9th National Congress on Civil Engineering, 10-11 May 2016
Ferdowsi University of Mashhad, Mashhad, Iran

Effect of unsaturated expansive soils on canal linings: A case study on Tabriz plain canal, Iran

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Abstract

Based on the linear nature of water conveyance projects, they include various geological formations and are usually in contact with water. Because of these reasons, most of the constructed irrigation and drainage networks are subject to deformation and displacement due to problematic soils. One of these problematic beds is unsaturated expansive soil. The unreinforced trapezoidal canals are damaged when constructed on this type of soils. In the current paper, this phenomenon has been studied using field observations, experimental tests, and numerical modeling. In practice, a filter layer is used to reduce the soil swelling effects on canal lining in Tabriz plain project. For performance investigation of this layer, the amount of soil swelling and relative displacement of canal section panels are measured by recording of surveying points. This phenomenon is also modeled numerically. Using the obtained results, the swelling of the bed soil is calculated at different parts of the canal section with filter and without it and the locations of maximum movements are determined. In order to predict the interaction behaviour between unsaturated expansive soil and concrete lining at different moisture conditions, the special constitutive unsaturated soil behaviour model is selected in software. The results of analysis show the location of maximum deformation and lining bending moment on the canal section. In addition, comparison between the results of numerical modeling and field data illustrates acceptable precision of the numerical modeling.

Keywords: Canal, Expansive soil, Lining, Filter, Bending moment.

1. INTRODUCTION

Expansive soil is a main type of problematic soils. These soils are causing a lot of problems in different projects for civil engineering and especially for geotechnical engineering. The volume of expansive soil changes during variation in its moisture content. It swells when its water content increases and shrink when water loses. These volume changes lead to serious damages in most light structures found on or in expansive soil [1,2].Expansion is generally occurred in some clay minerals because of absorbing water by particles. This phenomenon lead to change the distance between particles and finally distortion of internal stress equilibrium.

Some of the most important lightweight structures that are damaged as a results of swelling and shrinkage can be mentioned following: the foundation of light buildings, retaining walls, pavements, airports, sidewalks, canal linings and beds. Evidence indicated that in Iran, most of the lining canals in irrigation and drainage networks cracked after first impounding [3]. If the swelling pressure of bed soil is more than the weight stress of light structure, it cannot endure this pressure and cracking occurs. The range of such damages can be varied from fine cracking of pavements or small displacement of foundation, which is very common, to impressive cracking of canal lining or large displacement of footings.

Repairing cost of civil engineering structures which damaged due soil expansion was estimated many billion dollars per annum worldwide. Every year many new structures are constructed on the swelling soils in Iran, over 60% of these structures suffered minor damages such as cracking, and about 10% of these structures are heavily damaged that cannot be repaired [4]. After occurring first cracks in hydraulic canal lining, over time they become larger because of thaw and freeze cycles. This factor may be gradually destroy all surface of canal section.

Several methods are suggested in technical references to control or prevent of clay swelling effect on engineering projects. One effective technique for this reason is soil stabilization. Lime is one of the best material for stabilization of clay to reduce the swelling characteristic and improve the mechanical properties of this soil type. This change in clay behavior is happened with replacing the calcium in Lime chemical structure with sodium in the soil [5,6]. However, in some projects with high volume of earthworks, such as irrigation canals or highways, chemical stabilization is not suitable option to deal with swelling and impose huge costs on project. So in such project could be used other simple method instead chemical stabilization method to reduce costs and save time.

Because of the behavioral characteristics of expansive soils, the theory of unsaturated soils is used to study of them. The formulation of this theory consists of two independent stress variables and corresponding constitutive relationships [7,8].

In this paper, the effect of expansive soil on Tabriz Plain canal project and the countermeasure against this destructive phenomenon are studied. In order to experience the performance of this method a part of canal is selected and soil-lining interaction behavior has been studied as in situ investigation, experimental tests, and numerical modeling.

In practice, considering a filter layer under lining is used as a proposed method to reduce the soil swelling effects on canal lining. To investigate the performance of this layer, the amount of soil swelling and relative displacement of canal section panels are measured by recording of surveying points. This phenomenon is also modeled numerically.

2. PROBLEM STATEMENT AND GEOTECHNICAL INVESTIGATION

Tabriz plain irrigation and drainage network consists of six regions and forty thousand hectares which is under construction in East Azerbaijan province of Iran.The main canal of this network is 29 km long, floor width and height of canal section change respectively between 2.5 to 5.0 m and 2 to 2.75 m. The canal wall slope is 1 (vertical) to 1.5 (horizontal). The kind of lining is unreinforced concrete and lean concrete is also considered under lining. There are three series of joints in section: two series in walls in the level of 0.5 meter from the floor, and one of them in canal floor.

In the first step, a few phase of canal path was constructed. Because of raining and surface stream, some part of this length was filled with water. After discharging of canal, hairline cracking and uplift were observed in some length (as seen Figure 1). It appears the water of canal has infiltrated from joints into the lean concrete. Since this type of concrete is porous material and it has so relatively high permeability that water penetrate in the bed soil and change moisture content of it and this causes to expand of bed soil.

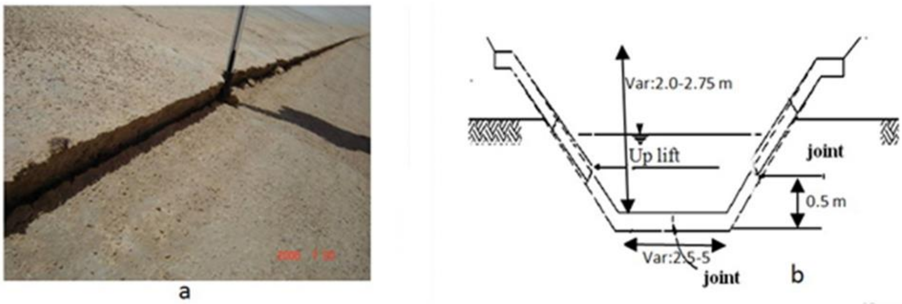

Fig.1. a. Locations of damage to the concrete lining of canals and
b. Schematic section view of concrete lining uplift in Tabriz Plain project

In order to investigate this phenomenon, an undisturbed soil specimen was obtained from heaved zone(km 5+300) and a free swelling test was performed using ASTM D 4546 -96 test method. This test shows that the soil can swell about 4% and the swelling pressure is about 40 kPa. The 12 cm lining concrete and 10 cm lean concrete can make only a pressure of about 5 kPa on soil. As a result, soil can heave the concrete lining.

Extensive geotechnical studies have been done to evaluate the soil swelling behavior in path of project Tabriz canal. These studies include field investigation, sampling, and laboratory tests. The gradation curves of samples, obtained from main canal bed soil (AMC (Ajichai Main canal)), are shown in Figure 2 (ASTM Standard D422). The types of soil samples are clay in most of cases based on unified classification method. The Plasticity Index (PI) and soil Activity of samples are also shown in Figure 3(ASTM Standard D4318).

These samples were obtained from the depth of canal base, every 250 meter along 16 kilometers length of canal path. The tests results show that the Plasticity Index of samples varies from 0% to 33%, and these variations have no regular rate in canal length. Also the Activity value of bed soil varies from 0 to 1.0.

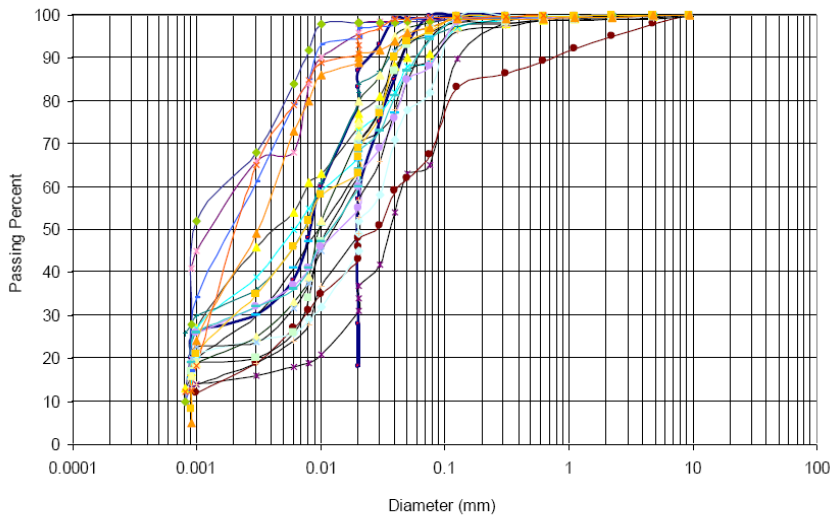

Fig. 2. Gradation curves of samples obtained from main canal bed soil of Tabriz Plain project (AMC, km 0.0 to 29.0)

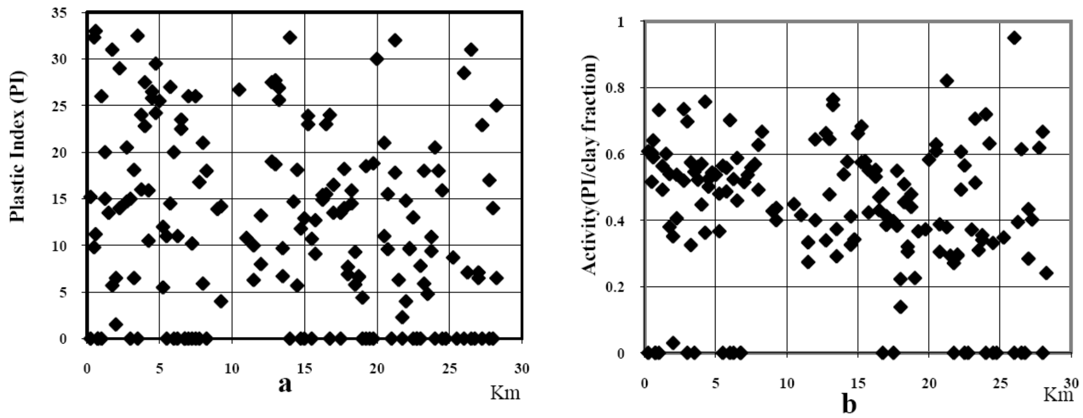

Fig. 3. Variations of a. Plasticity Index b. Clay Activity in canal path of Tabriz Plain project

Generally, there are two frequently used indirect methods for expecting the swelling potential in technical references: Seed et al. method (1962) and Van der Merve method (1964) [9,10]. The results of experimental tests are drawn in Figure 4 based on these methods. As shown in Figure 4, the swelling potential of soil samples varies from low to high values. It is inferred from these result that the percent and type of clay material is varied along the canal path. In other hand, all of results emphasize that the expansive soil behavior should be noticed in all length of Tabriz canal path.

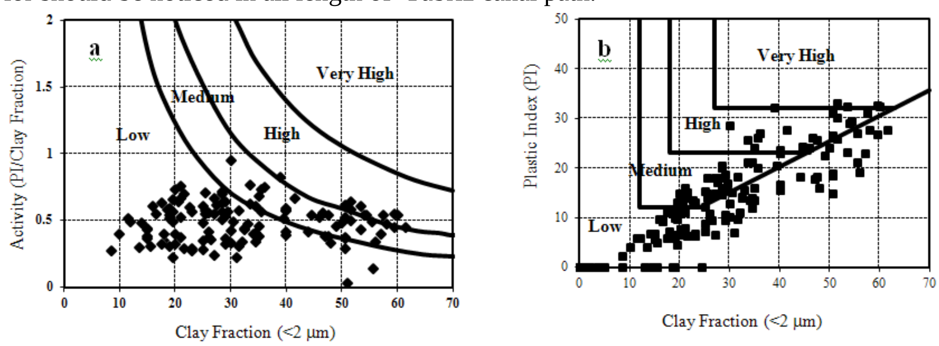

Fig. 4. Swelling potential evaluation of soil samples in Tabriz Plain canal a. Seed et al. (1962) b. Van der Merwe(1964)

As discussed the mechanical characteristics of bed soil aren't constant in all canal paths. So in this research, critical values are selected as input parameters of numerical modeling.

3. USE OF FILTER LAYER UNDER CANAL LINING

Different methods were studied to reduce or eliminate the swelling effect on lining. These methods consist of pre-wetting, stabilization using lime or cement, and soil replacement. Since the water conveyance projects are linear nature so they may be passed long length through expansive soils. On the other hand, these structures have slopes in walls. So these treatment methods were either expensive or practically very difficult in canal section. In stabilization methods, the compaction of soil after adding the chemical material is very important but this operation in slopes is very difficult.

As observed in in situ investigation, the soil swelling phenomenon led to the cracking of concrete lining and relative displacement of canal panels in joint locations from little amount to 30 mm as shown in Figure1. To prevent the occurrence of these damages, using a filter layer with a thickness of 30 cm in loose to medium state of compaction under canal lining was proposed in this project.

The application of filter layer doesn't have direct effect on soil heave, but the properties of filter material lead to the reduction of swelling potential. The filter is composed of loose granular material, so it can uniformly transfer the local pressure of bed soils to lining and reduce the relative displacement of adjacent panels. So, this is the important role of filter layer in reducing the swelling amount. The weight of the filter layer is another resistant factor against swelling pressure. This layer weight applies additional pressure about 5 kPa on expansive bed soil. Although this pressure is not more than the swelling pressure but it can reduce the amount of heave.

In the following sections, the efficiency of the proposed method was evaluated simultaneously using experimental tests, in situ tests, and numerical modeling. First the experimental works will be presented.

4. ON SITE INVESITIGATION

This proposed way was tentatively performed in 50 m length of the canal. The gradation of filter layer was designed based on canal bed soil gradation using USBR method. For evaluating the efficiency of this method, surveying points were considered on canal section and displacements of these points were measured. Locations of these considered points on canal section are shown in Figure5.

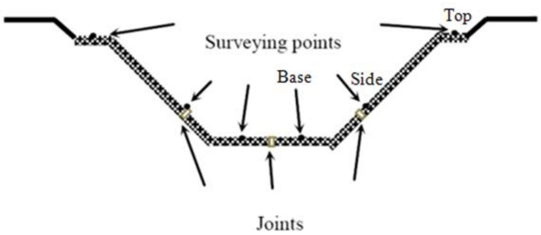

Fig. 7. Surveying points location on canal section

To implement this proposed method, 50 m length of the canal path was selected. Then, the filter and concrete lining layers were performed, and after closing the two endings of this zone, it was filled with water during 30 hours, and water level was kept constant for 10 hours. After that, the canal water was discharged during 2 days. Before impounding the canal, surveying points were considered on canal section according to Figure 5 and their initial levels were also recorded. For evaluating the swelling potential, these levels were again recorded at 12 and 18 days after impounding.

The results of surveying point records at 12 and 18 days after impounding are shown in Figures 8. In Figure 8, the variation of swelling rate for each of the surveying points considered on canal section is drawn separately. According to these results, 12 days after impounding, the maximum amount of uplifting was about 10 mm in upper part (Right Top point, see Figure 8) of canal wall in distance 43 to 45 meters of surveying points. The minimum amounts of uplifting were recorded about 2 mm in floor and wall of canal section as seen in Figure 8 at left and right base and left side diagrams. The maximum relative displacement of panels has been recorded 5 mm and seen in kilometer 15+713. This value obtained from in site measurements. The records of surveying points show that 18 days after impounding, the maximum amount of displacement was about 11 mm in left and right side of canal wall in distance about 40 meter of surveying points(see Figure 8). The minimum amount was about 2 mm in floor (right base). The maximum relative displacement of panels has been measured 5 mm and seen in kilometer 15+713.

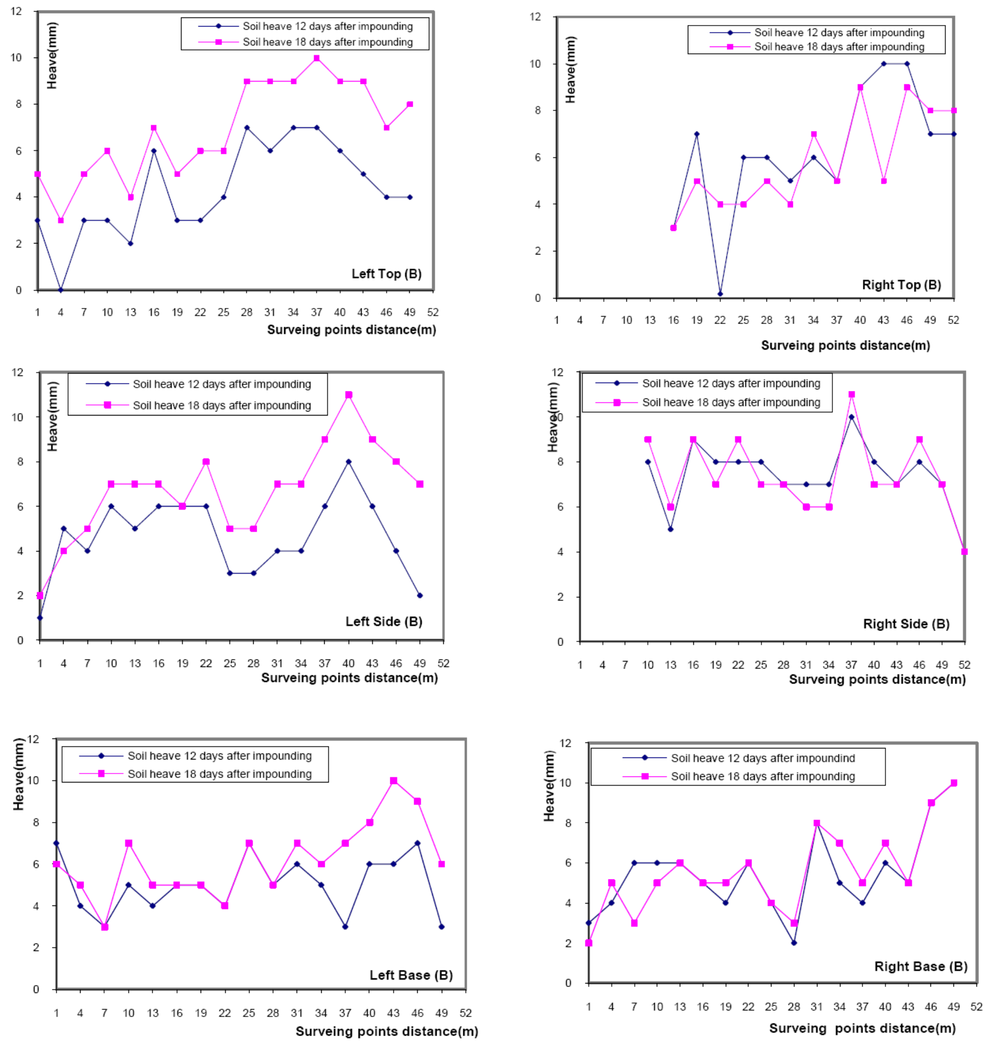

Fig. 8. Heave compared evolution of different points on canal lining

As a result of above discussion, the in situ records showed that the performance of filter layer led to the reduction of the swelling potential and the relative displacement of panels decreased from 30 mm to 5 mm [4]. These values show the efficiency of this way to control soil-lining interaction behavior.

This phenomenon is also studied numerically. For this purpose, the section of trapezoidal canal with actual dimensions has been modeled with Geo-Studio (2007) software and interaction of the soil-concrete lining and the effect of considering filter layer under canal have been studied in the impounding conditions, and finally the result of numerical analyses have been compared to in situ observations.

5. NUMERICAL MODELING

In this research, SIGMA/W 2007 software is used for numerical modeling. SIGMA/W, which is one of the software programs in Geo-Studio software package, is based on the finite element method for stress-deformation analysis of earth structures. When this software is used together with other products of GeoStudio package such as SEEP/W software, changes in pore pressure and its distribution in soil mass due to the external loading can be computed by using coupled and uncoupled formulation. The basis of this software for modeling of unsaturated expansive soils is the behavioral model and presented equations by Vu and Fredlund (2004). As mentioned before, in this research, the actual dimensions of the under construction water canal of the irrigation and drainage network of Tabriz Plain, which is located on the expansive soils, is used for modeling.

Geometric characteristics of canal section have previously been introduced. As a real condition for modeling of joint, 2 cm space is vertically considered in lining surface.

For simulation of the initial conditions (local conditions), it has been assumed that the canal bed soil is somewhat dried and a constant suction is established in the soil. For modeling the infiltration into the soil, water level inside the canal is applied as a head to the lining elements. This water penetrates from joints into lean concrete. This layer has about 0.001 m/day permeability coefficient. So water seeps the soil and changes its moisture. The lining has been modeled using beam elements. Generally, it is assumed that in the initial conditions, a suction equal to 200 kPa was available in the environment. This value of suction is calculated using the environmental soil moisture content and Fredlund and Xing (1994) method[12].

Soil moisture content is about 20 percent in most parts of canal path. The other required parameters for analysis are presented in Table 1. These parameters are selected based on characteristics of bed soil in highly expansive zone.

Table 1-Input data for modeling simulation

Expansive soil of canal bed					lining			
γ (kN/m^3)	Φ	C (kN/m^2)	μ	E_0 (kN/m^2)	γ (kN/m^3)	μ	E (kN/m^2)	K (m/day)
19.2	20	50	0.4	12000	21	0.2	1.8×10^7	0.001

In the above table, γ, Φ, C, μ, E and K are, respectively, unit weight, friction angle, adhesion coefficient, Poisson's ratio, modulus of elasticity and permeability coefficient.

6. NUMERICAL ANALYSES RESULTS AND DISCUSSIONS

Because in practice, the swelling values were recorded at 12 and 18 days after impounding of canal so all of numerical analyses were also done for 18 days. In addition, as discussed before the critical values of bed soil parameters were selected for numerical modeling, therefore the results of numerical analyses were only comparable with maximum values of measured deformations.

Figure 9 and 10 show the heave of unsaturated soil under canal and deformation shape of lining without and with filter layer, respectively. As seen in these figures, the results of numerical analyses and in situ observations are satisfactory adaptation in lining behavior (the relative displacement of panels). The status of panels after swelling is shown in Figure 1. Without the filter layer under lining, the numerical analysis results show that the unsaturated soil under canal swells about 12.5 mm during 18 days, so this phenomenon leads to relative swelling of lining panels about 1.5 mm in joint locations in canal walls. As discussed before, this relative swelling was reported as 30 mm in actual observations during few months. For the casing that filter layer don’t applied under canal, these obtained values of numerical modeling and in site measures for relative displacement of panels aren’t comparable because they happened in different time ranges (18days and 6months, respectively). Another result that is obtained from numerical modeling is that the relative displacement of panels in the location of joint in canal floor is negligible. This result was also obtained from in situ observations.

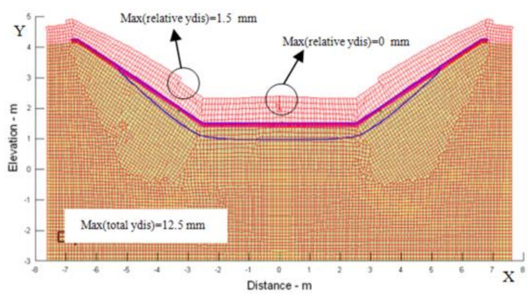

Fig. 9. Canal section swelling without considering filter layer

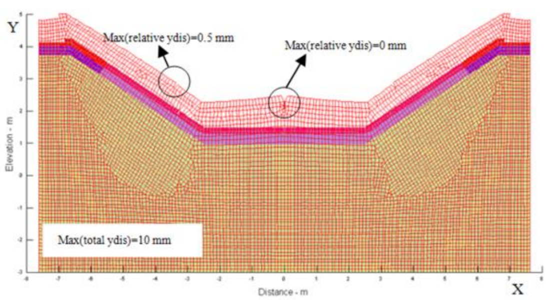

Fig. 10.Canal section swelling with considering filter layer

In Figure 11 the values of lining bending moment are seen. They are caused by the swelling of the soil in two cases of analysis (with and without filter). In current graph, the horizontal axis is the distance of lining to the centerline of the canal section. It shown that, in both cases, bottom corner of the canal (junction of canal wall and floor) and mid-height of section are critical points and in these points the bending moment receives to maximum values. According to Figure 11, analysis results show that without considering a filter layer, 18 days after the impounding, the resulted moments in the bottom corner of the canal and side wall are near the cracking moment and concrete lining will crack in these locations in next days. Therefore, by considering only one joint in canal wall, cracking cannot be prevented. As seen in Figure 11, there is another critical position in the canal section around x= 4.8m. In this location, the moment reaches its maximum value. It can stated that the upper length of lining does as a pin-ended beam thus the maximum moment is created near the mid span of it. By referring to the results in Figure 11, it can be seen that considering a filter layer under the canal leads to the reduction of the value of bending moment. It seems that considering a filter layer leads to the reduction of the expansive unsaturated soil-lining interaction force and prevents the creation of additional forces in soil-lining boundaries. Therefore, it can be concluded that considering a filter layer leads to the reduction of the bending moment to lower than cracking moment of concrete equal to 4.08 kN.m. So, the probability of cracking is eliminated in canal section length. This effect of considering filter layer is also observed in in situ investigations.

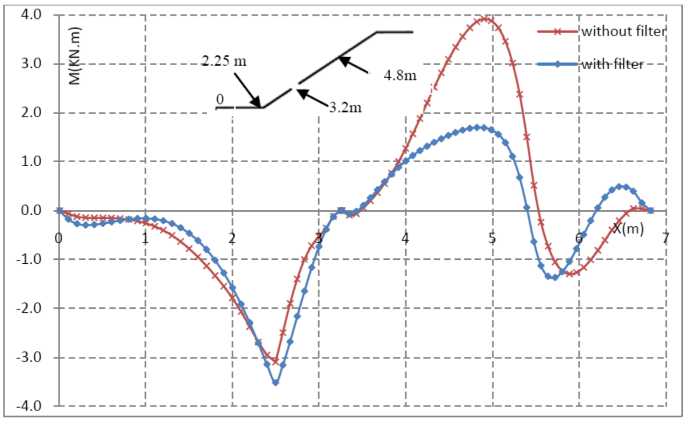

Fig. 20. Bending moment diagrams of the canal lining with filter and without it.

7. CONCLUSIONS

Field observations in Tabriz water conveyance line show that after filling it with water, the cracks on lining and uplifts were generated randomly. Therefore, extensive studies are planned and performed as field investigations, laboratory experiments, and numerical modeling. Based on test results, the soil type is clay in length of project line and swelling potential of canal path aren't constant in this area. As obtained from experimental test results, swelling potential of soil are variable in Tabriz plain. In addition the Plasticity Index of samples and the Activity parameters of bed soil are obtained from 0% to 33%, and from 0 to 1.0, respectively. Generally it inferred from test results that swelling phenomenon should be considered in most length of canal.

For reduction of soil swelling effect on canal lining, using a filter layer in loose state with a thickness of 30 cm was proposed. For evaluating the efficiency of this method, surveying points were considered on canal section and the displacements of these points were measured. The in situ records showed that the performance of filter layer led to the reduction of the swelling potential and the relative displacement of panels. These site observations show the efficiency of this method to control soil-lining interaction behavior. This phenomenon is also studied numerically. For this purpose, the Vu and Fredlund [13]model was selected to predict unsaturated expansive soil heave. This constitutive model can predict the behavior of unsaturated expansive soils in various moisture conditions and gives satisfactory results. This model is implemented in SIGMA/W finite element software [11]. This software and current model were used for modeling unsaturated expansive soil-lining interaction behavior. The obtained results of numerical analyses and field observations have acceptable consistency in anticipation of canal lining deformation shape, the values of displacements, and the effect of filter layer on these phenomena. In addition results of numerical modeling indicate that using a filter layer under concrete lining leads to relative reduction of general heave in unsaturated expansive bed soil and also prevents the lining from cracking. The intersection point of the canal wall with floor, the upper corner of the canal wall, and middle point of lining length are found as the locations of concentration of stress in canal section. The value of bending moment in joints is zero because they work as hinge on lining surface therefore the location of these points have vital role to control and reduce cracking an panel uplifting. According to this fact optimization joint's arrangement and numbers is one of the best effective approach to decline the damages of canal lining in unsaturated expansive beds.

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