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Evaluation of Seepage Force and Overall Stability Factor Along Proposed Baghdad Metro Tunnel Across Tigris River

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ABSTRACT

Baghdad Metro is a vital project to fulfill the rapidly increased traffic volume requirements. The proposed metro will connect both sides of Baghdad City, passing under the Tigris River. This study employed finite elements software (PLAXIS 3D) to evaluate the seepage force developed around the sub-river segment during different construction stages and for other water levels of Tigris. The study found that when the water level changes from maximum to minimum, the developed seepage force decreases by (8 to 13%) and (22 to 27%) respectively. The seepage forces were found to be maximum during the excavation stage. The concrete lining process led to a noticeable reduction in seepage forces at all locations. The study also implemented the strength reduction theory to assess the overall stability of the tunnel. The study shows that the overall stability factor was minimum during the concrete lining process. As the water level decreased, the overall stability factor increased by (5% - 8%).

Keywords: Baghdad Metro, Seepage force, Plaxis 3D, Overall stability, Finite elements, Tigris River

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تقييم قوة التسرب ومعامل الاستقرار العام على طول نفق مترو بغداد المقترح عبر نهر دجلة

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الخلاصة

مترو بغداد هو مشروع حيوي تم اقتراحه لتلبية متطلبات حجم المرور المتزايد بسرعة. سوف يربط المترو المقترح كلا جانبي مدينة بغداد، ويمر تحت نهر دجلة. استخدمت هذه الدراسة برنامج العناصر المحدودة (PLAXIS 3D) لتقييم قوة التسرب التي ستتولد حول الجزء الذي سيمر أسفل النهر خلال مراحل البناء المختلفة، ولمستويات المياه المختلفة لنهر دجلة. خَلُصت الدراسة الى ان تغير منسوب مياه نهر دجلة من الحد الأقصى الى الحد المعتدل والادنى سببت خفضاً في قوى التسرب بمقدار (8 – 13%) و (22–27%) على التوالي. تم تسجيل اعلى قوى تسرب خلال مرحلة حفر النفق. وجدت الدراسة ان قوى التسرب تنخفض بشكل ملحوظ خلال عملية تبطين النفق بالكونكريت. تقوم الدراسة أيضًا بتقييم عامل الاستقرار الكلي للنفق باستخدام مبدأ تقليل القوة. أظهرت الدراسة ان ادنى معامل الاستقرار كان خلال عملية تبطين النفق. عند انخفاض مستوى الماء في النهر فإن معامل الاستقرار الكلي يزداد بمقدار (5–8%).

1. INTRODUCTION

Tunnel engineering is overgrown in the near past, with more and more tunnels excavated in various types of soils worldwide to supply the grown demand for more land excess. When tunnels are to be constructed beneath the groundwater level, water seepage can cause unfavorable conditions and may sharply affect the overall stability of the tunnel. Several approaches have been presented to accurately evaluate the seepage force **(Zhang et al., 2020)**. **(Bouvard and Pinto, 1969)** studied the behavior of circular tunnels in homogeneous isotropic soil with the assumption of a non-dropped water table. The study suggested that the seepage force induced by water inflow toward the tunnel is:

$$F_{BP} = -\frac{\gamma_w h}{a}\ 1/\ln\left(\frac{R}{a}\right) \tag{1}$$

where: F_{BP}: Seepage force calculated by Bouvard-Pinto's equation, N.

h: depth of tunnel centerline, m

a: radius of the equivalent circular tunnel, m.

They suggest that R is an arbitrary radial distance at which the seepage-induced pore water pressure is negligible **(Bouvard and Pinto 1969)**. In 1986, Schleiss modified Bouvard – Pinto equation by suggesting that the arbitrary constant R is equal to the depth of the tunnel centerline, so Bouvard and Pinto equation can be written in the form of:

$$F_S = -\frac{\gamma_w h}{a}\ 1/\ln\left(\frac{h}{a}\right) \tag{2}$$

where:

F_S: The seepage force is calculated by Schleiss's equation **(Schleiss, 1986), N.**

Fernandez and Alvarez do a further modification by using the method of image well, presented by Harr in 1962 (**Fernández and Alvarez, 1994**), to evaluate the seepage force around the tunnel as a function of tunnel crest open angle (θ') as follows:

$$F_{FA} = -\frac{\gamma_w h}{a}\ \frac{\left[\left(-8\frac{h^2}{a^2}\right)+\frac{4h}{a}\cos\theta'\right]}{1+\frac{4h}{a}(\frac{h}{a}-\cos\theta')}\ \frac{1}{\ln\left[1+\frac{4h}{a}\left(\frac{h}{a}-\cos\theta'\right)\right]} \tag{3}$$

Where: F_{FA}: seepage force obtained from Fernandez-Alvarez's equation. Park and his coworker proposed a new analytical closed-loop equation to determine the seepage force around a circular drained type tunnel in the case of steady-state groundwater flow using the conformal mapping plane given in **(Park et al., 2008)**. the suggested equations have been compared with other existing equations, especially Schleiss' and Fernandez-Alvarez's equations. Two boundary conditions were considered, the first of zero-water pressure and the second is a constant total head (H).

The tunnel's stability during construction is a fundamental matter. Some methods have been proposed for stability evaluation **(Al-Khailany et al., 2022)**. Based on the strength reduction theory of stability, Li YX and Fu H. investigated the stability number of shallow depth tunnels was investigated by Li YX and Fu H., considering the tunnel to be under seepage pressure. The stability number of the tunnel is obtained and compared with the case of no-seepage stability. The study concluded that the stability number significantly dropped when seepage took place. The study shows that the difference between stability numbers before and after considering seepage increases as the depth ratio of the tunnel increase. As the permeability of soil increases, stability number decreases, and water table depth has the same effect **(Yang and Huang, 2009)**. The stability of a large shield tunnel crossing a river with consideration of seepage force has been analyzed by Lu and his coworker using the strength reduction finite elements method. To validate the analysis, two centrifugal models were tested to find the relation between the shield tunnel's support pressure and mid-span settlement. The elastoplastic finite element was adopted to calculate the required support pressure to keep the tunnel stable. Lu et al. concluded that if the tunnel face is supported by pressure more petite than the at-rest pressure of the earth, the stability number under seepage conditions is smaller than that in the case of no seepage. Seepage force increases the stability of the tunnel if it is initially supported by a pressure larger than at-rest pressure **(Lu et al., 2018)**. **(Wang et al., 2017)** tested the long-term effect of seepage on tunnel stability. To effectively treat the tunnel seepage in limestone, it is necessary to clarify water sources and mechanical mechanisms near the tunnel. The geological and hydrogeological information of the Pishuang'ao Tunnel is analyzed. Firstly, finding out that the surface water is the principal supply of the tunnel and that the underground water supply is secondary. According to the field test results, the water source of the tunnel seepage was known. The numerical simulation approach using finite elements software (ANSYS) was used to calculate the stability of the tunnel, the lining, and the surrounding rocks. Also, the analysis was conducted during different development periods of karst and analyzed the changes in its stress, plastic area distribution, bending moment, and shear force. The study concluded that economic and feasible methods could be found to treat the tunnel only when the sources of the seepage in the tunnel are clarified

2. CASE STUDY FOR BAGHDAD METRO TUNNEL CROSSING TIGRIS RIVER

In a city of nearly eight million per capita, traffic congestion has been an enormous problem affecting people's life. The proposed Baghdad metro tunnel will solve this problem with over (21 km) of rails connecting both sides of the city (Karkh and Rasafa) through the Tigris River. The current study profoundly focuses on the crossing-river segment of the tunnel. The general geometrical properties and the soil stratification of the study are presented briefly in **Fig. 1** (Mayoralty of Baghdad) and **Table 1. (NCCLR).**

3. METHODOLOGY

Numerical simulation software (PLAXIS 3D) has been adopted to model the case study under the above geometrical and geological conditions. The software gives results for hydraulic gradient **(PLAXIS 3D Scientific, 2020, PLAXIS Verification manual, 2013)**. The hydraulic gradient has been multiplied by the unit weight of water to obtain the seepage force value according to the principle presented by Das **(Das and Sobhan, 2014)**. The principle of strength reduction has been employed to investigate the overall stability factor of the tunnel. The left and right routes of the tunnel have shown a small margin of difference due to the symmetry of both the geological and geometrical conditions of the tunnel. Therefore, this study will only show the result for the left route of the proposed Baghdad Metro Tunnel **(Hamid and Hussain, 2021)**. The current study adopted the same water level suggested by Hamid and Hussain but with three different construction stages. The first stage is the excavation stage (10 days), the second stage includes the lining of the concrete shield (30 hours), and the third stage represents the consolidation stage (1 year). The adopted period for each stage has been selected based on the limits suggested by **(Al-Taee 2018)**.

Table 1. Soil strata properties for location under Tigris **(Source: NCCLR)**

Layer No.	Depth of layer (m)		Thickness	ρ_s	E	υ	$\phi°$	c	k	e
	From	To		Ton/m^3	kPa	-	-	kPa	m/s	-
1	0	6.5	6.5	2.23	7000	0.4	25	10	1.0 E -8	0.7
2	6.5	8.6	2.1	2.07	2528.2	0.5	5	100	3.0 E -7	0.25
3	8.6	25.8	17.2	1.996	10000	0.45	30	15	5.0 E -8	0.65
4	25.8	27.7	1.9	2.434	17000	0.48	35	14	1.75 E -7	0.75
5	27.7	41.79	14.09	1.996	10000	0.45	30	15	5.0 E -8	0.65

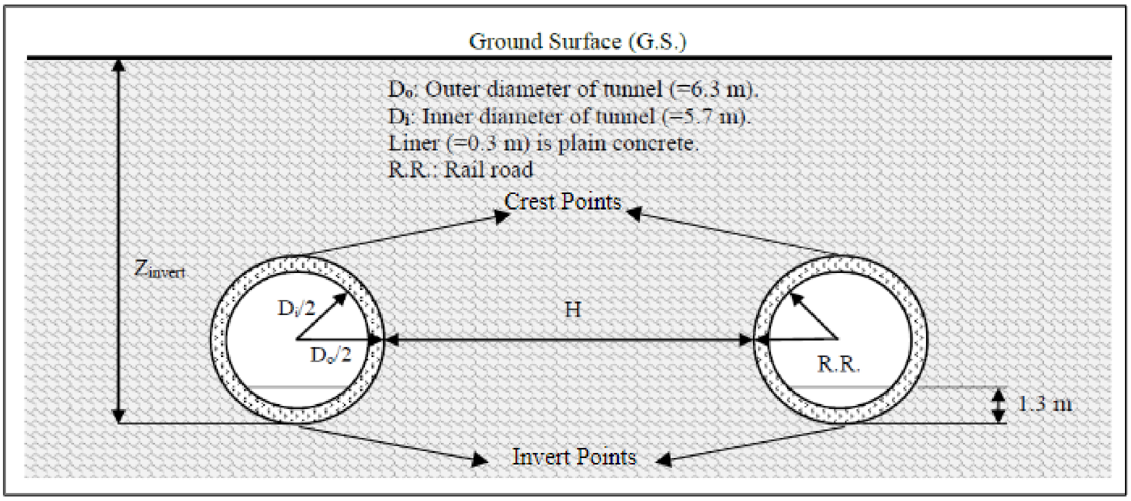


Figure 1. Cross section of the proposed Baghdad Metro Tunnel **(Baghdad Mayorality)**

4. NUMERICAL MODEL

4.1 Validation Model

Su (2017) investigated the influx of water into a submerged circular tunnel built in rocky soil. A new analytical equation was developed to determine the rock mass's seepage amount. A two-dimensional flow in a plane perpendicular to the tunnel axis was used to conceive the case study. Even when the groundwater level is inclined, the analytical calculation that takes the influence of the excavation-induced drawdown into account gives a better estimation of the tunnel inflow than the previous analytical methods. The derived expression was evaluated, and its findings were compared to those obtained via finite element numerical analysis using ABAQUS software. **Fig. 2** is a schematic picture of a circular tunnel constructed beneath a horizontal water table in a semi-infinite aquifer with unlimited width and depth. The tunnel case is modeled as a flow problem in a two-dimensional plane orthogonal to the tunnel axis. Three assumptions were made: (1) The surrounding rock has homogeneous and isotropic permeability; (2) the fluid is incompressible; and (3) there is no flow along the tunnel axis. A two-dimensional numerical mesh was created with a 10 m diameter tunnel drilled at 70 to 350 m beneath the ground surface from the tunnel center. The numerical model boundaries were assumed to be located at a distance not less than 50 times the diameter (D) from the tunnel center to the vertical and bottom boundaries so that the influence of the boundaries on the tunnel water inflow and pore pressure distribution can be omitted, according to **(Zhou 2017).** The ground surface and the permeability of the rock layer were 1.0×10^{-7} m/s.

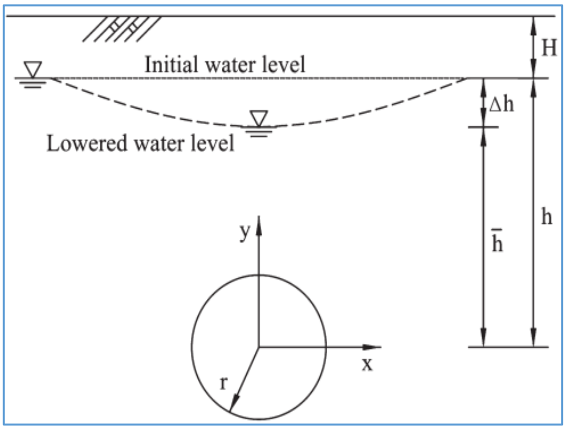


Figure 2. Circular tunnel profile **(Su 2017)**

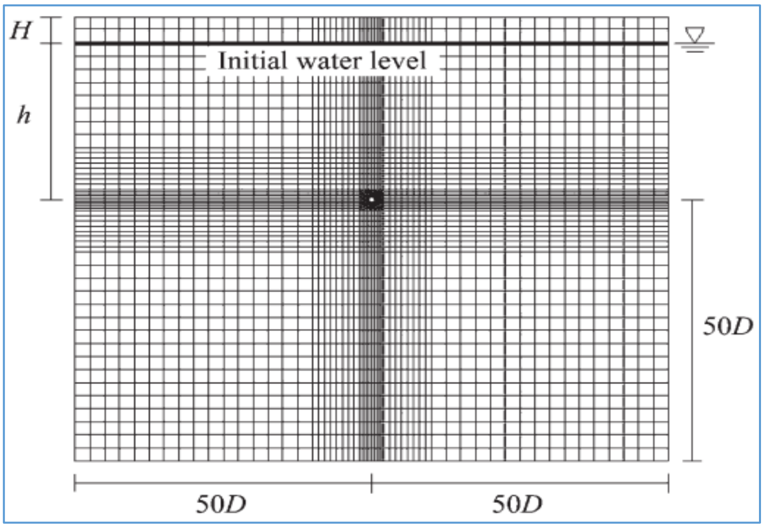


Figure 3. Numerical model of the verification

In **Fig. 3,** the tunnel diameter D = 10 m, the depth from the ground surface to the initial water table H = 50 m, and the initial piezometric head above the tunnel center h = 20 – 300 m. Very fine mesh was generated, the model consists of (12207) elements and (25096) nodes. The results of the numerical analysis of water inflow, due to the excavation of the tunnel and the change in water depth above the tunnel are shown in **Fig. 4.** By comparing the results with the upper bond solution given by Goodman and the lower bound solution given by Moon, Plaxis results are well-located between them and are approximately identical to ABAQUS results obtained by **(Su 2017)**.

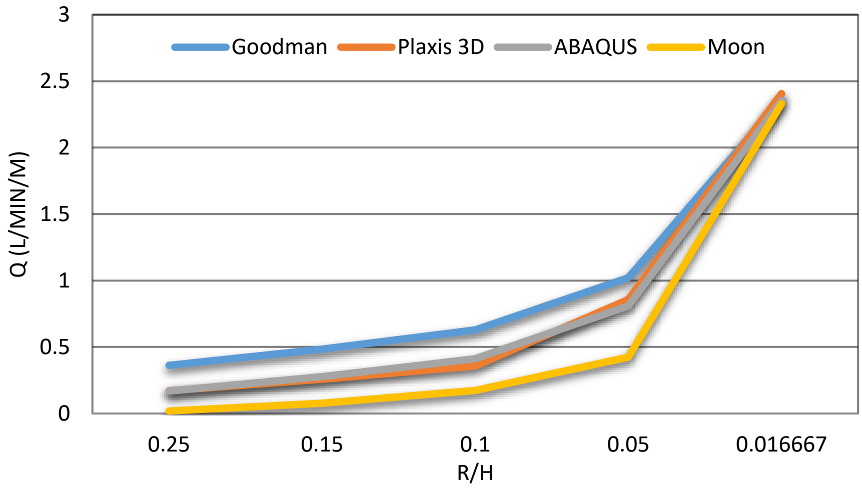


Figure 4. Results of validation model analysis

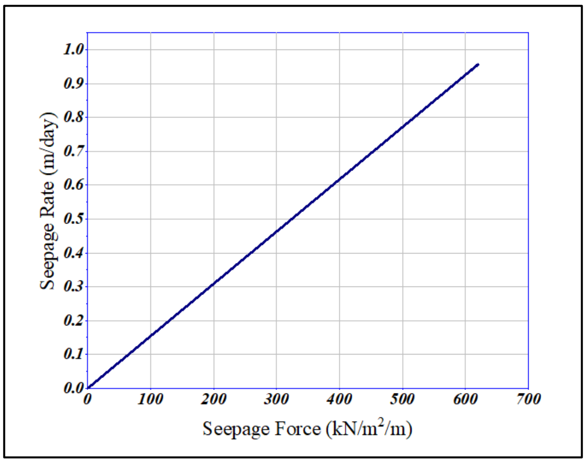
4.2 Case study model

In this study, a three-dimensional finite element model is created using the PLAXIS 3d V20 software to investigate the impact of changing water levels on the quantity and rate of seepage at several chosen sites along the tunnel as it passes beneath a river. The Moher-Columb type of soil strata has been modeled. Tigris river water level is varied and has significantly drooped during the past few years **(Asaad and Abed, 2020)**. The river's height was chosen as the water table site. The average maximum, average lowest, and average mean river depths have been represented by three water table levels (6.09, 3.9, and 1.8) meters **(Issac, 2019)**. With the aid of a tunnel design tool, a fully coupled flow-deformation study has been done on the tunnel. The horizontal extent of the finite element mesh (X-direction) from the centerline of each tunnel route is eight times the outer diameter, and the vertical extent (Z-direction) below the tunnel invert for each tunnel route is 1.5 times the outer diameter. Additionally, a distance (in the Y direction) is eight times the outside tunnel diameter away from the vertical depth. The positions of these borders have been chosen so that the stress-strain-pore pressure field in the domain is not considerably affected by the existence of barriers beyond them **(Yoo, 2005, Yoo et al., 2005, Yoo et al., 2007, Yoo and Kim, 2008)**.

5. RESULTS AND DISCUSSIONS

The relation between seepage rate and seepage force at any time and water level only depends on the permeability of the soil mass as described by Darcy law. For the current case study, the relation is graphically represented by **Fig. 6**, which shows that the ($Q - F_s$) relation is linear with a slope equal to the permeability coefficient.

The results of seepage forces developed at the selected location during the excavation stage are presented in **Tables 2, 3, and 4**. The results indicate that in each section, the maximum seepage force will be developed just after the excavation of that section. Frontal points exhibit higher forces. The seepage forces that act at the crest and invert points of the mid-plane are relatively smaller than forces at the frontal and rear face. This proves the theory of two-way drainage, as water particles will flow out of the soil mass through the nearest end. With the maximum level of Tigris River, the maximum seepage force acts at the frontal face crest and invert point are (611 kPa) and (757 kPa), respectively. The numerical analysis shows that when the Tigris water level dropped from maximum (6.09 m) to average (3.9 m), the seepage force reduced by (7% – 9%). Further decrease is noted (22% - 26%) when the water level of the Tigris falls to its minimum value (1.8 m).



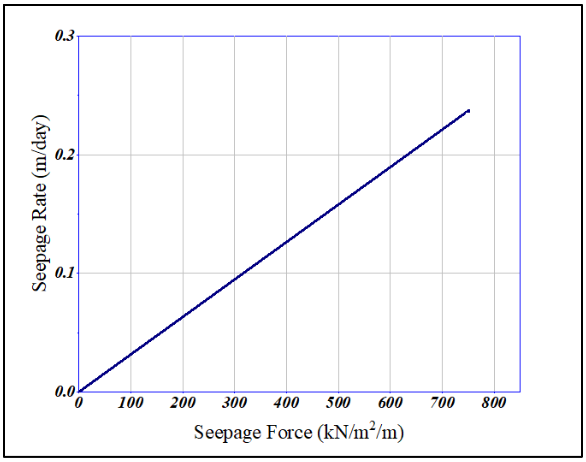


Figure 6. Relation between seepage rate (Q) and seepage force pressure (F_s)

Table 2. The variation of seepage forces (kPa) at the fontal face of the left route of the Baghdad metro tunnel with different Tigris water levels during the excavation process

Time (day)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
1	614.7385	783.7011	573.1822	729.9392	456.8737	578.7633
3	608.9799	756.2665	567.8129	704.3866	452.5939	558.5028
5	611.2023	756.5908	569.885	704.6887	454.2456	558.7423
7	611.3539	757.5499	570.0264	705.582	454.3582	559.4506
9	611.1413	757.2339	569.8281	705.2876	454.2002	559.2172
10	611.1077	757.1241	569.7968	705.1854	454.1752	559.1361

Table 3. The variation of seepage forces (kPa) at the midplane of the left route of the Baghdad metro tunnel with different Tigris water levels during the excavation process

Time (day)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
1	0.6123	0.4937	0.5691	0.4628	0.4563	0.3622
3	6.7526	5.3725	6.2759	5.0362	5.0314	3.9413
5	110.6673	164.4532	102.8542	154.1585	82.4582	120.6429
7	2.1260	56.2514	1.9759	52.7300	1.5841	41.2660
9	11.3599	73.6503	10.5579	69.0398	8.4643	54.0299
10	11.7334	77.4460	10.9050	72.5979	8.7426	56.8144

Table 4. The variation of seepage forces (kPa) at the midplane of the left route of the Baghdad metro tunnel with different Tigris water levels during the excavation process

Time (day)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
1	0.4742	0.5925	0.4404	0.4403	0.3508	0.5518
3	0.6832	0.0659	0.6345	0.0490	0.5053	0.0614
5	0.8535	2.6186	0.7927	1.9459	0.6313	2.4390
7	2.6276	0.9222	2.4403	0.6853	1.9436	0.8590
9	48.6034	67.2078	45.1380	49.9421	35.9520	62.5973
10	612.6152	727.0759	568.9357	540.2901	453.1514	677.1985

The effect of the concrete lining process on the seepage forces has been investigated, and the results are shown in **Tables 5, 6, and 7**, which show that the seepage forces are reduced noticeably during the lining. At the end of the lining stage, the seepage force at the frontal face of the left route of the proposed tunnel was found to be (8.5 kPa) and (23.25 kPa) at the crest and invert point, respectively. The results indicated that a vital caution should be taken when installing the concrete lining to the midplane due to the presence of (375.65 kPa) force at the inverted point; meanwhile, the seepage forces matrix at the crest point of the same location is approximately nil. The numerical analysis shows that when the Tigris water level dropped from maximum (6.09 m) to average (3.9 m), the seepage force reduced by (7% – 13%). When the water level of the Tigris falls to its minimum value (1.8 m), seepage forces are (23% - 28%) less than that recorded at the maximum water level.

When the consolidation occurs in the soil mass, no further considerable seepage forces have been recorded, regardless of water level or point location. The numerical results are presented in **Tables 8, 9, and 10.**

Table 5. The variation of seepage forces (kPa) at the fontal face of the left route of the Baghdad metro tunnel with different Tigris water levels during the lining process

Time (hours)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
0.5	134.9847	377.3811	125.8598	351.4927	100.3206	278.6959
5	12.3541	85.3841	11.5189	79.5268	9.1816	63.0562
10	5.0718	21.7164	4.7290	20.2266	3.7694	16.0375
15	17.7617	38.3405	16.5610	35.7104	13.2005	28.3145
20	14.8601	43.3646	13.8556	40.3898	11.0440	32.0247
30	8.4915	23.2564	7.9174	21.6610	6.3109	17.1749

Table 6. The variation of seepage forces (kPa) at the midplane of the left route of the Baghdad metro tunnel with different Tigris water levels during the lining process

Time (hours)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
0.5	11.4152	77.9097	10.6093	73.0325	8.5055	57.1545
5	6.6419	58.9165	6.1730	55.2283	4.9489	43.2211
10	5.6394	48.3157	5.2412	45.2911	4.2019	35.4444
15	2.2669	375.6450	2.1068	352.1296	1.6890	275.5732
20	0.0181	12.8400	0.0169	12.0362	0.0135	9.4194
30	0.0107	5.0006	0.0100	4.6876	0.0080	3.6684

Table 7. The variation of seepage forces (kPa) at the rear face of the left route of the Baghdad metro tunnel with different Tigris water levels during the lining process

Time (hours)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
0.5	609.2353	716.6044	565.7968	667.4453	450.6514	532.5087
5	582.4422	592.7424	540.9141	552.0803	430.8325	440.4669
10	597.1130	601.1385	554.5388	559.9004	441.6845	446.7060
15	560.6449	551.8821	520.6709	514.0230	414.7090	410.1036
20	579.9815	584.7299	538.6288	544.6175	429.0123	434.5128
30	98.3115	123.0226	91.3019	114.5833	72.7210	91.4181

Table 8. The variation of seepage forces (kPa) at the fontal face of the left route of the Baghdad metro tunnel with different Tigris water levels during the consolidation process

Time (months)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
0	8.58E-01	9.74E-01	8.00E-01	9.07E-01	6.38E-01	7.19E-01
6	2.67E-04	4.07E-04	2.49E-04	3.79E-04	1.99E-04	3.01E-04
12	1.47E-04	1.92E-04	1.37E-04	1.79E-04	1.09E-04	1.42E-04

Table 9. The variation of seepage forces (kPa) at the midplane of the left route of the Baghdad metro tunnel with different Tigris water levels during the consolidation process

Time (months)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
0	5.33E+02	4.27E-01	4.96E+02	4.00E-01	3.97E+02	3.13E-01
6	3.27E-03	4.68E-04	3.04E-03	4.39E-04	2.44E-03	3.43E-04
12	2.25E-04	2.29E-05	2.09E-04	2.15E-05	1.67E-04	1.68E-05

For the overall safety analysis, it was found that at the end of the excavation process, the safety factor was found to be (2.403, 2.511, and 2.609) at maximum, average, and minimum water levels, respectively. The results show that the factor of safety at the end of the concrete lining process is (2.497) for maximum water level and increased to (2.551) and (2.713) at average and minimum water levels, respectively. For the consolidation period, it was found that the overall safety factor is (2.391) at maximum water level and (2.557) at minimum water level. The results of the safety analysis are summarized in **Fig. 6**.

Table 10. The variation of seepage forces (kPa) at the rear face of the left route of the Baghdad metro tunnel with different Tigris water levels during the consolidation process

Time (months)	Maximum Water Level		Average Water Level		Minimum Water Level	
	Crest	Invert	Crest	Invert	Crest	Invert
0	5.04E+00	2.60E+00	4.68E+00	2.42E+00	3.73E+00	1.93E+00
6	5.04E-04	2.39E-03	4.69E-04	2.22E-03	3.73E-04	1.77E-03
12	4.08E-04	7.21E-04	3.79E-04	6.71E-04	3.02E-04	5.36E-04

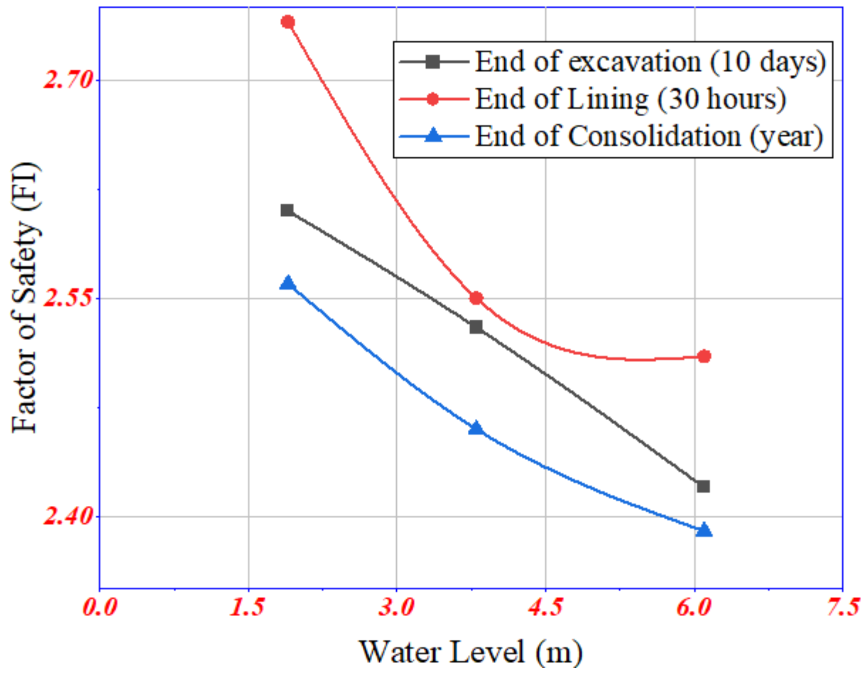


Figure 6. Results of overall stability analysis variation with Tigris water level

6. CONCLUSIONS

- The invert point of each longitudinal cross-section exhibited a higher seepage force than the crest point of the same section due to the relatively higher permeability coefficient of sandy soil.
- The magnitude of seepage forces is directly proportional to the river water level. Still, the depth of the water level above the tunnel does not affect the seepage force – time relation when the water level change from maximum to average and minimum, the developed seepage force is decreased by (8 to 13%) and (22 to 27%), respectively.
- The seepage forces are shown to take place only during the tunnel construction, as the results show no significant forces developed during the consolidation (working) stage.
- The tunnel stability analysis indicates that the overall stability factor of the tunnels falls in the range of (2.35 – 2.75) regardless of the construction stages and the Tigris water level, which is considered stable. However, the lining stage is regarded as the most critical stage (the least safety).

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