more correct management and exploitation of the hydrothermal resource.

Keywords: Euganean liydrothennal field, Subsidence, Finite element modelling.

1. INTRODUCTION

Systematic multidisciplinary studies about the euganean thermal field (Regione Veneto, North Eastern Italy) (Fig. 1) began in the early 1970 (Piccoli *et al.*, 1976).

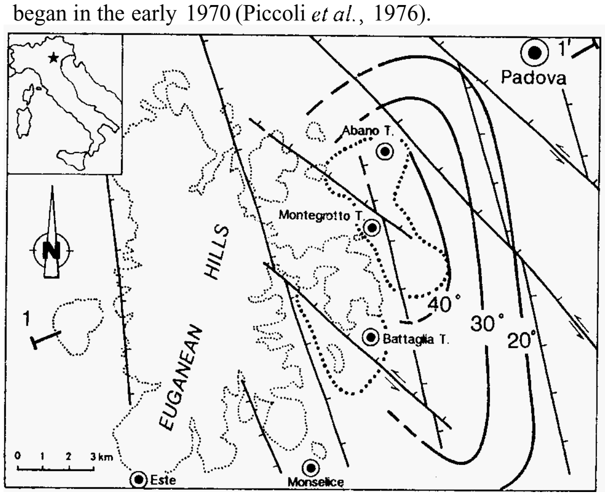

Figure 1 - Tectonics map and hydroisotliermal (depth 150 m) map.

The geological and chemical-isotopic investigations brought to hypothize the euganean waters thermalization through a deep circuit with a remote feeding (alpine and prealpine zone of the western Veneto). *An* hypothesis still holds today.

A first physical modelling of the thermal hydrostructure and improved understanding of the complex hydrogeological relations between the alluvial cover and the bed-rock has been achieved by means of hydrogeological and geophysical analyses. Supported by a research contract between Regione Veneto and University of Padova, the above investigations have been carried out since 1986. Multidisciplinary capabilities like hydrogeological, geophysical, geotechnical and mechanical sciences, applied to the euganean field from both the experimental and computational viewpoints. The main goals of this research have been the following: a spatial-temporal check of subsidence and its modelling by suitable computational tools.

In fact such a phenomenon between seventies and eighties had achieved remarkable values in some zones of Abano and Montegrotto.

2. GEOLOGICAL SETTING

The Euganean Hills (Veneto, North Eastern Italy), located Southeast Padova and extending over a 100 km^2 area, are mainly composed by volcanic rocks which are surrounded by alluvial plain with silty clay deposits (Fig. 1). The stratigraphic sequence begins with the Rosso Ammonitico fm (Upper Jurassic) represented by nodular limestones; it follows the Biancone fm (Upper Cretaceous - Upper Jurassic), which is composed by micritic limestones. Then the Scaglia rossa fm (Lower Eocene - Upper Cretaceous) is the most diffuse sedimentary formation in the Euganean Hills; it is represented by micritic limestones as well. The Marne euganee fm (Lower Oligocene - Lower Eocene), constituted by clayey marl is the most recent term in the sedimentary sequence. The volcanic rocks are prevailing in the Euganean Hills. They were produced by two volcanic events: the first one (Upper Eocene) gave rise to breccias and basaltic lavas; the second event (Lower Oligocene) which is characterized by more siliceous magmas (trachites, rhyiolites and latites), gave rise to volcanic and subvolcanic apparatus (domes, laccolithes and above all discordant bodies). Most of these bodies were intruded at different levels in the sedimentary sequence rising and dislocating the same levels. The geothermal field here investigated extends over Abano, Montegrotto, and Battaglia - Galzignano areas. The thickness of the quaternary cover ranges

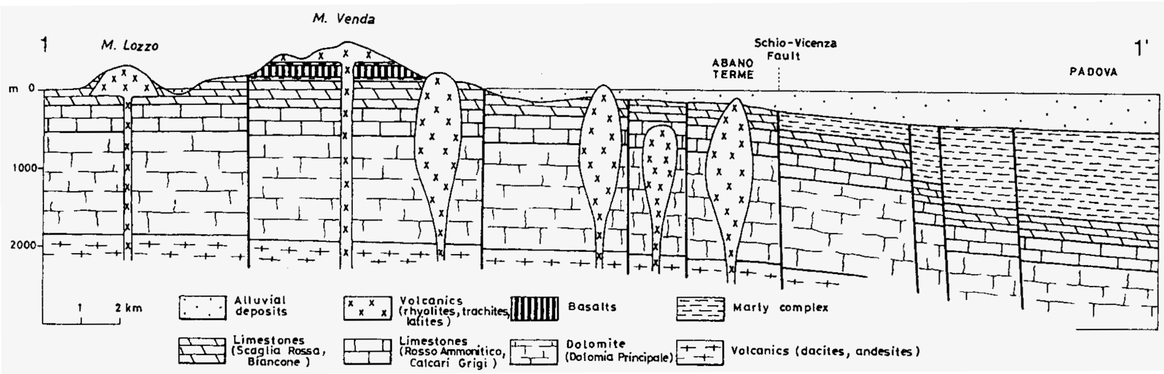

Figure **2** - Geological cross section

from some ten meters to **a** maximum of about 230 meters. It increases towards Padova (north-east) where it is more than 500 meters thick (Fig. 2). The various wells drilled in the thermal area allowed to acquire some litostratigrapliic data. These data enabled us to check the presence of the same rocks that outcrop on the Euganean Hills under the alluvial cover. Some deeper wells have crossed also the formations of the Veneto sequence under the Rosso Ammonitico fm represented by the Calcari grigi di Noriglio fm (Lower Jurassic), the Dolomia Principale fm and the volcanics (Upper Triassic).

The regional geological knowledge, the litostratigraphic data of deep wells and the geophysical investigations allowed **a** reconstruction of the geological and structural situation existing in the ground soil of the plain between the Euganean Hills and the city of Padova (Fig. 2). The bed-rock deepening from the eastern side of Euganean Hills can be seen **in** figures 1, 2 and **3.** This situation is connected with the activity of the extentional tectonics controlled by different fault systems of regional importance, being the Schio-Vicenza line the most significant one. Bouguer isoanomalies obtained from gravimetric measures on **a** wide band of plain are shown in figure 3. **A** rotation trend of the isoanomalies can be clearly observed (NW-SE in the northern part and NNW-SSE in the eastern one). The high gradients of the anomalies near the hills are attenuated Soutward, hence a structural evolution of the bed-rock can be argued, showing **a** more simple tectonics situation in the same direction.

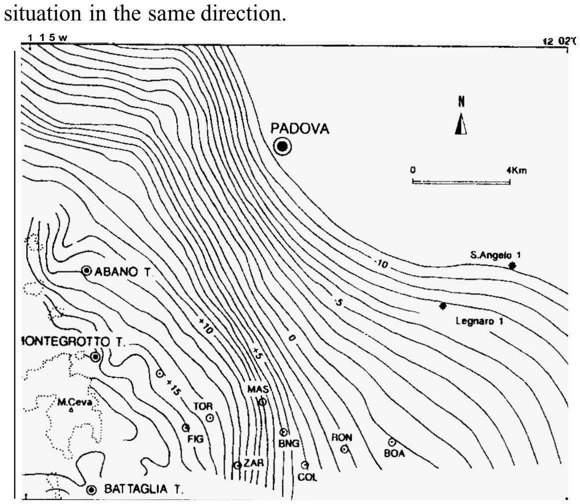

Figure 3 - Bouguer anomaly map

The geological interpretation correlating the carbonatic Mesozoic formations, where the main thermal aquifer is located, to the coevals sequences crossed by some deep drillings (**S.** Angelo 1 and Legnaro 1 - AGIP) about 20 km eastward, has been performed using suitable gravimetric studies carried out by means of 2.5D profiles.

3. HYDROTHERMAL EUGANEAN FIELD

The Euganean thermal field can be classified as a hydrothermal convection system, where the water represents the dominant phase. It extends on a plain band of about 20 km^2 immediately eastern of the Euganean Hills (Figure 1).

After having reached a depth of more than 4000 m, the heated fluids go up again along the circuit because of their low density and they are replaced by colder waters coming from the recharge area. Such **a** circulation rapidly transfers by convection a notable quantity of heat to the geothermic carbonatic reservoir, located at a relatively low depth, which is exploited by about 250 wells.

An account of the produced results is shown in what follows. The more relevance of vertical permeability with respect to the horizontal one, the piezometric maps and the hydroisothermic maps confirm the presence of upward flows with a high thermalization through **a** cross section areas of some thousands m^2. When the shallow zone of the reservoir is achieved by the thermal water, a lateral expansion of the water is allowed. The thermal fluids are partly stored inside the fractures or they can move sideways, partly go up again to the alluvial cover until some ten meters from the surface, mixing with the overhanging cold waters.

The temperature of the thermal water where the vertical flux is more pronounced, varies from 80°C to 87°C. This temperature remains practically constant up to the bottom holes, confirming the presence of a system "with a high up flow rate".

The chemism of these waters is characteristic of hydrothermal circuits in sedimentary deep basins (T.D.S 6g/l), with main presence of Cl and Na (70%) and secondary of SO_4, Ca, HCO_3, SiO_2, Mg.

The exploitation is concentrated in the urban centres of Abano, Montegrotto and Battaglia where the density of the wells is about 10-15 wells/Ha. During the last investigations, also considering the requirement of more balanced distributions of the exploitation points, some temperature logs have been performed in wells outside the thermal area. Consequently an attempt has been made to give an unified hydrogeological interpretation on the surrounding areas (Fig. 1), using contour-line hydroisothermic map.

The temperatures have been measured at the bottom holes, whose depths range from 40 to 120 m. Hence they are related to aquifers located in the quaternary sediments. The isolines in figure 1 correspond to the geological interpretation of the bed-rock where a degrading extentional tectonics eastward could favour an expansion of the hydrothennic anomaly in the same direction. On the contrary in the Euganean Hills the presence of a cold continuos aquifer has been ascertained.

The bed-rock is crossed by production drillings for hydrothermal exploitation up to some hundred meters, or sometimes to more than seven hundred meters. The casing is only placed in the quaternary cover. The total average flow-rate of thermal water in the two principal production poles of Abano and Montegrotto is about 0.7-0.8 m^3/s.

Recently a drilling of a borehole *(APONUS* 2) (Fig. 4) in the centre of Abano allowed some interesting observations to be performed on the two water bodies (alluvial cover and bed-rock). For this purpose some geophysical logs have been carried out, e.g. natural gamma, neutron, temperatures, sonic, PS and resistivity.

The utility of correlation among geophysical parameters and litostratigraphic sequences is straightforward. For example it was found that the quaternary cover electrically behaves as a very conductible body because of the presence of thermal waters.

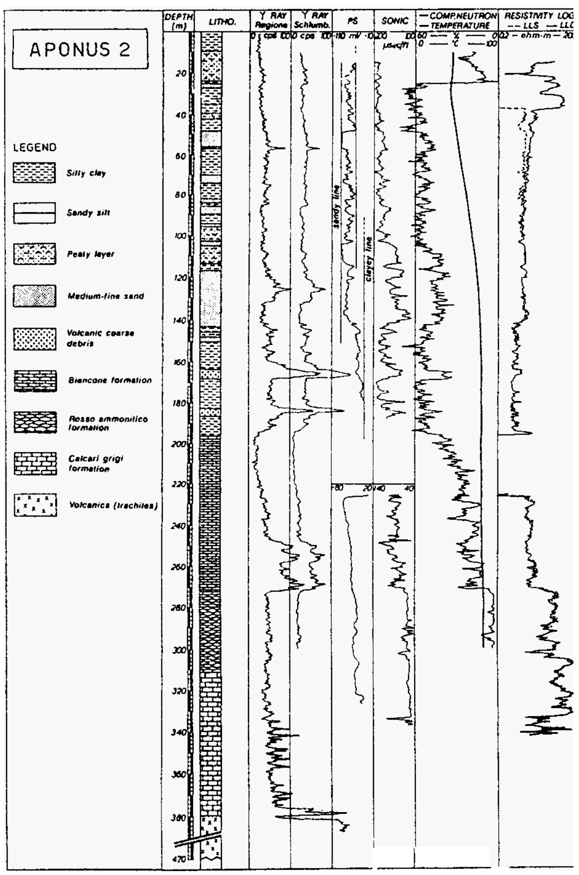

Figure 4 - Litostratigraphy and geophysics logs in the "APONUS 2" borehole

These logs have been particularly important for hydrogeological applications, in fact they permitted to locate some fractured levels with a very active water movement, in the bed-rock. The results obtained with natural gamma log in the more fractured zones of the Biancone fm are unusual. These data are probably connected with the presence of radon in the thermal waters (Antonelli *et al.*, in press).

Piezometric heads between the high exploitation (spring and autumn) and low exploitation regimes (winter and summer), seems now to be stabilised between 7-10 m.

It must be pointed out that both because of the high concentration of the production wells and of the considerable variation in the transmissivity values (from 13 m^2/g to 2230 m^2/g), drawdowns of about 30-40 m can be achieved in some field sectors.

The performance of the continuously sampled well (Aponus 2) allowed an accurate characterisation of the main confined sandy aquifers in the alluvial cover, with a permeability coefficient ranging from 1.1 2×10^{-5} to 7.7×10^{-6} m/s.

The observation wells (P13, P58 and P136) corresponding to these levels have allowed to ascertain that the piezometric phases caused by pumping rates in the deep carbonatic aquifer are completely transferred nearly the total thickness of the

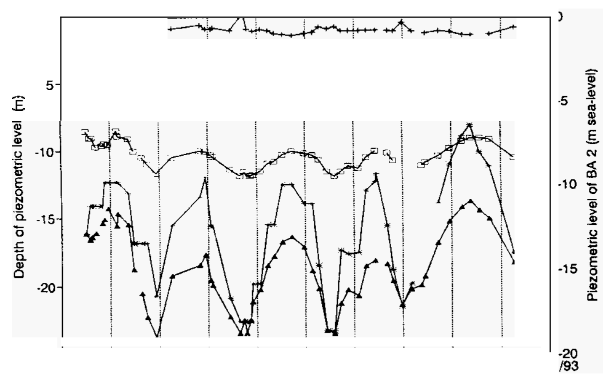

Figure 5 - Piezometric levels in Barillari 2 well (BA2) and in P136, P58 and P13 observation wells.

The average oscillation of about 10 m in the thermal aquifer determines a variation of 2 m in the alluvial aquifer SO-60 m deep (P58), while in the one 100-140 m deep the variation is of 7-8 m (P136).

Changes in neutral pressure related to the phases of hydrothermal exploitation have been recorded also in the clayey silty levels by BAT type piezometers, with maximum oscillations of about 2.4 m (BAT 46 m depth) and 0.4 m (BAT 16 m depth) (Antonelli *et al.*, 1993).

The obtained results clearly demonstrate a hydrogeological connection between the alluvial sequences and the deep carbonatic complex which is more developed than it could be supposed on the base of the hydrostructural euganean model. Nevertheless the local influence of technical arrangements of the casing, its imperfect cementations, and its anchorage to the productive bed-rock, should be carefully evaluated.

4. SURVEYED SUBSIDENCE IN THE EUGANEAN THERMAL FIELD

In the Euganean area two different altimetrical movements are observed. The first is connected to geological factors (elevation of the alpine sector and lowering of the northern Italy plain) and the second is related to local artificial conditions (e.g. pumping rates).

The elevation measures started not organically from 1959 in the thermal area. Nevertheless it was observed the more important phase in the Abano and Montegrotto centres, was about some dm/year at the apical subsidence cones. This subsidence was reduced during the eighties and today it is equal to few mm/year (Fig. 6).

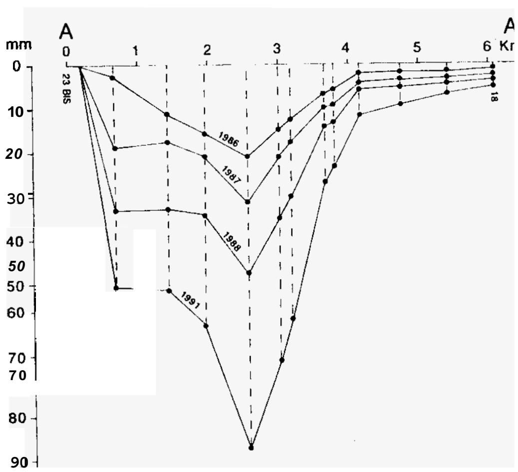

Figure 6 - Elevation differences during 1991-1985 along the N-S profile (A-A' line is reported in figure 7)

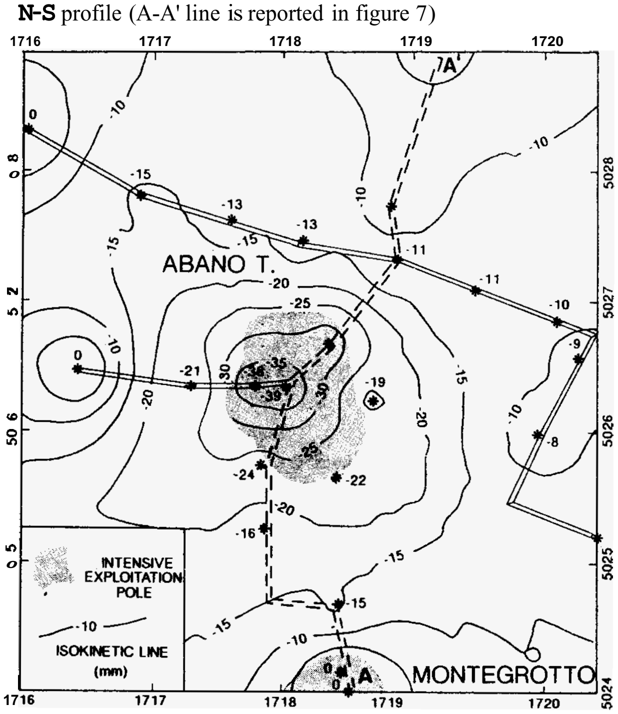

Figure 7 - Isokinetic lines at Abano and Montegrotto

Within Italian "Geothermics" program, sponsored by C.N.R. systematic microgravimetric and high precision levelling measures began in 1985 (Di Filippo *et al.*, 1985). The last measures of this program were carried out in 1991.

Simultaneously other measures were carried out (Balestrazzi *et al.*, 1991) and the results could be compared with the previous ones. The attenuation of the subsidence phenomenon is related to a closure of the thermal water pumping rate from quaternary alluvial cover. Now the pumping rate comes from calcareous bed-rock. The isokinetics related to subsidence during the period 1988-1991 are shown in figure 7.

The principal subsidence cone located at Abano and the second one located at Montegrotto are indicated together with surrounding isolines in the same figure.

5. GEOTECHNICAL PROPERTIES

The research presented in this section regards geotechnical investigations. Some of these elaborations, in particular those concerning the geotechnical properties of the soils forming the alluvial quaternary deposits of Abano thermal field are also used to calibrate the mathematical model of subsidence.

An accurate description of the soil profile has been obtained by means of the 300 m deep borehole. Some elaborations on samples (33 undisturbed and 80 remoulded) have been reported in figure 8, emphasising the role of the geotechnical properties. Atterberg limits and in situ water content were determined on undisturbed samples; most of them lie within the very silty clay types ($10 < PI \leq 22$, $35 < w_L \leq 50$), close to the A line of the Casagrande plasticity chart.

Conventional oedometer tests were performed on 26 specimens with diameters of 70 mm. The vertical preconsolidation stresses, detennined from e-log σ' plots using the Casagrande method, appear in figure 8; in the same figure the trend of vertical effective stress with depth is drawn, considering both hydrostatic and in situ measured pore pressure distributions. Note that only some samples are slightly over consolidated, especially in the upper layers of the Quaternary deposit, whereas the others appear to be normally consolidated or slightly under consolidated with respect to the present effective stress situation.

The oedometric modulus $M = \delta\sigma'/\delta e$ was calculated in correspondence to the in situ vertical effective stress. Even if experimental data are rather scattered, a general increase of M with depth can be observed. The equation $M = 490\ z^{0.84}$ (where z is expressed in m and M by kPa), fitting the experimental data, was assumed as a reasonable trend of soil stiffness with depth (Gottardi *et al.*, 1994).

Although the difficulty of obtaining reliable and representative values of the consolidation coefficient c_v from oedometer tests is well recognised, nevertheless c_v values were determined from oedometric settlement-time plots (in the normally consolidated range) using Terzaghi's one-dimensional consolidation theory and Casagrande method.

These parameters are also reported in figure 8. A large scatter of experimental data is again observed and no particular trend of c_v with depth was appreciated.

The same considerations can be expressed about the vertical permeability coefficient, which was calculated using the well known relationship $k_v = \gamma_w c_v / M$. Most k_v computations lie in the range 5.10^{-10} m/s to 10^{-8} m/s.

To characterise the soil defonnability at high temperatures (Eriksson, 1989), some special oedometer tests were also

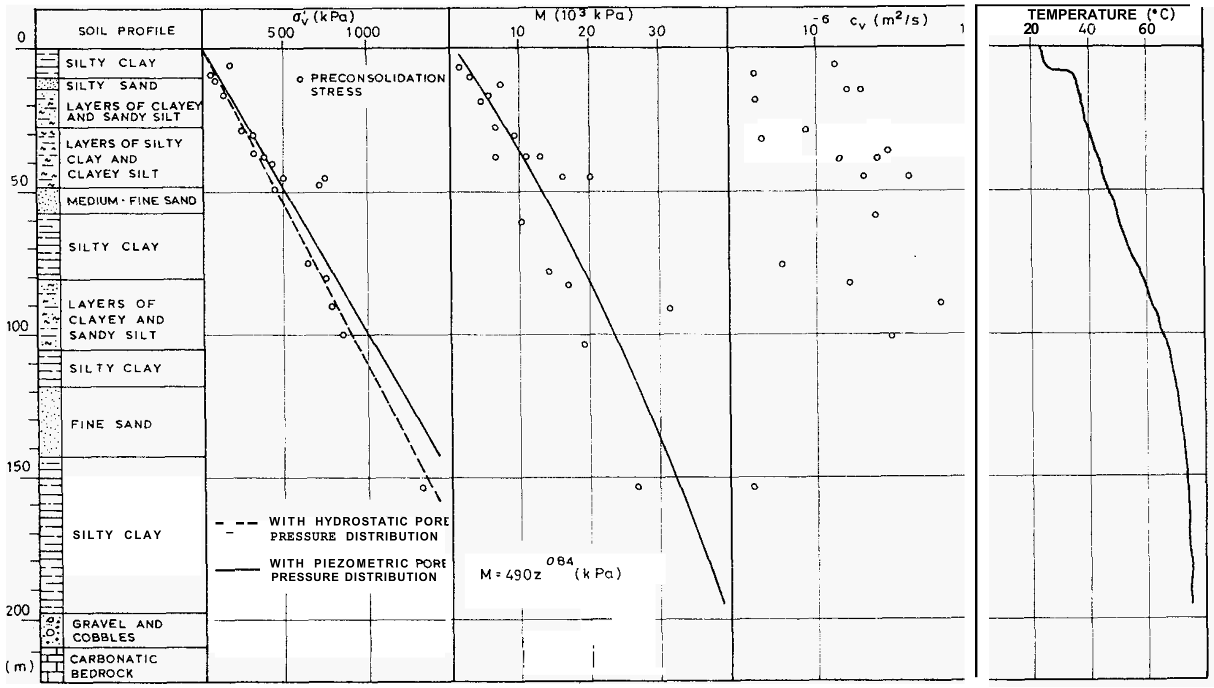

Figure **8** - Simplified soil profile from the deep borehole, preconsolidation stresses compared to the vertical effective stress trend, oedometric modulus, coefficients of vertical consolidation and temperature vs. depth

carried out. In this case the oedometrr apparatus was installed in a thermostatic cell, capable of maintaining the soil sample at **a** fixed temperature. Three samples (taken at the following depths: **38,** 45.3 and 81.3 m) were tested at the constant temperatures of 25 °C and S0 °C. From the experimental results it has been shown that the oedometric moduli of all samples at 25 °C are lower than those determined at 50 "C. That means, a temperature increase produces an appreciable (10%÷30%) increase of their oedometric stiffness.

6. MATHEMATICAL MODELLING

The mathematical model used in this paper to analyse the subsidence problems of Abano Terme area is based on an averaged technique presented in Simoni and Schrefler (1989). This technique allows to study the referenced problem without recourring to expensive fully 3-D models or oversimplified 2-D solutions like axisymmetric, plane strain or stress ones. In the actual case, the governing equations are integrated (or averaged) over the smallest dimension of the domain (thickness). The resulting model is solved numerically with **a** partitioned procedure. **A** two-dimensional problem is obtained, in which the three-dimensional nature is accounted for. In this case the boundary conditions involved in the averaging procedure are known, hence also the 3-D simulation is obtained. In this volume fraction theory the real multiphase system is replaced by **a** model in which each of the phases of the system is assumed to fill up the entire porous medium domain (overlapping continua). In the assumed macroscopic level, the dimensions of the representative volume element (R.E.V.) satisfy lower an upper bounds depending on the characteristic lengths of the microscopic and macroscopic inhomogeneities, see e.g. Bear and Corapcioglu (1981).

Here we assume one of the dimensions of the R.E.V. is equal to the smallest dimension of the domain (thickness). This requires the thickness of the domain to be sufficiently small with respect to the other dimensions of the porous medium domain. In this situation the field variables are averaged quantities over the thickness. Furthermore the balance equations are valid for the whole thickness. The governing equations are stated using the mean values of the field quantities defined from averaging procedure. The ***solid phase*** behaviour is analysed by means of the momentum balance equations. These are Written using the virtual work principle, in which macroscopic values of all variables appear and the integration is performed over the whole porous medium domain. The equilibrium equations are modified to take into account Terzaghi's principle, whose validity is assumed here. Purely elastic material modeling is also accounted for. The ***fluid phase*** behaviour is governed by the mass balance equation of the fluid phase. This is performed integrating over tlie thickness the point mass balance equation (or by writing the equation directly in terms of the mean values of the variables). In this equation, the following terms are included: fluxes through the upper and lower surfaces, rates of changes of total strain, of the grain volume due to pressure changes, of fluid density and of grain size due to effective stress changes. Darcy's law is accounted for at mega-level for liquid transport and unknowns are the mean values of displacements and pressures. Since the modelling is carried out in isothermal conditions, because measures performed over a time span of more than thirty years has shown an almost constant value of tlie temperature of the reservoir, energy balance equation is cancelled out. The numerical solution of the problem **is** carried out by means of finite element method. Displacements, thickness and pore pressures are interpolated with suitable interpolation functions and **a** Galerkin procedure. Hence **a** system of partial differential equatians in time is obtained. Partitioned solution techniques are adopted for which stability and convergence is demonstrated. **A** predictor/corrector scheme in the form of the last solution is used. Iterations are necessary in small number at the first time steps. The model is applied to

the reservoir of Abano. This case-study is'well represented by an averaged model.
432 finite element are used in the model, with 1381 nodal point and 5524 d.o.f. (displacements in the horizontal domain, compactions and pressures). The fluid is drilled from 63 boreholes, with pumping rates between 150 and 600 l/min. The following data are used: Young's modulus 22 daN/cm^2, Poisson's ratio 0.4, permeability coefficients 10^{-9} m/s, porosity 0.5. Other modelling data are shown in what follows:
(i) variable aquifer thickness,
(ii) irregular distribution of the pumping stations (Fig. 9),
(iii) every well has different time history of pumping rate.

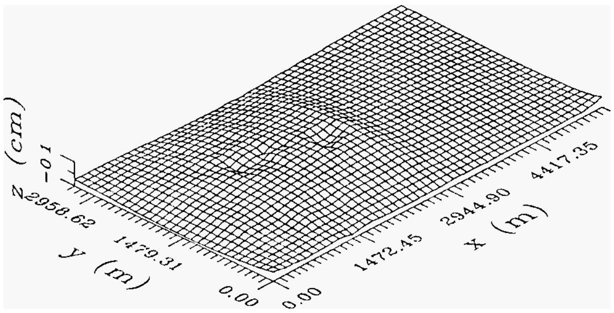

Figure 9 - Spatial distribution of the aquifer compaction at regime

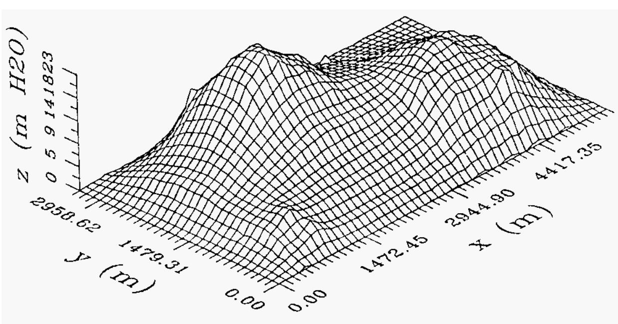

Figure 10 - Spatial distribution of the excess pore pressure at regime

Some results are presented in figures 9 and 10, where the spatial distributions of the aquifer compactions and excess pore pressures at regime are presented. It is confirmed a subsidence of about 1 cm/year.

7. CONCLUSIONS

The different contributions from various scientific areas allowed to obtain a deeper insight about the topic of hydrothermal euganean field exploitation. The geological, hydrogeological and geophysical investigations lead to a critical revision of the hydrostructural configuration of the euganean region together with a detailed parametrization. The latter has been applied for setting a mathematical model of subsidence. Such a relevant aspect which is also strictly connected to the thermal water exploitation has been systematically recorded in the last five years by means of suitable levelling.
Field data measurements and geotechnical laboratory tests carried out on samples of the quaternary cover have been used for modelling purposes. The subsidence analyses have been capable to find the mechanical response in terms of compactions, horizontal displacements and pore pressures at the nodal points of the finite element mesh spanning an area of over 20 Km^2.
Future calibrations related to alternative exploitation programs of the same area can easily provide the corresponding responses.

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