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A Practical Geotechnical Analysis of in situ Stress Variations and Hydraulic Stability of Small Weirs Using SEEP/W and SIGMA/W Simulation

Riaed S. Al Siaede

Geology and Geotechnics, Missan University, Engineering College, Missan, Iraq

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Abstract

Geotechnical soil problems underneath foundation of hydraulic structures occurs due to engineering soil properties, geological setting and hydraulic properties of the projects. Two finite element programs of Geoslope 2012 software, SIGMA/W and SEEP/W, were used for analysis of in situ stresses, load deformation behavior, seepage quantity and vertical gradient below Teeb weir foundation, to compute factors of safety against seepage uplift. The site soil is a granular (gravel, sand and silt), weakly cemented soil cohered by gypsum and clay materials. The area has low lying topography, with slightly tectonic activities. The model results show that the upstream side stresses are reduced while the pore pressure are increased, indicating decreased stability. Soil displacement and settlement were measured and the effects of these displacements on the low cemented soil particles were discussed. The pressure distribution and vertical hydraulic gradient measured and used for analyze the weir stability. Finally, the soil potential failure zones were drawn to fix the main risks in each sides of the weir.

Keywords: Factor of Safety, Failure zone, Effective stress, Load deformation analysis, in situ analysis, Steady state analysis.

تحليل جيوتقني عملي لتغيرات الإجهاد في الموقع والاستقرار الهيدروليكي للأوزار الصغيرة باستخدام محاكاة SIGMA / W و SEEP / W

رائد ساعي الساعدي

قسم الهندسة المدنية، كلية الهندسة، جامعة ميسان، ميسان، العراق

الخلاصة

المشاكل التي تحدث في تربة الأساس للمنشآت الهيدروليكية عموماً والسدود خصوصاً تعتمد على المواصفات الهندسية للتربة والخواص الجيولوجية للموقع إضافة إلى المواصفات الهيدروليكية للسد نفسه.

تم استخدام تطبيقي SIGMA/W, SEEP/W ضمن برنامج Geoslope 2012 لحساب الاجهادات الاولية في التربة الواقعة تحت اساس سد الطيب الغاطس، في محافظة ميسان، قبل انشاء المشروع كما تم حساب التغيرات المتوقعة في هذه الاجهادات بعد انشاء السد. إضافة إلى حساب التشوه العمودي وكمية المياه المتسربة أسفل جسم السد وتقدير التغير في الضغط الهيدروليكي العمودي للماء في التربة وذلك لحساب معامل الامان. تربة المنطقة تمتاز بكونها تربة خشنة إلى ناعمة الحبيبات تتدرج في الحجم من الحصى إلى

السلت وتكون حبيبات هذه التربة مترابطة فيما بينها بمواد الجبس او الطين. كما تمتاز منطقة السد بطوبوغرافيتها المنخفضة ونشاطها التكتوني المنخفض. بينت نتائج الدراسة ان قيم الاجهاد الفعال والكلي تتخفف مع ارتفاع الضغط المسامي في جانب اعلى السد مما يشكل منطقة عدم استقرار. كما تم حساب الازاحة في التربة ضعيفة التماسك تحت جسم السد وتأثيرها على استقرارية المشروع. اخيرا تم حساب توزيع الضغط والتغيرات في التدرج الهايدروليكي كما تم تحديد مناطق الانهيارات المتوقعة تحت جسم السد و اقتراح المعالجات لها.

Introduction

Hydraulic structures as dams, weirs and ducts are important to protect the areas of flooding and to gather and supply water during drought seasons [1,2]. The construction, operation and maintenance costs of these structures are increased with the unexpected site foundation problems due to the treatment operation to support these types of soil problems. Examples of these problems include seepage piping erosion and quick sand in the upstream and underneath structure foundations [3, 4]. Climate changes increased the drought and water crisis in arid and semi-arid areas, causing a requirement of new facilities to control and benefit from water resources in these areas [5]. Weir is an overflow structure that stretches across an open channel of water and alters the channel's flow characteristics, blocking the flow of water and causing it to pool behind until it is deep enough to flow over the top of the weir [6]. The velocity and flux of the seep water underneath weir foundations, the uplift pressure, and piping erosion resulting from this seep represent the most serious problems in weir stability [7]. Numerical modelling is an approach developed to simulate solid materials and fluids before and after completing and operating the project [8]. The Geo-studio software of GEOSLOPE company is a package of geo-engineering software developed to deal with different geotechnical problems. This software includes many programs to deal with different geotechnical problems, including SIGMA/W and SEEP/W that were used in this study. According to GEOSLOPE International, "SEEP/W is a finite element CAD software product for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock". Its comprehensive formulation allows one to consider analyses ranging from simple, saturated steady state problems to sophisticated, saturated/unsaturated time-dependent programs. SEEP/W is a useful tool that uses numerical modelling to solve complex groundwater seepage problems [9,10,11], while SIGMA/W is a program used to simulate and analyse soil stress distribution, the effect of static load on initial stress redistribution and the nature and amount of resulting deformations [12]. The properties, limitations and specifications of these programs were explained by many researchers [13,14].

1. Objectives of the Study

This study uses a practical approach to simulate and solve Teeb weir project model and find soil problems underneath weir structure. The following objectives were determined for this study.

- a. To compute in situ ground stresses (total and effective), using SIGMA program.
- b. To estimate post construction deformation (elastic vertical settlement), stress redistribution and potential weak soil zones underneath weir foundation.
- c. To find the flow rate beneath weir foundation and compute the factor of safety against uplift pressure.
- d. To estimate the stability of the foundation against liquefaction by studying pore water pressure distribution model.

3. Teeb Weir Location

Teeb weir site is shown in Figure -1 at UTM coordinates of 38 S 702085 m E and 3582581 m N. The site is located to the northern east of Missan province, Southern Iraq.

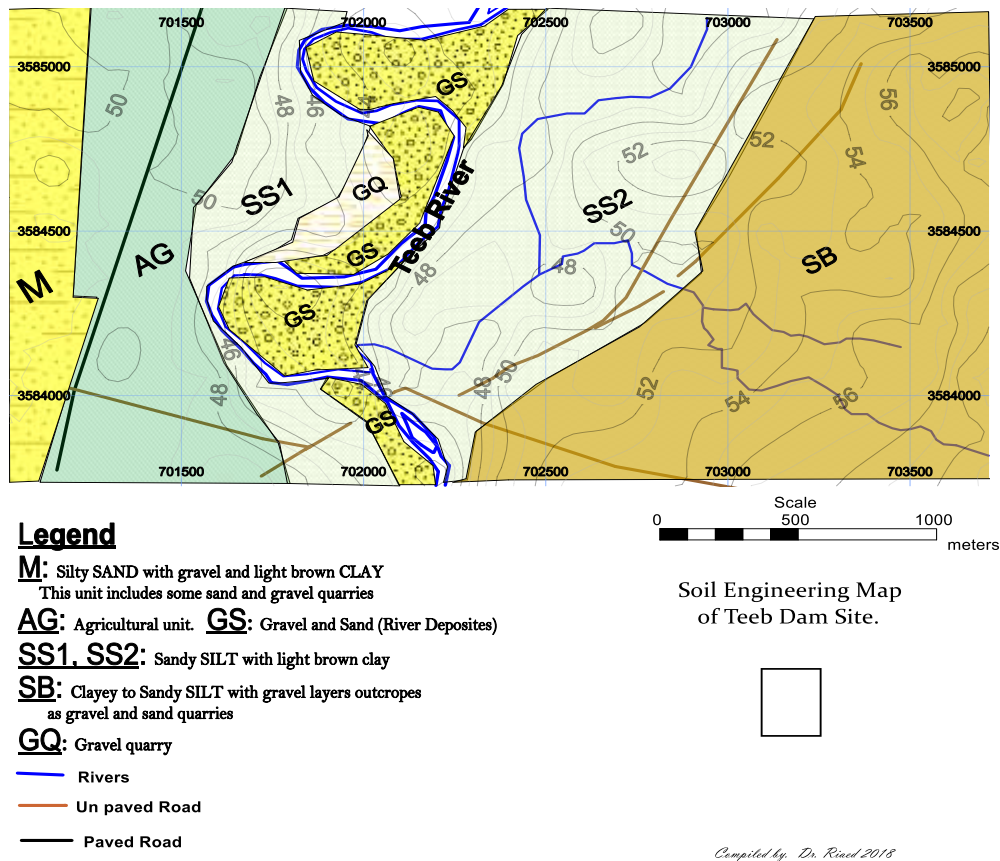


Figure 1- The Location Map of Teeb Weir.

4. Geological and Hydrological Setting

Topographically, the area is of a flat, low-lying topography (elevation is about 25m above sea level), blanked by alluvium, dunes, marsh or inundated plain deposits in relation to drainage systems of Zagros mountains to the north and north east [1]. These deposits form alluvial fans in some parts of the area. North and north east, the ground rises slowly then more abruptly to reach elevation of 300m in the mountainous area. The tertiary formations outcrops in the anticlinal structures North West-South East trending, an echelon, and characterized by steep southwest limbs. Those structures outlined the southern limit of Zagros folded belt. Teeb River flows from Zagros Mountains, Iran, crossing Iraq borders to the North East part of Missan province (Figure- 1). The River length, from the source to estuary, is about 165 km with a basin area of 3637 km². The slope of the River course is about 50 cm/km. The hydrological properties were measured [15] in four stations along the river course (Table-2).

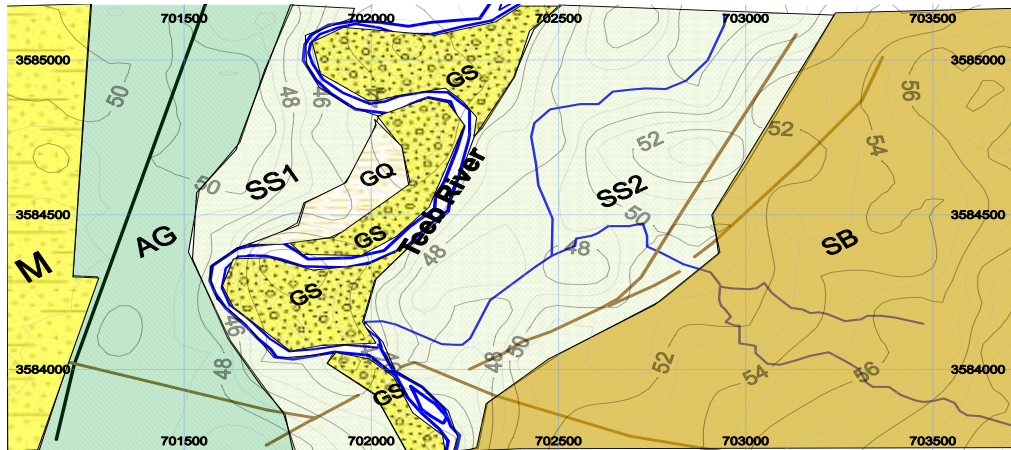
5. Geotechnical Soil Properties

The geotechnical and topographical surveying data were used with the geological and remote sensing data to draw an engineering geological map (Figure-2). The construction material quarries near the weir site, the soil succession of which is shown in Figure- 3. Missan Engineering Bureau completed the geotechnical investigation of the weir site [15]. Eight boreholes were driven along the proposed weir axis to a depth of 25m below the ground level. The soil succession and soil engineering properties are represented in Figure- 3 and Table- 1;

- An upper layer: very stiff brown silty gravel SAND. This layer extends to 3.5 meters below the ground surface.
- A lower layer: Dense brown sandy gravel with silt and gravelly sand with silt. This layer extends to a thickness of 24m.

Table 1-The Geotechnical Properties of Teeb Weir Site [15, 16]

Soil Type	Soil Cohesion C (kN/m ²)	Friction Angel ^o ϕ	Elastic modulus E (Mpa)	Poisson's Ratio ν	Soil Unit Weight (kN/m ³) γ	K Hydraulic Conductivity m/sec
Silty Sand	10	15	8	0.35	18.5	10 ⁻⁵
Sandy Gravel	3	14	9	0.4	20	10 ⁻³



Legend

- M:** Silty SAND with gravel and light brown CLAY
This unit includes some sand and gravel quarries
- AG:** Agricultural unit. **GS:** Gravel and Sand (River Deposites)
- SS1, SS2:** Sandy SILT with light brown clay
- SB:** Clayey to Sandy SILT with gravel layers outcrops as gravel and sand quarries
- GQ:** Gravel quarry
- Rivers
- Un paved Road
- Paved Road

Scale
0 500 1000
meters

Soil Engineering Map of Teeb Dam Site.



Compiled by: Dr. Riad 2018

Figure 2- The Teeb Soil Engineering Units Map.

Table 2-Hydrological properties of Teeb River [15,16].

No	Metering station site	UTM Coordinates (m)		Cross-sectional area m ²	Flow rate m ³ /sec	Discharge m ³ /sec	Distance from Iranian borders (km)
		E	N				
1	Teeb station bridge	704405	3590062	950	1.5	1425	2
2	Syed Youssef Bridge	703179	3573888	910	1	910	19
3	Engineering bridge	705406	3565328	900	1	900	26
4	AL-Shuwaikh Bridge	712085	3249402	800	1	800	35

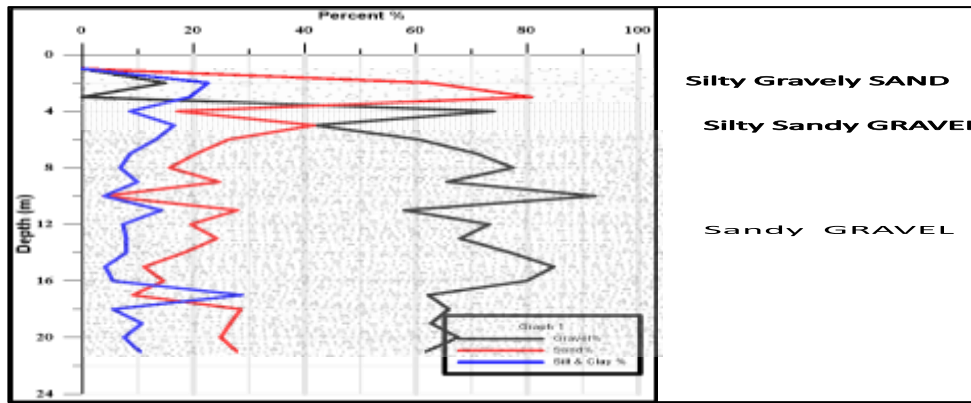


Figure 3- Teeb soil succession in the soil investigation bore holes in the weir site.

6. Methodology

a. Insitu Stress Analysis

The pre-construction soil stresses are important to analysis the expected soil behaviour. SIGMA/W in situ linear elastic analysis method was used where initial vertical total and effective stresses and pore water pressure were computed according to the following approach [17];

$$\sigma_v = \gamma h \quad \dots (1)$$

$$u = \gamma_w h_w \quad \dots (2)$$

$$\sigma_v' = \sigma_v - u \quad \dots (3)$$

Where, σ_v are total vertical stress, σ_v' effective vertical stress and u pore water pressure, respectively. h are depth and γ unit weight of soil, h_w : unit weight and depth of water

The water table is taken as 1m below ground surface [16]. Table-3 shows the parameters of the study model.

b. Stress Variations after Weir Construction

Load deformation analysis of SIGMA/W was used to simulate the stress variations in Teeb weir foundation soil. The total vertical stress and pore pressure is increased due to weir body load and the upstream water level height. The linear elastic approach was used to solve this model. The weir load was computed according to the geometry and reinforced concrete density as 88 kPa, while the material properties were the same as in the in situ model (Table-3). The elastic settlement and soil shear stress distribution in the foundation soil were also computed to find the unstable foundation soil zones.

c. Seepage Flux and Factor of Safety

The volume and velocity of water seeps through weir underneath soil were simulated by SEEP/W software. The downstream weir toe is the most critical area under any weir structure, whereas piping and excessive seepage can occur. In the steady state analysis, only saturated material properties were selected to represent soil regions, with hydraulic conductivity equal to 0.001 m/sec. The horizontal to vertical effective hydraulic conductivity ratio was simulated with a value equal to 1 ($K_y'/K_x'=1$). The interface material type was used to represent the cutoff wall (Table-3).

The seepage flux below weir foundation was computed directly by a solved model. Factor of safety against piping (FS_{exit}) is not computed directly by SEEP/W and, thus, information of seepage gradients at nodes within the finite element mesh were provided for computing factors of safety against piping [11]. The factor of safety is computed by equation (4) as follows;

$$FS_{exit} = \frac{\sigma_v}{i \cdot \gamma_w} \quad \dots (4)$$

Where;

γ_w : Submerged unit weight of weir foundation soil.

i is the y gradient or vertical hydraulic gradient of water.

The head boundary conditions were used in the study model because there was a free water present in the model. In this type of boundary condition, water elevations in upstream and downstream are used.

d. Finite Element Model

The Models in SIGMA/W and SEEP/W were built by the same procedures. These procedures started with drawing the geometry of the model then defining the model regions. The boundary

conditions and material properties were used as input to the software and fixed on the model. These procedures were explained in the software manuals in detail [11,12]. For this study the geometry and meshing are explained briefly in the following;

Geometry: The design of Teeb weir was achieved by the Engineering Designs Directory, Ministry of Water Resources [16]. This design was used to draw the weir cross section (Figure-4). The crest has a 6.5m height above ground level and a width of 6.5m. The weir upstream cutoff wall has a depth of 5.9 m below ground level. The cutoff was suggested to reduce water seepage pressure and seepage velocity of the soil underneath weir foundation. The thickness of the cut off wall is 0.75m.

Table 3- The Input parameters of SIGMA/W and SEEP/W models

Model Property	SIGMA/W	SIGMA/W	SEEP/W
Analysis Type	Insitu	Load-deformation	Steady state
Boundary Condition	Fixed X Fixed XY	Fixed X Fixed XY Weir Load	Hydraulic Head
Material Properties	Linear elastic Effective drained	Linear elastic Effective drained	Saturated only (Soil) Interface (Cut off)
Soil Unit weight (kN/m ³)	20	20	-----
Poisson's Ratio	0.4	0.4	-----
Modulus of Elasticity (kPa)	9000	9000	-----
Hydraulic Conductivity (m/s)	-----	-----	10 ⁻³

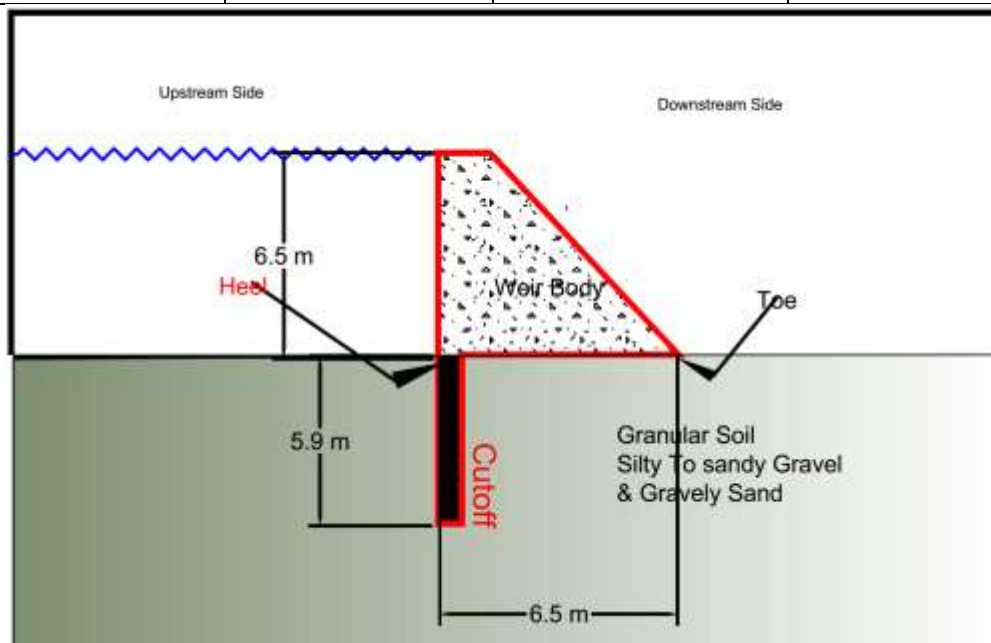


Figure 4- The cross section of Teeb Weir [16].

Meshing: The finite element model of quads and tringle mesh pattern was used to simulate the study problem. The approximate global element size is 5m, while the constructed mesh has 2232 nodes and 2132 elements (Figure- 5).

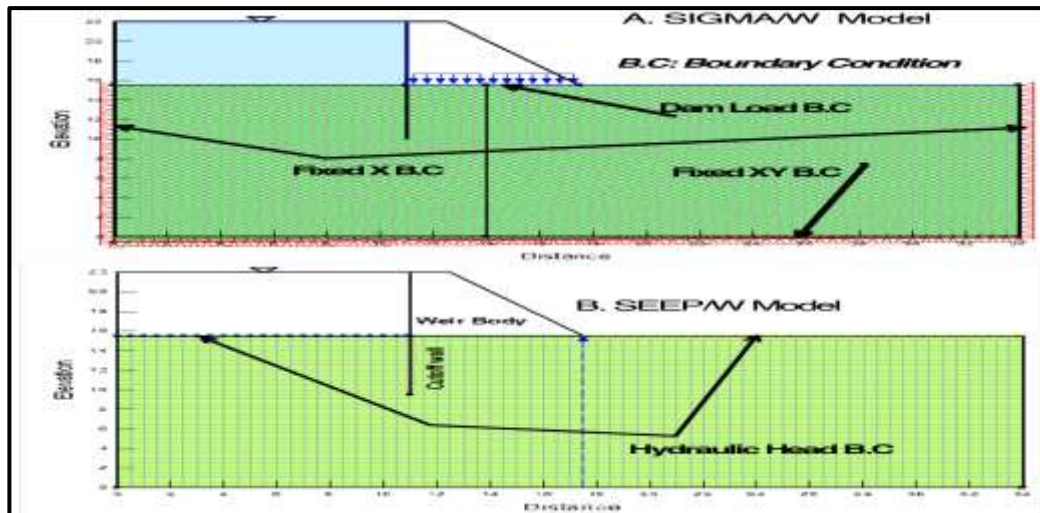


Figure 5- Finite element mesh and geometrical elements of Teeb Weir (A. SIGMA/W and B. SEEP/W)

7. Analysis of Results

The SIGMA/W results of in situ and load deformation analysis methods are represented in Figures-6 and 7, where the increase in the vertical total stress will increase the soil stability below weir structure due to surcharge load, while the total head increase in the upstream dam side, due to water level rising in the weir reservoir, will reduce the total stress due to the increase in pore water pressure. These in situ and post load stresses are represented in Figure- 8, where the in situ curves (Figure 8.a) before the dam's body construction (Figure- 8.b) show stress changes after dam body installing (before filling the dam reservoir). It is obviously shown that the soil stability against the liquefaction effect will increase after the dam body construction as a result of the increasing of the total and effective vertical stresses. The load deformation curves show the redistribution of the weir body load through the soil column underneath the dam body, as well as the behavior of the effective stress curve. The previous discussion showed that the load imposed on the granular soil will increase the total vertical stresses and reduce water pressure, and, hence, the stability is increased. The problem is situated in the upstream dam side where the pore pressure is increased (Figure-(7.b) while the total and effective stresses are reduced as shown in Figure -9. Pore pressure increases the vertical stress and effective stress is negative, while the sand and silty soils will be unstable due to the quicksand effect. Also, the soil shear stresses will increase in the soil below heel and toe weir sides (Figure-10) causing high shear potential failure zones [18-21].

The imposed weir load caused an increased vertical stress, as discussed before, and soil displacement (settlement) will take place as a result (Figure-11). This displacement and elastic settlement is very low (1cm) (Figure-11.a) and will be reduced with depth (Figure-11.b). However, the weakly cemented sandy and silty soil in the upper soil layer will lose the cement cohesion due to the displacement. Consequently, then can be quickly eroded with seepage water forces and, causing erosion and holes in the pipes.

The model results of total head, pressure head and pore water pressure underneath dam are shown in Figures-(12 and 13), respectively. Increasing water level in the upstream side caused an increased water seepage, and this will increase water pressure in the downstream weir toe and the downstream vertical gradient (toe) (Figure-13). SEEP/W model of the total and pressure head of seepage water underneath Teeb weir depends mainly on the hydraulic difference between the upstream and downstream heads (Figure-12.a and 12.b). The maximum gradient is under weir toe (Figure-13.a.), indicating that the seepage velocity and water energy will increase at this point. The water pressure beneath weir foundation is represented in Figure-(13.B), where the pressure is reduced below weir body as a result of the cutoff effect. SEEP/W model value of seep water quantity through the soil is $0.004305 \text{ m}^3/\text{sec}$ (Figure-12). The factor of safety FS_{exit} was computed for the soil below Teeb weir toe by equation 4 and its value was 1.3.

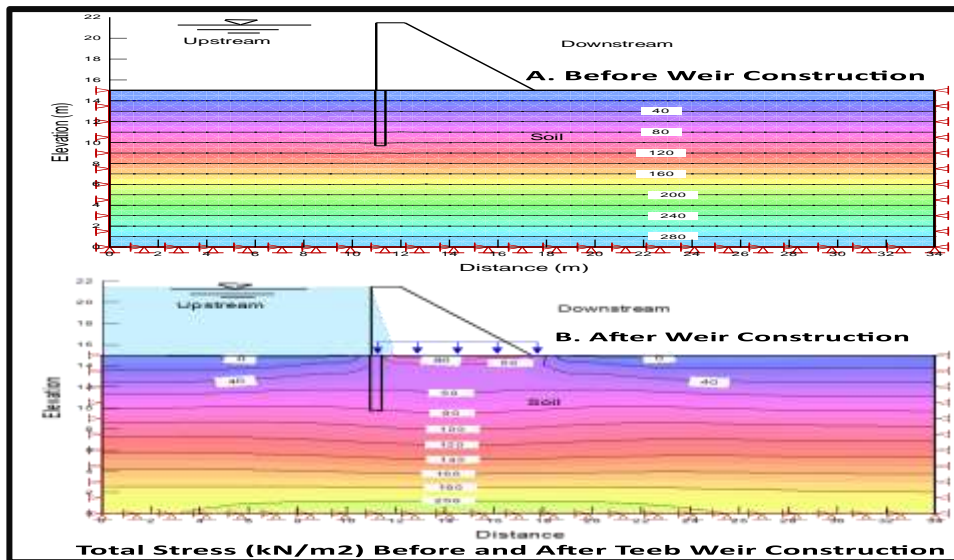


Figure 6- SIGMA/W total vertical stress model of soil A. Before weir construction, B. After weir construction

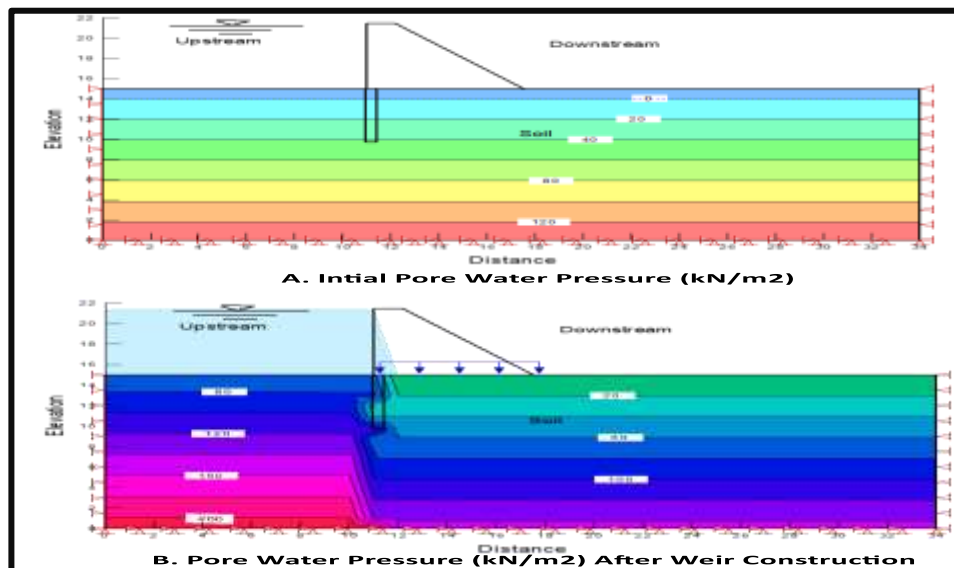


Figure 7- SIGMA/W models of pore water pressure A. Before weir construction, B. After weir construction

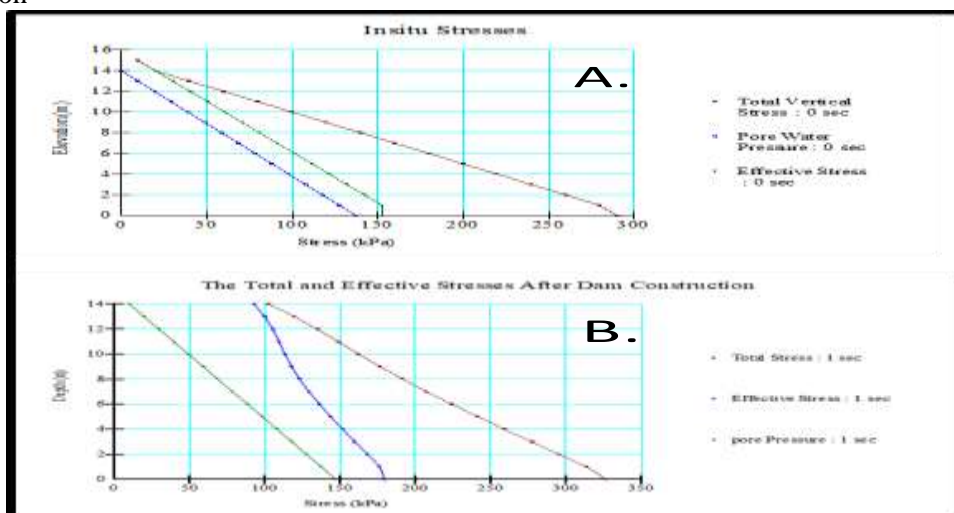


Figure 8- SIGMA/W model results of; A. Insitu soil stresses before weir construction. B. Soil stresses below weir structure after construction

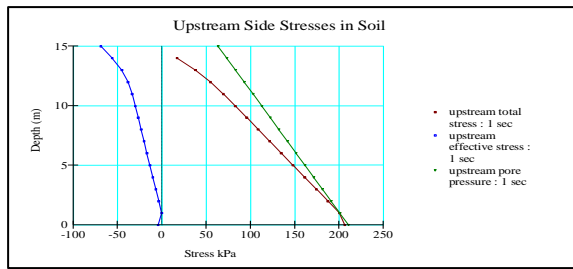


Figure 9- Vertical total and effective stresses and pore pressure in the soil underneath upstream Teeb weir side.

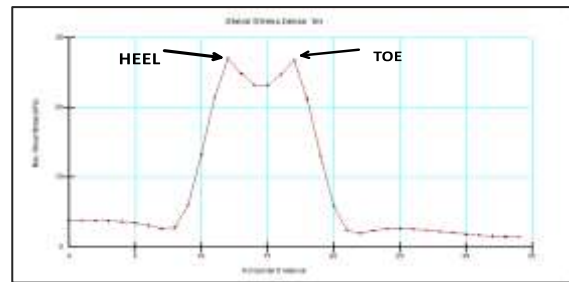


Figure 10- SIGMA/W calculated soil shear stress after weir construction.

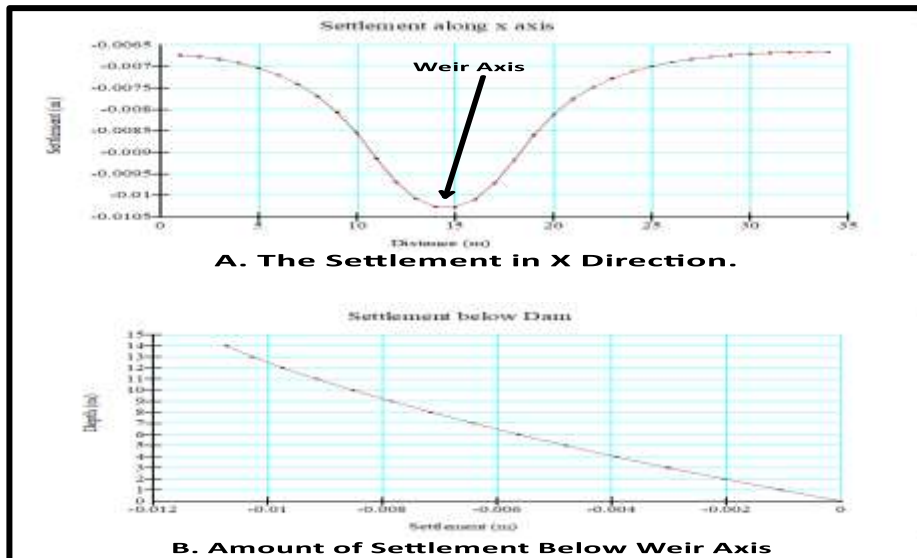


Figure 11- SIGMA/W soil displacement graphs A. along x axis at 1 m below weir base, and B. Along y axis below weir Axis

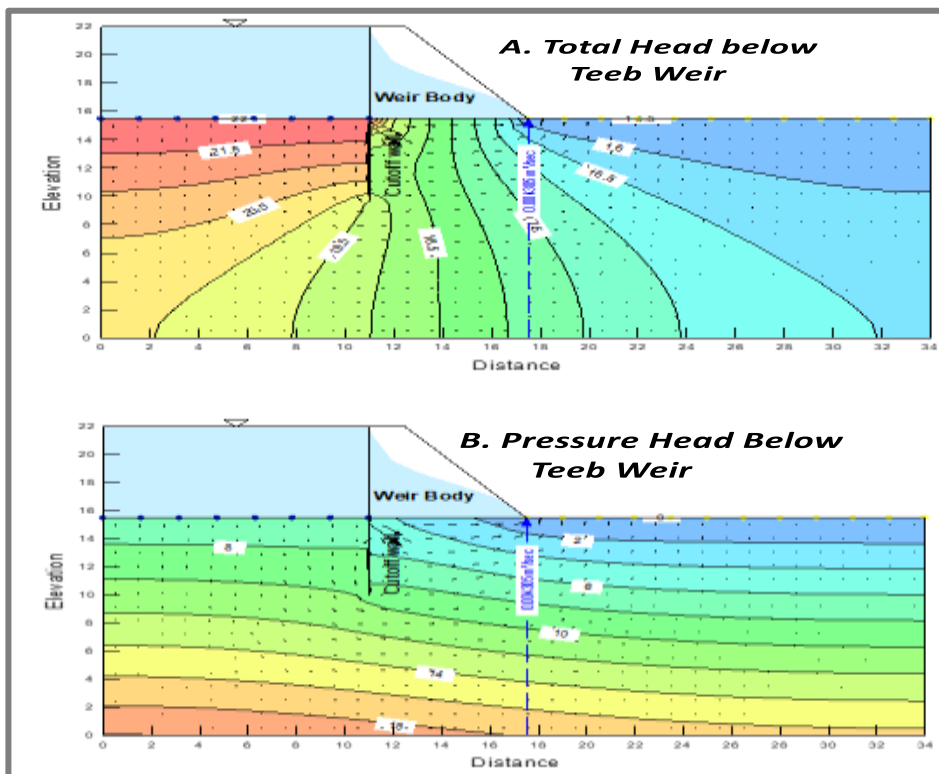


Figure 12- SEEP/W Model of Teeb weir for; A. Total head, B. Pressure head.

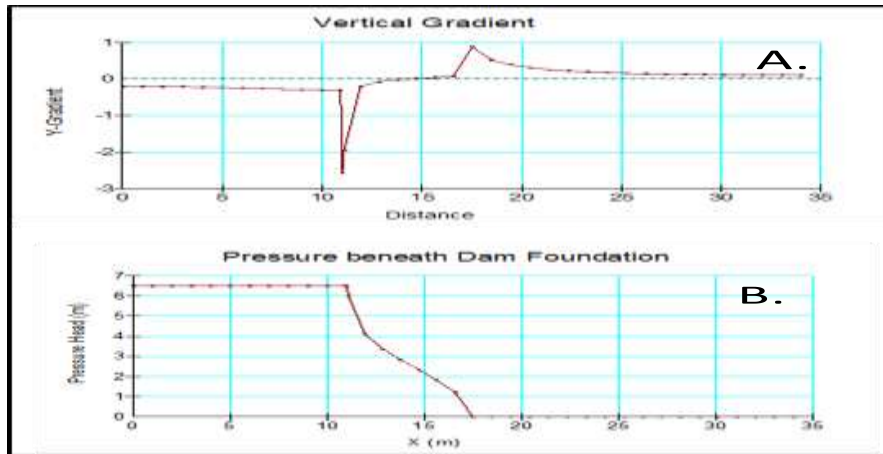


Figure 13- SEEP/W model results of A. Vertical gradient, B. Uplift pressure

8. Conclusions

1. The Numerical methods provided a good, cheap and quick tool to analyse the soil during pre- and post-construction stress redistributions. This redistribution changes the stability and zones of weakness below the structure. Therefore, finding and understanding these weak zones is the main role of the geotechnic team. The potential weak zones underneath Teeb weir (Figure-14) were denoted after the analysis of the results from the SIGMA/W and SEEP/W models and after deep understanding of geotechnical soil properties.
2. This study approved that the analysis of the stability of hydraulic structures needs to use the low of convergence of evidence, and that one tool will not give a sufficient image of a realistic expectation of the soil behavior after constructing and operating the project.
3. Teeb weir needs careful design to withstand the difficult foundation soil and a grouting program must prepared to stop any emergent foundation or weir shoulder failure.

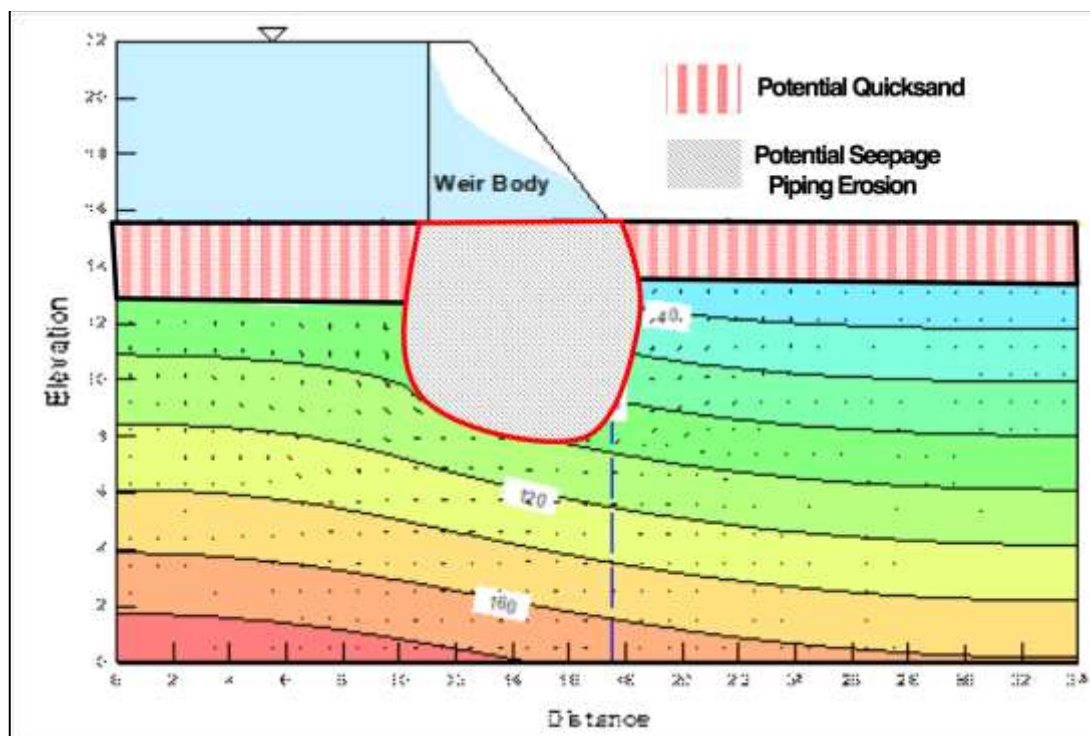


Figure 14- The critical soil parts below Teeb weir according to the SIGMA/W and SEEP/W model results.

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