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Field consolidation of thin layers of dredged material

Tassements de couches de faible épaisseur formés par des matériaux dragués

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SUMMARY - Preliminary results of a research programme on the geotechnical behaviour of thin layers of organic hydraulically deposited dredged material are reported and discussed. The paper focuses on the spatial variability of the properties of soils and on the singularities of the pattern of settlements. The layers present intricate,yet non-random, variations in geotechnical properties. The initial heterogeneities, mainly controlled by the flow regime of the slurry within the containment area, govern the progress of consolidation, in so far as they entail selective evaporation, desiccation and crack formation processes, which are strongly coupled. The related one-dimensional moving boundary problem might be solved by a step-by-step procedure, the most important single factor to be accounted for being the formation of desiccation cracks. Deterministic prediction of settlements of the layer appears, however, overwhelmingly difficult.

1 - INTRODUCTION

Fine-grained organic dredged materials are frequently deposited within diked disposal areas, in order to control unfavourable effects on the physical environment. The performance of the impoundment basins and of the containment structures are governed by sedimentation, seepage, consolidation, diffusion, evapotranspiration processes. The analysis of these is complicated by initial heterogeneities and by variations - in space and with time - of the properties of the material and of boundary conditions.

While classical consolidation models fail to describe adequately the behaviour of the layer, recent studies point to the feasibility of reliable predictions, provided the layer is homogeneous and that unidimensional deformation conditions apply (Salem & Krizek, 1976). When the layers are heterogeneous, the prediction of the progress of settlements still proves to be uncertain.

A research programme on the mechanical behaviour of thin layers of organic dredged materials, hydraulically deposited within confined basins was recently started in connection with dredging of the bottom of Pergusa Lake. The study is directed toward investigating the spatial variability of geotechnical properties of soils after deposition, the progress of settlement, the feasibility of modelling the actual consolidation process, the diffusion of slurry particles into the containment dikes. Concurrently, assessment of the effectiveness of probability-based subsoil exploration of deposits built-up by oriented processes is being investigated. Some of the data and observations as yet collected on the soil formation and on the field consolidation processes are outlined and discussed in the paper, that is primarily concerned with the identification of main factors which determine actual behaviour.

2 - ENVIRONMENT, FOUNDATION SOILS, CONTAINMENT STRUCTURES

Pergusa Lake, in Sicily, was once renowned for the reddening of its waters. Some years ago, it reached an eutrophic condition, associated - among other events - with the overgrowth of sea-weeds. The lake is fed by a small watershed; no stream flows into it; the outflow is prevented by a calcarenitic relief which develops round the basin. The volume of the lake is about 2 x 10^6 m^3.

Soils below lake bottom consist of recent organic sandy silts and of sands down to depths ranging from 10 to 15 m. Decay of sea-weeds adds more and more to the organic content of the upper layers. Recent soils are underlain by a clay formation which is conch-shaped at the top. The lake beach is formed by loose sands interbedded with soft silt lenses. The permeability coefficient of the sands ranges from 10^{-3} to 10^{-5} cm/sec. Among the measures taken to give the lake normal biological conditions, removal by dredging of a layer, 1 to 3 m thick, of organic sediments from the lake bottom was included. Land disposal of dredgings at considerable distances, though feasible, was disregarded on account of the limited volume of the lake, which might have turned dry in consequence of heavy water removal. It was, on the contrary, necessary to return, as soon as possible, into the lake the waters subtracted during dredging. For this purpose, six sedimentation and accumulation basins were built on the lake beach, fig. 1. The basins were enclosed by embankment dikes, formed with very soft calcarenitic rocks, that after compaction were almost completely reduced to a fine-medium sand. Seepage through the dikes and filtration was required for the intended functions of the basins.

The permeability coefficient of the uncontaminated material forming the dikes, as backfigured from field data, is about 3 x 10^{-4} cm/sec. Maximum height of dikes is 2.5 m. The basins were connected in series, three by three, at crest level, by small overflow weirs, fig. 1.

3 - SEDIMENT FORMATION

Dredged sediments were pumped in slurry form into basins, through an inlet pipe, 0.3 m diam. and 500 m long. At inlet head, the solid fraction, ranging from 3 to 6% by weight, was completely disgregated with the exception of some well rounded "boulders" formed by indurated hard sandy silt.

The discharge of slurry into the basins was carried out

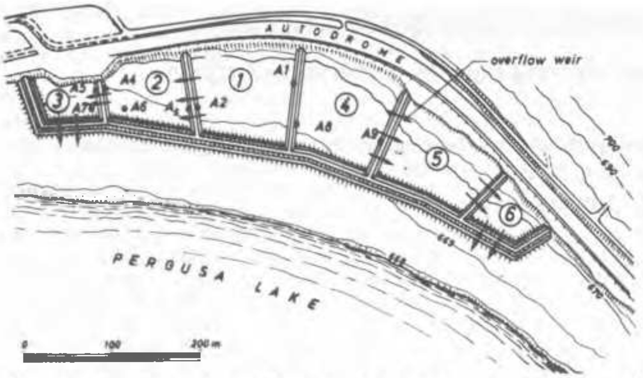

Fig. 1 - Plan of diked disposal area; A1, A2, .. settlement beacons.

discontinuosly, 5 days per week and 12 hours per working day. The discharge took place into a basin at a time, until the containment area was filled up to dikes crest level. The average slurry discharge rate was 350 m^3/h. The configuration of the upper surface of the layer being formed during filling in basins 1 and 2 was periodically surveyed. Collected data point out that the top surface of accumulated sediments is never horizontal, and that the rate of sediment formation varies markedly with space and time. Rates of layer thickening vary likewise. Monthly accretion rates range from 0.1 to 5.4 cm/day, yearly rates from 0.2 to 0.7 cm/day; their spatial distribution show no simple pattern, although it is not random. In fact, it depends upon the flow regime, which is, in turn, influenced by former configuration of the top of the layer. Streams departing from the discharge point were detected by observing the paths of small polystyrene balls and were found to be winding up and meandering within the basin. Higher accretion rates were distributed near the paths of the "streams". Flow velocities never exceeded 1 m/min.
The accretion rates could not have been predicted on the basis of results of "tube" sedimentation-consolidation tests carried out under one dimensional vertical seepage conditions. Results of such a test are shown in fig. 2. The tube, 2 m in diam. and 2 m high, was filled with slurry recovered at the inlet pipe head. Test duration was 175 days. Immediately after filling, sand-sized particles settled to the bottom; during next 30 minutes, flocculation and sedimentation took place. Curve B in fig. 2 shows that sediment formation was complete after 50 hours and selfweight and seepage induced consolidation started. After 200 h gas bubbles were observed; after 1000 h sea-weeds grew on the surface of the sediment. After 700 h from test beginning, consolidation did not progress, although the sand filter was not clogged, as confirmed by curva A in fig. 2 and by direct inspection at the end of the test. This standstill is probably due to gas generation, and to the high degrees of freedom of each particle within the particulate system. Due to the very high void ratio, the interaction of particles is so limited that intergranular stresses are vanishingly low and the effective stress state is not uniquely determined. This "indeterminacy" is confirmed by the experiments of Been and Sills (Been & Sills, 1981).

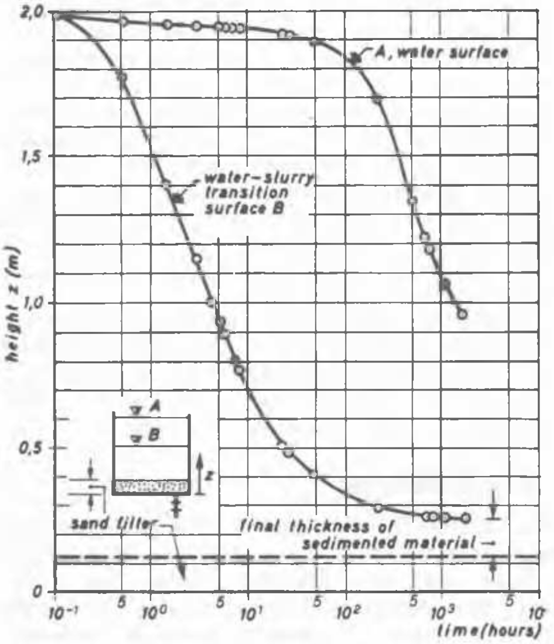

Fig. 2 - Results of tube sedimentation-consolidation test.

At the end of the test, the water content of the sedimented materials was found to vary linearly from 136% at bottom up to 466% at the top; corresponding void ratios ranged from 3.4 to 11.2.

Actual sediment formation within the basins was much more rapid, due to boundary conditions very different from those of the tube test, to the effect of drag forces associated with the movement of the slurry, to heterogeneities and to desiccation during interruptions of filling. To get an indication of the overall influence of the above processes - considering that selfweight and seepage induced effective stresses in the test cylinder were not less than in the field - it suffices to mention that 1.05 x 10^6 m^3 of slurry was discharged into basins 1 and 2 in the period between April 1980 and July 1981, and that the volume of accumulated sediments during the same time interval amounted to 30,178 m^3 whereas it would have been 70,000 m^3 should the results of the test apply.

4 - SPATIAL VARIABILITY IN GEOTECHNICAL PROPERTIES OF ACCUMULATED MATERIALS

Hydraulic deposition of sediments implies selective sorting of the particles in function of their grain-size and specific gravity, the rate of discharge, the flow velocities and the composition of the slurry. Once the slurry has been discharged in the basin, the coarser particles settle near and around the inlet zone, silt particles are carried farther away from the discharge point, the fines reach the dikes or the overflow weirs. The process, in reality, is not so paradigmatically regular, especially when the discharge rates and the flow velocities within the disposal area are low. Under such circumstances, "currents" and streams do not conform to fixed stable patterns. As a consequence, the distribution of geotechnical properties of dredged materials is not easily identifiable. However, it may be hardly assumed that the soil properties vary randomly, since the formation process, though irregular, is definitely oriented. Accordingly, geotechnical properties must show definite patterns. The operational definition of these for engineering purposes is, of course, related to the size of

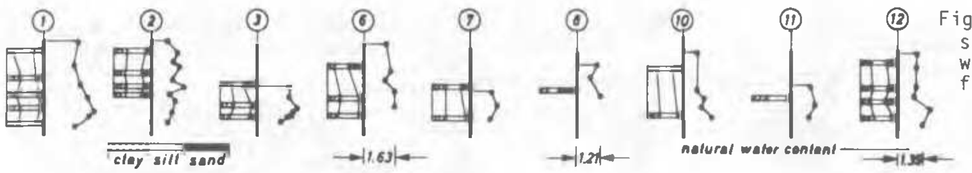

Fig. 3 - Variation of clay, silt and sand fractions, and water content within basin 1 (1982). Refer to fig. 6 for location of verticals.

the geotechnical system to be dealt with.

Available data, while not yet sufficient to precisely describe the macrostructural arrangement of the layers and the spatial distribution of geotechnical properties, do point to conspicous heterogeneities and to a marked influence of the deposition mode. Heterogeneities - original and induced by the consolidation process - are reflected by the peculiarities of the distribution of settlements. Some of available data are reported below.

Index properties

The range of **grain-size distribution** is rather large. Soil fractions vary as follows: sand 0 - 0.50; silt 0.18 - 0.57; clay 0.18 - 0.43. Clay, silt and sand fractions within basin 1 are shown in fig. 3. Particle-size distribution varies appreciably with depth, and from vertical to vertical. Sand fraction is larger in correspondence and near the discharge point, farther from this variations of granulometric composition along a single vertical are much less sharp. Apart from this general trend, differences between verticals located a few meters from each other are relevant. Direct inspection of excavation walls, in the central part of basin 1, put into evidence sand lenses and laminations that do not appear to be located at random nor equifrequently distributed.

Organic matter content (OMC), ranges from 0.1 to 0.7; maximum relative frequence corresponds to OMC values between 0.4 and 0.5. Distribution of OMC within basin 4 is shown in fig. 4.

Specific gravity range from 21 to 26 kN/m^3; lower values are associated with higher organic matter content. **Unit weight** of saturated material ranges from 11 to 14 kN/m^3.

Void ratio values depend on depth and on the time after filling completion. Typical values are 3.3 - 4.1 near the top, and 2.1 - 2.4 in the vicinity of the bottom. Since the range of specific gravity of solids is narrow and the degree of saturation is almost always 1, the distribution of void ratios is conformable to that of water content, shown in fig. 4.

Water content profiles are shown in figures 3 and 4. Water contents are very high, spatial variations being relevant. In general higher water contents are related to higher organic contents; however, no clear correlation is apparent probably because consolidation is still in progress and has reached different stages within the basin. The materials can be classified as organic silts of high compressibility. The **liquid limit** ranges from 0.48 to 0.93 the **plasticity index** from 0.10 to 0.24.

Table I - Typical data on compressibility of dredged material, from basin 1, sampled six months after completion of filling.

sample	W_n initial	e_o	γ_{sat} (KN/m^3)	γ_s (KN/m^3)	σ'_v (KN/m^2)	E' (KN/m^2)	C_c	C_a	C_v (cm^2/sec)
8g	1.03	2.62	12.0	21.6	58.8	324	075	0.013	-
11a	1.05	2.91	12.4	23.6	98.1	294	1.15	0.014	$2.5 \cdot 10^{-4}$
102b	1.38	3.45	13.1	24.5	73.6	608	1.04	0.006	$1.7 \cdot 10^{-5}$
103	1.82	4.18	12.4	22.6	78.5	324	1.60	0.007	$1.0 \cdot 10^{-6}$

Compressibility

Volume change behaviour under low applied stresses was investigated by means of oedometer tests on samples recovered, from basin 1, six months after filling completion. Each load increment was maintained about one month. Typical data are summarized in table I. It must be noted that e - log σ'_v curves are nearly linear.

Shear strength

Laboratory vane tests were performed on samples from basin 1; c_u values are overestimated due to compression of the material during sampling and range from 6.7 to 22.5 kN/m^2. A detailed in situ vane test programme has been recently initiated. Preliminary results confirm that c_u values are very low, except for the desiccated crust.

Penetration resistance

To uncover details of the constitution of the layers, and obtain a simple - yet effective - description of the spatial variability of mechanical characteristics, 26 penetration tests were carried out within basin 4, 22 months after completion of filling. A special, light, hand operated, penetrometer consisting essentially of a conical point of standard dimensions and shape (angle: 60°; area: 10 cm^2) and of a hammer dropping apparatus was used. The hammer weight is 102 kN; the height of fall was established in 10 cm, after preliminary investigations, which proved that a height of 20 cm would be ineffective for the detection of variations. Usual penetration tests would yield a "flattened" picture of the deposit.

Uncorrected results are shown in fig. 4. Penetration induced by a single blow of the hammer is reported, instead of the number of blows necessary to obtain a fixed length of penetration. The diagrams in fig. 4 clearly point out that:

- the variations along each vertical are relevant even when the layer is thin;
- the difference in penetration resistance is enormous within the basin; it is, moreover, very marked from one vertical to the adjacent, compare for example verticals S9 and S10, section b-b in fig. 4;
- the penetration logs accurately depict the pattern of consolidation progress at each location within the basin, and are in good agreement with the water content distribution;
- bottom and upper drainage appears to be more effective than drainage toward the containment dikes. In fact, penetration resistances are lower along S4, S1, S15, S14, S13, S21, S25, S11 and S26 than along inner verticals, irrespective of their distances from the containment structures;
- the penetration resistance distribution along each vertical strongly correlates to the presence of ridges and troughs on the upper surface of the layer:

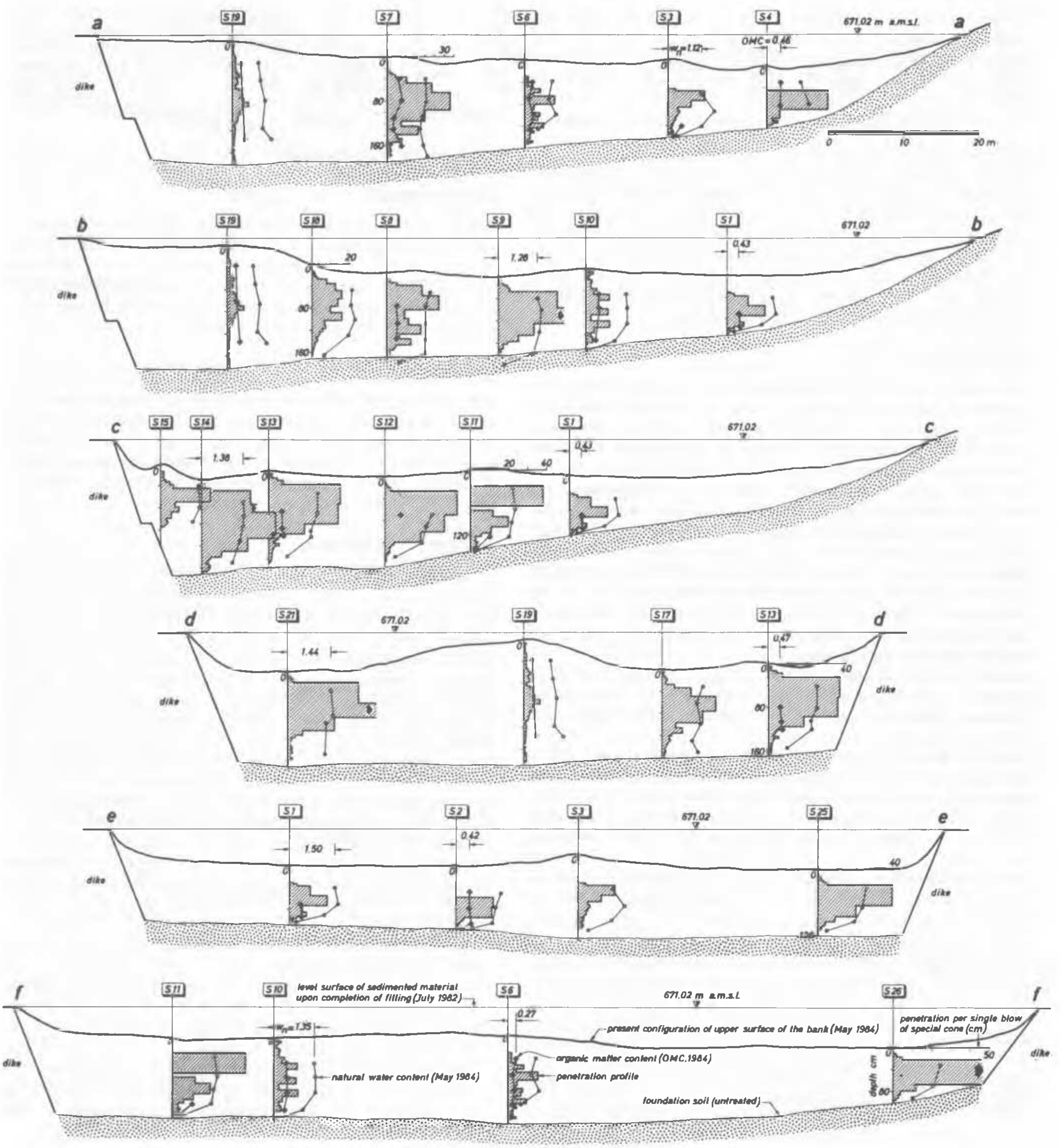

Fig. 4 - Penetration resistance within basin 4, 22 months after completion of filling. The arrow signals free penetration of the cone under the weight of the rod. Settlement profiles, water and organic contents are also shown.

resistance is higher in correspondence of the ridges and very low below the troughs, compare verticals S9 and S10. S10 corresponds to a ridge and S9, about 10 m apart, is below a trough; despite the fact that the surface settlements do not differ appreciably, that the initial thickness of the layer was the same, penetration resistances are strikingly different; in the central part along S9 the cone freely penetrated under the weight of the rod.

The recorded penetration resistances reflect the influence of many factors. It is, however, readily apparent from fig. 4 that effects depending upon deposition modalities

Table II - Ratio surface settlement/initial thickness of the layer in function of time elapsed from filling completion.
t: days; **t** = 0, June 1981. Initial thickness in cm: **A3**: 56; **A4**: 68; **A6**: 214; **A7** 135. For location of settlement beacons refer to fig. 1.

time t / beacon	25	38	45	126	540	1,082
A 3	0.11	0.20	0.25	0.39	–	–
A 4	0.13	–	0.26	0.48	–	–
A 6	0.06	0.07	0.09	0.16	0.44	0.53
A 7	0.14	0.22	0.33	0.36	–	–

play a remarkable - direct and indirect - role. This conclusion is supported by the pattern of settlement distribution of the upper surface of the layer.

5 - FIELD SETTLEMENTS

Settlements of the upper surface of the layers were measured, after the completion of filling, by means of settlement beacons, placed prior to the initiation of filling. Only six of the installed beacons survived long enough to allow assessment of the progress of settlement. Data are summarized in table II. Beacons A1 to A4 were placed on the shells of dikes; A6 and A7 rested on the bottom of basins at a distance of about 10 m from the bunds. Referring to the time interval 0 - 126 days, for which it is possible to compare the deformational behaviour, it may be noted that strains and strain rates are very large everywhere. Strains increase almost linearly with time near the dikes (beacons A1 - A4) in the first 45 days; then the strain rates slow down. The behaviour along A7 is similar to that of A1 - A4 in the first period; afterwards, the progress of settlement rapidly slows down. The settlement in A6 progresses almost linearly with time up to 540 days, with an average strain rate of 8 x 10^{-4} /day. The observed behaviour cannot be traced back solely to selfweight and seepage induced consolidation. On the contrary, it largely results from desiccation processes which start soon after completion of filling and are activated and sustained by high evaporation rates. In this regard, it should be reported that monthly average values of temperatures of the air range from 5.5° C (January) to 25° C (July) and that during daylight, in summer period, temperature is higher than 35° C. Desiccation entails the formation of a network of cracks, which in turn increase the rate of evaporation of soils. Cracks were observed to develop firstly near the dikes and in the spots where the upper part of the layer was formed by clayey silts. Cracks formed in a few days near the edges of the dikes and after about 20 days within the basins. Spacing, depth and opening of cracks decreased from the dikes toward the central part of basins. Where the sand fraction was relatively high, cracks either did not develop, or were spaced more than 1 m, whilst where silts prevailed the spacing was about 0.2 m, fig. 5. The presence of sand fractions from 15 to 20% considerably delayed the development of cracks. The depth of cracks is likewise conditioned. The progress of settlement with time is correlated to the above processes. Along vertical A1 - A4, cracks develop rapidly due to the vicinity of a draining boundary, and to limited thickness of layers. In A7 the influence of the dikes is not appreciable, but the development of cracks is rapid as the material predominantly consist of clayey silts: as a result the settlement rate is similar to that observed in A1 - A4 in the first period; at the onset of winter season the rate slows down.

Fig. 5 - Differential settlements in correspondence and in the vicinity of a ridge, basin 6. Crack spacing in the ridge is larger than in the adjacent zone.

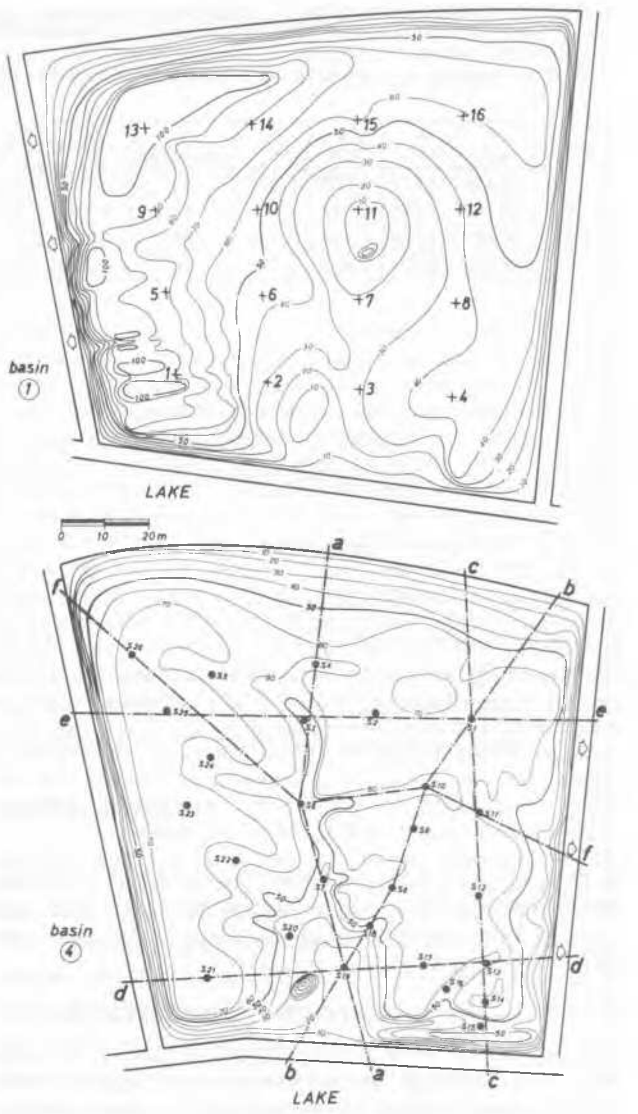

Fig. 6 - Basin 1 and 4 - Settlement contours of upper surface of the layer, May 1984 - Settlements in cm.

Table III - Volume reduction of accumulated material after completion of filling. **V**: initial volume; **A**: area of basin; Δ**V**: volume reduction up to May 1984; Δ**Vc**: volume of open cracks; w_m: average settlement over the basin.

basin	V (m^3)	A (m^2)	ΔV (m^3)	ΔV_c (m^3)	t (months)	$\frac{\Delta V}{V}$	W_m (m)
1	19,490	11,812	5,506	2,953	38	0.30	0.50
2	10,688	7,125	6.413	1,781	32	0.60	0.90
3	16,875	11,250	6.122	2,812	22	0.36	0.54
4	13,872	10,937	6.016	2,734	18	0.44	0.55

The behaviour recorded in A6 is, again, related to desiccation and to crack progress: cracks develop later and slowly due to material composition and to the presence of heterogeneities. The effects of these factors on the distribution of settlements within the single basin are strikingly evidenced by settlement profiles, fig. 4, and by settlement contours shown in fig. 6. In all basins, the upper surface of the layer is characterised by ridges and troughs; differential settlements over short distances are marked and sometimes sharp. Ridges and troughs are not randomly distributed; their location can be traced back to the flow pattern during deposition. This oriented process determines the initial spatial variability of the geotechnical system and controls the pattern of cracks and their propagation rate. Induced heterogeneities are associated with the above processes, which are coupled.

Data on volume reduction, after hydraulic deposition, are summarised in table III. Average settlement over each basin range from 0.5 to 0.9 m; the rate of volumetric strain varies from 0.019 to 0.024 per month.

Volume decrease, in reality, is larger due to the presence of open cracks. The horizontal area of these is estimated to be, in May 1984, about 50% of the basin area; their average depth amounts to about 0.5 m; associated volume decrease is reported in table III.

6 - FEASIBILITY OF MODELLING THE CONSOLIDATION PROCESS

The possibility of modelling the actual process is currently being explored. Two distinct problems may be envisaged. The first refers to one-dimensional consolidation of thin layered banks of soil; the second to the prediction of the behaviour of the deposit within each disposal area. The first, moving boundary, problem, may be solved by a step-by-step procedure, taking account of field indications. The major difficulty appears to be the interdependence of the many different involved processes. The most relevant factors - as yet overlooked by researcher in this field - to account for are the growth of cracks, their widening and deepening.

Steps toward modelization should include consideration of accretion history of the layer, consolidation induced by selfweight and by seepage forces, large strains, induced heterogeneities, evaporation, crack growth and propagation. It is also to note that the effects of capillarity actions, which would slow or hinder downward movement of water, may be greatly reduced at the onset of cracks. Each single aspect of the process may be handled by known theories (Gibson et al., 1967 and 1981; Gardner, 1961). The second problem, i.e. deterministic modelization of the process taking place within the single basin, is overwhelmingly difficult, if not impossible. Statistical and probabilistic treatment must be resorted to. Usual methods of analysis fail, however, to account for the non-random nature of spatial variations in physical and mechanical properties of the layer and for the selective pattern of desiccation and crack formation and may well lead to unsafe prediction of the expected range of differential settlements and distorsions.

7 - CONCLUDING REMARKS

Results of preliminary investigations point out that the hydraulic deposition of dredged materials within containment basins give rise to marked spatial variations in the physical and mechanical properties of accumulated soils. The initial state of the layer is marked by intricate but non-random heterogeneities, which are controlled to a great extent by the flow regime of slurry within the basin. Initial heterogeneities govern the progress of consolidation in so far as they entail selective evaporation, desiccation and crack formation. Induced heterogeneities further enhance differential settlements. Due mainly to desiccation and to the development of closely spaced cracks, which continously alter the upper boundary conditions, field progress of settlement is faster than could be predicted by classical consolidation models. It is suggested that modelling of local behaviour of the layer, under one-dimensional deformation conditions, is feasible provided coupled effects of the various involved processes be accounted for. In this regard growth and propagation of cracks appear to be the most important factors. Deterministic prediction of the settlements of the whole layer is reputed overwhelmingly complex. Statistical or probabilistic treatment of this latter problem requires to account for the non-random nature of the deposition and subsequent processes.

Although the field experiments referred to cannot be taken as representative of natural deposition and deformational processes, field observations give some insight into the origin of variabilities in the geotechnical properties of recent natural soil deposits.

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