PROPERTIES OF SALINE SOILS USED IN CONSTRUCTION

LES PROPRIETES DES SOLS SALINE ET LEURS UTILISATION DANS LES TRAVAUX PUBLICS

СВОЙСТВА ЗАСОЛЕННЫХ ГРУНТОВ, ИСПОЛЬЗУЕМЫХ В СТРОИТЕЛЬСТВЕ

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SUMMARY. The paper deals with the specific physicomechanical properties of saline soils in arid and semiarid regions (Sec.I) and of clayey water-saturated saline soils (Sec.II). Characteristics are given for five categories of saline soils classified according to their granulometric composition. Features of the deformation of saline soils with time upon wetting the soil base are discussed. Laws are set forth for the changes in the properties of saline soils in the leaching process depending on the quantitative content and qualitative composition of the salts. Proposals are made for standardizing and studying the properties of saline soils under field and laboratory conditions, and also for carrying out measures that ensure normal maintenance of structures erected on saline soils.

Saline soils possess certain specific properties which vary with time in the leaching process (leading to desalination) under the action of loads from structures, hydrologic, climatic and other factors prevalent in the utilization of hitherto vacant territories. Until recent years the properties of saline soils and problems arising in the erection of structures on such soils have not been sufficiently investigated. There are practically no standardized classification and generally accepted methods for determining the basic physicochemical and structural-mechanical characteristics of saline soils.

An analysis of the special literature, conducted research and experience gained in the maintenance of buildings and structures led to the proposal to divide saline soils into five categories depending on their granulometric composition: half-rock, coarse-fragmental, sandy, clayey soils (sandy loam and loam), and clays. These categories can be the basis for a further classification of saline soils with respect to the genesis, structure, quantitative content and qualitative composition of the salts (Bezruk, 1957).

This paper deals with the features of saline soils (containing readily and moderately soluble salts) in arid and semiarid regions in which the soils are air-dry in natural occurrence (Sec.I by Mikheev and Petrukhin) and of clayey water-saturated soils (Sec.II by Kronik).

I. A feature of territory formed of saline soils in hot and dry regions is the low natural ground-water level. In the construction and subsequent utilization of buildings and structures, the soil strata are intensively watered and the process of long-term filtration (seepage) of solutions begins through the soil. As a result, the salt complex is leached out, the physico-chemical and structural-mechanical properties of soils containing soluble salts are changed, with simultaneous development of suffosion deformation S_s which qualitatively differs from compaction settlement caused by loads in ordinary soils and subsidence due to the wetting of subsiding soils.

The main features and properties, determining the categories of saline soils used in industrial and civil construction in arid and semiarid regions,* are listed in Table I.

The properties of saline coarse-fragmental soils vary in wide ranges: unit weight γ = 1.7 to 2.1 g/cm^3; coefficient of permeability k = 0.04 to 10 m/day (sometimes from 30 to 70 m/day) and the modulus of linear deformation from E = 100 to 1000 kg/cm^2 (in the air-dry state). Experiments conducted on gruss-detritus saline soils (salinity $C < 5\%$) with test loads showed

* Since saline clays usually swell upon being watered, and have no suffosion settlement, this category of soils is not dealt with in Sec.I of this paper.

(Fig.1) that upon wetting the base under the test plates (at constant pressure $p = 5\ kg/cm^2$), an additional settlement S_w of the soil is observed. In test II the settlement curve is of a smooth nature; in tests III and IV, an abrupt change is observed. This is followed by undamped settlement of the plate. The amount of additional settlement S_w upon wetting is comparable with the total settlement S_n of air-dry soil in the interval p (pressure) from 0 to 5 kg/cm^2. Rapid settlement of the plate upon wetting the soil occurs, evidently, as a result of the dissolution of salts at the points of contact of the fragments, softening of the argillaceous cement, and subsidence of the filler. Slow, prolonged settlement is due, mainly, to the leaching out of the salts and creep of the filler. The wetting of the soil in the base under the testing plates continued for two weeks. Settlement was not stabilized during this time. Observations of structures erected on such soils, carried out for many years, showed that within 0.5 to 1.5 years after the ground-water level rises, a process of intensive leaching is developed with the removal of gypsum and considerable nonuniform settlement of the building occurs (Mikheev and Sinelshchikov, 1971). Of great significance in this case is the nonuniform distribution of the salts along the depth and area of the site.

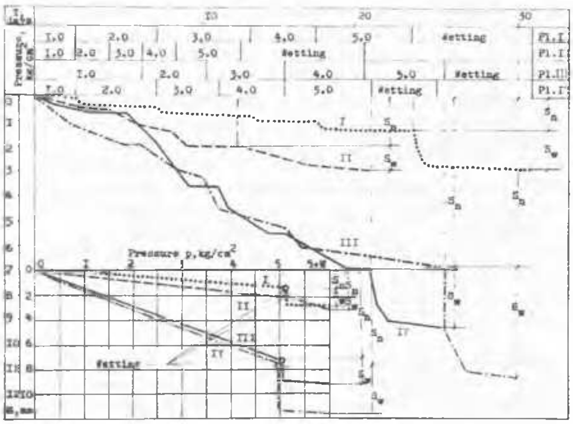

Fig.1.
Results of static load tests on coarse-fragmental and sandy saline soils. Deformation vs time curves (above) and pressure vs deformation curves (below). I - sand, plate area F = 600 cm^2. II - coarse-fragmental soil, F = 600 cm^2; III and IV - coarse-fragmental soil, F = 5000 cm^2.

The physicomechanical properties of saline sandy soils vary in wide ranges:

$\gamma = 1.5$ to 2.2 g/cm^2, e = 0.45 to 0.9 and k = 0.05 to 10 m/day. The strength of sands is high in their natural state: the angle of internal friction $\varphi > 30^\circ$ (usually 35° to 40°), and the angle of repose $\beta = 33^\circ$ to 40°. The modulus of linear deformation E varies from 400-500 kg/cm^2 to 1200-1500 kg/cm^2. When wetted, the strength and deformative properties of saline sands are sharply changed. The reduction in φ reaches 25%, that in β reaches 30% and E is reduced by 50 to 67%, and sometimes by 75 to 80%.

Presented in Fig. 1 is a characteristic curve (I) of the results of tests conducted on saline weakly cemented dust-like sand ($C \cong 1\%$). In the air-dry state, the sand is only slightly compressible (E = 600 kg/cm^2). After wetting this sand for one day, sharply defined settlement ("subsidence") of the plate occurs. The values S_w frequently exceeds S_n in the interval of p from 0 to 5 kg/cm^2. Consolidation (laterally confined compression) tests show that the quantity S_s for saline sands may also be equal to and sometimes exceed the amount of "subsidence".

Commonly, intensive "subsidence" in saline sanes occurs within the limits of the acting pressures 3 to 5 kg/cm^2 and ends during one day (24 hours). The amount of the relative "subsidency" reaches 0.04 or 0.05. A characteristic features of "subsiding" sands are their salinity, surplus porosity, and the presence of a considerable amount of dust-like particles. In many cases (especially at $p < 2$ or 3 kg/cm^2) no "subsidence" occurs, and long-term suffosion settlement is observed. Suffosion settlement of saline sands occurs at $C > 0.5\%$ and may reach substantial values at $C > 1$ or 2%.

Field and laboratory investigations of saline clayey soils established (Kirilov and Frolov, 1963; Rubenstein, 1960) that suffosion settlement S_s occurs in both subsiding and nonsubsiding loams and sandy loams. The amount of suffosion settlement may reach 6 or 8% in loess soils and 20% or more in ordinary high gypsum-content loams and sandy loams.

The classifications of saline soils, existing at the present time and based on the quantitative content of salts, require refinement with respect to the influence of the salt complex on the behaviour of the soils in the bases of industrial and civil structures. The lower limit of salt content in these classifications is taken from 0.3 to 0.5%. However, investigations (Lomize, 1961) show that suffosion settlement is observed in loessial soils beginning with a content of readily soluble salts equal to 0,2% or of gypsum equal to 1%. On the other hand, in nonsubsiding loams and sandy loams, suffosion settlement may occur when the con-

Table I

Saline soils of arid and semiarid regions

Category	Name	Criterion for classification as saline soil (salinity C,%)	Natural salinity, %: Readily soluble salts	Natural salinity, %: Gypsum	Genesis	Structural features	Characteristics of the granulometric composition	Form of salts in soil
1.	Half-rock soil	>2	Negligible	From 1-2 to 25-30 and even more	Bedrock	Fissured, porous	-	Dispersed, grains, aggregates, fragments, veins and intercalations
2.	Coarse-fragmental soil	>2 in the skeleton or >5 salts in the filler (for a filler content <30%)	up to 3 - 4	Up to 10; less frequently 10 to 20, but sometimes 30 or more	Proluvial, talus material, eluvial, mixed types (proluvial-talus, etc.)	Uncemented, weakly cemented (cement: gypsum, carbonate, argillaceous)	Gruss-detritus; sandy-loam filler up to 25-30% less frequently 40-50%	Dispersed crystallic, lenticular, interbeds
3.	Sandy soils	>0.5	From 0.2-0.3 to 3-4, less frequently to 8-10	From 0.2-0.3 to 2-3	Eolian, talus material, proluvial, marine, old-alluvial, mixed types (eolian-talus, etc.)	Uncemented, weakly cemented (cement: carbonate, saline, argillaceous)	From dust-like to gravelly	Crystallic, dispers-shells of particles
4.	Sandy loam and loam — Loessial	>0.2 readily soluble or >1 gypsum (at n=40%)	From 0.2-0.3 to 2-3, less frequently to 4-5		Eolian, aqueous deposits, activity of weathering and soil formation processes	Coagulation-crystallization structure	From dust-like sands to loessial clay; predominance of dust-like particles	Crystallic
	non-loessial (ordinary)	>5	From 0.2-0.3 to 1-2, sometimes up to 8.0-10.0	Up to 20-40, sometimes over 40	Talus material, proluvial, eluvial, marine, mixed types.	Crystallization structure	I_p from 1 to 17	Crystallic

tent of water-soluble salts* reaches >5%.

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* Of great influence on the physicomechanical properties of soils (especially with the salt leached out) is the presence of calcium carbonate in the content of the salt complex. This problem requires additional investigation and is not dealt with here.

When subsiding clayey soils are used for the bases (foundation beds), measures are usually resorted to that practically exclude the possibility that suffosion settlement may develop. In this connection, attention should be paid mainly to a study of nonsubsiding saline loams and sandy loams. In their natural occurrence, these soils are frequently cemented together so that they are as strong as half-rock soils. Consolidation (confined compression) tests of specimens wetted for 1 or 2 days yield results which do not practically differ from those of tests in the air-dry state. In experiments with the specimens subjected to long-term percolation, suffosion settlement develops (at $C > 7$ to 10%) and the strength characteristics are reduced.

II. The properties of saline water-saturated clayey soils, found outside of regions with an arid climate, are due both to the physicochemical nature of the interaction of the salts with the clayey particles, and to the genesis, mineral composition, the kind and ratio of the salt ions contained in the soil, the composition of the exchange complex and other features. With respect to their salinity, clayey soils can be classified in accordance with Table II.

Upon low concentrations of the pore solution ($C_{ps} \leqslant 0.05$ g/cm^3) a coagulation of clayey particles is observed in soils (Fig.2a) with a dispersion of sandy particles and a simultaneous accumulation of dust fractions. Dispersion, however, exceeds aggregation, especially if NaCl predominates in the pore solution. At this, the strength and plastic limit of the soil are increased and the value of k is reduced (Figs.2b and 3). At C_{ps} near to normal concentration, the disperse structure acquires maximum strength (Fig.3).

This concentration has been called the aggregation threshold (or dispersion limit) C_a for clayey particles. Any increase in C_{ps} leads to the predominance of coagulation processes, and the coagulated clayey and colloidal particles form the primary microaggregates, which, upon a further increase in concentration, are united into macroaggregates. In the range of medium concentrations (C_{ps} = 0.05 to 0.25 g/cm^3) a dynamic equilibrium is observed between the processes of coagulation and dispersion in the soil. At high concentration of the pore solution ($C_{ps} > 0.25$ g/cm^3), when a state of complete saturation is reached for certain kinds of salts, an intensive aggregation of the soil particles is observed. This leads to a considerable reduction in the plastic limits (Fig.2b) and strength (Fig.3). In addition, the adsorptive and water-absorbing capacities are increased, as well as the compressibility. In the process of leaching out the salts, the coefficient of permeability of clayey soils (with a predominance of the chloride type of salination and monovalent cations) is reduced to 1/700 of its previous value for the medium- and low-density soils being investigated, down to complete cessation of percolation in overcompacted clayey soils. Upon percolation in highly or excessively saline soils, containing salts with multivalent cations, a certain increase in k may be observed after leaching.

Table II

Saline clayey soils

No.	Degree of salinity	Salinity C,%	Form of salts in soil: Readily soluble	Form of salts in soil: Moderately soluble	Predominent kind of soil structure
1.	Weakly saline	0.25 to 0.50	In the pore solution		Dispersion and coagulation
2.	Moderataly saline	0.5 to 2	In pore solution	In pore solution and crystalline form	Coagulated and coagulated-condensed
3.	Highly saline	2 to 5	In saturated pore solution and in crystalline form		Coagulated-condensed and crystallization
4.	Excessively saline	>5	In saturated pore solution and in crystalline form	In saturated pore solution, crystalline form, aggregates and salt layers	Crystallization and coagulation-crystallization.

It has been shown to be expedient to take the following indices as the principal physical characteristics of saline soils (Kronik, 1970; Tsytovich, et al, 1968): γ_{sal} - unit weight of the soil, G_{sal} - specific gravity of the solid particles, γ_c - unit weight of the crystalline salt, w_{sal} - water content by weight, C - salinity, W_{nv} - moisture content, corresponding to the nondissolving volume of pore (ground) moisture, and p - weight content of coarse-fragmental particles (when there are over 10%). If it is feasible to determine the concentration C_{ps} of the pore solution without making a chemical analysis of the salt (for example, by means of a salinometer), this may serve as the basic characteristic of the salt content.

A change in the water content leads to a corresponding change in the concentration of the pore solution and in the ratio of the free pore solution to the nondissolving volume of pore moisture. This predetermines the processes described above of micro-structurization in clayey and the formation of coagulative structures (Rebinder, 1956). An increase in soil density accelerates the formation of coagulative and crystallization structures. In a density range, 0.98 to 1.03 of the maximum standard density, intensive formation of coagulated-condensed and partly cementation or crystallization structures begins.

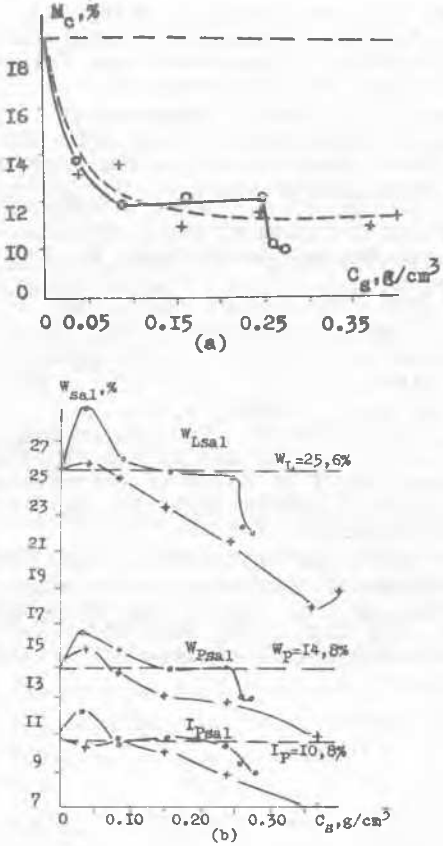

Fig.2.
Dependence of the clayey particle content M_c(a) and plasticity indices w_L, w_P and I_P (b) on the concentration C_s of solutions of NaCl and $CaCl_2$ introduced into loamy soil.

This leads to a sharp growth in strength of the saline soils upon further compaction. For this reason, overcompaction of saline clayey soils over 1.03 of the maximum standard density is one of the methods of strengthening them.

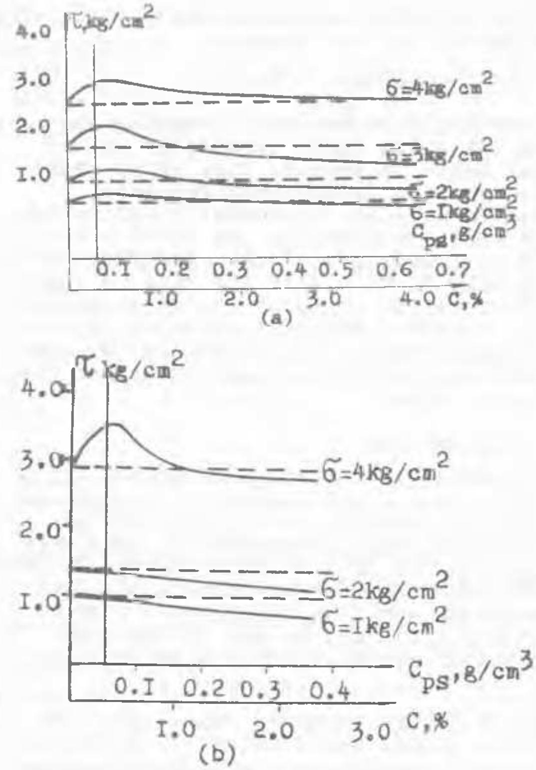

Fig.3.
Dependence of the shear strength of saline loam on the concentration C_{ps} of the pore solution and the salinity C.
a - sodium chloride salination
b - calcium chloride salination.

The character and the rate of desalination, or leaching, is determined by three basic facotrs: percolation leaching, diffusive desalination and desalination by the action of climatic factors - under the influence of a temperature change in the soils and, especially, upon multiple freezing and thawing. For practically complete desalination of saline soils it is necessary to percolate through the soil an amount of water at least 2 to 4 volumes of the pore solution (Verigin and Oradovskaya, 1960; Kronik, 1970). The time t_d required for desalination of a layer of soil of a thickness l upon one-dimensional percolation with a gradient i and coefficient of permeability k can be determined by the following proposed formula

$$t_d = \frac{0.02\,\gamma_{ssal}(w_{sal} - w_{nv})^l}{\gamma_w\ i\ k} \qquad (1)$$

where γ_{ssal} is the unit weight of solid particles of the saline soil.
For dense clayey soils the main process providing for desalination is the diffusive removal of salts. The actual cross-section of the diffusion flow characterizes the

diffusion porosity n_d which can be determined approximately by the formula

$$n_d = \gamma_{ssal}(w_{sal} - w_{nv}) \quad (2)$$

Salt removal from seasonal freezing and thawing of soils takes place only in the thawing cycle. A thawing time of at least one or two days is required for this process to develop. Intensive desalination of the soils proceeds in the first 4 or 5 cycles of freezing and thawing. After 16 cycles only 20 to 27% of the salt is carried out of saline soils of medium density; and 37 to 42% of the salt after 40 cycles in overcompacted soils. In the latter case, the salt removed in the last 15 cycles does not exceed 10%.

III. Conclusions.

1. The specific properties of saline soils should be taken into account in geological engineering surveys, and in the design, construction and maintenance of buildings and structures. Saline soils should be characterized, not only by their qualitative composition and quantitative content of water-soluble salts, but by the distribution of the salts in the stratum as well.

2. The following measures can be applied to ensure normal maintenance of buildings and structures: devices to prevent wetting of the base (foundation bed); increased rigidity and strength of such buildings and structures; use of designs with low susceptibility to settlement; the application of end-, or point-, bearing piles; overcompacting of saline soils above the maximum standard density; etc.

3. Subsequent research on the physicomechanical properties of saline soils should be concerned with experimental work under field conditions to measure the deformation of the base under test plates upon long-term percolation and laboratory laterally confined compression (consolidation) and percolation tests of saline soils. The minimum length of time for conducting the tests with continuous percolation is 4 or 5 days. Complete information on the character of deformation of saline soils in erecting important structures on high-salinity soils (tentatively 3 to 4% for coarse-fragmental, 1 to 2% for sandy and 7 to 10% for ordinary sandy loam and loamy soils) can be obtained after a more prolonged wetting of the soil base (at least 3 or 4 months) up to practical stabilization of the settlement.

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