Journal of Structural Engineering and Geotechnics,
1 (2), 1-9, Fall 2011

The Stability Assessment of Dasht-e-Abbas Pressure Intake Tunnel Subjected to Ground Strength Reduction-Iran

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Received 30 October 2011, Accepted 29 November 2011

Abstract

The hydraulic pressure is one of the most important factors in the design of pressure intake tunnels. Since the surrounding media cannot usually resist the high internal pressure of these tunnels, they are usually finished with an adequate lining mostly of reinforced concrete, which is an interaction problem between water, soil or rock and concrete lining. Although reinforcing the concrete lining may reduce the width and number of the developed cracks in the lining, the penetration of water into the surrounding media can still happen due to high water pressure in the tunnel. Thus, it may lead to the development of hydro pressure on the external surface of the lining. There are some theoretical methods that are developed for the design of tunnel lining in this condition. When the tunnel is located above the underground water table, the seeping water may lead to strength reduction of the adjacent soils, particularly when the ground, like the mudstone layers existing in Dasht-e-Abbas region, south-west of Iran, is cohesive and consists of soils that are susceptible to water.
In this paper, the hydrostatic interaction between soil and concrete lining of Dasht-e-Abbas pressure intake tunnel has been investigated when the shear strength parameters of the mudstone layers decrease due to the seepage of water to the surrounding media. To evaluate the stability of the tunnel, a two dimensional numerical simulation is developed using the finite element code called PLAXIS and interaction analyses are carried out. The analyses are done in stages to assess the maximum internal forces induced in the lining. The structural stability of the tunnel is evaluated and discussed in this condition. Based on the obtained results, it is noted that for more realistic understanding of the behavior of infrastructures like pressure intake tunnels under various conditions, numerical analyses should also accompany experimental and analytical approaches such as Schleiss method which is described in this paper, especially for tunneling in media that is susceptible to water and ground strength reduction. The numerical analysis results show a considerable increase in the lining internal forces when subjected to the reduction of ground strength. However, the tunnel structure is still stable under the effect of surrounding ground degradation with the constructed lining specifications.

Key Words: Pressure intake tunnel; Ground strength reduction; Ground-lining interaction; Numerical analysis

1. Introduction

Due to developing important projects regarding water conservancy in recent years, underground pressure intake tunnels have been mostly applied in order to convey water from dam reservoirs to hydropower stations. They may also be built up for the purpose of supplying water for downstream lands. These tunnels may pass through soil or rock masses and the ground might have various topography of different amount of overburden. In practice, it is a key problem to design such underground high pressure tunnels.

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First pressure tunnels without lining were applied in Norway [1] and following it some principles such as the Minimum Overburden Principle and the Hydraulic Fracturing Principle have been proposed. Since the surrounding rock mass cannot usually resist high internal pressure of the tunnel, reinforced concrete lining has usually been used, which involves interaction between water, mass of rock or soil and the concrete lining. This lining is always subjected to cracks creating different problems such as water leakage and lining collapse and sometimes causing serious damages. These cracks cause the inner water to flow out to the rock mass. Although using reinforced concrete can reduce the number of cracks, there is always water seepage through it.

Schleiss [2- 4] studied the behavior of pressure intake tunnels and offered a method applicable to the design of such tunnels. The assumptions of this method, which will be discussed in section 2, show that it is applicable to rock masses with acceptable results while for the soil masses, it is preferred to use a method that can consider the behavior of surrounding soil better.

Bian et al. [5] studied couple seepage and stress fields in the concrete lining of the underground pipe with high pressure based on three dimensional elasto-plastic finite element numerical modeling. The coupling principle can be described as follows: the change of stress field leads to the change of permeability coefficient and the redistribution of the seepage field; the new seepage field will produce new seepage force and lead to the change of stress field. The crack expansion and its influence on the seepage and stress fields are studied and computation results show the coupling method is reasonable.

During past years, many researchers have carried out laboratory tests and numerical analyses on this issue and according to the results they have proposed some principles exhibiting the actual mechanism [6-8].

In practice, design of reinforced concrete lining is carried out with the assumption that water pressure acts on just internal surface of the tunnel and the lining is considered rigid. However, this does not come true in reality, because the inner water flow penetrates the soil mass surrounding the tunnel through the developed fractures of concrete lining. It will insert a specific hydro-pressure on its external surface depending on the amount of head loss inside the tunnel. Therefore, the applied loads on rock and lining due to seepage flow and consequent deformations and stresses in the lining system should be taken into account because of hydro-mechanical interaction between the concrete lining and rock. On the other hand, crack width in concrete lining and its permeability vary considerably with rock deformations.

The influence of water penetration on soil mass has been found critical especially in the cases that tunnel is located above the groundwater table and soils are unsaturated and susceptible to water. The most significant phenomenon in this regard is the noticeable variation of the mass of soil parameters such as permeability, friction angle, elastic modulus, and cohesion adjacent to water or while being saturated. It can play an important role in the variation of internal forces in concrete layer. In this paper the effects of the ground strength reduction on stability of concrete lining have been investigated and discussed by studying the case of Dasht-e-Abbas tunnel.

2. Review on Principles of Schleiss Method

As discussed before, cracks occurring in the concrete lining of underground tunnels in high water pressure can cause the inner water to flow out through the crack towards the rock mass and it has been considered as one of the critical issues in this regard. According to previous observations, in unreinforced concrete lining the depth and width of cracks have been found more problematic than the number of cracks. Reinforcing concrete lining for the purposes of decreasing the number of cracks and reducing their widths in a controlled process prevents flowing waters and collapse of the lining [3].

Generally for the design of reinforced concrete lining in underground tunnels only water pressure on internal surface of the lining is considered. This can be reasonable in the absence of water flow through the lining layer and rock mass, which is mostly against the real conditions. It should be noted that in most cases, either ordinary or under pressure tunnels, water flow from the tunnel into the rock mass increases the depth of cracks in concrete lining and consequently due to each head loss in cracks, specific hydrostatic pressure on external surface of lining must be taken into account. The material properties of the cracked concrete, especially its permeability characteristic, will change and hydraulic- mechanical interactions should be considered as well. The commonly used theory for the design of reinforced concrete linings of pressure tunnel [2, 4] considers rock mechanics and rock hydro-mechanics. The rock mechanics is based on deformation analysis and considers the influence of seepage force obtained from seepage calculation, while the rock hydro-mechanics is based on seepage field analysis and considers the change of material permeability induced by deformation.

In addition, after flowing the water into the mass surrounding the tunnel, concrete lining of tunnels may be subjected to external loads caused by water head while discharging the tunnel. It is assumed that external pressure on concrete lining equals underground water height above the tunnel surface. Applying this assumption to pressure intake tunnels with concrete lining seems to be adequate and necessary.

Linings are not completely impermeable. Thus lining in nearly all situations has been shown permeable due to its nature and fractures developed from shrinkage and internal pressure. Hence water may flow in voids of rock mass as tunnel discharge and this causes loading on lining due to less permeability of concrete compared to that of rock. Design method explained in this section accounts for these loads on the lining by considering a greater permeability of rock mass than that of concrete lining.

2.1.Required Assumptions Regarding the Tunnel under Internal Pressure

Regarding the static and hydraulic behaviors of the tunnel and lining, three specific zones are involved in design analyses as illustrated in Fig. 1.

- Zone 1: Cracked concrete lining,
- Zone2: Rock mass affected by seepage flow, and
- Zone3: Rock mass not affected by seepage flow

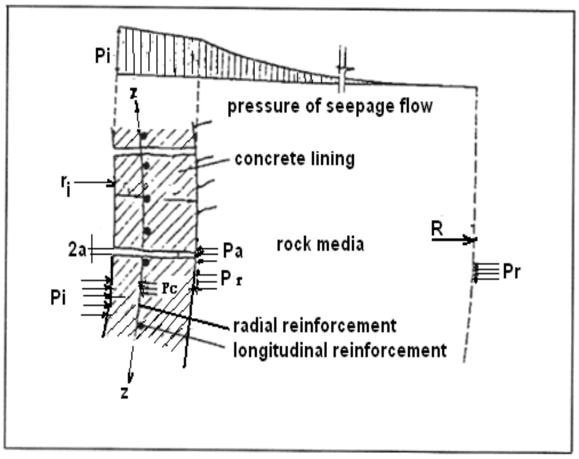

Fig. 1. The analytical model [3]

In this method, radial and axisymmetric behavior in all three zones is assumed. Deformation and permeability characteristics of rock mass are considered homogenous and isotropic and elastic behavior is taken into account. It is assumed that water penetrates just through the cracks and the permeability of concrete located among cracks is ignored. Tension force in reinforced concrete is considered constant and for the calculation of width and spacing of cracks, stress distribution in reinforced concrete between two cracks is assumed parabolic. Total effective pressure is arisen from seepage in cracked concrete lining and mass of rock. In order to estimate the amount of loads on each three zones, mechanical stresses and water pressure should be obtained in boundary zones. It should be mentioned that water pressures are determined from continuity conditions and boundary stresses using consistency equations.

2.2.Required Assumptions Regarding Permeability under External Pressure

In the analytical model used in this method, the axisymmetric condition is taken into account as depicted in Fig. 2. and permeability characteristics of the following zones are assumed to be homogeneous and isotropic:

- Concrete lining
- Crushed stone zone due to explosion affected by the compaction grouting
- Uncrushed stone zone, affected by the flow net.

Permeability of the concrete lining is derived from permeability of the concrete without cracks and also the permeability of the developed cracks in the lining. Permeability of concrete without cracks has usually been quantified less than 10^{-8} m/sec.

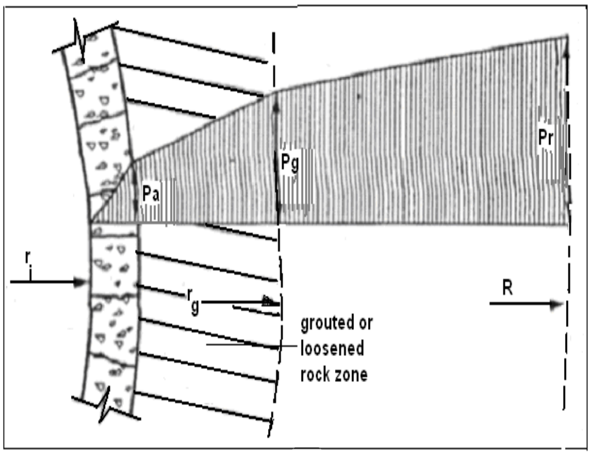

Fig. 2. Seepage flow through cracks of concrete lining in ground mass surrounding the tunnel [4]

In concrete lining, two types of cracks are observed: Radial cracks as a result of concrete shrinkage during construction and longitudinal cracks due to internal water pressure. Table 1 presents an estimation of width and spacing of cracks in concrete lining as a standard.

In this method, to be conservative about external water pressure, minimum values for width of cracks and maximum values for their spacing are used (Table 1). The cracks induced due to the influence of internal pressure tend to become closed while the tunnel is empty or is being discharged because of the compaction of concrete lining by water pressure. However, it has been shown practically that permeability of rock mass cannot be decreased to less than 1 Logan by the grouting method. Therefore, the explosion and plastic deformations of a weak and cracked rock mass which are likely to happen near the underground spaces will increase the permeability of the rock mass [4].

Table 1. The amount of width and spacing of cracks in the concrete lining [4]

	Radial Cracks		Longitudinal cracks	
	Width	Spacing	Width	Spacing
	(mm)	(m)	(mm)	(m)
Unreinforced concrete lining	0.5-1.00	0-12	0.2-0.5	Minimum two cracks
Reinforced concrete lining	0.1-0.3	0.3-0.6	0-0.1	Several cracks at 0.3-0.6

3. Site Specifications of Dasht-e-Abbas Tunnel

Dasht-e-Abbas tunnel has been built for the purpose of transferring water from the reservoir of Karkheh storage dam to the Abbas plains and also to areas of Fakkeh, Ein Khosh, Dehloran and Mousian. With an area of 16450 hectares in south-west of Ilam province, Dashte-e-Abbas is situated at the west of the Karkheh large embankment dam, and is constructed in north-west of the Khoozestan province in south-west of Iran. The location of Dasht-e-Abbas tunnel and the area under irrigation is drawn in Fig.3. According to estimations in primary studies of Karkheh Earth Dam, water demand of this plain was predicted as 178 million m^3/year and it had to be transferred by an adequate tunnel. It was suggested to build a tunnel with the diameter of 4 meters, length of 6.7 km having a capacity of 21.5 m^3/sec. In supplementary survey, by expanding the region of irrigation and considering plains of Fakkeh and Ein Khosh with an area of about 26200 hectares, the required flow rate of this tunnel and its diameter were increased up to 43.6 m^3/sec and 5.5 m, respectively.

In the design, water flow in tunnel was of under pressure type. According to topographical maps, tunnel length is limited to 6.1 km and due to high agricultural potential of the region and its strategic location, it was decided to modify the tunnel design so that it can irrigate cultivation lands of 1000000 hectares. Hence a modified alternative was proposed on the basis of providing flow capacity of 80 m^3/sec at the elevation of 195 meters in the Reservoir of Karkheh dam. Ultimately, after assessing the different design conditions, Dasht-e-Abbas tunnel has been constructed based on the properties presented in Table 1. The longitudinal profile of Dasht-e-Abbas Tunnel is depicted in Fig. 4.

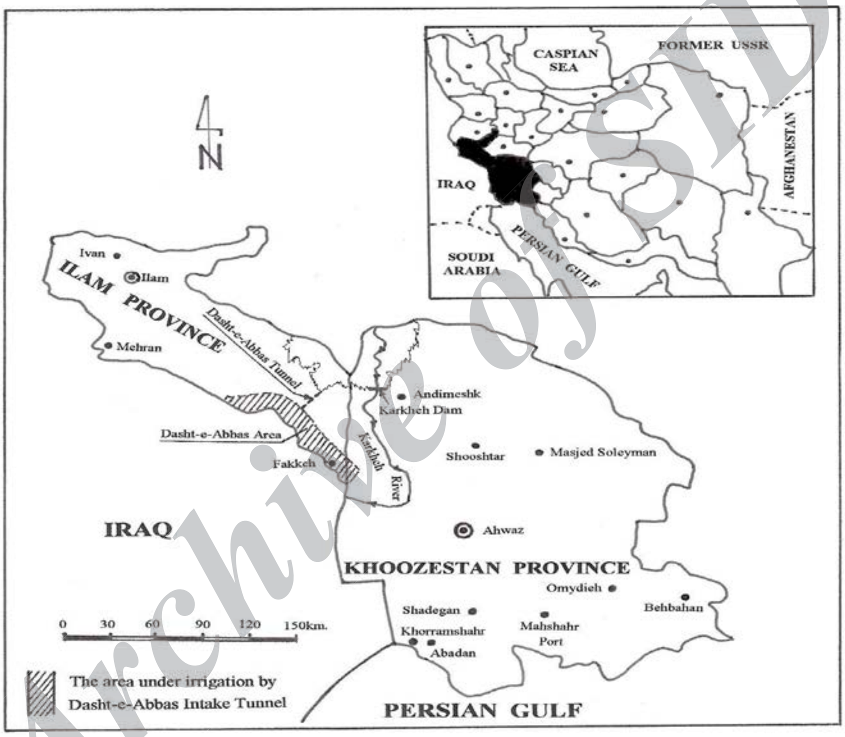

Fig. 3. The location of Dasht-e-Abbas pressure intake tunnel and the area under irrigation [9]

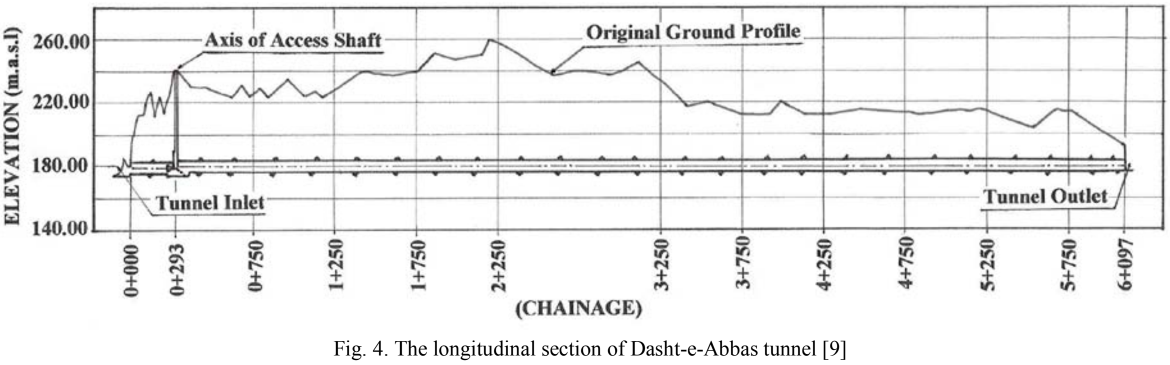

Fig. 4. The longitudinal section of Dasht-e-Abbas tunnel [9]

The ground, in which the tunnel has been excavated, consists of different layers of mudstone and sandstone. Geological report prepared by the consulting firm clarifies the general features of rock masses through the tunnel path as presented here:

- In general, masses of rock in the tunnel path are classified as weak rocks.
- Rock masses have been weathered due to the change in humidity conditions and their strength parameters are reduced.
- These rock masses especially mudstone layers are found to have high potential of swelling.
- Strength parameters of rock mass are subjected to degradation when subjected to water.
- System of joints and cracks in rocks appear haphazardly and non-systematically.
- Ground water level as a local hydro regime is situated below the tunnel invert.

The engineering geology and geotechnical report of the tunnel [10] is based on site investigation including in situ tests in boreholes and specimen laboratory experiments. The parameters of the ground determined from experimental tests on samples taken in exploration boreholes are presented in Table 2.

Table 2. Parameters obtained from experimental tests on samples taken in boreholes [10]

Property	Unit	Range
Dry Density	kN/m^3	23
Saturated Density	kN/m^3	24
Uniaxial Strength	MPa	0.2-25
Cohesion	MPa	0.1
Friction Angle	Degree	25-30
Deformation Modulus	MPa	300-500
Swelling Pressure	MPa	0.2-1.2
Swelling Strain	%	0.5-2.8
Poisson's Ratio	-	0.35

Parameters obtained from triaxial tests in mudstone samples both in the natural state and in the state of being subjected to water are given in Table 3. It can be observed that parameters of materials are characterized highly sensitive to water. According to the parameters in Table 3., the internal friction angle, cohesion and deformation modulus decrease about 1.4, 6 and 7.5 times respectively when subjected to water.

The as built specifications of the tunnel are also summarized as followings:

- Tunnel length: 6100 m
- Internal diameter of the tunnel: 5.5 m
- Lining concrete thickness: 0.55 m
- Concrete cross section reinforcing percent: 0.8%
- Longitudinal slope of the tunnel: 2.5/10000
- Design hydraulic head: 50 m
- Design Flow capacity: 80 m^3/sec

Table 3. Parameters obtained from triaxial tests on mudstone specimens [10]

Property	Unit	Natural State	Adjacent to water
Internal Friction Angle	Degree	28	20
Cohesion	MPa	0.3	0.05
Deformation Modulus	MPa	640	86.25
Unit Weight	kN/m^3	23.76	24.72
Poisson's Ratio	-	0.33	0.33

4. Finite-Element Simulations

In order to study the stability of Dasht-e-Abbass pressure intake tunnel under the conditions of ground strength degradation due to the water penetrating from inside to the media, a two-dimensional numerical model is developed by a finite-element program called PLAXIS [11]. The dimensions of the model were chosen 100m×73m so that the boundaries are far enough not to influence the stress-deformation conditions. The continuum media include 15-node triangular elements in a plane strain model. The typical finite-element mesh used for analysis is illustrated in Fig. 5. Minimum value of Overburden height i.e. 23 meters is selected so as to consider the most critical section in the design. There was no ground water table in the model before the water pressure in the tunnel is inserted but it is assumed that after the tunnel is in the operation stage, the pheriatic surface goes up to the ground surface due to penetration of water under pressure inside tunnel through the cracked lining to the media. In the following sections, the stages of the selected modeling and analysis are explained.

The tunnel surrounding media was assumed to be in dry condition at first, but after applying the internal pressure, it was affected by water. Ground material constitutive model was considered Mohr-Coulomb with the properties given in Table 3. The concrete lining was a 55-centimeter-thick elastic beam element with axial stiffness of EA=1.1×10^7 *(kN/m)* and bending stiffness of EI =2.77×10^5 *($kN/m^2/m$)*.The internal pressure of water was considered radially symmetric and equal to 5 bar.

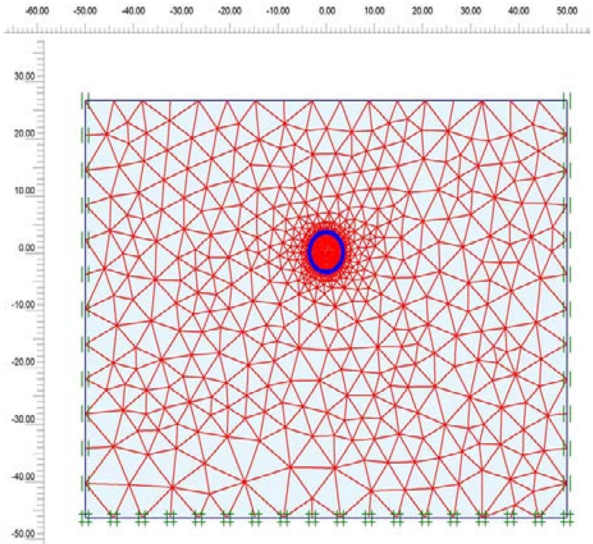

Fig. 5. Typical finite element mesh used for analysis

In order to study the interaction between ground and lining, the interface element was also modeled.

Construction stages in the model and the results of each phase are as follows:

i)Initial Stress Determination By the Properties of Material in the Natural State

In the numerical analysis, the weight of the mass by its natural properties has been made active and the initial stresses were determined.

ii)Tunnel Excavation

In this phase of the analysis, the tunnel space was excavated. Fig. 6 shows the plastic points around the excavated area which is concentrated in wall sides and the relative shear contours i.e. the ratio of existing shear stress to shear strength are illustrated in Fig. 7 which shows that the tunnel walls have become plastic and the relative shear stress reaches 1, verifying the necessity of using a supporting system.

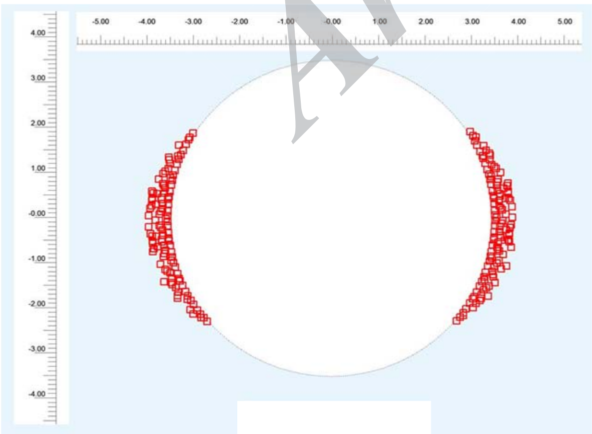

Fig. 6. Plastic points due to tunnel excavation
□ Mohr-Coulomb point, ■Tension Cut-Off point

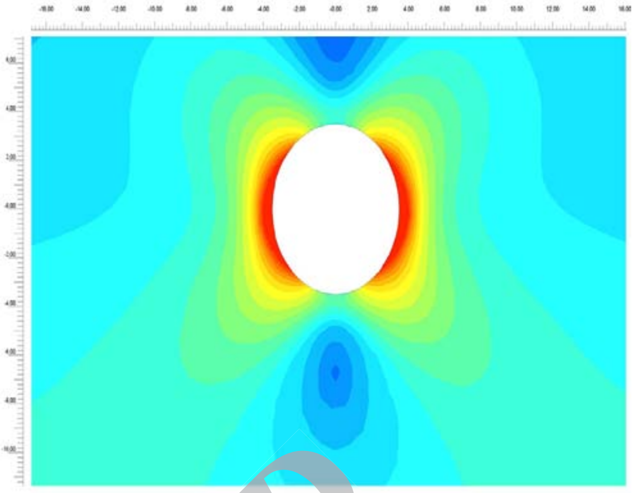

Fig. 7. Relative shear stress contours due to tunnel excavation
Extreme relative shear stress 1.00

iii) Lining Installation

In this stage, the concrete lining is activated and the interaction between the rock mass and the lining is considered in the analysis and the internal forces in the lining before applying internal pressure are determined. Fig. 8 presents the axial force diagram in the lining indicating that all sections of the lining in this stage is under compression.

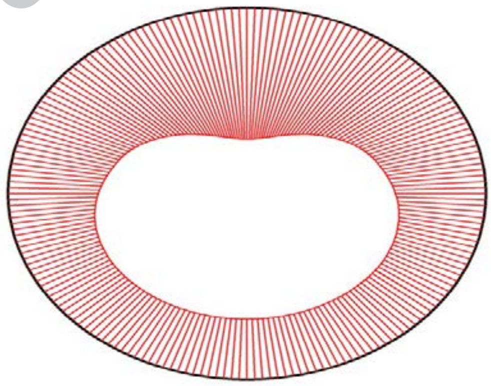

Fig. 8. Axial force diagram in the lining
Extreme contraction 655.97 kN/m

iv) Applying Water Pressure to the Lining

It is assumed, in this phase, that the tunnel is under operation and the water applies its pressure to the lining surface. As exhibited in Fig. 9 lining displacements are in outward direction and they are almost symmetrical. Maximum displacement takes place at the crest equal to 2.34 mm. Fig. 10 presents the axial force diagram in the lining indicating that the lining is subjected to the maximum tension force of 656 kN. The maximum shear force and bending moment are determined 97.93 kN and 8.75 kN.m, respectively.

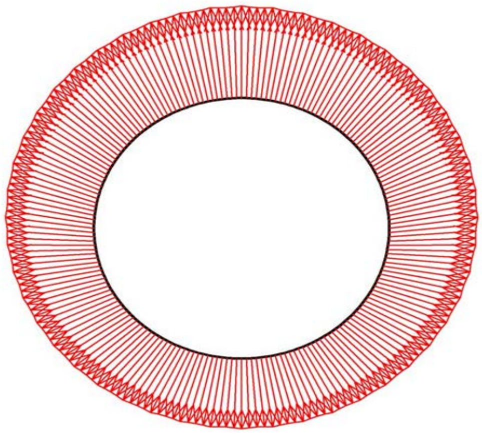

Fig. 9. Displacements of tunnel lining under internal pressure
Total displacement (Utot).Extreme Utot 2.34*10^{-3}m

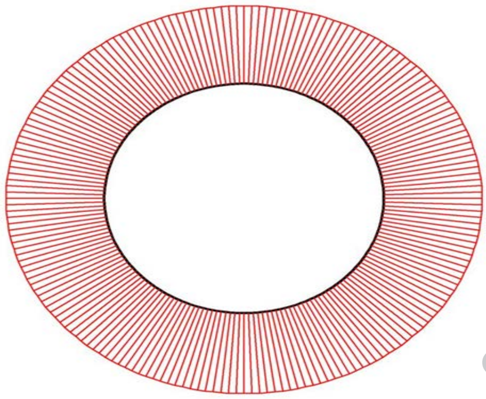

Fig. 10. Axial force diagram in tunnel lining under internal pressure
Extreme axial force -42.39 kN/m

v) Ground Strength Reduction due to Water

To assess the influences of seeping water on the interaction between tunnel lining and rock mass, analyses have been performed varying the level of the water table. The ground water table has been raised up to the surface of the ground and the strength parameters of media around the tunnel are decreased. In spite of anticipation of downward displacements due to reduction of ground strength, upward displacements were observed which can be a result of a decrease in effective stress. Deformed mesh due to ground strength reduction and pore water pressure generation is shown in Fig. 11. Displacement of tunnel lining is presented in Fig. 12 with the maximum value of 188 mm upwards. The analysis results also show that lining is under compressive axial force and shear forces and bending moments are increased significantly. The increase in the bending moment is more than that in the shear force because of the greater displacements happened in the lining. The maximum values of axial force, shear force, and bending moment are *P= 1180 kN, V=136 kN & M= 72.4 kN.m*, respectively.

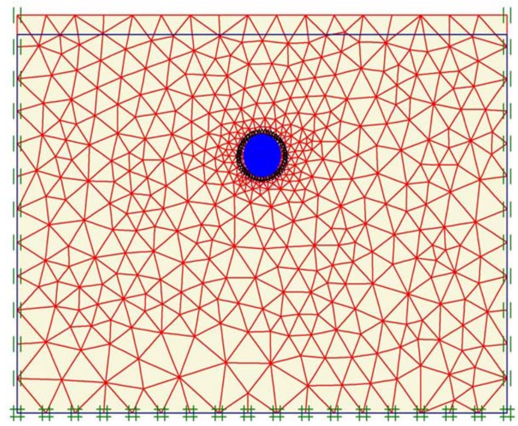

Fig. 11. Deformed mesh due to the ground strength reduction
Extreme Total displacement 187.96*10^{-3}m

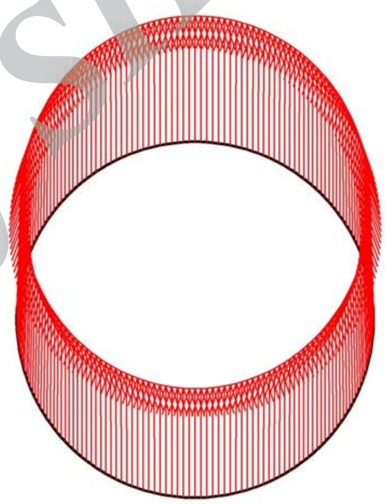

Fig. 12. Displacements of tunnel lining due to strengthReduction
Total displacement (Utot).Extreme Utot 171.15*10^{-3}m

vi) Deleting the Water Pressure to the Lining

In this phase of analysis, the internal pressure on the lining was omitted to study the internal forces in the lining when the tunnel is empty. It was found that the amount of forces diminished but the decrease could not be considerable due to the presence of pore water pressure effects. Fig. 13 includes the axial force diagram in the lining after the elimination of water pressure. The result of maximum axial force, shear force, and bending moment are *P=821.05 kN, V=112.32 kN & M= 13.69 kN.m* respectively.

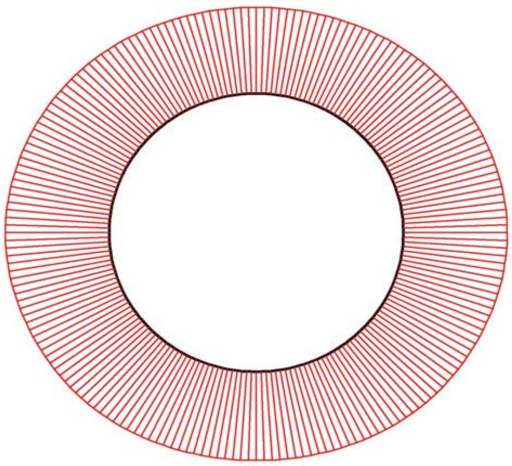

Fig. 13. Axial force diagram after elimination of the internal water pressure. Extreme Axial force 821.05 kN/m

vii) Descending the Ground Water Table

In this phase, the ground water table is lowered to the bottom level of the tunnel. Fig. 14 presents the axial force diagram in tunnel lining and the result of maximum axial force, shear force, and bending moment are $P=-977.12$ kN, $V=10.28$ kN & $M= 13.01$ $kN.m$ respectively which are obviously reduced in comparison with previous stage.

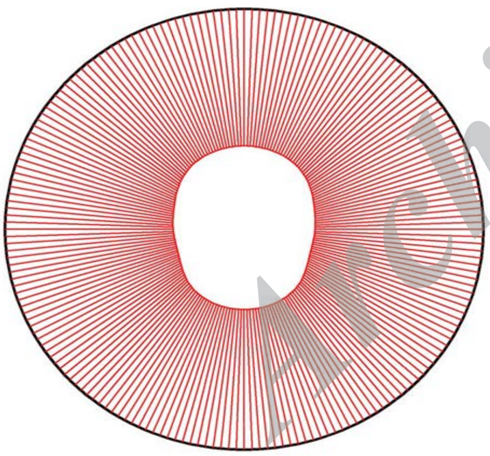

Fig. 14. Axial force diagram in tunnel lining after lowering the ground water table. Extreme Axial force -977.12kN/m

5. Discussion of the Results

The results of internal forces in the critical section of concrete lining in the states of natural ground and ground with the reduced strength due to water are summarized in Table 4. It can be observed that the lining axial force and shear force have an increase of 80% and 40% respectively when subjected to pore water pressure and reduced ground strength parameters. Most important of all is the lining bending moment that is increased more than 8 times indicating the significant influence of ground mass strength reduction on the lining internal forces and displacements.

Stability control of the lining structure of Dasht-e-Abbas Tunnel including the axial force-bending moment interaction capacity and shear capacity in the state of reduced ground strength parameters show that the lining has still the ability to withstand the increased internal forces but the safety factor of the system reduces. However, in case of designing without considering mass strength reduction, the system may face some serious damages. On the other hand, if the reduced strength is less effective on the lining internal forces, the design may be conservative. Meanwhile, using the reduced parameters for analysis on the basis that the tunnel is initially under the effect of water, may lead to unreal responses.

Table 4. Maximum lining internal forces in the critical section

Lining Internal Force	Natural Ground State	Ground with Reduced Strength State
Axial Force (kN)	656	1180
Shear Force (kN)	98	136
Bending oment (kN.m)	8.8	72.4

6. Summary and Conclusions

Sufficient knowledge of material behavior under different loading conditions is essential in obtaining the exact and real responses of structures. Performing structural analyses without considering the soil-structure interaction under the specific condition may lead to noneconomic or unsafe results. The numerical methods including staged construction phases based on sufficient knowledge of loading steps, besides using empirical and analytical methods, may result in appropriate and optimum designs. Using the empirical methods when the ground is sensitive to water and subsequent changes of the media is not recommended. Simulations via numerical methods in these conditions seem essential. In the present investigation, the effect of ground strength degradation on the stability of the tunnel is studied and the following results are obtained:

1) The underground structures are complicated structures dealing with the interaction of ground and lining. The pressure intake tunnels are more complicated, though. The interaction between water, structure, soil, rock and seepage effects, hetrogeneousity in permeability, and hydrostatic or

hydrodynamic pressures during ground motions make the exact analysis of these tunnels difficult. However, since all mentioned factors don't have the same influences, the relatively exact response of the tunnel can be achieved by simplified assumptions.

2) The structural analyses without the consideration of ground-structure interaction cannot solely result in safe and economical design.
3) The empirical methods can be useful for the primary and conceptual design and evaluation. However, in order to have a safe and economical design both empirical and numerical methods are recommended to be used together.
4) The Schleiss analytical method developed for tunnels in rock is better not to be used for tunnels in soils provided without numerical simulations.
5) The sensitivity of the parameters to water has to be evaluated accurately in pressure intake tunnels. The changes of material properties due to water are so important and can have a significant influence on the design and the effect of probable ground strength reduction should be investigated and considered in the lining design.
6) The heterogeneity of materials and their different responses to water may lead to different changes in effective stresses which have to be taken into account in analyses.
7) Due to the conservative design of the lining of Dasht-e-Abbas pressure intake tunnel, the structure is evaluated statically stable during the ground strength reduction due to water.

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