Engineering and Technology Journal
Journal homepage: engtechjournal.org

Safety Assessment of Hadithah Dam Under Extreme Operations and Collapsible Foundation Challenges

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Submitted: 25/09/2019 Accepted: 02/03/2020 Published: 25/12/2020

K E Y W O R D S

Collapsible gypseous soils, cutoff diaphragm wall, grout curtain, drawdown rate, rising rate, seepage analysis, slope stability

A B S T R A C T

The present study involves a coherence steps to re-analyze the scenario of presence of collapsible gypseous layers in the foundation of Hadithah dam under extreme operating conditions. The motivation for such analysis was to explore the problem of construction and operation of large earth dams on collapsible soils if similar cases exist in Iraq. This study was carried out to evaluate the adequacy of the diaphragm wall and the safety level of the side slopes during the drawdown and rise period. The results were verified by the in situ design that confirmed the validity of the analysis.

How to cite this article: I. H. Obead, H. A. Omran, and M. Y. Fattah, "Safety Assessment of Hadithah Dam under the Extreme Operations and Collapsible Foundation Challenges," Engineering and Technology Journal, Vol. 38, Part A, No. 12, pp. 1771-1782, 2020.
DOI: https://doi.org/10.30684/etj.v38i12A.611

1. Introduction

The possibility of dam failure due to various geological challenges and extreme operation conditions introduces a serious issue for engineers which requests to be directed through a consistent approach involving numerous institutions and experts. However, guarantee hydraulic structure safety remains critical to attribute such a problem. It has been imperative to present an investigation plan that can potentially assess the impacts of the synchronization between geological and operational hazards.

Reference [1] conducted a nonlinear finite differences analysis to study the contacts of cut off walls at weak stratified rocks in surrounding at different operation periods, the impounding at first and end of construction conditions. They concluded that the strain of cut off wall rather consequent to the foundation strain or deformations indicates the occurrence of shear failure at the foundation of cut off wall as expected. Although the higher strength of construction materials of cut off wall reduces the deformations of the interfaces of wall-foundation. Among many of different problems that affect the safety of rockfill dams, [2] investigated the arching and hydraulic fracturing in Chenareh rockfill clay core dam in Iran. Such consequences caused by various stiffness and as a result different settlements of the dam core and shells for staged construction condition by finite elements method. It was found that the seepage through the core and its corresponding effective stress decreases due to the primary impoundment of the dam, they recommended to model and analyzing this case to determine the range of effective stress decrease in the core and its influence on arching. The largest settlement of the dam for end of construction condition drops as the modulus of elasticity for filter and transition zones increases, as a result increasing the arching ratio.

2. HADITHAH DAM-CASE STUDY

This study has been carried out on the Hadithah Dam, which is one of the largest Iraqi dams. The objective is therefore to re-analyze the seepage, and stability under extreme hydraulic and geological conditions. This will be discussing the hypothesis of the presence of collapsible gypseous soil in foundation layers. The dam materials were adapted based on unsaturated hydraulic functions. Construction of the Hadithah hydropower development on the Euphrates River in Iraq continued from 1977 and completed in early 1986 [3]. A general layout of the dam and the final design cross section of the dam in the river section is shown in Figure 1.

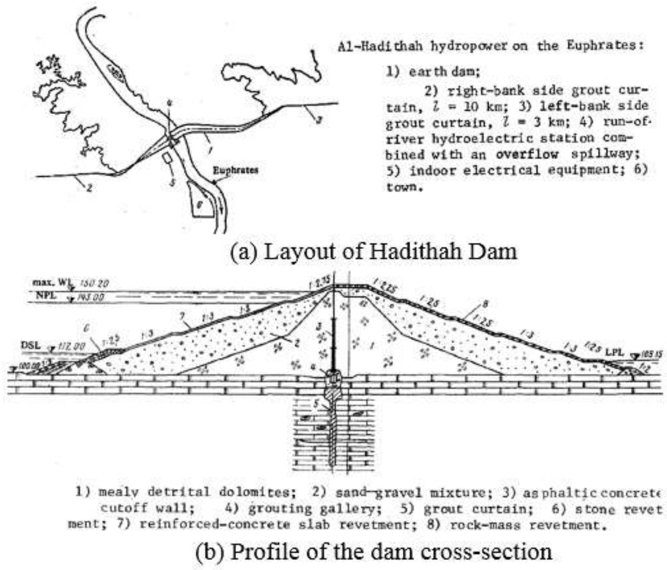

Figure 1: Typical layout and final profile of the dam cross-section [3]

Geological Features of Dam Foundation

Hadithah Dam has been constructed on the Euphrates River in Iraq, the foundation is comprised of layers of carbonate rocks contains limestones, fractured-porous dolomites, marls, and gypsums with interlayers and lenses of breccia and clays at different depths. There are rocks of almost all horizons of the Euphrates formation and they are represented by clastic (detrital) limestone of the organic origin (8 m) thick, mealy dolomite with marl and clay inter-beds totaling about (20 m) in thickness, fine detrital dolomite (14 m) thick, mealy dolomite with thin inter-beds of soft plastic clay totaling (6 m) thick, limestone and dolomite (6 m) thick. The lower horizon of Euphrates formation represented by organogenic-clastic limestone and dolomite (6m) thick and mealy dolomite (10-14m) thick serve the formation of the channel portion of the dam [4]. In this study, the material properties for each material type, as shown in Table I, are collected from various references [5-10]. Some input parameters required by the analysis not found directly in the adopted references were either arrived at through appropriate relations to other parameters (e.g. uses the "Mohr-Coulomb" material model) or for unavailable data assumed within reasons.

3. Methodology

The steady and transient states of seepage for the case study have been analyzed using the 2D-SEEP/W finite element code (developed by GEOSLOPE International Ltd.), real geological scenario maybe modeled concerning the various extreme operation scenarios and two geological formations of dam foundations.

Table I: The geotechnical properties for the material of Hadithah dam

Properties / Soil Material	γ_{total} (kN/m^3)	$\gamma_{sat.}$ (kN/m^3)	c (kN/m^2)	ϕ (deg.)	$k_{vertical}$ (m/sec)	$k_{horizontal}$ (m/sec)	E (MPa)
Sand-Gravel mixture (Shells)	17	20.3	0	27-30	$\geq A^{*}\times10^{-03}$	$\geq A\times10^{-03}$	100-300
Mealy detrital Dolomites (Core)	20.3	21.4	12.7-78.5	30	6.10×10^{-07} to 1.44×10^{-06}	1.44×10^{-06} to 6.1×10^{-07}	70-100
Limestone and Dolomite (Foundation)	22	22	100-200	30-35	1.0×10^{-09} to 6.0×10^{-06}	1.0×10^{-09} to 6.0×10^{-06}	100-300
Mealy Dolomite with Marl (Foundation)	22	22	20-40	24-28	6.10×10^{-08} to 1.15×10^{-07}	6.10×10^{-08} to 1.15×10^{-07}	50-100

[*] A is An integer between 1 and 10.

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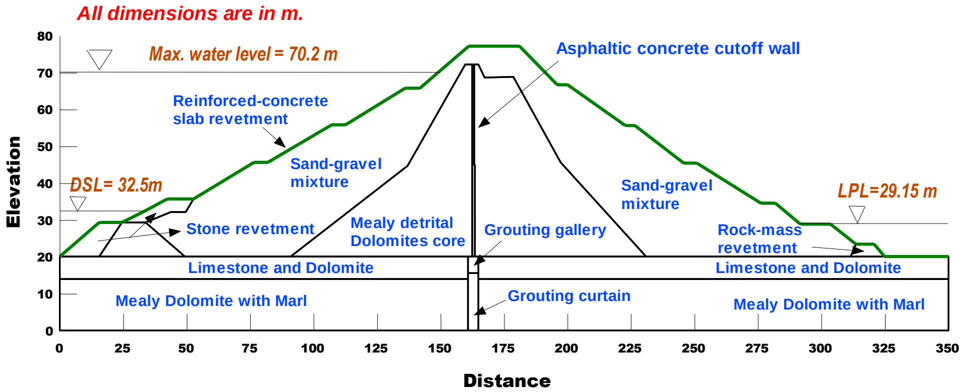
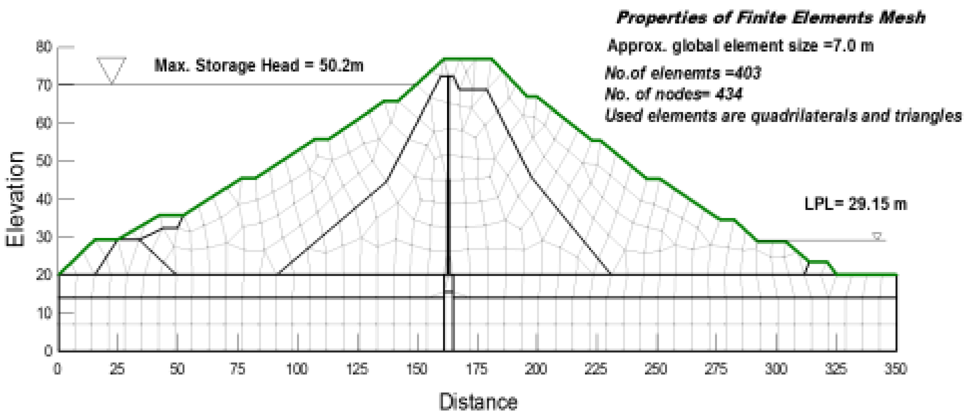


The zones of the dam and its foundation with their materials and finite elements mesh characteristics are shown in Figure 2.

a) The zones material of the dam



b) Discretization of the Finite elements mesh of the dam cross-section
Figure 2: Characterizations of the dam section in the Present analysis

In this study, the following initial and boundary conditions are applied for the steady-state and transient-state conditions under extreme operation circumstances:

(a) The initial condition for steady maximum reservoir water level:

$H(x, y) = h_{max.}$ (1)

Where, $h_{max.}$ is the initial pressure head through the zoned dam.

The boundary conditions for steady maximum reservoir water level:

$H(x, y, t) = h_0 - \zeta$ along the upstream side slope (2)

Where, h_0 is the maximum upstream water level in the reservoir.

$\frac{\partial H}{\partial x} = 0, \frac{\partial H}{\partial y} = 0$ along upstream side slope beyond the water surface in the reservoir and along downstream side slope. (3)

$\frac{\partial H}{\partial y} = 0$ along the dam crest and the baseline of the dam embankment. (4)

$H(x, y) = 0$ along the exit face in the upstream side slope. (5)

(b) The initial condition for a transient condition:

$H(x, y) = \bar{h}_j$ (6)

Where, $\bar{h}_j$ is the pre-calculated pressure head for steady-state resultant from the normal reservoir water level.

(c) The boundary conditions for a transient condition:

$H(x, y) = 0$ along the upstream side slope during the drawdown process. (7)

$\frac{\partial H}{\partial \eta} < 0$ the net out flux across in the upstream side slope (8)

Where, η is the normal direction to the upstream side slope.

$\frac{\partial H}{\partial \eta} = 0, H(x, y) < 0$ the no flux across the rest of the upstream side slope beyond initial water level prior to the drawdown. (9)

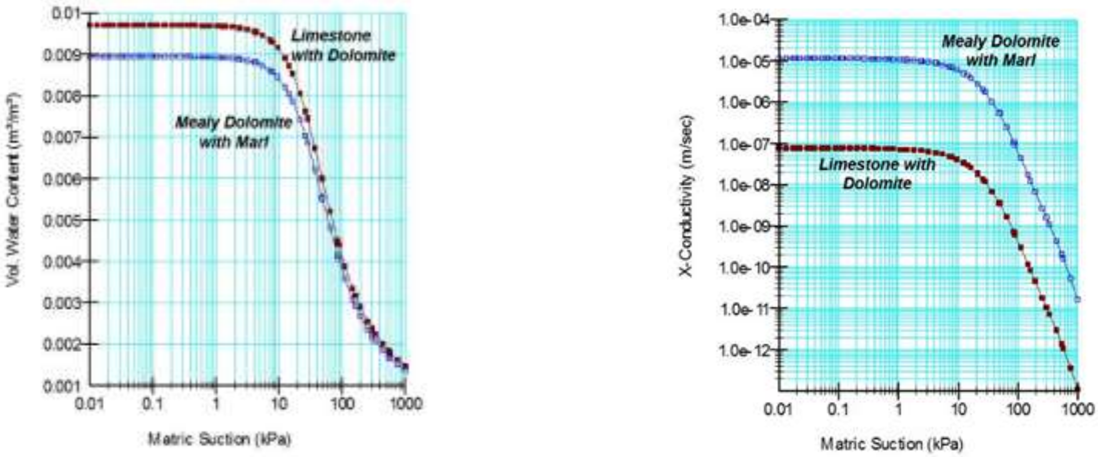
4. RESULTS AND ANALYSIS

I. Analysis of Water Flow Scenarios for Hadithah Dam

As mentioned, the construction began in 1977, whereas the opening date in 1987 and the impounding probably started in 1988 or further. In this analysis, the impoundment of the reservoir is assumed to cause a delayed saturation of deeper layers of foundation, these effects on the behavior of saturated-unsaturated zones could be then according to the author's perspective to divide the entire depth of foundation into two zones. The upper zone is fully saturated, while the rest is saturated-unsaturated. These more realistic scenarios to be compared with model computations. Thus, soil-water characteristics (SWCC) and unsaturated hydraulic permeability function (Kunsat.) were fitted with the Fredlund and Xing function [11], created by SEEP/W, and presented in this study for limestone-dolomite and mealy dolomite with marl layers respectively, as shown in Figure 3 (a and b), respectively.

II. Maximum Reservoir Level

In this extreme operation condition, the water level in the upstream side is (150.20 m a.s.l.) as shown in Figure 1-b [3]. For the purposes of simplify the handling with the dimensions of the Hadithah dam cross-section, it was considered that the lower elevation of the bed layer for the foundation of the dam to be 0.0 (a.s.l.) as a geometric convenience. Accordingly, the maximum storage head is (50.20 m), the location of the free surface is shown in Figure 4.



(a): SWCC **(b): $K_{unsat.}$ Functions**

Figure 3: Hydraulic functions for foundation layers of the Hadithah dam

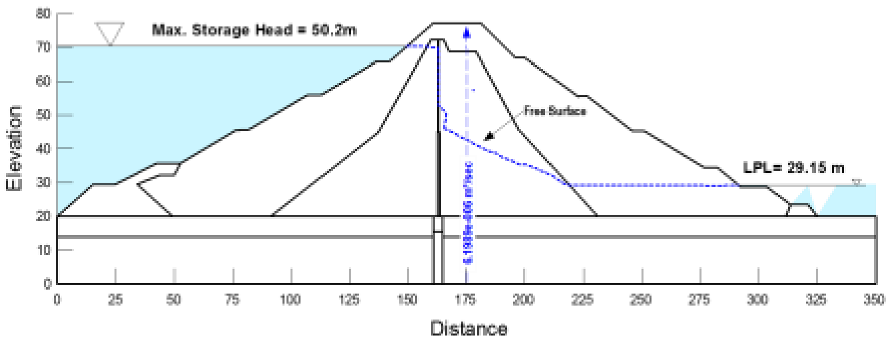


Figure 4: Location of the free surface corresponding to maximum water level

Results of Figure 4 reveals that the free surface is nearly horizontal and to be predominant in the shells due to it is high permeability, which was ranged between 1×10-5 to 1×10-4 m/sec, this is reliable with [12] as cited in [13]. For the dolomite core with low permeability ranged between 1.44×10-6to 6.10×10-7 m/sec, [8], an abrupt recession in free surface occurs intensely near the interface of the cutoff wall-core, and core- downstream shell.

All the above results are obtained for real geological formations. Collapsible gypseous soil samples were collected from three various locations of Bahr-Al-Najaf depression border, from Baher Al-Najaf in Iraq. Physical properties tests and chemical composition tests are conducted to determine the most collapsible soil in accordance with their gypsum content and collapsibility potential. The location characteristics of soil samples taken from site #1 is given in Table II.

Table II: Location characteristics of site #1

Site	Location	Symbol	Depth (m)	Elevation[a] (m)	Coordinates
#1	I	$SI_{\#1}$	0.50	54.6	44° 11′ 06.58″ E 32° 09′ 52.13″ N
	II	$SII_{\#1}$	0.90		
	III	$SIII_{\#1}$	1.25		

[a] Ground surface as per GPS data.

The physical properties and results of chemical tests for the samples of higher gypsum content of site #1 are given in Tables III and IV, respectively [14]. The soil-water characteristic curves and the unsaturated hydraulic conductivity functions established by Fredlund and Xing model which are relevant to this study for site #1 are shown in Figures 5 (a and b), respectively. To investigate the problem of hydraulic properties of the presence of gypseous soils in the foundation layers of the dam, several computations are carried out to locate the positions of the free surface as shown in Figure 6.

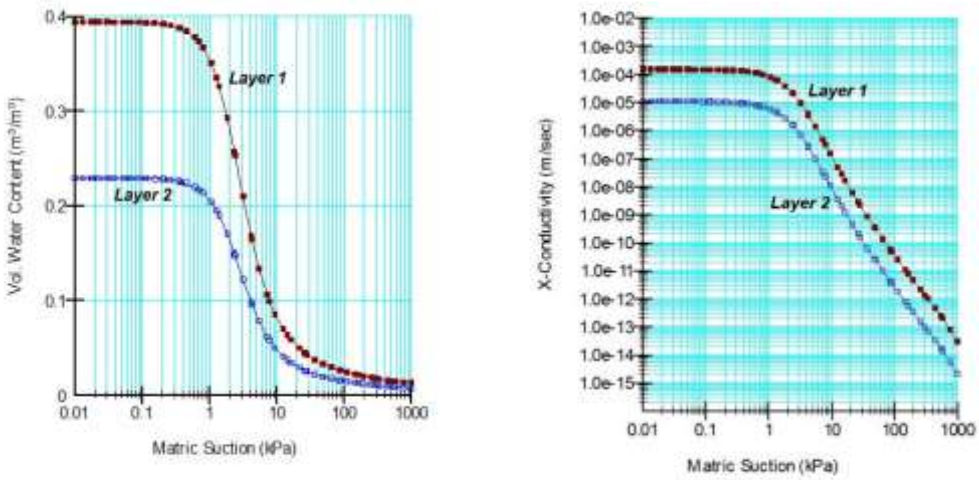
Table III: Physical properties and chemical results for soil samples taken from site#1

Natural moisture Content (%)	Field unit weight (kN/m^3)	Initial void ratio	Gravel > 4.75 (mm)	Sand 4.75–0.075 (mm)	Silt and Clay < 0.075 (mm)	Mean grain size, D50 (mm)	USCS
1.25	13.896	0.79	20.50	78.90	0.58	1.80	SP[a]

[a]SP = Poorly graded sand with gravel.

Table IV: Results of chemical tests for soil samples taken from site#1

Gypsum content (%)	SO_3 (%)	Cl^- (%)	TDS (%)	pH (%)
35.98	16.72	0.117	15.2	8.0



(a): SWCC for site #1 **(b): Kunsat. for site #1**

Figure 5: Hydraulic functions for gypseous soil samples taken from site #1

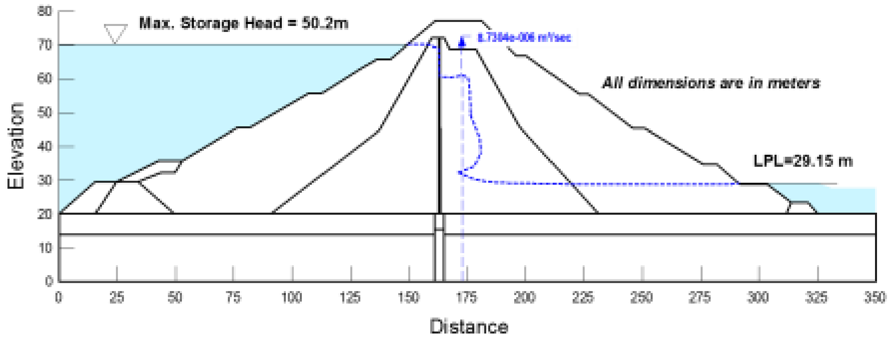


Figure 6: Location of the free surface corresponding to maximum water level for the case of presence of the collapsible gypseous layers in the dam foundation

In order to assess the effect of the severe geological challenges, the author's mainly study the hypothesis of the presence of gypseous soil in the foundation layers. The impacts on the water flow through the dam body and foundation are predicted, the calculated value of seepage discharge through the dam core was compared with those values from the in situ foundation layers (i.e. 6.1989×10-06 and 8.7304×10-06 m3/sec/m), respectively. The percentage of relative absolute difference (RAD %) between these values is about (40.8 %). The adequacy and functions of seepage control devices (central diaphragm wall and grout curtain) were evaluated based on the relative drop of free surface throughout the dolomite core (□core) by comparing the Figures 4 and 6. For both the in situ and gypseous foundation layers are (40.525 m and 40.13 m), respectively. The drop in the free surface elevations around the diaphragm wall (□diaphragm) for each of the material scenarios are (16.875 m and 8.225 m), respectively. These values can be interpreted by the mean of (RAD %) as given in Table V.

$$RAD\% = \left|\frac{x_i - x_j}{x_i}\right| \times 100 \qquad (10)$$

In which; xi and xj are respectively the measured and predicted values of the variable (x). The role of collapsible formations on the provision of seepage control devices is assessed based on the results obtained above; the location of the free surface was directly affected by such challenging geological conditions.

Table V: Percentage of relative absolute difference of drops in free surface elevation due to two geological formation in the dam foundation.

Foundation Material	RAD%	
	δ_{core}	$\delta_{diaphragm}$
In situ	58.10	24.20
Gypseous	58.20	11.93

The seepage discharge through the core and foundation was increased significantly and rapidly by about 41% than of the in situ state. This reflects the damaging role of the presence of the gypsum in the foundation layers of the dam. On the other hand, from the results of Table IV, the relative drop of free surface elevation throughout the dolomite core is approximately the same, but the drop around the central cutoff wall decreased by almost a half when the gypseous layers were presence in the foundation. This is attributed to the inefficiency or inadequacy of the seepage control device.

III. Transient State of Flow

The water levels in the reservoir fluctuate usually because of operational purposes. Drawdown rates of (1.0 m/day) and greater are relatively practical. However, schemes of reverse pumping storage or discharges from the dam through low-level of the reservoir could imply to these rapid variations in water levels in the reservoir [15]. Otherwise, a high flood inflow causes the reservoir water level to rise (particularly during the recent years). These two extreme operation conditions were analyzed for the states of in situ and the presence of gypseous layers in the dam foundation. Figure 7 shows the elevations of water levels corresponding to all operating conditions in a manner consistent with present analysis dimensions.

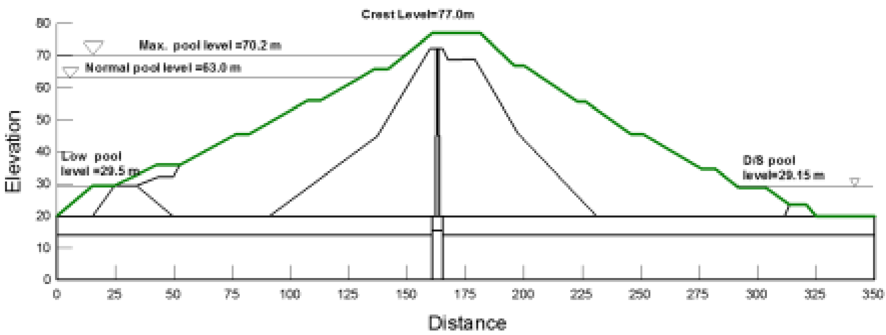


Figure 7: Operation water levels of Hadithah dam

Hence, the water level in the reservoir drops from the normal operation elevation +63.00 m to +29.50 m measured from the bottom of mealy dolomite with the marl layer. Whereas in the flood condition, the water level will rise from normal operation elevation to the crest elevation of +77.00 m. Figure 8 shows the hypothetical variation rate of water level for both extreme operation conditions. The locations of free surface consequents for different periods during the drawdown process for both in situ and gypseous layers in the dam foundation are shown in Figures 9 and 10, respectively. Likewise, Figures 11 and 12 display the locations of free surface results during the rising process for both in situ and gypseous layers in the dam foundation.

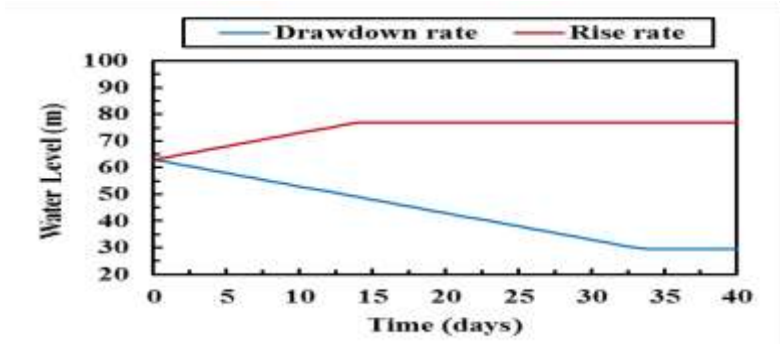


Figure 8: Hypothetical drawdown and rise rates of water level in the dam reservoir

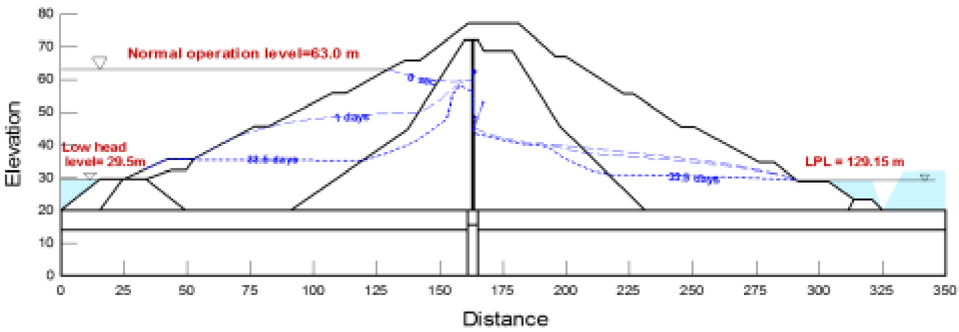


Figure 9: Locations of the free surface in the Hadithah dam during the reservoir drawdown for in situ foundation layers

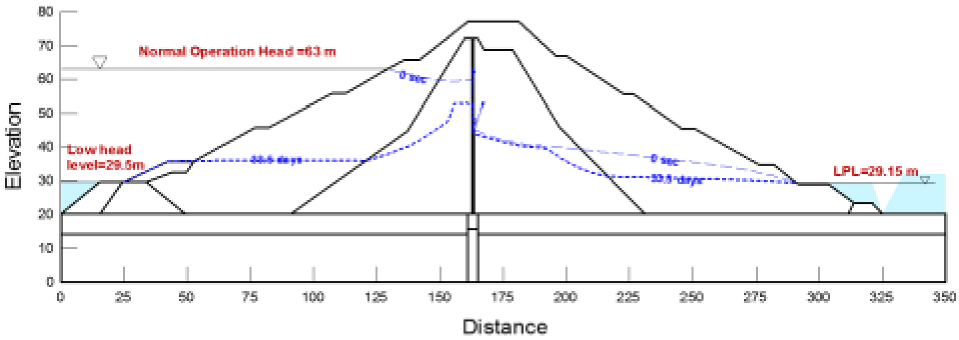


Figure 10: Locations of the free surface in the Hadithah dam during the reservoir drawdown for gypseous foundation layers

The results of Figures 9 and 10 indicate that the drop in the free surface due to drawdown in reservoir water level was highly affected by the presence of the gypseous layer in the dam foundation as compared with the in situ foundation layers. This behavior is attributed to the volume change of the gypseous layer structure especially in the downstream portion of the dam beyond the cut off the diaphragm. Figures 11 and 12 show the effect of the rising in reservoir water level on the upward movement of the free surface.

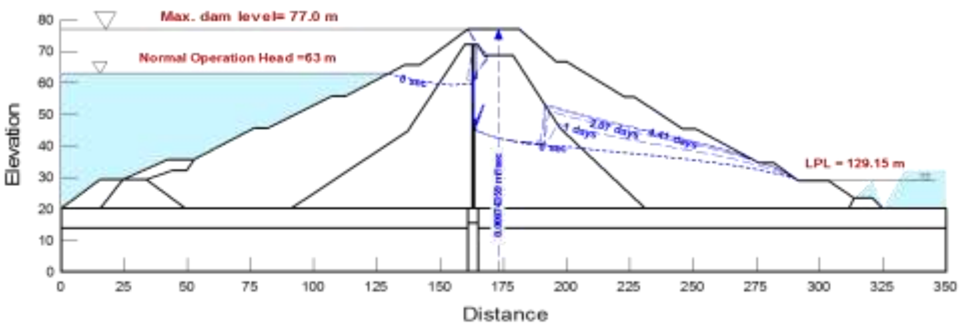


Figure 11: Locations of the free surface in the Hadithah dam during the rise in reservoir water level for in situ foundation layers

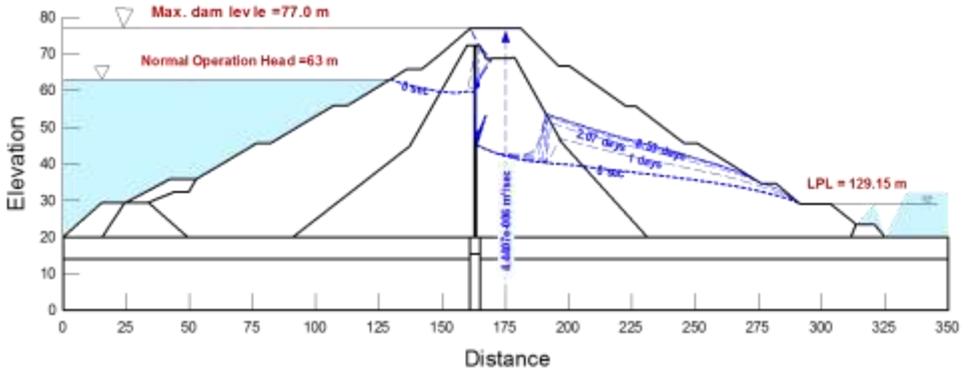


Figure 12: Locations of the free surface in the Hadithah dam during the rise in reservoir water level for the gypseous foundation layers

It is evidently noticed from results of Figures 11 and 12 that the trend of upward movement for the free surface location was approximately the same. However, an advanced rate of seepage for in situ soils due to higher permeability of dam embankment zone. The quick settlement that occurs in gypseous layers after several hours of rising process began that cause a semi-porous barrier in gypseous layers induced by the vertical stresses of dam embankment.

5. Slope Stability Scenarios for Hadithah Dam

In this study, the results of the slope stability analysis by limit equilibrium approach using Bishop's method is carried out under SLOPE/W software. Figures 13 and 14 show the slope stability analysis for the upstream and downstream side slopes for the in situ foundation layers, respectively.

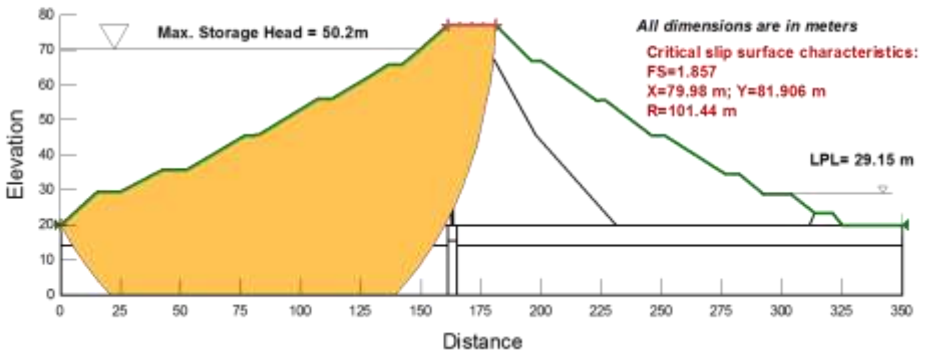


Figure 13: Critical slip surface position for the upstream slope for the in situ layers

The predicted values from this study indicate an underestimation for the upstream slope if compared with the designer obtains (2.40 according to the ordinary method of slices), while for the downstream slope was a rather overestimation if compared with a value of (1.40 based on the designer slip plane method). In general, the results indicate the safety of the dam side slopes as it was greater than 1.50 for the investigated cases. The results of analysis performed accounting for the presence for gypseous foundation layers are displayed in Figures 15 and 16, respectively.

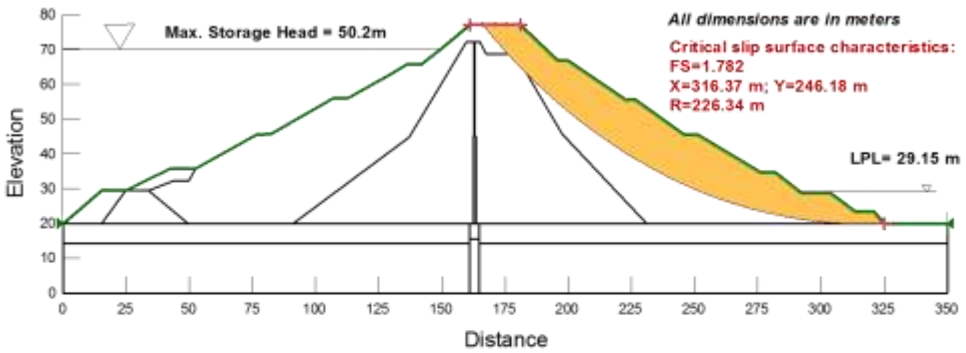


Figure 14: Critical slip surface position for the downstream slope for the in situ layers

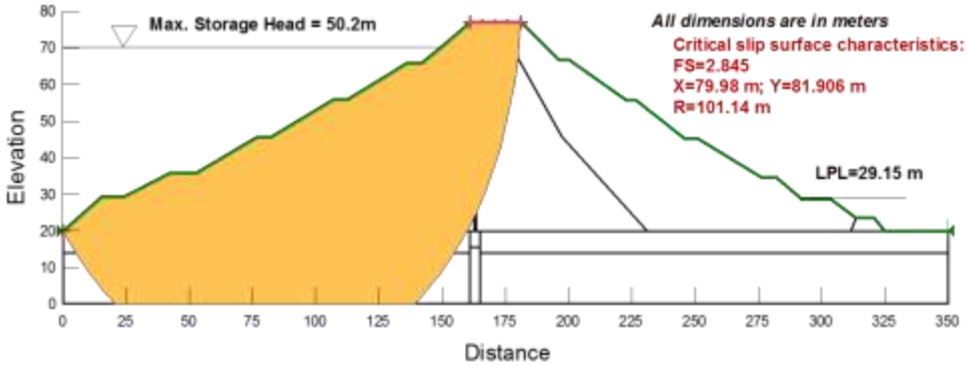


Figure 15: Critical slip surface position for the upstream slope for the gypseous layers

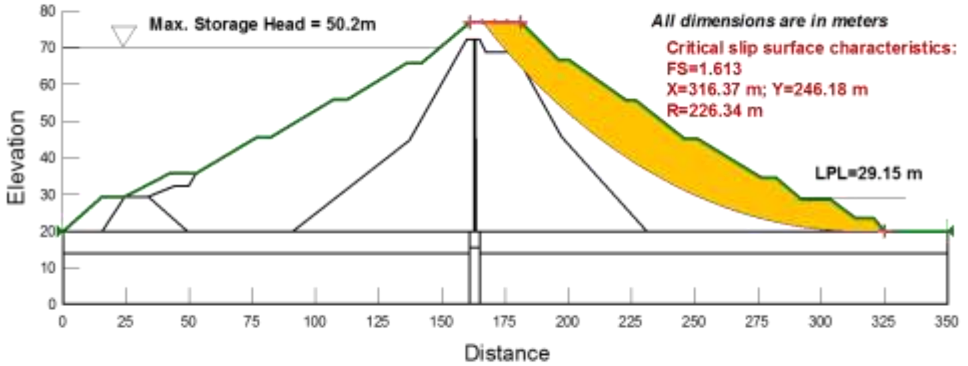
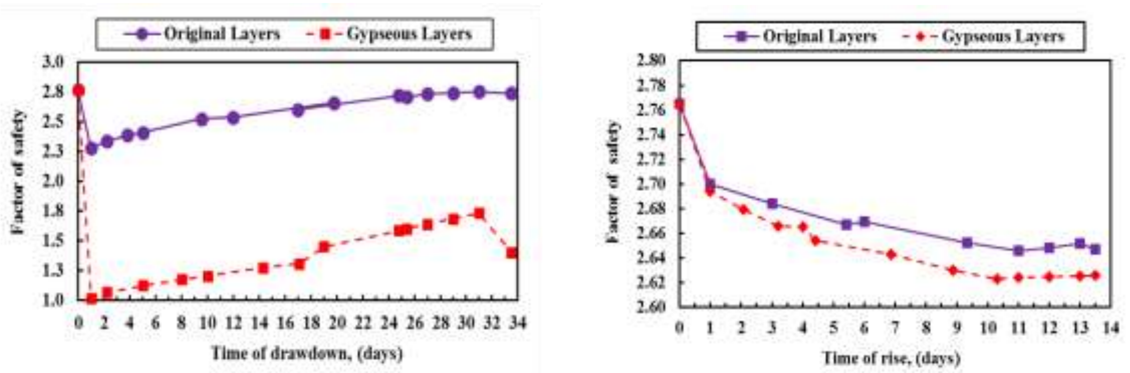


Figure 16: Critical slip surface position for the downstream slope for the gypseous layers

The findings of Figures 15 and 16 reveal deep penetration through foundation layering for the upstream slip surface. The value of the factor of safety for this case leads to a higher estimation for upstream slopes of gypseous soil in comparison with in situ layers. The failure arises through the region of the weakest material of gypseous soils extended to include a long slip surface that passes adjacent to the downstream shell interface. For the extreme operation scenarios as drawdown and rise in water levels, the results of slope stability analysis for both side slopes and geological conditions are carried out as follows. Figure 17 (a and b) show the factors of safety versus the time of drawdown and time of rising, respectively.



(a) Factor of safety vs. the drawdown **(b) Factor of safety vs. the rise**

Figure 17: Variation of the factor of safety versus the time of water level drawdown and rise for the upstream side slope of Hadithah dam

From Figure 17(a), it is clear that the factor of safety decreases in the initial of drawdown process and progressed to the end of the drawdown period, the rapid reduction occurred for the case of presence of gypseous layers. After 1 day of the drawdown period, the factor of safety raised slightly. The dissipation delay in the excess pore water pressure, which exerted because of the slow rate of drawdown and the relatively short time, associated it provided high energy to the water in the dolomite core and sand-clay shell zones. This will enormous shear stresses on the soil particles where they will cause a loss in shear strength to resist slipping. A comparison between the present work factor of safety and the designer values (i.e. 2.765 and 1.89 respectively) reflected higher estimation obtained by the author, this may be attributed to the Bishop's method which produced higher accuracy than Fellenius or Ordinary method that adopted by the designer. Figure 17(b) shows a comparison between in situ and gypseous layers in the dam foundation in terms of the factor of safety for the upstream side slope under the rise in water level conditions. The findings reveal the reduction in the factor of safety for both cases with a higher rate for gypseous layers. However, in general, the upstream side slope was sustained safe over the water rise period of 13.5 days, although the factor of safety decreased by (4.27% and 5.03%) for each in situ and gypseous layers respectively. It is worth mentioning that the Australian National Committee on Large Dams standard [16] specified the safe factor of safety for upstream side slope under drawdown condition by (1.25-1.3) as cited by [17].

6. CONCLUSIONS

Based on the analysis of the results and discussion, the following conclusions can be written:

1. It is probable to reveal that most challenges related to geological formations and operation conditions were adopted in this study. It can be argued that the dam response to these severe conditions was satisfactory implicitly because of the role of the control seepage devices.
2. Slope stability was further provided by the diaphragm cut off wall in addition to the grouting process prior to the construction of the dam, these measures were contributed to reduce the impact of the presence of collapsible gypseous layers in the foundation layers.
3. Safety factors for the upstream slope under the rise in water level condition are decreased for two geological formation, in particular, with a high rate for gypseous layers. However, the upstream side slope was sustained safe during the water rise period of 13.5 days, although the factor of safety decreased by (4.27% and 5.03%) for each in situ and gypseous layers, respectively. It is necessary to point out that [16] identified the safe slope stability criterion under drawdown condition by (1.25-1.3) for the upstream slope of the dam.
4. From the obtained results, a combined case of drawdown operation scenario with gypseous layers produces a noticeable increase in seepage discharge through embankment and foundations of the dam and a less factor of safety against sliding in the upstream side slope. Such geological formations and operation circumstances are concluded as" Extreme Challenges".
5. A considerable viewpoint revealed for the danger of failure potentials and risks that conjugated to extreme operating conditions in case of the presence of collapsible gypseous soil in the foundation of earth dams. Finally, an extension to investigate the impacts of the earthquakes may be recommended as further work.

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