TWO DEEP BOREHOLES FOR THE ANALYSIS OF RAVENNA'S SUBSIDENCE

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ABSTRACT. This paper shows the case of Ravenna, an Italian town, subject to a troubling phenomenon of anthropic subsidence. This is mainly due to the unchecked withdrawal of water from the subsoil. The control of the settlement due to subsidence was made by means of performing periodic precise levellings on the land in the 70's and 80's. On the other hand, the analysis of the subsidence made use of geotechnical information obtained through soil samples, taken during two deep boreholes driven down to -500 and -1500 m. In this paper, the main results obtained with geotechnical laboratory tests are summarized.

1. INTRODUCTION

The cases of subsidence in Italy are mostly concentrated in the Northern region, the Po Valley, where the longest Italian river flows. The subsidence phenomena started to interest Italian researchers after 1950, when the rapid industrialization of the country and the increasing demand of water and energy for industrial, civil and agricultural aims caused a series of local problems extremely dangerous for the protection and the working order of the cities affected. This happened where the nature of the subsoil was particularly sensitive.

Periodic levellings, carried out in Northern Italy from the beginning of the century till now, have shown the actions of three phenomena, indipendent of each other, but causing summing effects on the land: natural and anthropic subsidence and eustatism.

Natural subsidence concerns the whole Po Valley and originates from the tectonic deformations of bedrock and from the continous consolidation of geologically more recent deposits. The extent of the phenomenon increases moving towards the Eastern part of Italy, particularly along the coastal lands from Venice to Ravenna. Until now, the

the researchers could not differentiate the effect due to the tectonic deformations of bedrock from the effect due to the natural consolidation of recent sediments.

Eustatism is connected to sea-level variations due to the earth climatic fluctuations. Although it is completely indipendent of subsidence, eustatism also can contribute to make the limit of dry land withdraw during the raising of the sea-level.

Finally, in Italy the anthropic subsidence depends mostly on the unchecked withdrawal of water and sometimes gas from subsoil deposits. The most important cases of subsidence which took place in Italy are indicated in Fig.1.

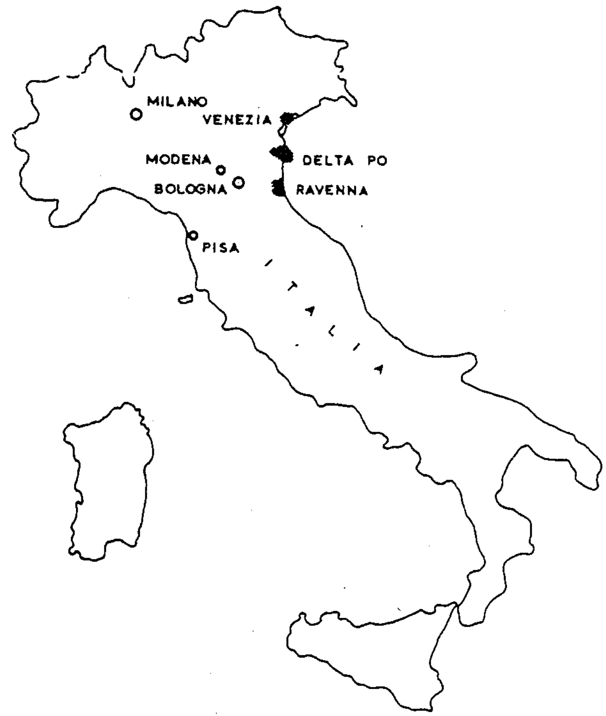


Fig.1: The most important cases of subsidence in Italy.

This paper deals with subsidence in Ravenna, a small town located on the South-Eastern part of the Po Valley. It became a political and artistic center when it was designated capital of the Western Roman Empire (V century A.D.). In that period several important monuments were buit, such as S.Vitale Basilica (VI century A.D.), which have made Ravenna famous all over the world.

After the Second World War, the Ravenna area was subjected to generalized subsidence, which has increased progressively until the 70's. The phenomenon was more evident in the industrial zone, but it also caused serious problems in the historical center, in the harbour and along the coastal lands.

The analysis consisted of the estimation of the effects on land caused by both the unchecked withdrawal of water from the shallowest aquifers and the deep gas reservoirs. The analysis of such a complex phenomenon, involving a wide area (hundreds of square kilometers) and extending to a considerable depth, would have required a large series of data extending over the whole territory. This because of the natural heterogeneity of the physical medium, of the different possible causes of subsidence, and of the problems involved. This, though, was not possible for economic reasons. Therefore, only a few representative areas were accurately investigated. Afterwards, the results obtained were extrapolated to include the remaining territory.

The analysis of the effects (A) caused by withdrawal of water was limited to a depth of -500 m, while the analysis were driven as far as -4000 m in depth in order to estimate the effects (B) caused by the withdrawal of gas. The effects A involve a wide area of land, while the effects B are restricted to a limited area.

This paper presents a part of the analysis. In particular it shows the results of precise levellings, carried out periodically in the Ravenna area as well as the geotechnical laboratory testings carried out on more than a hundred undisturbed soil samples, drawn during two deep boreholes.

2.GEOLOGICAL BACKGROUND OF THE RAVENNA AREA

The Ravenna area is located in the South-Eastern part of the wide sedimentary basin of the Po Valley. The subsoil is characterized by a series of sea, delta, lagoon, marsh and alluvial deposits of the Quaternary and the Upper Pliocene. Their thickness and distribution is conditioned by deep geological structures and by local geological history. In fact, the Prequaternary bedrock consists of a complex structures with folds and folds-faults, forming traps of rich concentrations of hydrocarbon minerals. The Quaternary sediments have a variable thickness from -1500 m to -3000 m and a structural framework which follows the bedrock pattern. At depths inferior to -50 m, recent alluvial sediments follow the downflow direction of present Apennine streams, with only a slight inclination towards North-East.

In the shallowest part (Holocene), several paleo river beds have been identified. They are variously oriented and sometimes superimposed and contribute to complicate water circulation in the phreatic aquifer. Therefore, the Plioquaternary complex consists of alternations of layers mostly of a cohesive or granular nature. The total thickness in the Ravenna area reaches its highest values in the whole Upper Adriatic Basin, thus confirming the theory that the examined area has been subsiding since remote ages. Geological subsidence was estimated at 1.5-3.0 mm/year.

3. SUBSIDENCE EVOLUTION IN THE 1950-1986 PERIOD

The Ravenna area was subjected to a generalized phenomenon of subsidence. In the 70's and 80's several precise levellings were carried out to check the evolution of the subsidence and to verify some hypothesis on the relations between causes and effects induced. These levellings were carried out in the years '72-'73, '77-'78, '82 and '86. The results obtained were compared with those of the 1949 levelling, carried out in a period when anthropic subsidence had not begun yet. The points characterized by an equal rate of subsidence were connected by isokinetics, which clearly points out the areas most subject to the phenomenon.

In Fig.2 the trends of the isokinetics in the period 1949-1972, 1972-1977, 1977-1982, 1982-1986 are reported. The peak values of the subsidence rates were registered in the years '72-'77 in the industrial zone. The maximum settlement, which took place in the period 1949-1986 was about 1.15m; the peak subsidence rate increased from 30-40 mm/year

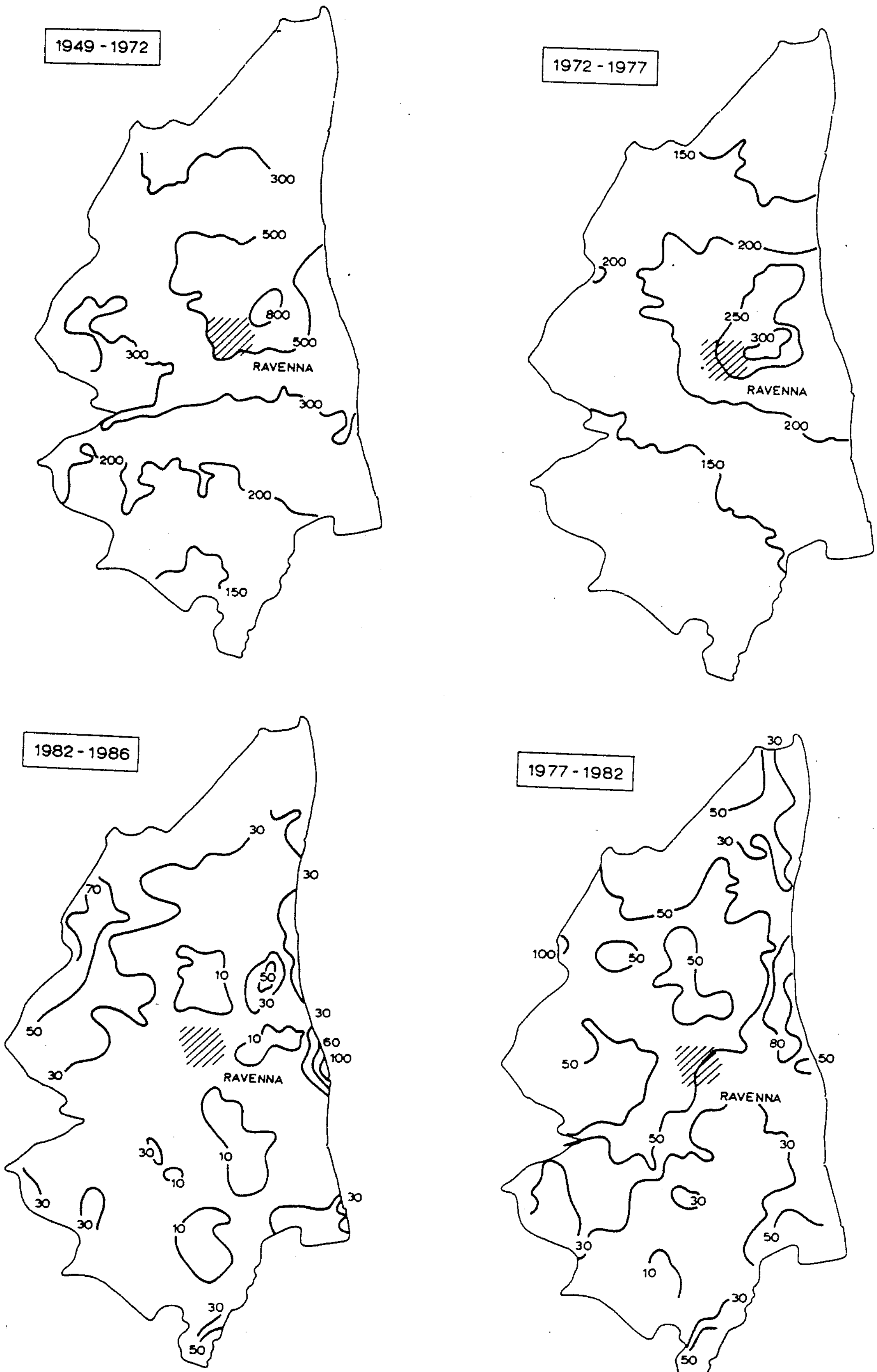


Fig. 2: Evolution of subsidence (in mm) in Ravenna area from 1949 to 1986.

in the period '49-'72 to 60-70 mm/year in the period '72-'77.

Until 1972, the phenomenon seemed to be limited only to the industrial zone. On the contrary, later it began to extend. In order to give evidence to this, it is sufficient to notice that the highly subsiding area was of about 4 Km^2 until '72, whereas it was of 80Km^2 in '77. The deleterious effects on the land became progressively more frequent causing the withdrawal of the coastal land (intensely exploited from a touristic point of view), frequent floods of the monumental, industrial and harbour zones and hydraulic problems of sewers, drainage system and reclaim channels.

In Fig.3 the average piezometric declines registered in five main aquifers from '50 to '86 are reported as well as the average settlement registered in the same period in the monumental and industrial zone (Fig.4). The peak subsidence rate decreased from 10-15 mm/year in the period '82-'86 to 5 mm/year. Rates of 10-15 mm/year still occur in some centers in the coastal lands (Marina di Ravenna, Lido Adriano). This is due to the consolidation induced by materials, transported by the rivers flowing into the sea, on the shallowest sediments.

4.THE TWO DEEP BOREHOLES 'ZORABINI 1' AND 'RAVENNA 1-SUBSIDENZA'

The reconstruction of Ravenna's soil profile was difficult initially because of the almost absence of historical data and the scant reliability of the few data available. At the beginning of the 80's, in order to fill this gap, it was decided to carry out a continuos sampling borehole down to -500 m. At the same time, AGIP (National Italian Oil Company) was commissioned to take a hundred representative soil samples during an oil drilling at more than 1000 m in depth.

The two boreholes were called "Ravenna 1-Subsidenza" and "Zorabini 1" respectively. Both boreholes were carried out inside the industrial zone, that is, in the area which suffered the most from the effects of subsidence. The "Zorabini 1" borehole allowed a series of geotechnical informations to be obtained on a limited number of very deep samples. On the other, the "Ravenna 1" borehole allowed the determination of the borehole log and the complete geotechnical characterization of the lithotypes, all with extreme accuracy.

By means of the informations obtained by the "Ravenna 1" samples, a mathematical model for the simulation of subsidence due to the withdrawal of water was developed. In fact, this phenomenon concerns the first 350-400 m of depth. The borehole samples were taken with two different types of samplers, from 68 to 476 m of depth with a Christensen Rubber Sleeve, from 476 to 496 m with a Christensen Plastic Liner. The first allows a continuos sampling of 6 m of soil, the second of 9 m. In both cases, the borehole sampler were divided in 1 m pieces for transportation reasons. Each piece was lodged into a wooden box and drenched in a bath of melted paraffin so as to allow the maximum guarantee of preservation of the chemical-physical characteristics of the soils and an

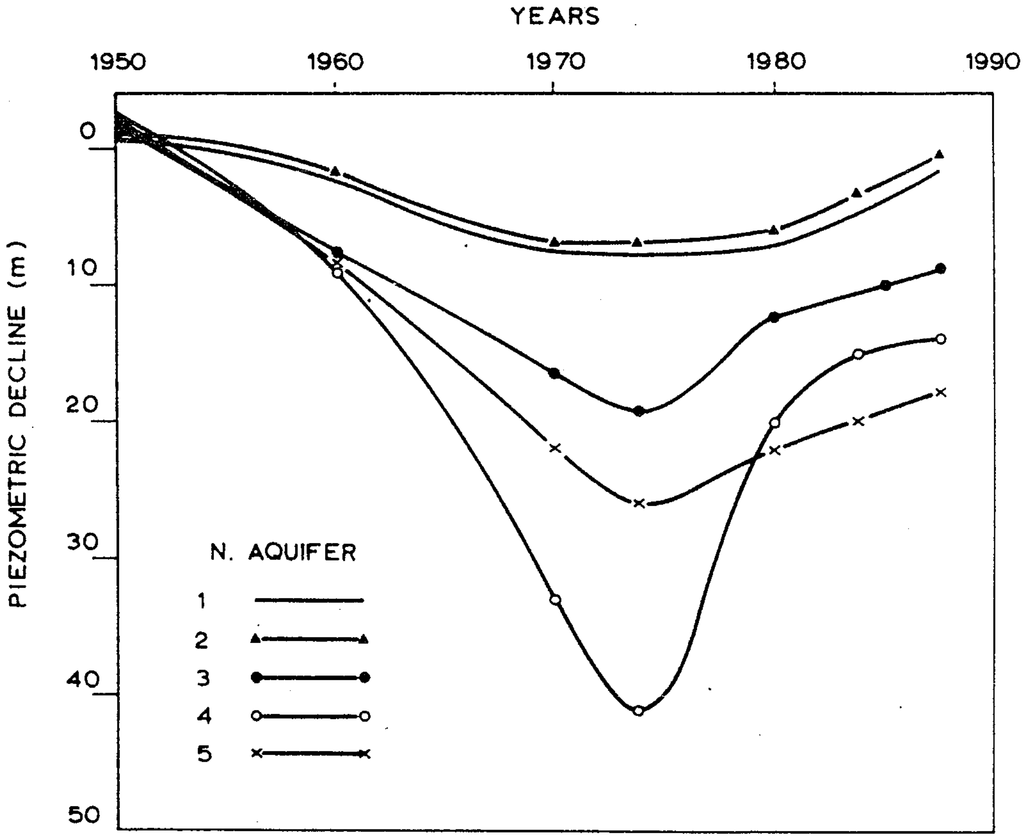


Fig. 3: The average piezometric levels observed in five main aquifers from 1950 to 1986.

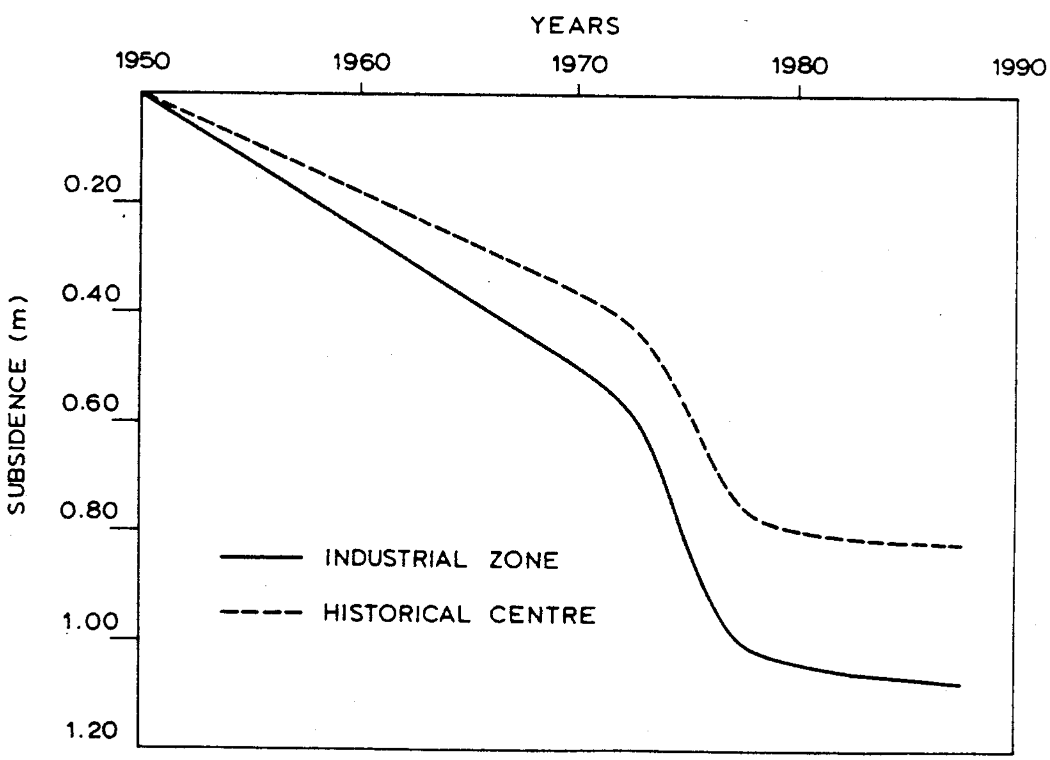


Fig. 4: The average land subsidence registered from 1950 to 1986.

optimum packing for transportation.

In order to limit the disturbance, all necessary devices were adopted to preserve the rectilinear state of the samples, both when coming out of the borehole and in the transportation to the cut bench. With the "Rubber Sleeve" sampler, 68 borehole samples were taken for a total of 408 m of sampling. With the "Plastic Liner" sampler, 2 borehole samples were taken for a total of 18 m.

The total recovery, registered with the two different types of samplers, was equal to 94% for the "Rubber Sleeve" and to 75% for the "Plastic Liner".

5. ANALYSIS OF THE LABORATORY RESULTS

Geotechnical laboratory testing on samples of soil, taken during the two boreholes, was carried out almost entirely at the Soil Mechanics Laboratory, Engineering Faculty, University of Padova, Italy. Oedometer tests on samples, deeper than 500 m, were carried out at the Mining Science Institute of Bologna.

Each wooden box containing a piece of sample was opened completely on all sides in the laboratory. The paraffin which surrounded the sample was then eliminated. The Rubber Sleeve or Plastic Liner was cut along one or more generatrixes: the outer lateral surface of the sample was made free of the residual drilling fluid. It then proceeded to the visual classification of the various lithotypes present, to the granulometric description of coarse soils, and to the recording of the color, the smell and of the possible shells and fossils present. Besides the visual classification tests, several oedometric consolidation tests were carried out as well as permeability falling-head tests.

The borehole log obtained through Ravenna-1 boring is reported in Fig.5. A systematic succession of granular layers (sands, silty sands, sandy silts) can be observed as well as other cohesive layers (clays, silty clays, clayey silts, sandy-clayey silts). This is typical of areas of alluvial origin. In the same figure a series of Atterberg's limits is summarized; they were determined in the cohesive layers. In Fig.6 Casagrande's Plasticity Chart is reported with the obtained liquidity limit W_l values and plasticity index I_p. It can be observed that the experimental points are placed along a regression straight line of equation $I_p = 0.84\ W_l - 15.59$, with a regression coefficient of 0.96. This line is translated slightly upwards as to Casagrande A-line ($I_p = 0.73\ W_l - 14.60$), though more or less preserving the incline. Their classification groups, according to ASTM Standards are CL and CH.

As far as granular soils are concerned, their grain size distribution shows the presence of medium sands, fine sands, silty sands and sandy silts. The size of the grains ranges between a maximum of 0.7-0.8 mm and a minimum of 0.002 mm, with coefficient of uniformity C_u ranging between 2 and 5. For these types of soils, their classification groups are SP and SM.

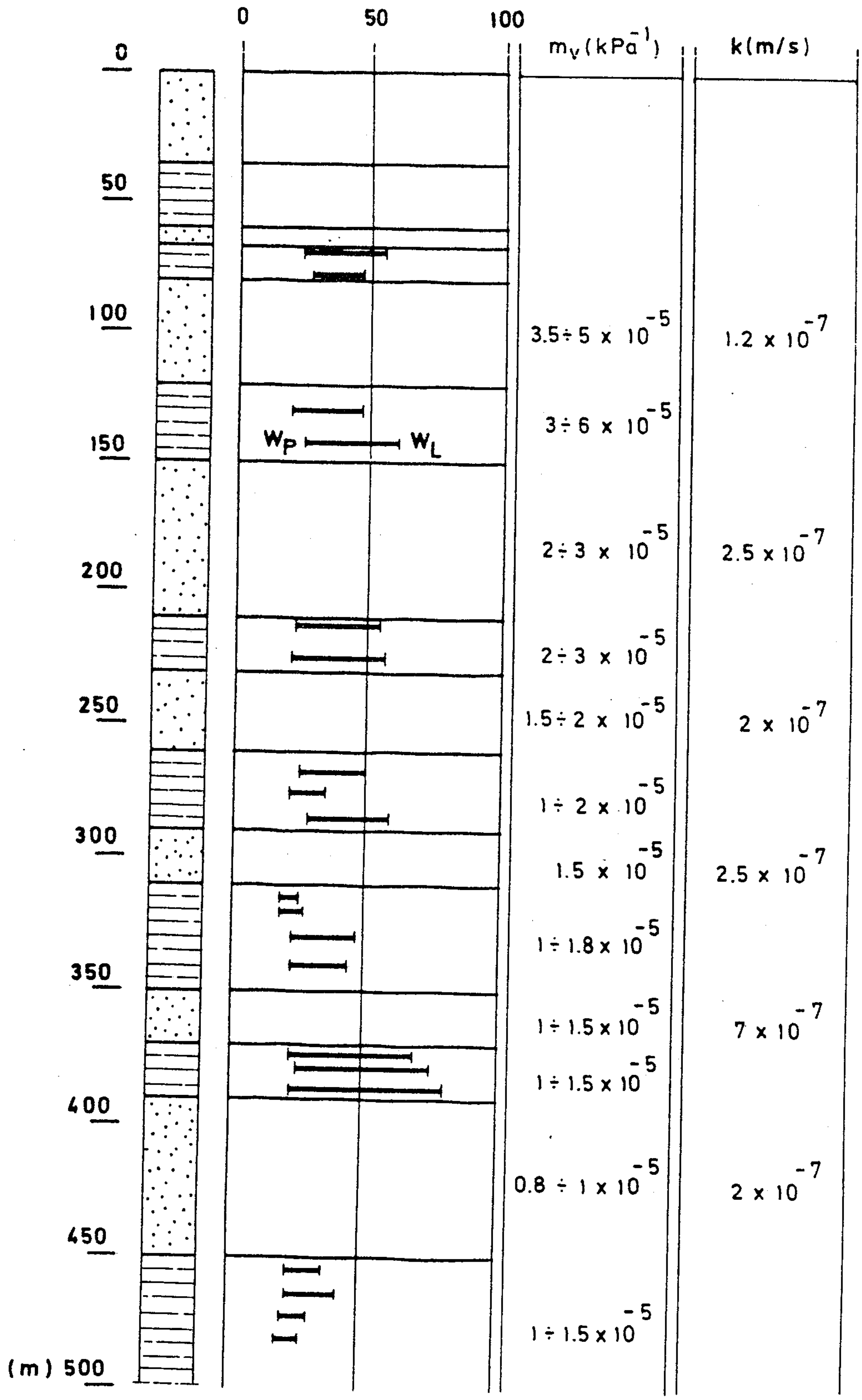


Fig. 5: The soil profile from "Ravenna 1-Subsidenza" deep borehole.

Oedometer consolidation tests were performed on both cohesive and granular soils. A range of pressure between 0.05 and 8.05 MPa was investigated, trying to obtain maximum pressures at least twice as high as preconsolidation pressure, even for the deepest samples.

In Fig.3 some values characteristic of the coefficient of volume change m_v were reported, while in Fig.7 all m_v coefficients determined on samples taken during "Ravenna 1" and "Zorabini 1" drillings were shown. The range of variation of m_v is between $3x10^{-6}$ and $3x10^{-5}$ KPa^{-1} for sands, and between $2.5x10^{-6}$ and $5x10^{-5}$ KPa^{-1} for clays.

m_v coefficient decreases with depth according to the following exponential equations:

$$m_v = 1.533\ Z^{(-1.175)} \qquad \text{for clays}$$

$$m_v = 0.430\ Z^{(-1.013)} \qquad \text{for sands}$$

The regression line which characterizes clays is translated downwards compared to that of sands. That scattering is quite high for shallow samples, while it decreases progressively going towards high depths. It can be observed that the behaviours of clayey soils and sandy soils coincide for the samples taken at high depths. Obviously, the high relative density, which can be recorded on all samples at depth, makes the differences which can be found in the surface less sensible. A series of representative

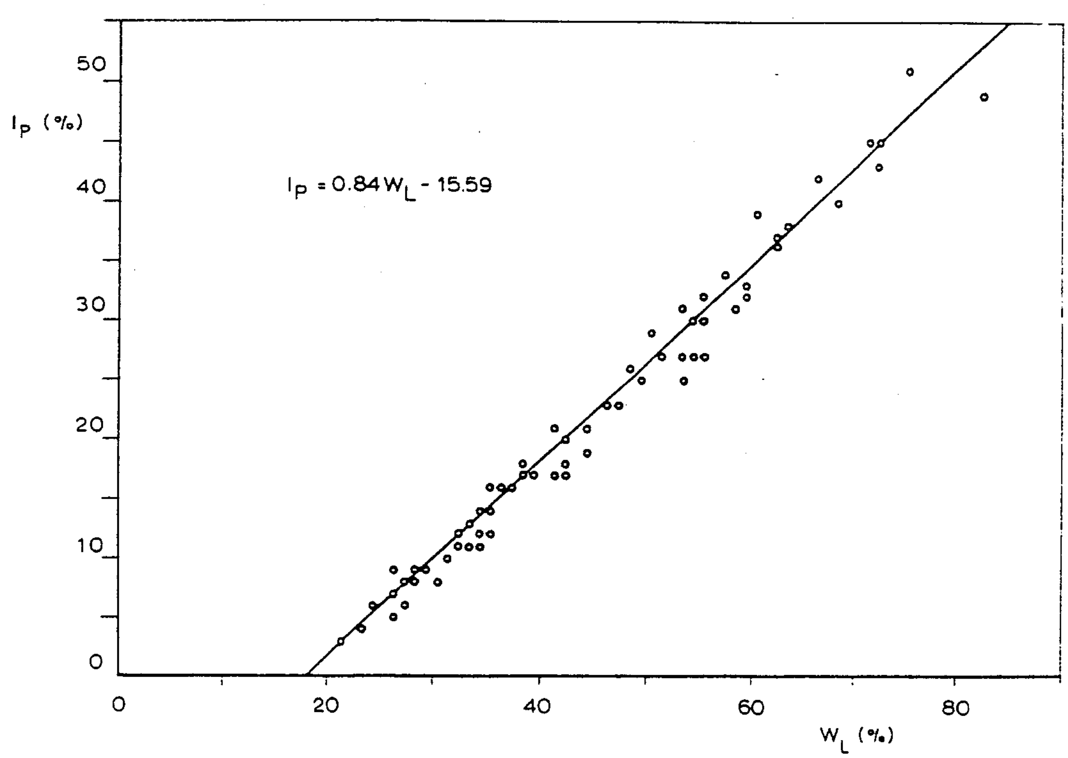


Fig. 6: Casagrande's Plasticity Chart.

oedometer tests, carried out on cohesive samples, are reported in fig.8. The compression index C_c ranges between 0.20 and 0.35.

Permeability tests were performed only on granular soils, by using a falling-head apparatus. The samples was prepared before the longitudinal cut of the Rubber Sleeve so as to preserve the existing stress state. The sample was chosen on the basis of the borehole log, carried out during boreholes. At the end of the test the usual classification tests were performed on the sample examined. Characteristic values of the coefficient of permeability k, connected with the different aquifers are reported in Fig.9. k variability range is limited to 1.2 and 7 $x10^{-7}$ m/s. These rather low values for granular soils are explained both by the difficulty in finding clean sands, without consistent silty fractions, and the high relative density which characterized all the samples examined.

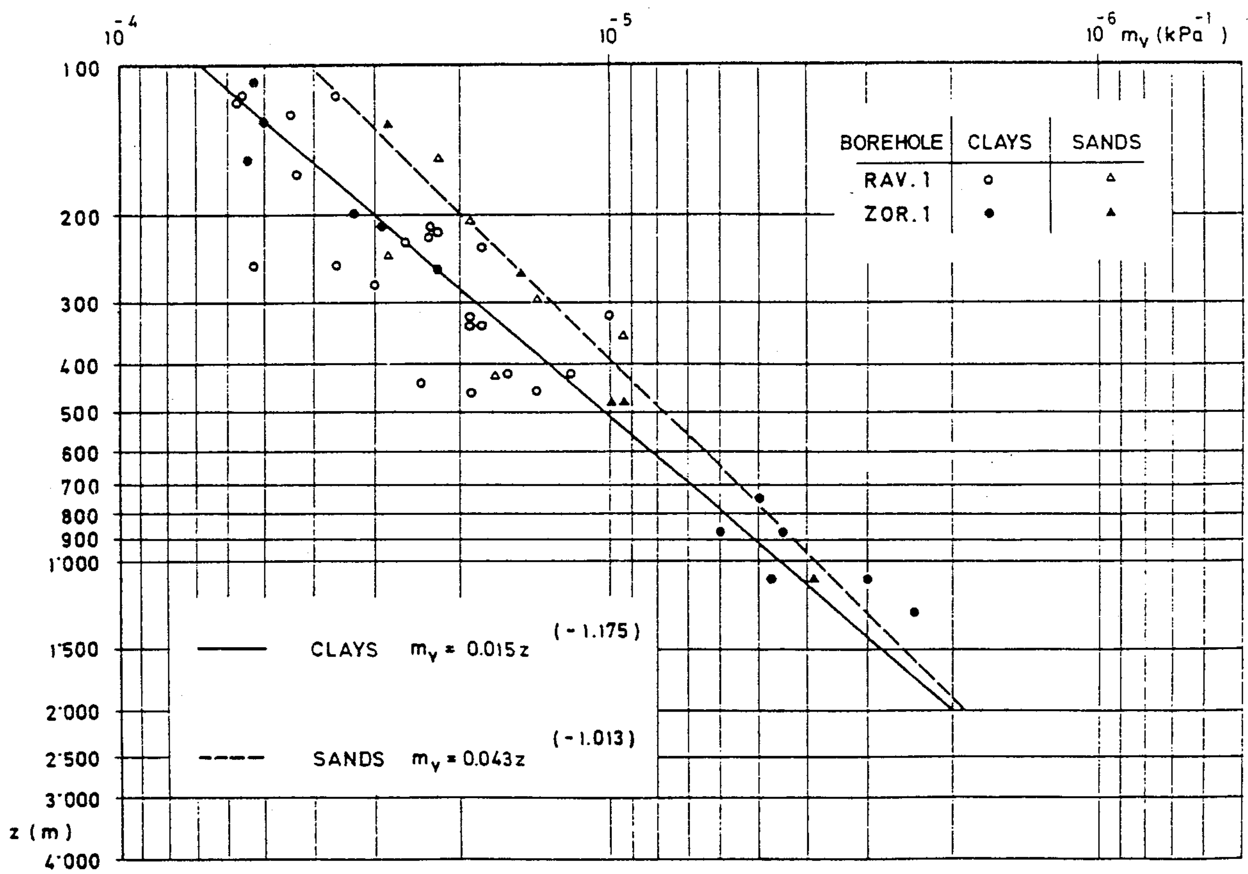
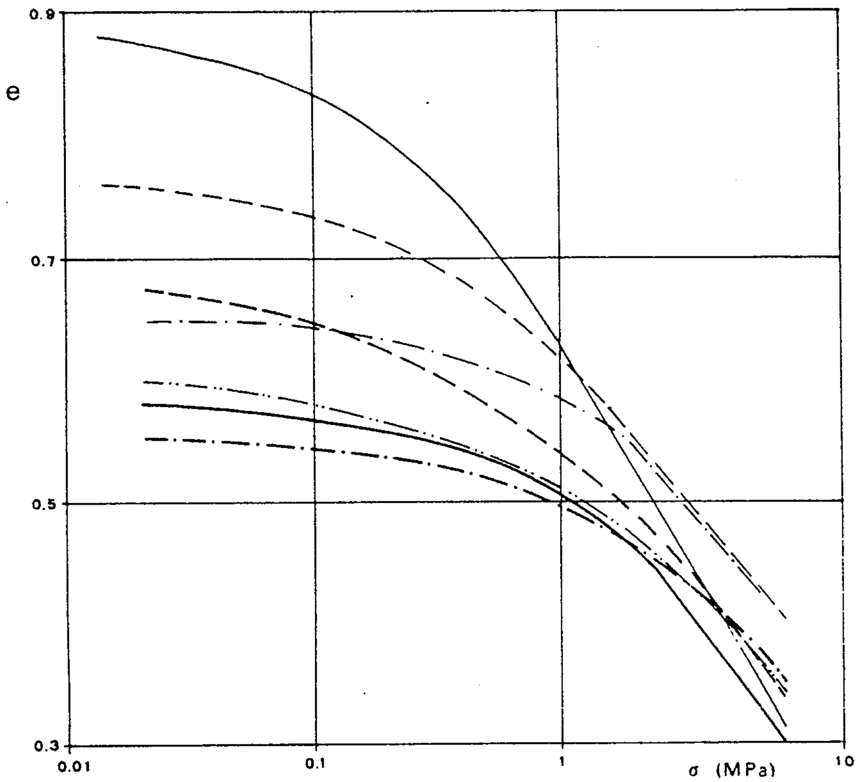


FiG. 7: Coefficient of volume change versus depth.



	depth	w_l	w_p	I_p
	73	52	27	25
	140	59	27	32
	218	54	22	32
	276	37	20	17
	325	41	23	18
	371	65	26	39
	477	35	22	13

Fig. 8: Selected oedometer test results.

6.CONCLUSIONS

This paper presents the case of the Ravenna area (Italy) which has been subjected to a troubling phenomenon of subsidence since 1950. To geological subsidence and to the effects of eustatism, the effects caused by human action, with the unchecked withdrawal of water from the subsoil, were added, especially in the 60's and 70's.

The results of the levellings carried out in the 70's and 80's are reported. They were compared with the situation in 1950. Both the most affected areas and increases and decreases of subsidence rates, in different periods of time, could be determined.

Then the problems connected with the performance of two deep boreholes (-500 and -1500 m) were reported and some considerations on the two types of samplers utilized were made.

The borehole log of Ravenna subsoil was schematically carried out. The compressibility characteristics of the soils examined, whether cohesive or granular, are less and less different with the increase of depth. The coefficient of permeability k determined on granular layers resulted to range between 10^{-7} and 10^{-6} m/s. The modesty of this value may be due to the high relative density of the sample.

The phenomenon of subsidence in Ravenna is not very important at the moment, because it settled around a rate of 5 mm/year.

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