Special aspects of design and construction of irrigation systems on loess soil

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Abstract. The article describes the problems of construction and design of irrigation and drainage structures on loess subsidence when soaking soils. Irrigation and drainage structures are widely used for laying canals, dams and other water facilities. The difference between these structures from industrial and civil is that water is soaked at the base of irrigation and drainage structures over a very large area. Moreover, depending on the properties of subsidence soils and the thickness of the layer at the base of the structure, subsidence can range from several centimeters to several meters.

A large number of accidents were recorded during the design and construction of such structures in natural conditions on the territory of the Republic of Uzbekistan, Kazakhstan, Tajikistan, the Republic of the North Caucasus and in the south of Ukraine, where subsidence loess soils occupy a large area and extend for 10 meters.

The article motivates the necessary laboratory and field studies of soils at the stage of research and design. Methods of research on experimental sites are described in detail and the results of the research are presented. It has been established that large subsidence deformations at the base of irrigation and drainage structures begin from a certain depth, which depends on the results of laboratory studies of the characteristics of subsidence properties.

The conclusions of the article indicate various factors that determine the occurrence of emergencies at irrigation and drainage facilities and how to predict the operation of such facilities in time, taking into account the results of laboratory and field studies.

1. Introduction

Specific loess deposits, which produce settlement problems caused by their tendency for subsidence, when wetted, cover a large territory of Middle Asia and North Caucasus. When industrial or civil construction develops on such soils, the settlement problem can be easily solved by wetting loess foundation within a small area of a designed structure. However, during construction of agricultural irrigation systems, the saturation extends for a greater area into loess foundations under water supplying canals, ditches, and other special irrigation facilities; this tends to wet the loess foundations under all components of irrigation systems. It should be reminded, that the rate of saturation of loess soils as much as anything else depends on hydraulic gradient’s behaviour in vertical direction. Even though, water constantly filtrates into loess foundations under irrigation structures, the varying
downward permeability and macropore structure of loess soils sometimes provides differential settlement of in-situ loess, when wetted. This phenomenon is evidently worth to be accounted for.

2. Methods
Observations made on the territory of Tadzhikistan, Kazakhstan and Uzbekistan showed dissimilar rate of settlement of loess foundations under different parts of an irrigation structure. Thus, one part of wetted loess foundation experienced settlement during 24h, and the other one wetted to the same degree of moisture content suffered settlement within the period of 37 days.

Up-to-date agricultural irrigation systems commonly include storage reservoirs and water intake facilities, transportation canals, and special structures regulating water discharge and pressure head, as well as long-range sprinklers and auxiliary ditches for distributing irrigation water. The operation mode of irrigation canals depends both on the type of agricultural crop and weather conditions.

A few researchers discuss several available schemes of loess saturation with respect to the rate of water filtration into loess massive.

For example:

a) water filtrates from the large-scale water sources and wets a loess deposit over all its depth;

b) water filtrates from a middle sized water source, which produce enough amount of water to saturate a portion of loess massive, and

c) water filtrates from a small water sources to the depth less than 3 to 5m but, in this case, moisture characteristics of loess foundation significantly alter.

Engineering investigations were carried out in Tadzhikistan at the test site covered an area of 20 hectares. According to the engineering survey data, the loess deposit occurred at the depth of 45m below the surface. The water table was 30 m below ground level. The test site was divided into several portions each of which was watered with different amount water. As a result, three areas of loess soil distribution were revealed within the test site boundaries.

Investigations conducted by Abelev M.U. and Krutov V.I. indicate that subsidence phenomenon in wetted loess deposit develops in different ways. In general, to induce entire settlement of flooded loess layers, at least two essential factors should be involved: a definite axial load and water filtration into a layer of subsidence loess soil.

When constructing irrigation systems, axial stress conditions in loess deposit barely occur at a depth, at which the total weight of overlying soil mass is considered as an axial load, that produces settlement. Below this depth, the load increases with increasing thickness of the loess stratum, thus imposing severe stress on the lower loess layers, which settle under their own weight when wetted. Above this soil mass, loess massive either partially compacts or does not compact at all, and in some cases swells. The latter is, for the most part, a typical feature of clayey subsidence soil.

Special in-situ and laboratory tests have revealed an increase in the settlement of a lower fully wetted loess layer even after compaction of overlying layer. Such a phenomenon occurs due to high salt content in loess soil. Salts contained are usually fast, medium, or hardly soluble. Flowing water firstly washes out fast soluble salts and, then, medium and hardly soluble. This leads to an increase in the magnitude of the settlement of a loess foundation under irrigation and drainage structures over time. Researches made on the soil foundation of irrigation structures in 1958-1964, disclosed that secondary compaction process induced an increase in a settlement magnitude (due to dissolving salts contained in subsidence loess soil).

Currently, construction of irrigation structures is often fulfilled with the help of up-to-date foreign-made earth moving machinery that performs grading operations, fills dams and embankments, and excavates water-supplying canals with much fidelity. This requires rather accurate prediction of settlement behaviour of subsidence soils in the base of irrigation systems. Evidently, an additional data on the properties of fast and medium soluble salts permit to define settlement magnitude of subsidence soils for the period of 30 years more accurately.
Special investigations were conducted at the test site No 7 (Turkmenistan) during the construction of Karakum Channel. Preliminary studies revealed numerous subsidence sinkholes with cracks and faults in loess soils in the area involved. According to chemical analysis, the loess deposit contained about 2.5% of calcium sulphate and from 12 to 65% of calcium carbonate. Moreover, lenses of gypsum in the form of small druses occasionally occurred.

Laboratory tests results showed that the relative settlement of this loess soils varied between 0.15 and 0.20% under the applied load of 0.1 MPa. The magnitude of the relative settlement varied in both longitudinal and vertical directions. The gross thickness of the loess deposit was up to 20.0 m beneath the surface. Loess layers mostly exposed to settlement occurred at a depth from 8 to 10 m.

Field soaking tests produced a number of solemn problems concerning the arrangement of the test pit itself. In order to force the process of soaking, boreholes to 12 meters depth at a 3x3m grid were drilled. The boreholes were filled with medium sand. In that case, the rate of the observed settlements increased as much as 2.7 times, thus indicating poor downward filtration properties of in-situ loess deposit.

Obviously, determination of the normative characteristics of settlement behaviour of loess soils subjected to construction of irrigating structures becomes a key question. These characteristics include the initial subsidence pressure (Rm) and initial moister content.

Ordinarily, while in-situ, the initial subsidence pressure assumes the value similar to the weight of a soil mass, bellow which settlements occur under own weight of this soil mass.

However, the correct meaning of the initial subsidence pressure can only be determined from in-situ soaking of large-scale pits.

Comparison of the results obtained from in-situ soaking tests conducted at the test sites located in Uzbekistan and Kazakhstan showed that for a pit covering the area of 15x15 m the initial subsidence pressure ranged from 0.8 to 1.1 kgf/cm², while for another pit covering the area of 32x32 m this meaning varied from 1.5 to 2.4 kgf/cm².

Time required for flooding loess foundations under irrigation structures essentially depends upon downward permeability of a loess stratum. The more so, it has been discovered that the presence of a great number of vertically oriented macro-pores does not have essential influence on the rate of downward water filtration into loess foundation under irrigation structures.

The settlement of a test pit bottom was observed in a good progress within the period of 3 to 4 days. Then, the process proceeded much more slowly.

If compared, the settlement defined by analytical processing the data obtained from compression and triaxial laboratory tests exceeded the settlement observed during in-situ soaking test by 140-200%. This indicated the difference between in-situ stress-strain state of loess massive and stress-strain state of soil samples.

On completion of the in-situ soaking test, two sampling pits dug to a depth of 4 m and two boreholes drilled to a depth of 7.5 m were arranged at the test site. Subsequent laboratory studies determined physical and mechanical properties of the soil samples collected from these unites.

The performed in-situ soaking tests showed uneven water filtration to a considerable depth of an open pit foundation. Unfortunately, the defined initial subsidence pressure varied from 0.4 to 1.6 MPa in the row of samples collected at a depth of about 2 m with spacing of 1 to 2 m in the longitudinal and transverse directions. Macro-pore structure of loess soils in the foundation of the tested pits also essentially changed. Engineers, when designing irrigation structures in the area with subsidence loess distribution, should take this in consideration.

Stress-strain state of a loess foundation is an important factor in irrigation systems design. Depending on the foundation preparation procedure, three reasons for a stress state occurrence in the foundations of irrigation structures ought to be considered. Like other types of soils, in-situ subsidence loess bare a pressure imposed by the overlying layer. If this pressure exceeds the initial subsidence pressure, deformation of the soil mass occurs. Actually, the stress under geological overburden increases with increasing depth. This is also typical for slightly moist subsidence loess soils, and such deformation is considered as potentially possible while irrigation water infiltrates into these layers.
In this case, settlement gradually develops as water penetrates these low loess layers. According to the practice of construction, the majority of linear irrigation structures have been arranged on the natural foundation for the current 30 years. As the monitoring data of irrigation systems in Tajikistan showed, settlement in loess foundations developed when irrigation water moved through the system of canals. When the water supplying structures stood empty, no settlement was observed.

Sometimes, irrigation canals run across hills terrain. In this case, grading fills, excavations or deep excavations in watershed areas were necessary to be arranged.

In special cases, in order to force the settlement process, loess soils were additionally loaded with reinforced concrete slabs or filled dams.

In Uzbekistan and Kazakhstan, before putting irrigation system into operation, loess foundation of designed irrigation structures was presaturated. After settlements had partially occurred, additional construction preparations were made.

As practice has shown, irrigation systems in the foothills of the Caucasus are usually arranged after loess foundation has been flooded with water. Unfortunately, a lack of additional engineering research on the experimental pits results in uneven settlement of the soil massive. Monitoring of the operation process of irrigation structures constructed on subsidence soils in the foothills of the Caucasus has shown that many sinkholes significantly increased and changed their shape in plan during operation of irrigation facilities. Plate-bearing test performed with a plate of 600 cm$^2$ in size showed that deformation modulus defined for soaked or moderately soaked thick loess massive significantly differed from that obtained from laboratory test results. As a rule, the meaning of the total deformation moduli obtained from plate-bearing test exceeded the meaning determined by laboratory tests by 30-70%. It worth to be pointed out that such a difference occurs due to the presence of fast and moderately soluble salts in loess soil.

The water loss from irrigation systems is also a very important characteristic, which explains the timing of settlement development.

Essential studies were carried out at a test site near the town of Kolkhozabat. Preliminary, four sampling pits and boreholes with a diameter sufficient to place a plate of 600 cm$^2$ in size were arranged. The maximum thickness of loess soils varied between 28 and 32 m in the area involved. Samples collected at a same depth had nearly same stress and deformation properties. The initial subsidence pressure for the loess soils at the test site varied from 1.3 to 1.9 kgf / cm$^2$.

Flooding of the entire test pit resulted in differential settlement of loess foundation. The magnitude of settlement varied from 80 to 120 cm. This obviously confirmed non-homogenous distribution of various soluble salts in the loess soil.

In Dangarinsky vicinity, a test site including a few test pits buried to a depth of 0.6 to 3.0 m was organized.

Apparently, the reason for development of differential settlement can be explained by varying meanings of hydraulic gradient within a test pit.

Calculation of the foundation settlement under irrigation structures located in a hilly area is rather difficult procedure. It usually includes construction of various benches in the base of which subsidence deposits of different thickness occur. However, when a large amount of water from irrigation structures infiltrates into a soil foundation, the slope may lose stability. In this case, it is necessary to calculate the slope stability for each specific location of irrigation and drainage structures. For this purpose, laboratory tests on loess samples collected from that slope ought to estimate behavior of loess wetted with different amount of water and under action of different axial loads. If laboratory tests use shear device developed by Gidroproekt, a quick test procedure is recomended. It is generally assumed that a soil sample does not compact within 6 minutes.

Design of irrigation structures providing natural water movement considers construction of embankments, low-head dams and protection dykes. Usually, such structures with a height of 3 to 5 meters impose additional stress of 0.5 to .8 kgf/cm2 on the foundation soils. This additional stress
produces observed settlement if the initial subsidence pressure of the soil massive is rather small. In this case, testing of soil samples taken from the base of these embankments should be carried out accounting for the increase in the effective and actual loads on the foundation soils.

Accounting for the phenomenon of incomplete water saturation of loess soils during short-term operation of structures is a significant problem in the construction of various irrigation and drainage structures on subsiding loess soils.

Analysis of the properties of soil sampled from boreholes drilled both in the center and at the edges of the “subsidence sinkholes” showed that in the overwhelming majority of cases, the moisture degree in the samples taken under the center of the "subsidence sinkholes" was 8 to 15% higher than in those taken at the edges.

The analysis of numerous studies carried out by engineering investigations in the territories suitable for locating irrigation and drainage facilities shows that the properties of subsidence loess soil, when wetted, significantly change not only in the adjacent territories, but also within the boundaries of one test site. The difference is the fact that with the same deposits of subsidence macropore loess soils, their total deformation changes significantly both in time and along the strike of the test pits, when wetted, and significantly depends on the inclusions of buried plant layers and lenses of harder soils. In the North Caucasus, especially in the foothill regions, deformation of loess deposits often and significantly changes in zones where the percentage of macropores distribution in relation to the total number of pores is large. That is why it is believed that in order to obtain reliable information about the possible settlement of loess foundation under irrigation and drainage structures, as well as reliable prediction of loess foundation behavior it is necessary to undertake long-term field soaking test.

Due to the withdrawal of lands from agricultural use, the exact dimensions of irrigation systems often change during the engineering survey and design process, therefore field soaking test is one of the most reliable test procedures. The size of the pit is usually taken equal to the thickness of subsidence soils. The minimum size of a test pit covers the area of 20x20 m with a depth of 0.5 to 1.5 m below the surface. The constant water level in the pit is maintained during the entire soaking process. It is believed, that the settlement of depth marks installed at different depths within the boundaries of wetting massive shows the complete wetting of subsiding loess foundation under the test pits.

It should be noted that irrigation and drainage systems also include canals with small cross-sections and the water flowing through such canals installed in the massive of subsiding loess soils does not cause complete water saturation of the foundation soils under the canals. In recent years, in order to solve the above problem, different types of test pits were arranged during operation of irrigation systems in the regions of the North Caucasus. Foremost, a test canal exactly corresponding to the size and cross-section of small singular canals was installed. Typically, the width of the test canal was 10 to 15 m, and depth marks were installed in the massive of subsiding soils at different depths and at different distances from the canal. The results of research showed that in most cases, when the water filtrates from a test canal into a massive of subsidence soil, a suspended contour of moisture distribution in wet zone developed. Such method found application in construction of irrigation and drainage structures on the territory of the Azerbaijan, performed under the supervision of A. A. Mustafaev in 1962-1975. Similar studies were carried out in 1974 - 1991 at the Kolkhozabat test site (Tajikistan).

Analysis of the numerous studies on wetting subsidence loess soils performed during the operation of irrigation and drainage facilities has shown that results of the field soaking test provides opportunity to accurately predict both the size of the settled soil portion in the bottom of the test pit and the duration of settlement. Several numerical approaches have been applied to describe water distribution in the loess foundation under test pits of different sizes. However, these calculations are very approximate and do not take into account the processes of filtration through the already compacted subsidence soil massive either when the water mainly penetrates through macropores or when it moves in horizontal direction, or in both cases occurring at the same time.
Thus, for reasonable calculations of loess soil settlement and its duration, it is necessary to know the meaning of hydraulic gradient for downward and horizontal water distribution, as well as hydraulic gradient for soils settled during the compaction process.

For the research work to be carried out, deep observation wells with a diameter of at least 127 mm are usually arranged at test sites. In recent years, sensors with radioisotopes lowered into such wells have made it possible to appreciate not only the movement of water, but also the direction of this movement. The annular space of observation well is usually tampered with the bentonite clay, when constructed. Pipes are lowered with the help of vibrating device, namely a pocker vibrator I-50, which is largely used to compact monolithic concrete structures. Ordinarily, it takes 45 to 70 minutes to install an observation well to a depth of 25 meters. The pocker vibrator is also used to immerse deep deformation marks at different depths in the massive of subsiding loess foundation of irrigation and drainage structure.

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