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HYDROTECHNICAL STRUCTURES ON LOESSIAL COLLAPSIBLE SOILS

CONSTRUCTIONS HYDROTECHNIQUES SUR SOLS LOESSIQUES SENSIBLES A L'HUMECTATION

ГИДРОТЕХНИЧЕСКИЕ СООРУЖЕНИЯ НА ЛЕССОВЫХ ПРОСАДОЧНЫХ ГРУНТАХ

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SYNOPSIS. A great number of various hydrotechnical structures erected in Romania during the last years on loessial soils, collapsible or not under their own weight, demonstrated that a complete dismissal of collapsing subsidences is difficult to obtain and involves special measures concerning connection between the motionless and the adjacent settling parts of the structures. The solutions involving structure adaptability to differential subsidences and reduction of water accessibility below foundations proved to be rational and advantageous. Water access was hindered by placing the main sources at a certain distance away from the structure and connecting them by steel pipe lines provided with flexible or hinged terminal joints; by lowering the subsidence progress velocity towards the structure through appropriate waterproof lining and so on. The first one or two years of operation were included in the construction period. Simple, quick and non-expensive remedial measures were sufficient for restoring the few damages, without serious consequences, occurred during structure operation. No soil collapsing phenomena developed on water distribution non-permeable networks (elevated flumes or buried pipes). Theoretical and experimental research enlightened various aspects of the collapsing subsidence mechanism.

1. INTRODUCTION

Loessial collapsible soils (LCS) cover about 11,4 % of Romanian territory. Thus founding on such soils represents a major and difficult problem for Romanian civil engineers. LCS classification is based on the additional settlement i_{mp} (cm/m) of oedometer samples when moistened under pressure p. For Romanian LCS i_{mp} gets up to 10-12 cm/m for p = 2...3 kgf/cm^2. The total collapsible potential of a soil natural deposit is conventionally characterized by the factor

$$I_{mg} = \sum_{1}^{n} i_{mgj} \cdot h_j$$

where h_j = thickness of the component layers; i_{mgj} = oedometric additional settlement when moistening a sample from the "j" layer under corresponding overburden.

For about 51,5 % of the Romanian territory covered by LCS $I_{mg} \leq 5$ cm ; for other 37 % I_{mg} = 5...40 cm ; the remaining 11,5 % overpass I_{mg} = 40 cm and get up to I_{mg} = 150... 200 cm. LCS deposits thickness decreases and clay content grows up from valley slopes to interfluvial plateaux. Their maximum thickness reaches 50 m. LCS deposits are frequently underlain by impervious loam or clay formations, but also fine sands, gravels or calcareous fissured bedrocks may be encountered. Studies performed by the Bucharest Institute of Civil Engineering pointed out to a representative correlation between LCS sorptional index pF and climatic index I (proposed by Thornthwaite) and their distribution over the Romanian territory (Andrei, 1971a). There is a good correspondence between arid regions (negative climatic index) and LCS occurrence; moreover, higher i_{mp} values correspond to more arid zones. The correlation between climatic factors and loess-water interaction demonstrates the validity of the conception of loess as an underconsolidated soil introduced by Prof. Denisov (1953).

The arid or semi-arid climatic conditions result in a loose, macroporous structure of loessial aeolian deposits. The low moisture content induces a high contact friction between silt particles, hindering initial consolidation, and also a time increasing interparticle cementation due to clay matrix, salt recrystallization and silica gel hardening (Andrei et al., 1963). The high soil suction values in arid zones (H = 200...6,000 cm water head) contributes to maintain an important interparticle friction and thus a loose but strong structure of loessial formation (Andrei, 1971b).

All above-mentioned hardening factors diminish under the influence of increasing water content. Water absorbtion and structural

breakdown get a remarkable intensity in very dry loessial soils: air tappered bubbles, violently expelled by water intrusion, provoke destroying microblasting, stimulated by the wide variety in pore size.

A general account of difficult foundation problems induced by large area and sensitivity to moistening of loessial soils on Romanian territory has been presented to the VIIth ICSMFE (Botea et al., 1969). Thus only hydrotechnical and especially reclamation structures on LCS are related herein.

In the last 4 or 5 years several hundreds of thousands hectares of irrigated land went in operation on LCS (I_{mg} up to 200 cm) including very large hydraulic systems (total area reaching tens of thousands ha, specific reclaimed discharges 0.5...0.8 l/sec,ha, large supply canals up to 75 m^3/sec). In spite of short construction terms (2...3 years) and difficult soil conditions, operation develops normally. No essential difficulties induced by soil collapsivity were encountered.

Recent literature references from all over the world emphasize the acuity of peculiar problems of hydrotechnical construction on collapsible soils (e.g. VSN 4 - 66; Kirillov et al., 1969; Darmograi, 1969; Gibbs and Bara, 1967; Minkov, 1969). Therefore a short survey of Romanian experience in this field of interest was considered seasonable.

2. DESIGN AND BUILDING SOLUTIONS

2.1. Water supply networks

More than 1,000 km of open water supply canals are presently in operation for irrigation purposes on LCS. There are mainly cut-off canals; embankment canals were provided only on collapsible layers having a thickness less than 15 m. Generally 1 : 1.5 slopes werw adopted, with an intermediate bench at the maximum water level when cut-off depth was more than 5...6 m.

Some statements regarding open canals on LCS in Romania may be made (fig. 1) :

- when I_{mg} = 5...10 cm (collapsible layer thickness H less than 7...8 m), no surface deformation occurred ;
- negligible settlements occur when I_{mg} rises towards 30 cm (H = 8...12 m). Longitudinal cracks and subsidences of 10...20 cm develop when I_{mg} reaches 40...50 cm (H = 12...15 m).
- major subsidence phenomena correspond to higher values of I_{mg} and H (fig. 2). Successive elliptical contours of large cracks develop (the major axis, directed along the canal, reaches 200...300 m ; the minor axis rises to 60...80 m, i.e. 20...30 m of each side out of canal banks. Maximum

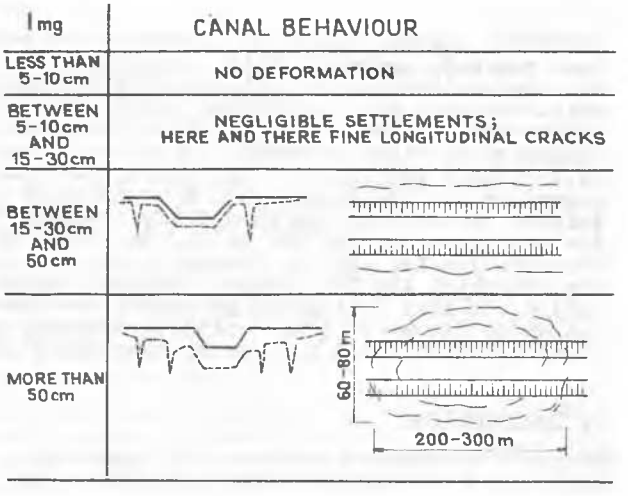

Fig. 1.

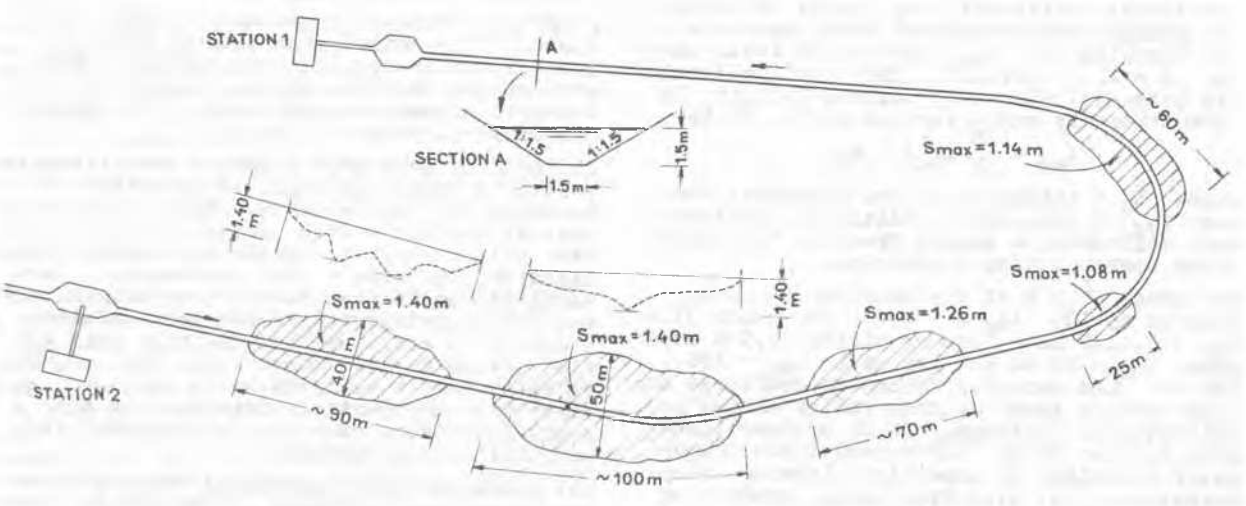

Fig. 2.

settlement in the center of affected zone gets up to 150... 200 cm. Subsidence and cracking development is relatively fast and similar to a chain reaction. During a period of 1...6 months of continuous flooding 80...90 % of final subsidences are already developed (about 50 % in the first month) The first 3...4 weeks of intensive watering are sufficient to reveal the probable intensity of subsidence phenomena. One irrigation season is generally sufficient for the complete development of such phenomena, when final settlement do not overpasses 100 cm ; two seasons are necessary when settlements are larger than 100 cm.

- the comparison between the forecast according to previous investigations and actual behaviour of open canals revealed the efficiency of initial division of the territory into zones of different sensitivity to moistening (collapsivity). Small diameter borings for collecting only identification and moisture content samples, located at 300...500 m apart along the canal axis (including points of declivity change) allowed a significant evidence of general soil collapsivity variation. Special field investigations (shafts or borings with devices allowing undisturbed sampling in loessial soils) at a frequency of one to every 4,000...5,000 ha (in a given geological unit) supplied the needed information on the order of magnitude of loess subsidence (i_{mp} and I_{mg} values).

canal lining was generally postponed until after 2...4 years of operation, in order to avoid breakdown due to subsidence and according to the much larger disponibility in

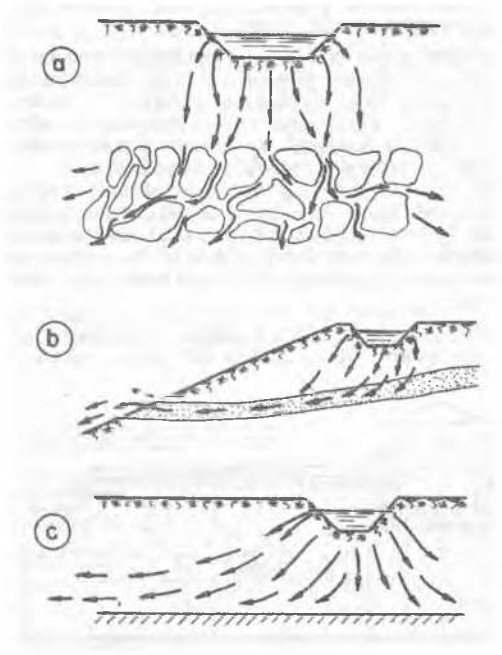

Fig. 3.

earth moving than in canal lining equipment. During the first 2...3 years of operation, infiltration losses resulted in about 2...3 m local water table rise, especially along natural collecting and evacuating underground waterways; no significant damages concerning topsoil were recorded so far (the affected area was less than 0.5-1.0 % of the total irrigated territory).

- some peculiar unfavourable conditions were revealed concerning detrimental influence of infiltration losses. Seepage through a thin loess layer (of several metres maximum thickness) underlain by fissured and cavernous limestone directed the infiltered water from a large canal towards a depressional zone some hundred metres aside (fig. 3 a). Accumulation of water infiltrated from an open canal in a lateral depression was favoured by a sand lense situated at a small depth below canal bottom (fig. 3 b). The occurrence in the loess deposit of a horizontal shallow impervious layer (e.g. buried topsoil) induced a quickly extending water table rising under the canal (fig.3c).

- subsidences up to 40...50cm did not disturb longitudinal earthfills bording the canals (maximum height 6...7m; inner slope 1:1.5, outer slope 1:2.5). Only elliptical contours of cracks around large subsidence lo locations (more than 50 cm) went across the earthfill body.

- postponing of canal lining caused substantial technical difficulties (about 10 % increase of earthworks; short and unfavourable construction period during winter break of irrigation activity; soft, moistened lining bed). The behaviour of extant canals emphasized the possibility to postpone lining work only for canals on loess deposits where more than 40...50 cm subsidences are expected.

No disturbance due to subsidences induced by soil collapsivity was encountered by the networks of buried pressure pipes (working under 7...8 atm.) or of concrete flumes.

More difficult are the conditions for drinking or industrial water pipe lines working under low pressure or with free water level. Pipe breaks cannot be immediately located (as for high pressure networks). Permanent and inherent water losses, the high network density on the territory resulted in some cases in a rise by several metres of groundwater table and disturbance of extant buildings.

2.2. Foundations of hydrotechnical structures

Foundation solutions adopted for the more important hydrotechnical works in the above-mentioned irrigation systems on LCS may be divided into three groups :

a. Piercing the collapsible deposit by deep foundations (concrete precast or bored piles or wells).

b. Maintaining some collapsible layers below structure, but removing away the water sources to distances as long as 2...3 times the collapsible deposit thickness; use of non-bu-

ried steel pipes for water transport between structure and neighbouring open basins or canals; providing compacted loess cushions under foundations.

c. Maintaining some collapsible layers under structure and adjacent water sources, but reducing water accessibility and possibility of moisture content increasing by various protective works: compacted loess cushions, waterproofing of adjacent basins or canals over a distance of 2...3 times the collapsible layer thickness.

The last two groups of solutions maintain the structure settlement risk if soil moistening occurs under foundations. They suppose that seepage extension would stop before reaching the understructure zone or its progress would be very slow. Foundation soil moistening risk would be less for " b " than for " c " solutions.

The following statements derived from first years operation experience :

a. Deep foundation system apparently ensures a complete avoiding of structure settlements. However, actual structures behaviour pointed out to two kinds of settlement occurred even the collapsible deposit was pierced by the foundations:

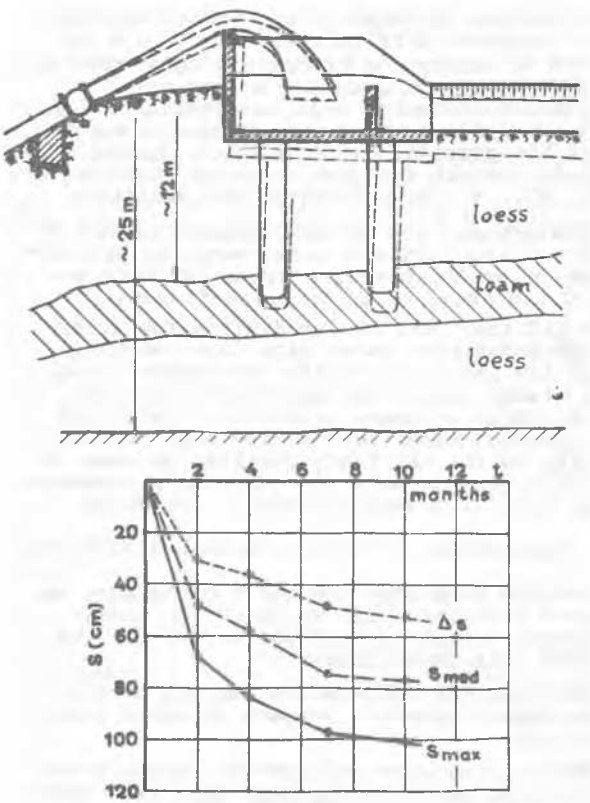

Fig. 4.

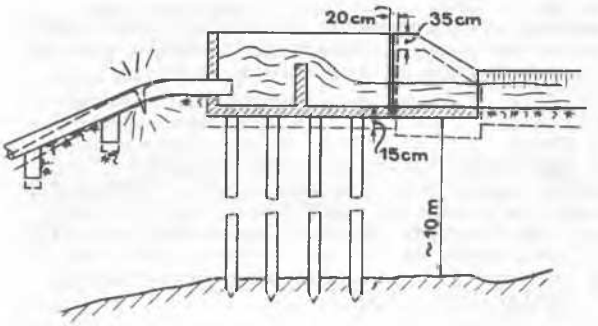

Fig. 5.

- settlement caused by the deformation of soil which surrounds or underlies piles and wells (effect of negative friction); it is the situation of a rigid concrete head basin on a 5 m^3/sec canal, founded on deep concrete wells, whose settlement rose to 101cm (maximum), 75 cm (mean value), and 48cm (maximum differential) (fig.4).

-initial settlement of adjacent shallowly founded building elements, joint opening, resulting in seepage and settlement increasing (when the main structure, deep founded, does not settle). Such kind of phenomena occurred around the concrete basin on a 18m^3/sec canal, rigidly founded on piles, in the underlying non-deformable layer. The soil around and beneath structure settled by about 15cm, uncovering pile tops. The concrete directly founded wings settled by about 35cm and twisted. The steel pipes, rigidly fixed in the basin wall, broke down (fig. 5).

b. There are some pumping stations connected by overground steel pipes to open basins or canals at some 50m distance which did not settle so far, although the settlement of basins or canals, caused by loess moistening, reached 50...100cm (fig.6). Settlement phenomena are now going to end, which means the moistened zone has been stabilized. Eventual, but quite unprobable, settlement extension towards the structure would be very slow and associated by moderate differential deformations.

c. According to initial design hypotheses, the lining over 50...100 m of open water

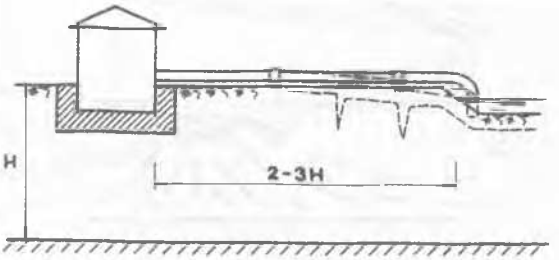

Fig. 6.

sources (basins or canals) near the structures did not eliminate their settlement, but diminished deformation rate and its final value. Settlements began at the contact between waterproofed and unlined zones, accompanied by specific fan-shaped cracks, gradually progressing towards the structure. Lining damages were not repaired, thus allowing settlement extension, but with such a slow rate that no serious disturbance occurred. Fig. 7 refers to a 17 m^3/sec canal and concrete head basin, founded on compacted loess cushion and protected by lining on an initial sector. After 16 months of operation settlements were going to complete stabilization. They reached 55 cm in the lined zone and 37 cm on the basin, whose maximum differential settlement was 7.5 cm. Operation was normally going.

2.3. Structure and foundation soil interaction ; design accepted risk

Specific LCS behaviour involves some unavoidable risk for reclamation systems, because a complete dismissal of settlements of structures and open water transport lines is not possible. Some statements concerning the amount of risk resulted after 1...3 operation years of large irrigation systems are presented below :

- specific LCS behaviour and its consequences did not substantially disturb current operation.
- there is only a negligible percentage of essential damages involving structure abandonment. For example, in a group of systems over a total area of 67,000 ha on LCS, where I_{mg} is more than 25 cm on 18,500 ha, reaching locally 150...200 cm, there are about 160 important hydrotechnical structures (pumping stations, basins, weirs, bridges etc.) placed on a network of 300 km canals with 1...75 m^3/sec discharges. Only 3 cases of structure abandonment were recorded: two of them were head basins founded on piles and were shot out of the flow line when adjacent building settlements, like those presented in fig. 5, occurred (but repair is still quite possible); the third, an excessive-settled weir-bridge, whose adjacent lined canal sectors were too short, was demolished and rebuilt.

Reduction of risk amount is possible if following solutions are applied :

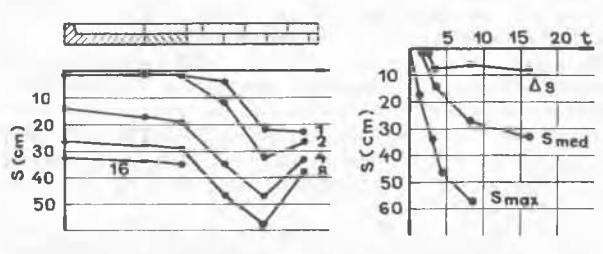

Fig. 7.

a. flexible connections between adjacent structures (e.g.steel pipes with movable joints; syphons instead of rigidly embedded pipes in the basin wall). For the above-mentioned examples, the average value of recorded maximum differential settlement was 25 mm/m along connecting pipes and 1 mm/m on structure perimeter.

b. a speedy contractor's intervention during subsidence development to interfere its dangerous consequences (e.g. complementary fill of side dykes, repair of lining joints, adjustment of equipment supports, maintenance of roads along canals a.s.o.).

2.4. Some remedial measures for protecting or restoring damaged structures founded on LCS

Loessial soil electrosilicification stopped water-tower tilting caused by soil moistening. Improved loess strength was moderate (2...3 kgf/cm^2) but collapsivity was completely eliminated.

Natrium silicate pressure grouting in very moistened loess soils (degree of saturation more than 0.7...0.8) is not efficient because the consolidation radius is extremely small. In such cases electrical treatment is advisable. It acts both by electro-osmosis and by electrolysis, inducing a gradual increase of sodium ion concentration towards cathode and of silica towards the anode. An additional D.C. treatment of 10...20 hours after grouting is required (Bally, 1971).

Tilting of some water towers was rectified by underdigging. Due to the gathered experience, recovering rate get up to 5...10 cm/day vertical motion and, once preparatory works performed, effective recovering operation was limited to few days. In order to avoid dangerous stress concentrations, underdigging followed successive, concentric (not radial) stripe 5...30 cm wide and maximum 10 cm deep, equal to a certain fraction of the differential settlement in the given point (Andrei et al., 1971).

3. SOME ASPECTS RELATED TO THE PROGNOSIS OF LOESS MOISTENING AND DEFORMATION

When ground surface is flooded, the wetted descendent zone may be divided into two parts: an upper fully moistened region and a surrounding partially saturated strip whose breadth is depending on soil suction. Using as starting point the classical uniaxial solution, the time-development of partially saturated strip was established, as a function of soil suction, expressed by equivalent water head (fig. 8) (Andrei, 1971 b). A satisfactory concordance between calculated data and actual moistening extension beneath experimentally flooded basins allowed suction forces intensity evaluation (Antonescu,1971).

For the general case of uniaxial water migration through a triphasic soil, a new analytical model was proposed, based on migration flow separation along flow lines.

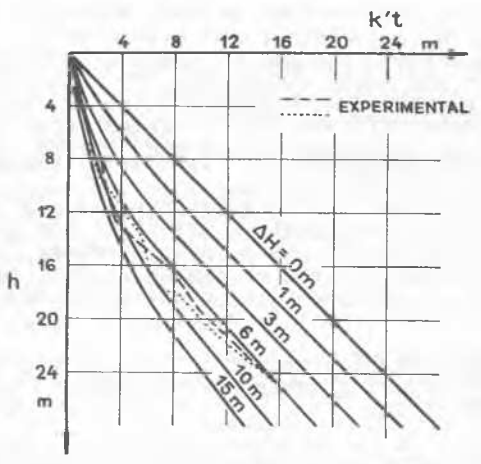

Fig. 8.

Each of obtained component supplies moistening of a soil transversal element (flow rate is constant between water source and soil element and equal to water amount equivalent to element moisture content increase rate). An equilibrium equation of active and passive forces acting on each flow component is established (soil element suction gradient; water weight; hydrodynamical seepage friction) (Bally, 1969).

Loading experiments on various areas (up to 10 x 10 m) pointed out to substantial differences against classical elastic theory (Bally, Antonescu and Perlea, 1969) :

- a three-phase pressure-settlement dependence for moistened LCS : I ($0...p_0$) - negligible settlement; II ($p_0...p_1$) - proportional dependence; III (beyond p_1) - large, undamped deformation. Average values for p_0 = 0.5... 0.8 kgf/cm^2; for p_1 = 1.5...2.0 kgf/cm^2.

- the actual depth of active zone is substantially smaller than the calculated one. The difference is greater for larger loaded surfaces.

In the interval ($p_0...p_1$) the dependence between loading pressure, soil deformation, and active zone depth may be evaluated by means of a double-layer model, i.e. the homogeneous soil mass is considered as formed by an upper elastic and a lower undeformable layer (Bally and Antonescu, 1971).

4. CONCLUSIONS

Experience of construction and operation over 1-3 years of some large irrigation systems on LCS in Romania where subsidences get up to 150...200 cm demonstrates (Bally, Antonescu and Perlea, 1965), (Bally and Antonescu, 1971):

- at the present technical level, forecasting of LCS behaviour as foundation base for irrigation systems is possible from the design phase, thus avoiding unexpected consequences during construction or operation phases ;

-engineering solutions based on the interaction between structures and deformable LCS and admitting a deliberate amount of risk proved as very efficient ;

- improvement of LCS behaviour prognosis and of analytical methods are possible, by using suction theory, double layer model and so on.

R E F E R E N C E S

ANDREI, S. (1971 a). Concepţii moderne privind starea de umiditate şi rezistenţa pămînturilor. A 2-a conf.naţ.geot.fund.,Bucharest vol. II, p.465-484.

ANDREI, S. (1971 b). Application of soil pore water suction in civil engineering. Proc. 4th Conf. Soil Mech., Budapest, p.15-28.

ANDREI, S. et al. (1963). Issledovanie chustvitelnosti pri zamachivanii nekotoryh lëssov RNR. Voprosy stroitelstva na lëssovyh gruntah, Voronej, p.147-160.

ANDREI, S. et al. (1971). Readucerea la verticală a dou ăstele de apa fundate pe loess. A 2-a conf.naţ.geot.fund., Bucharest, vol. I p.17-34.

ANTONESCU, I. (1971). Contribuţii la studiul comportării loessului ca teren de fundaţie. Doctor Thesis, Inst.Construcţii, Bucharest.

BALLY, R.J. (1969). Determination of water migration through loess. Proc. Wageningen Symposium - Water in unsaturated zone, p.245-255.

BALLY, R.J. (1971). Electrosilicatizarea loessurilor cu umiditate mare. Studii geot.fund. constr.hidr.ISCIF,Bucharest,v.XVI,p.103-142.

BALLY, R.J. and ANTONESCU, I. (1971). Loessurile în construcţii,Ed.Tehnica,Bucharest,367p.

BALLY, R.J.,ANTONESCU, I.and PERLEA,V.(1965). Loess as foundation soil for irrigation systems. Proc.Sixth ICSMFE, Montreal, vol. II, p.8-12.

BALLY, R.J.,ANTONESCU, I.and PERLEA, V.(1969). On stress-strain in highly compressible triphasic soils. Proc.Seventh ICSMFE, Ciudad de México. vol.I. p. 1-9.

BOTEA, E. et al. (1969). Loessial collapsible soils as foundation base in Romania. C.N.I.T., Bucharest, 22 p.

DARMOGRAI, V.P. (1969). Konstruktsii gidrotekhnicheskih soorujenii na orositelnyh kanalah v prosadochnyh gruntah. Trudy Soyuzvodproekt, Moskva, No. 2 (33), p.91-103.

DENISOV, N.I. (1953). Stroitelnye svoistva lëssa i lëssovidnyh suglinok. Gosstroiizdat, Moskva.

GIBBS, H.,and BARA, J. (1967). Stability problems of collapsing soil. Proc. ASCE, Journal Soil Mech.Found.Div. No.SM 4, p.577-594.

KIRILLOV, A.A. et al. (1969). Irrigatsionnoe stroitelstvo na lëssovyh gruntah. "Gidrotekhnika i Melioratsiia", No. 4.

MINKOV, M. (1969). Vyrhu stroitelnite svoistva na gornata vlajnosta zona v liosovia kompleks. "Hidrotehnika i Melioratsiia", Sofia, vol.14, No. 12, p.72-76.

VSN 4 - 66 (1966). Vremennye ukazaniia po proektirovaniiu orositelnyh sistem na prosadochnyh gruntah. Moskva, 139 p.