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Recent soils of the Po River: Statistical analysis of geotechnical properties

Les terrains récents du Pô: Analyse statistique des propriétés géotechniques

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ABSTRACT: During a study on salt intrusion in the branches of the Po River, several boreholes were drilled over a relatively small area. Several samples of soil deposited in same sedimentary environment meant that an extensive series of laboratory data could be studied using a statistical approach. In particular, frequency distribution curves relative to 11 geotechnical properties and possible linear regressions between pairs of the above variables were investigated. Other properties observed were: high scatter of the data from means values, the general tendency of frequency distribution curves to fit Beta distribution curves, and a strong and statistically significant influence of the liquid limit on other geotechnical properties.

RESUME: Pour une étude de la remontée de la salinité dans les bras du fleuve Po ont été effectués de nombreux sondages sur une petite surface. Etant donné que l'on s'est trouvé en presence d'un grand nombre d'echantillons de terrain qui s'étaient déposé dans un meme milieu de sédimentation, on a pensé d'analyser, en utilisant la statistique, les résultats des expériences de laboratoire. On a examiné en particulier les courbes de distribution des fréquences des 11 propriétés géotechniques et les possibles regressions linéaires de ces propriétés entre les différents couples. On a pu observer une dispersion élevée des données par rapport aux valeurs moyennes, une tendance générale des courbes de distribution des fréquences à se disposer selon les courbes de distribution du type Béta, une forte influence significative du point de vue statistique de la limite de liquidité sur les autres propriétés géotechniques considérées.

1 INTRODUCTION

The most important river in Italy is the Po, 652 km long, whose hydrographic basin occupies an area of more than 70,000 sq. km or about two-thirds the surface area of Northern Italy. The mouth of the river is of the delta type and the delta itself, about 500 sq. km in area, has undergone complex geological and anthropic events.

In the geological reconstractions of the Po delta, eight littoral bars of successive age and ten old cuspate deltas have been recognized (Ciabatti, 1966). The latter formed when the single mouth advanced, gradually accompained by banking of sand in littoral bars, due to sea action, on both sides of the river. More recently, the further advance of the Po, with strong sedimentation along the river branches, no longer prevented by sea action, gave rise to two lobate deltas, of which the southern one is the more recent.

On historical times, man's actions and activities have most greatly influenced the morphology of the Po delta. In particular, the largest operation was the southward diversion of the northern branches of the river, carried out by the Republic of Venice in 1604 with the aim of preventing the Lagoon from silting up. The river responded by changing the style of its delta structures; in particular, it has been calculated that delta advance went

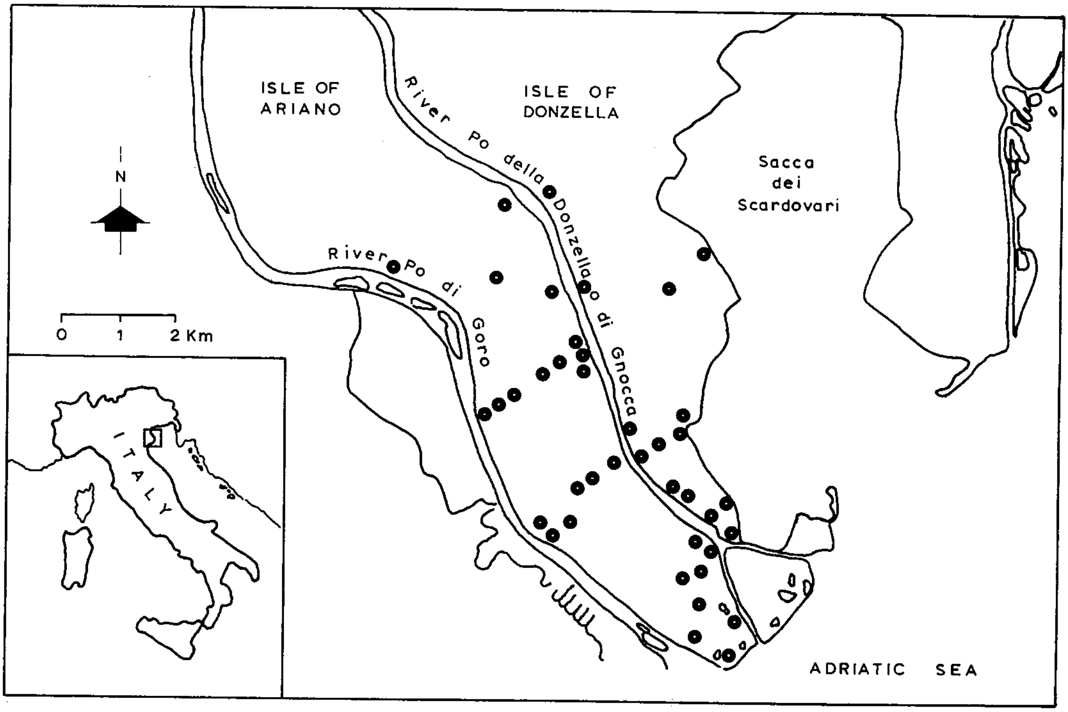

Fig. 1. Plan of the Po Delta and location of the boreholes.

from about 450 m/century to about 7 km/century. This speed of advance was arrested and the delta even began to retreat between 1950 and 1960, when methane-bearing waters were extracted, causing widespread subsidence over enourmous areas of the delta. The territory substantially entered a stationaty phase when the wells were closed down in the early 1960s.

The Po delta has recently been subject to salt intrusion through its branches, jeopardizing some of the crops in this area, one of the most fertile in the whole of Italy. In order to study the phenomenon of salt intrusion, a sample area (fig.1) was chosen in which to test the efficiency of a mobile barrage on one of the southern branches of the Po, at Po di Gnocca.

However, before examining the consequences of the barrage on groundwater regime, it was necessary to obtain detailed information on the characteristics of the superficial soils in the sample area. A total of 40 rotary drillings was thus carried out with continual sampling, over a surface area of about 32 sq. km. Average boring depth was 8 m. All samples were tested in the laboratory of the Istituto di Costruzioni Marittime e di Geotecnica of the University of Padova.

The results of many laboratory tests therefore exist on samples coming from a relatively restricted area. The examined soils are also of very recent origin; they were all deposited in the same sedimentary environment: the delta, i.e., a transitional environment between continental and strictly marine. All these facts suggest that the results of laboratory tests and the geotechnical characteristics found should be analyzed with statistical methods.

2 STATISTICAL ANALYSIS

Soil properties characterizing a specific geological deposit show a significant variability around their mean values, and

	COHESIVE SOILS							GRANULAR SOILS			
property X_i	W_l	W_p	I_p	W	G_s	c_u	C_c	d_{10}	d_{60}	C_U	C
units	(%)	(%)	(%)	(%)		(kPa)		(mm)	(mm)		
N	90	90	90	41	17	24	18	56	56	56	56
mean	47.6	30.8	16.8	41.8	2.76	25	.39	80E-3	15E-2	2.39	1.28
median	48	30.5	16	42	2.76	24	.37	81E-3	15E-2	2	1.20
mode	48	30	15	40	2.78	24	.34	.12	22E-2	1.4	1.10
variance	68	24	28	52	8E-4	12E+1	4E-3	2E-3	4E-3	1.4	.1
std.dev.	8.3	4.9	5.3	7.2	3E-2	10.8	7E-2	45E-3	6E-2	1.2	.3
var.coeff.	.17	.16	.32	.17	.01	.43	.17	.56	.42	.50	.25
minimum	29	21	6	28	2.71	10	.31	4E-3	3E-2	1.2	.8
maximum	73	48	34	55	2.80	46	.58	.18	.35	7.5	2.1
range	44	27	28	27	0.09	36	.27	.176	.32	6.3	1.3
skewness	.27	.64	.49	-.10	-.29	.58	1.89	.24	.41	2.19	1.08
kurtosis	.62	1.22	.35	-.78	-1.11	-.40	4.15	-.88	.28	6.03	.39
95% confid.	45.9	29.8	15.7	39.5	2.74	20.5	.35	68E-3	14E-2	2.1	1.2
interv.mean	49.4	31.8	17.9	44.0	2.77	29.5	.42	92E-3	17E-2	2.7	1.4

Tab. 1. Summary of Statistical Parameters for Different Soil Properties.

the degree and manner of this variability are always of concern in engineering design and evaluation of laboratory data. There is significant scatter in the measurement of soil properties. This is due to natural heterogeneities of soils and inconsistencies in testing procedures. A single-point value is usually chosen from variable results for deterministic analysis. Nowadays the trend is for a probabilistic approach. In order to apply the latter, it is essential to know the mean and dispersion magnitudes of pertinent soil properties. Statistical analysis of soil test data provides this information.

We had the opportunity to perform an extensive statistical study of geotechnical properties of several soil samples, obtained from a relatively small area where soils were deposited in similar environments. This study has consisted of measures of dispersion tendencies and departures from normal frequency distribution curves. Central tendencies were measured by the arithmetic mean, the median, i.e., corresponding to 50% of frequency, and the mode, i.e., occuring with the greatest frequency.

Dispersion tendencies were measured by standard deviation, variation coefficient and 95% confidence intervals for the mean. On a normal standardized distribution curve plus or minus 1.96 times the standard deviations account for 95% of measurements.

In order to study the frequency distribution of the experimental data, the following coefficients were considered:

1. Skewness is the degree of asymmetry or the measure of departure from the symmetry of a normal distribution. For perfectly symmetrical curves, skewness is equal to zero; it is positive or negative when the frequency distribution curve presents a longer tail to the right or left, respectively, of the mode.

2. Kurtosis represents a measure of the peakedness of the frequency distribution relative to a normal distribution. It is equal to zero for a normal distribution, and assumes a positive or negative values when the peak is higher or lower, respectively, than the normal distribution one.

Statistical analysis was carried out on 112 disturbed and undisturbed soil samples taken from forty boreholes drilled in the Islands of Ariano and Donzella in the Delta

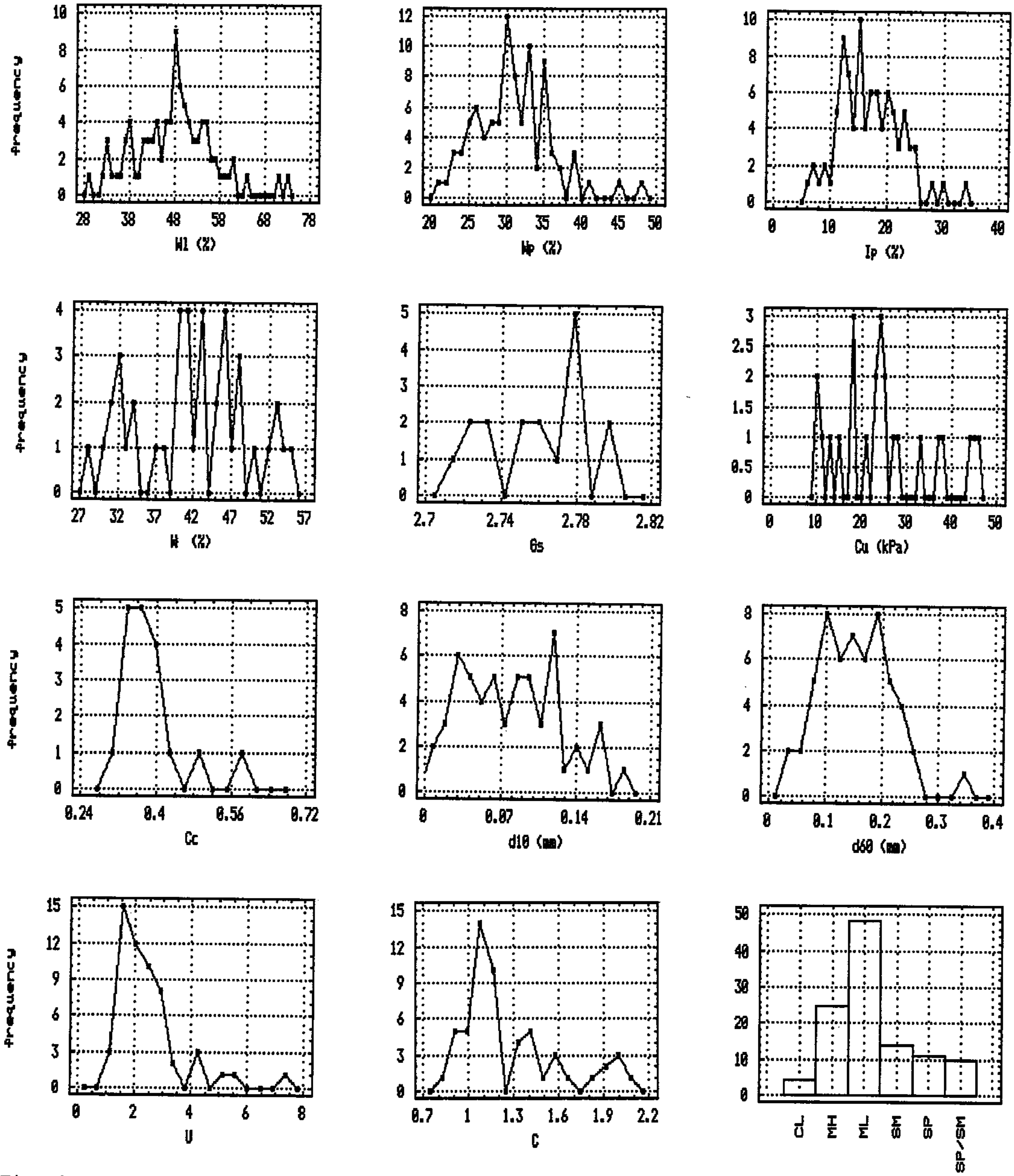

Fig. 2. Frequency distribution curves.

of the Po River.

The shallowest layers, to a depth of -10 m, do not show a planimetric continuity: this fact suggested that depth should be excluded from the variables considered in the linear regression analysis. It was observed that the nature of the investigated layers shows many similarities in both islands, with a greater presence of ML (or A-7-5) cohesive soils and of SP, SM (A-3, A-2-4) sandy and silty soils.

Statistical analysis was therefore performed considering all available soil samples as coming from a place instead of

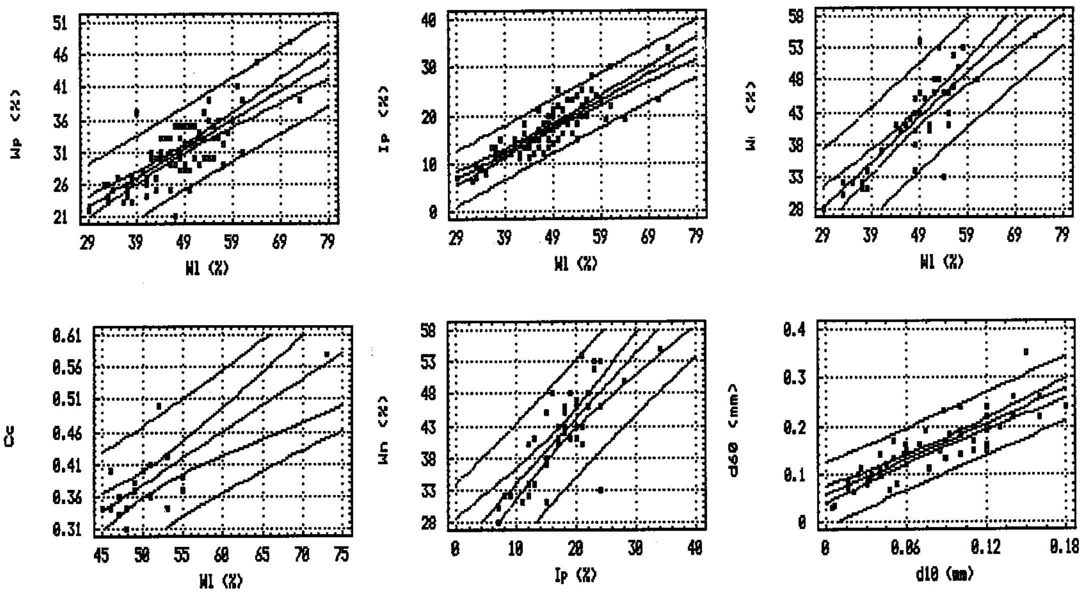

Fig. 3. Estimated regression lines with the confidence and prediction limits

from two smaller different sites.

The area was described, from a geotechnical point of view, by means of N_i observations of different soil properties X_i (i=1,...,11): liquid limit w_l, plastic limit w_p, plasticity index I_p, natural water content w, specific gravity of soil solids G_s, undrained shear strength c_u, and compression index C_c were considered for cohesive soils. Diameters d_{10} and d_{60}, uniformity coefficient C_U, and curvature coefficient C for granular soils. The frequency distribution of each variable X_i is unknown.

The computed statistical parameters (mean, median, mode, variance, standard deviation, variation coefficient, range, skewness, kurtosis, and 95% confidence interval for the mean) are summarized in Table 1.

The number of experimental observations ranged from a minimum of 17 for G_s to a maximum of 90 for w_l, w_p, I_p and w. All variables showed high values of variance and variation coefficient; in particular c_u, d_{10}, d_{60} and C_U showed the highest scatter from the mean. Only specific gravity G_s showed limited scatter, because the Po Delta clays have the same alluvial origin and a similar mineralogic composition.

Pearson's diagram was used in order to study the frequency distribution of each variable by means of skewness and kurtosis coefficients. Most of the frequency distributions showed a good fit with the Beta distribution curve, asymmetry to the righ,t and a high peaked curve.

Some possible relationships between pairs of different variables were investigated, asssuming a linear law between a dependent variable X_j and an independent one X_i of the following kind:

$$X_j = a + b\, X_i$$

where a is the intercept on the X_j axis, and b is the linear regression coefficient which represents the effect caused on X_j by a unitary variation of X_i.

	w_l	w_p	I_p	w	G_s	c_u	C_c
w_l	1	.446 .755 .57	.545 .848 .72	.698 .826 .68	2E-3* .401 .16	-.187* -.105 .01	8E-3 .787 .62
w_p	1.277 .755 .57	1	.365 .336 .11	1.143 .644 .42	2E-3* .171 .03	.215* .072 .01	7E-3* .337 .11
I_p	1.319 .848 .72	.309 .336 .11	1	1.017 .791 .63	2E-2* .397 .16	-.539* -.212 .05	.010 .779 .61
w	.978 .826 .68	.363 .644 .42	.615 .791 .63	1	1E-3* .173 .03	-1.086 -.566 .32	1E-3 .688 .47
G_s	91.03* .401 .17	18.63* .171 .03	72.39* .397 .16	33.45* .173 .03	1	4.76* .014 2E-4	.901* .383 .15
c_u	-.059* -.105 .01	.024* .072 .01	-.084* -.212 .05	-.295 -.566 .32	4E-5* .014 2E-4	1	2E-4* .053 .003
C_c	75.92 .787 .62	15.61* .337 .11	60.32 .779 .61	42.22 .688 .47	.163* .383 .15	14.71* .053 .003	1

Tab. 2. Regression, Linear Correlation and Determination Coefficients for pairs of cohesive soil properties.

Tabs. 2 and 3 show the estimations of linear regression, correlation and determination coefficients, for each pair of variables X_i (columns) and X_j, (rows).

Significativity analysis of the linear regression coefficient was carried out assuming a significant level of 0.05. The regression coefficients marked with an asterisk in Tabs. 2 and 3 indicate that the effect produced by X_i on X_j is not statistically significant (probability P greater than 0.05). In these cases, it is not possible absolutely to exclude that any relationship exists between the considered variables, but it means that a simple linear equation cannot represent such a relationship.

	d_{10}	d_{60}	C_U	C
d_{10}	1	1.232 .867 .75	-18.865 -.713 .51	-3.067 -.428 .18
d_{60}	.611 .867 .75	1	-9.706 -.521 .27	-.959* -.190 .04
C_U	-.027 -.713 .51	-.028 -.521 .27	1	.194 .717 .51
C	-.060 -.428 .18	-.038* -.190 .04	2.648 .717 .51	1

Tab. 3. Regression, Linear Correlation and Determination Coefficients for pairs of Granular Soil Properties.

In particular, it can be observed how specific gravity G_s never causes significant effects on the other variables. This may be due to the limited range of the G_s experimental values. Liquid limit w_l seems to be the most influential property: this fact, well-known in soil mechanics, was also founded in the statistical analysis.

Tabs. 2 and 3 show some cases of statistically significant regression coeffcents associated to not good correlation and determination coefficients; this fact may be explained by the high variability of the variables in question.

Fig. 3 shows estimated regression lines, characterized by determination coefficients greater than 0.57. The plots are scatterplots of the original values, and the estimated regression lines and two pairs of dotted lines represent 95% confidence and prediction limits. The size of the confidence interval, nearer the estimated regression line, than the prediction interval increase proportionally with departure from the mean.

3 CONCLUSIONS

Statistical analysis was performed considering 112 soil samples taken from 40 boreholes drilled in the delta of the Po River. The following considerations can be done:

1. All geotechnical properties showed high values of variance and variation coefficients.
2. Most of frequency distribution showed a good fit with the Beta distribution curve.
3. Liquid limit seems to be the most influencial property, while specific gravity of soil solids never causes significant effects.

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