Parametric Study of Concrete Dam Stability in the Case of Gallery and Tailwater Existence

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Abstract: A concrete gravity dam can simply be defined as a large structure constructed of concrete that can hold back and also store a large amount of water. Since it is held by gravity to the ground, the stability of the massive concrete dam depends on its weight. Concrete dam is subjected to many kinds of static and hydrodynamic forces which need considering design under different circumstances to satisfy the safety requirements. The shape of the dam is essential to settle the stability of the dam regarding the major forces and stresses. As the stability of the concrete dam depends on its weight, which in turn depends on the shape of the dam as concrete density is constant, the initial design using the preliminary section of the dam does not certainly lead to obtaining safety factors for the different failure modes. Therefore, this requires an increase in the dam base which consequently increases the dam weight and provides safety requirements. In this paper, the concrete dam was designed for different values of the storage water level, tailwater depths, in addition to the presence of the gallery in the dam. The stability analysis for the most common modes of failure is carried out by the Microsoft Excel program, and all the relevant safety factors have been satisfied for the cases gallery existence and different tailwater depths. The results show that tailwater has a significant effect on additional base part values required for safety in addition, this effect is extended obviously on the upstream values of shear and principal stresses. Many regression equations have been obtained from results analysis to facilitate the estimation of additional parts and the main stresses.

Keywords: Concrete Dam, Dam Stability, Dam Stresses

1. Introduction

A concrete dam is a hydraulic structure built across a stream or a lake that provides water required for human consumption, land irrigating, industrial processes, and hydro-electrical power generation. The process of designing and constructing concrete dams is receiving increasing attention from researchers, engineers, and companies concerned with construction to study all elements affecting the performance of dams and work to control them to be within the permissible engineering limits. According to the two standards methods, those have been established by the U.S Bureau of Reclamation (USBR) and the U.S Army of Engineers, the study of stability criteria was concluded on virtual dam cases to attain the safe operation and the strength of concrete to avoid overturning and slipping of the dam. The main requirements of concrete dam section design depend on the stability and economy, as the section dam should be chosen accordingly. The preliminary dam section is designed according to the U.S.B.R. recommendations.

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Using the two-dimension gravity method and finite element method, then stability and the stress conditions are estimated and analyzed for varying horizontal earthquake intensities are perturbed from 0.10g to 0.30g with 0.050g increment, keeping other loads unchanged, so the forces can be at the toe of the dam along with the stress condition of the dam. According to the U.S.B.R. initial dam section recommendation, stabilizing moments significantly decrease with the increment of horizontal earthquake intensity, which is an indication of the dam's stability is threatened. Therefore, to avoid failure and increase moment stability, a larger dam section is designed. (Chandrahekhar, 2015).

The seismic actions on the structure are derived from the deformations caused by the ground motions caused by the earthquake. Seismic forces differ from external winds or gravitational loads, which are also applied to the structure. Mathematical models are a suitable approach rather than the laboratory examinations to assess the effect of seismic forces on dam stability (Das & Cleary, 2013; Berrabah, 2012). Several tests for stimulating hydrostatic, hydrodynamic, and seismic loads were performed by (Ghbara & Gemianz,1998). Dynamic loads were calculated using a simplified method of analysis in concrete gravity dams. The two actuator loading mechanism is designed to apply four concentrated loads at the upstream interface of the dam model. The static load representing the hydrostatic pressure was constant. The dynamic load was applied continuously by initiation to represent the dynamic effects of earthquake loading. The effect of the gravitational load of the dam was calculated analytically. During model testing, strains measured with the same material properties in the prototype were in good relationships with strains calculated using the finite element approach. The pressures at the top of the dam model and the prototype for the same material properties are found in close agreement. The results of the experiments showed that it is possible to simulate the hydrodynamic load on the dam model using a limited number of concentrated mechanical loads.

(USBR) has indicated that on horizontal planes, the vertical normal stress (z) is determined as:

$$\sigma z = \frac{\Sigma V}{B} \pm \frac{12 \Sigma V e}{B^3}\ y \qquad [1]$$

Where,

ΣV = Resultant vertical load above the plane considered,

B = Thickness of the dam block, that is, the length measured from heel to toe,

e = Eccentricity of the resultant load,

y = Distance from the neutral axis of the plane to the point at the heel,

y = -B/2 and at toe, y = +B/2., and

Thus, at these points, the normal stresses ($Pv_{max.}\ and\ Pv_{min.}$) are found out as below:

$$Pv_{max.} = \frac{\Sigma V}{B}\left(1 + \frac{6e}{B}\right) \qquad [2]$$

$$Pv_{min.} = \frac{\Sigma V}{B}\left(1 - \frac{6e}{B}\right) \qquad [3]$$

The tension on the upstream face will be created if the overturning moments under the full reservoir state are increased so that e becomes B/6. The total vertical pressures at the upstream and downstream are obtained by adding the outer downstream faces which are achieved by adding the outer hydrostatic pressure.

One of the most common modes of failure in concrete dams is sliding, the first criterion used to evaluate failure against sliding, which depends on the coefficient of friction, μ (Johansson, 2009). This coefficient is calculated by dividing the sum of all horizontal forces or the forces which are parallel to the sliding plane, ∑H, by the sum of the effective vertical forces normal to the sliding plane, ∑V. To avoid the sliding, the coefficient of friction must be larger than a maximum coefficient of friction.

$$\mu = \frac{\Sigma H}{\Sigma V} \leq \mu\, max \qquad [4]$$

The study conducted by (R. B Jansen, 1988) confirmed that the slip resistance along any level above the base of the dam is a function of the concrete shear strength or the structural lifting joint. At the base, it depends on the shear strength of the concrete foundation or facade.

Lund, Boggs and Daley (1993) hypothesize that a crack will develop between the base and the foundation in the case where the normal pressure of the base is tensile. Since the gravimetric analysis method assumes an effective linear stress distribution along the weir base, the length of this crack is determined by the location of the product and the assumption of effective linear stress distribution.

Linear finite element analyzes have been used by Léger and Katsouli (1989) to simulate the behavior of gravity dam systems. However, the foundation is generally not able to develop any significant tensile stresses. Therefore, any tension occurring near the dam front is largely an illusion. Furthermore, conventional inversion and slip parameters have little meaning in the context of the oscillatory response of dams during earthquakes. Time-domain analyzes using nonlinear contact elements present in the dam-basement interface were used to determine the dynamic response of slip and lift from the gravity dam monolith taking into account different elastic bedrock properties. The magnitudes of the relative interface displacement, base non-contact percentage (PBNC), and compressive stresses at the heel or toe of the dam were used to monitor seismic stability. The numerical results have shown that the non-linear behavior of the foundation and dam interface reduces the seismic response of the system, indicating the possibility of more rational and economical designs. PBNC was determined as the critical seismic stability response coefficient for all analyzes except for highly elastic base conditions where extreme values of the relative interface displacement must be considered.

Ghobarah and Ghaemianz (1998) have studied a small model of a concrete gravity dam. Tests were conducted on a 1:100 monolithic model of a flat pine concrete gravity dam located on the Kings River near Fresno, California. These tests are intended to induce hydrostatic, hydrodynamic, and seismic loads. Dynamic loads were calculated using a simplified method of analysis in concrete gravity dams. The two-actuator loading mechanism is designed to apply four concentrated loads at the upstream interface of the dam model. The static load representing the hydrostatic pressure was constant. The dynamic load was applied continuously by a trigger to represent the dynamic effects of earthquake loading. The effect of the gravitational load of the dam was calculated analytically. During model testing, strains measured with the same material properties in the prototype were in good relationships with strains calculated using the finite element approach. The pressures at the top of the dam model and the prototype for the same material properties are found in close agreement. The results of the experiments showed that it is possible to simulate the hydrodynamic load on the dam model using a limited number of concentrated mechanical loads.

Amberg (2015) states that when the stability of a gravity dam is verified without taking the tensile strength into account, it is possible to identify the threshold when the concrete weight by itself becomes insufficient so that the dam stability cannot anymore rely exclusively on the gravity force. The upstream dam face is vertical, the unit weight of concrete varies between 23.5 and 24.5 KN/m^3 and the shear strength is provided only by friction, assumed to be at its residual angle of 48° according to two assumptions are made for the uplift pressure in case of crack initiation at the upstream face. Following the first, more conservative assumption, the pressure within the crack corresponds to the full water pressure, which then decreases linearly through the remaining section. In the second hypothesis, the uplift pressure simply varies linearly from 100% at the upstream to 0% at the downstream face. The first distribution is expected in the case of a dam partially cracked in its upstream part, while the second one corresponds to the case of constant permeability, i.e. if a dam is completely cracked at a certain elevation. The second assumption is rather unlikely and not particularly conservative since the permeability probably progressively reduces towards the downstream direction with the increase of the vertical compression. However, the crack opening might be quite complex as it is the case of dams affected by the concrete expansion.

According to Amberg (2015) a gravity dam is held exclusively by its weight if the bottom dam face tilts less than 0.80 to 0.84. Slip becomes the limiting criterion due to the maintenance value of the assumed residual shear force on the horizontal jack joints. In the case of high shear strength or inclined lifting connections, overturning may become critical if the weir thickness is less than 73 to 77% of the height. These basic stability criteria may allow the required gravity dam analyses to be greatly simplified. It is interesting to note that some gravity dams, those of limited height, show a thickness of 60% of the height or even less. The stability of these dams depends on the tensile strength. The known case history of the Bouzey dam in France, which collapsed in 1895, is minimal. One must always consider the potential loss of tensile strength, such as in the case of cracking during an earthquake or due to concrete expansion. The safety of a dam mainly depends on the appropriate design of the project which exposes only the basic issues related to the safety of the dam, however, continuous supervision during construction will help in the prediction of uncalculated phenomena that may need to be re-evaluated. The stability of a concrete dam by gravity depends on the thinness of the structure and the condition of the side blocks when considering the impact of the valley slope. The designer sometimes ignores the last point that can lead to a possible failure situation.

A parametric study is made to investigate the effects of the increase in the base of the dam on the principal and shear stresses developed in the dam (Ahmed 2016). In all cases, all the relevant factors of safety are satisfied. The stability analysis for all possible modes of failure is carried out to check the performance of the initial section of the dam due to several loading conditions. The study concluded a relationship between the water level in the reservoir and the required increase in the dam base to ensure safety requirements.

In the current study, many sections of the concrete dam with gallery and different values of tailwater depths were designed and analyzed using a wide range of water levels in the reservoir and identifying the elements affecting the safety of the dam.

2. Methodology

In this study, the concrete dam is designed and analyzed using different levels of storage water, and the safety of the dam is examined with different failure phases and under the influence of all major hydrostatic and hydrodynamic forces. The Excel program is used to facilitate the process of this large amount of calculations. The dam is analyzed by calculating all major forces and studying their impact on the stability and performance of the dam. The results were also presented and discussed to know the effect of all the elements included in the study on the safety of the dam. The following forces have been considered:

- Hydrostatic pressure (P) – ve
- Hydrodynamic force (Pe) –ve
- Uplift force (U) –ve
- Weight of dam (W) +ve
- Upward earthquakes forces –ve
- Horizontal and vertical acceleration of earthquakes forces toward D/S of the dam.

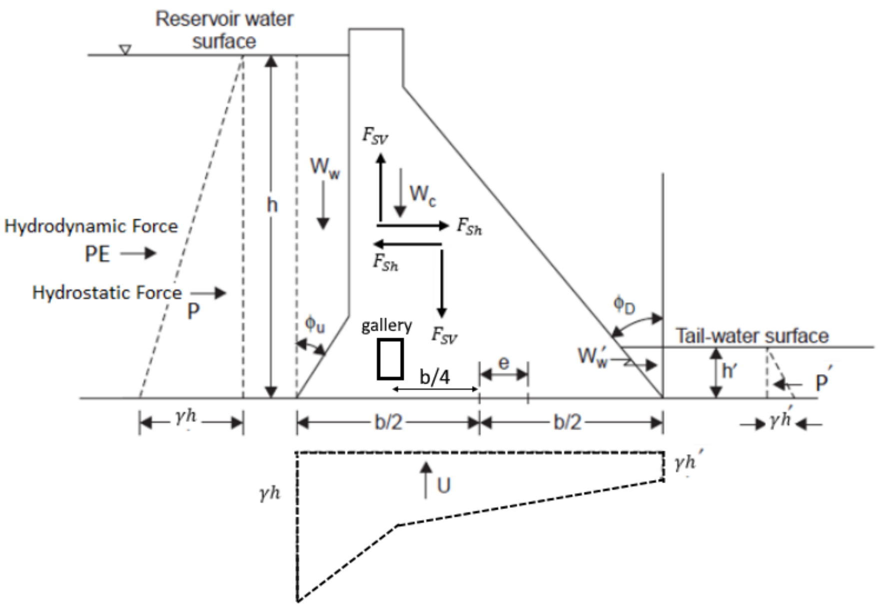

Figure 1: Forces acting on gravity dam (G.L.Asawa)

The study adopted the following hypotheses in the design and analysis procedure:

- The design equations of the dam section were used to ensure practical dimensions and correspond to the main objectives of the construction of the dam particularly those related to the top width of the dam.
- The impact of the worst-case seismic direction on the dam is considered.
- The development of the dam section to obtain an acceptable degree of safety was achieved through a successive increase in the base of the dam.
- The gallery is assumed to be located just above the base at a distance half of the top width length.
- All cases of analysis are examined with tailwater depths of 0,3,5,7,10 m.

The study aims mainly to find a relationship between the amount of increase in the base of the dam and the achievement of the safety factor of the dam under the influence of various hydrostatic and hydrodynamic forces and a wide range of storage levels. Additionally, to facilitate the task of determining the amount of the increase in the base of the dam without resorting to making many attempts to achieve the economy in time and effort and can give indicators with acceptable accuracy.

All the results of eccentricity and stresses obtained are for the case of the safe sections that have been established by using the optimum value of additional parts.

3. Results and Discussion

A concrete dam is considered a vital and strategic infrastructure structure due to the nature of the functions that it performs and its relation to the water and economic security of countries. In this study, most of the hydrostatic and hydrodynamic forces are calculated and their impact on the dam's safety and performance is monitored. This section specifically shows all the findings from the study, which are presented and discussed including the effect of several factors on the stability along with the operation of the concrete dam being explained.

3.1 Additional Part Effect

Concrete dams depend on their shape and weight to secure their safety requirements. Usually, the design of this type of dam begins with the adoption of the preliminary shape, which is subject to analysis and check of safety factors for expected failure modes. The shape of the dam is often modified by adding a concrete part to its upstream side to increase the weight and through it increases its resistance to all negative forces that may cause the failure of the dam.

In this study, the concrete dam section provided by the gallery was designed for a wide range of reservoir water levels and various tailwater depth values. Each section was analyzed by successive attempts of increasing the dam's base until attained the safe section against all failure modes.

Figure (2) shows the variation of safe additional concrete part length with corresponding reservoir water levels for different tailwater depths. It can be seen from the figure that as H and H' increase the additional part B' is increased accordingly. In addition, the figure shows clearly the influence of tailwater existence on the increasing of B' values limit. Such a figure can be useful in reducing the number of attempts and hence the time required to estimate the safe length of the dam base increment. Furthermore, in addition to foregoing, determining the value of the additional part of the dam is necessary to ensure the stability and safety of the dam, and with the intent of estimating the length of the additional part and in an approximate manner acceptable in terms of application and level of accuracy, the following equations, Table (1), can be used in a way that compatible with each value of the water level in upstream and downstream of the dam.

Table 1: Equations of additional part estimation for different tailwater depths

Additional Part Equations	H'(m)	R^2
$B' = -0.0001H^2 + 0.0747\,H - 0.8277$	0	0.9617
$B' = -0.0004H^2 + 0.1066\,H - 0.3531$	3	0.9889
$B' = -0.0006H^2 + 0.1366\,H - 0.6339$	5	0.989
$B' = -0.0008H^2 + 0.1648\,H - 1.16062$	7	0.9909
$B' = -0.0009H^2 + 0.2006\,H - 2.2842$	10	0.9937

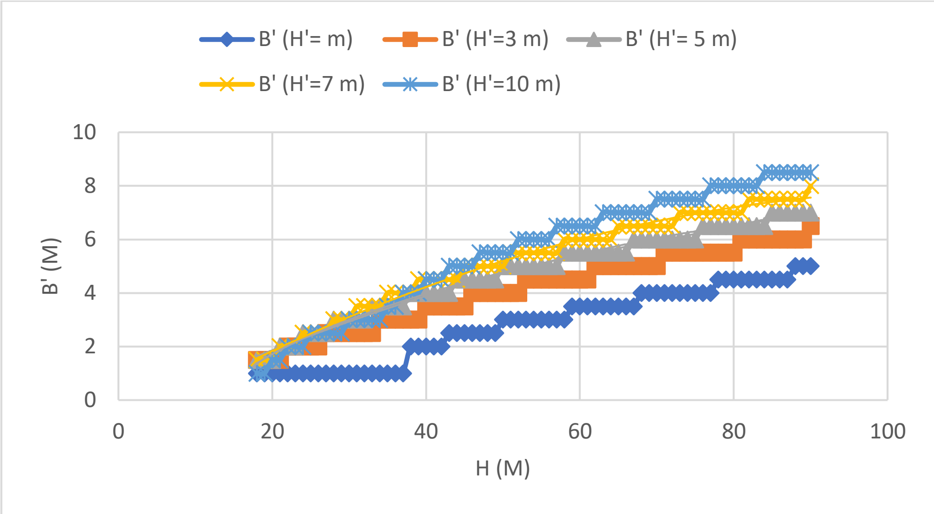

Figure 2: Variation of B' with H for different tailwater H'

3.2 Water Head Effect on Eccentricity

The stability analysis of the concrete dam is carried out on a wide range of water head values starting from 20m up to 90 m with an increment of 1 m. All factors of safety, overturning, compression, and tension are proven to be safe and for somehow the case of safety due to sliding. Eccentricity values (e) are taken as the main indicators of the tension development along the base of the dam, and it is known, that as the resultant force moves toward the toe, consequently, the maximum compressions are created at the toe and are gradually reduced towards the heel. The minimum regular heel compression will be either positive or negative. Therefore, the values of (e) are effectively affected by the movement of the resultant force. However, if the resultant force cuts the base of the dam outside the middle third part, then the tension will be produced in the area of the heel. As a result, if (e) is less than or equal to b/6, no tension would be formed along the base; on the other hand, when (e) is greater than b / 6 there can be tension on the base.

Figure (3) shows that the safe eccentricity values (e) increase as the reservoir water level increased uniformly, and no significant effect of tailwater depth has been found on the values of (e). The figure has also been viewed that the values of (e) are ranged as 2.531–12.895m. However, the positive sign will be used for calculating normal stress at the toe, since the bending stress will be compressive there. The negative sign will be used for calculating normal stress at the heel. The max compressive stress occurs at the toe and for safety, this should not be greater than the allowable compressive stresses both for the dam and foundation materials. When eccentricity (e) equals b/6, we get:

$$p_{n,\,toe} = \frac{2\Sigma Fv}{b} \quad ; \quad p_{n,\,heel} = 0 \tag{5}$$

As was mentioned earlier, the tailwater does not affect the values of e, so the following equation can be used to estimate the safe values of e:

$$e = 0.1302\,H + 0.352 \tag{6}$$

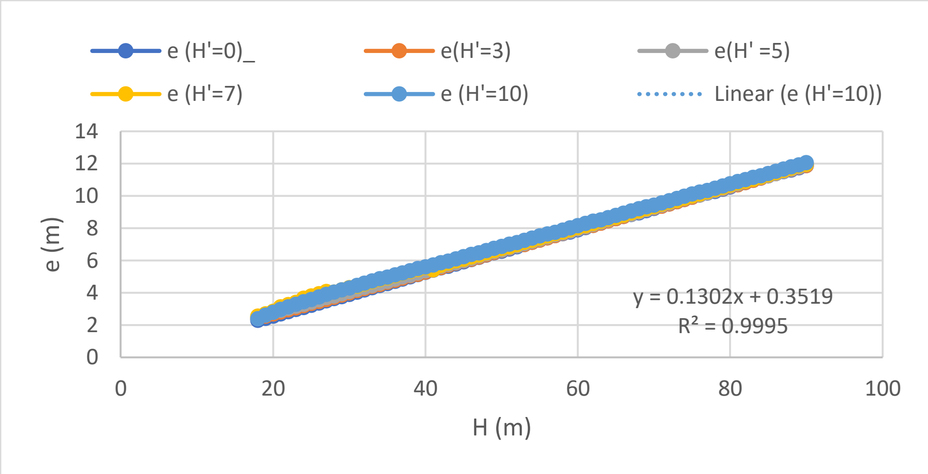

Figure 3: Variation of eccentricity (e) with H for different tailwater H'

3.3 Water Head Effect on Safety Factors

The concrete dam is exposed to several static and dynamic forces which accordingly produced different moments. In this context, studying the moments and determining their trends and values is necessary to ensure the dominance of positive moments that contribute to the stabilization of the dam and increase the safety factor against the failure due to overturning. Such challenges increase the importance of the dam's resistance against all types of expected failures.

Figure (4) shows that for different considered (H') values, the safety factor due to overturning is increases as (H) increases up to H=40 m, beyond which, the safety factor is invariant. The figure has also indicated that as tailwater depth increases the safety factor decreases accordingly.

The effect of reservoir water level (H) on sliding has also been investigated and the results show that (H) and (H') has no significant effect on safety factor due to sliding and the values of safety factor seem to move uniformly along the H values except for low reservoir water level of H'=10 m where the values are higher than others, Figure (5). Whereas, for safety factor due to Shear friction, the increases in (H) caused uniform decreases in (S.F.F.S) as shown in Figure (6).

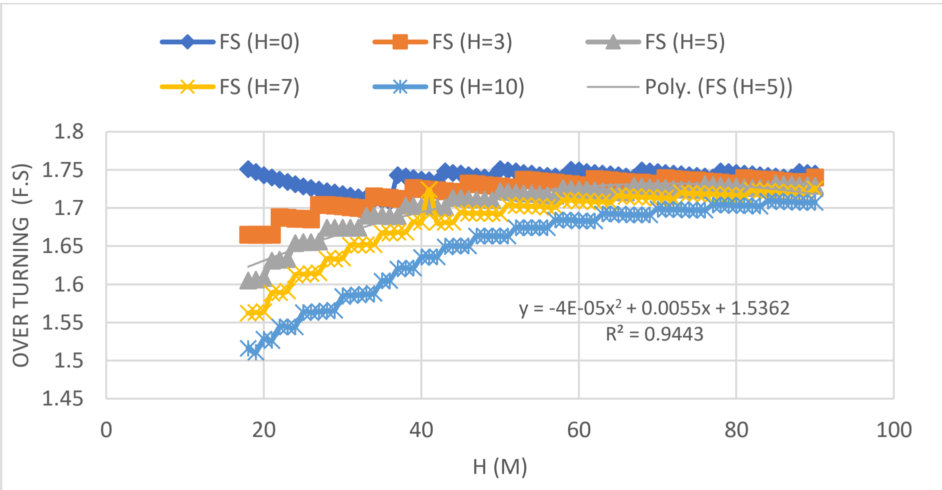

Figure 4: Variation of overturning safety factor with H for different tailwater H'

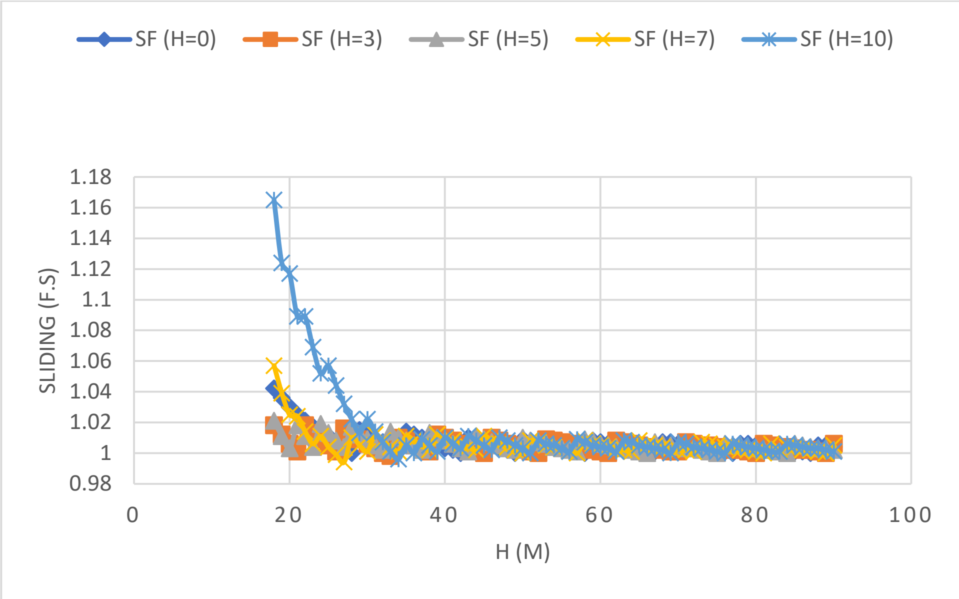

Figure 5: Variation of Sliding safety factor with H for different tailwater H’

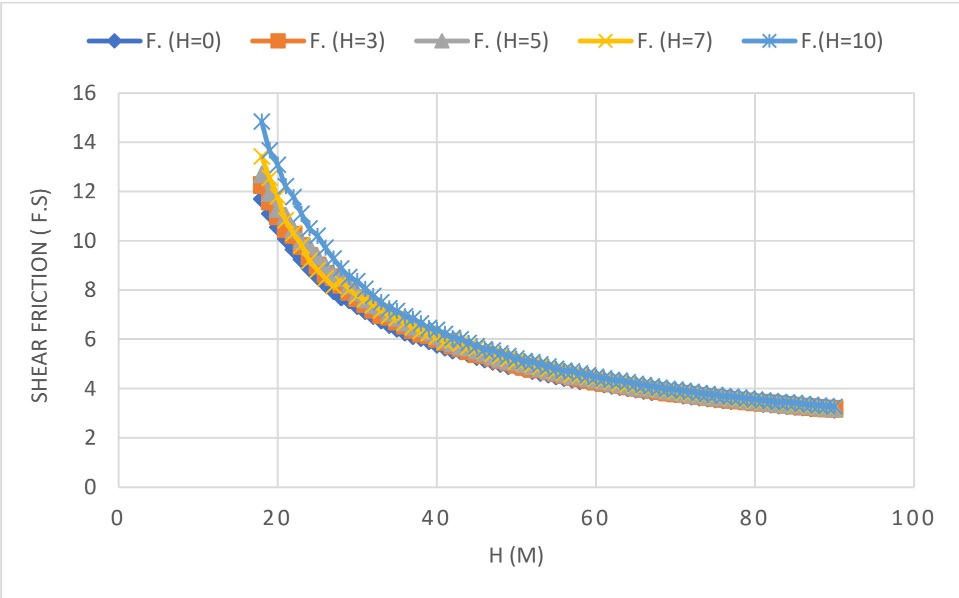

Figure 6: Variation of Shear friction safety factor with H for different tailwater H’

3.4 Water Head Effect on Stresses

As the concrete dam is subjected to numerous stresses as a result of the forces exerted by the different water levels in the reservoir, these stresses are affected in terms of values and behavior concerning the change in the water level.

Figure (7) shows the variation of U/S shear stress with H for different tailwater H’, It can be seen from the figure that as H increases the U/S shear stress ($\tau_{U/S}$) increases with some local fluctuation. Furthermore, it is found that the increases in the tailwater depths cause increases in shear stress. The values of shear stresses have seemed to range generally (40-120) Kpas.

$$\tau_{U/S} = -0.002H^3 + 1.142\,H + 22.662 \quad [7]$$

Figure (8) shows the variation of D/S shear stress ($\tau_{D/S}$) with H for different tailwater H', It can be seen from the figure that as H increases the D/S shear stress increases accordingly. Furthermore, the results also showed that tailwater has a limited effect on these stresses. The values of shear stresses have seemed to range generally (200-1400) Kpas. Since the results are somewhat similar for all the values of the tailwaters adopted in the study, it is possible to adopt the following equation in estimating the stress value in an acceptable approximate manner.

$$\tau_{D/S} = 15.545H - 37.394 \quad [8]$$

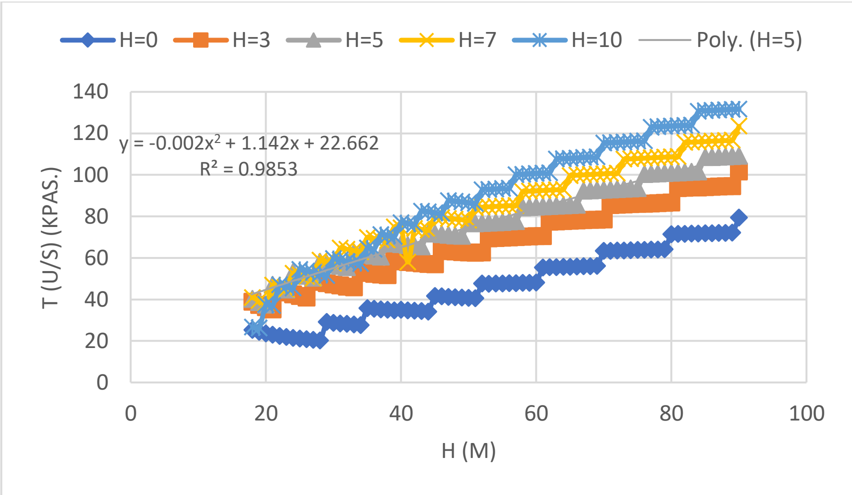

Figure 7: Variation of U/S Shear stress with H for different tailwater H'

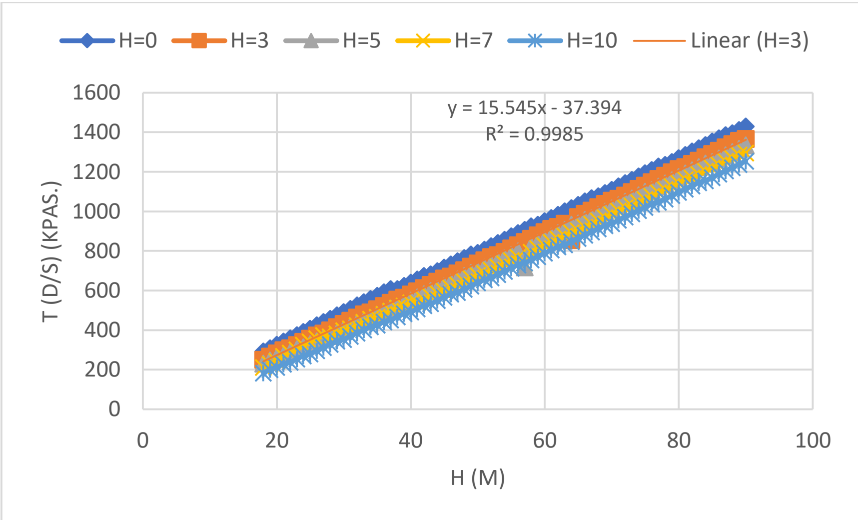

Figure 8: Variation of D/S Shear stress (τ) with H for different tailwater H'

Figure (9) shows the variation of $Pv(min.)$ with H for different tailwater, it can be seen from the figure that as H increases the $Pv(min.)$ increases accordingly with some discrepancy which stepped from low to high values. Furthermore, the results also showed that tailwater has for somehow limited effect on these stresses. The values of $Pv(min.)$ range from 10 Kpas. up to 75 Kpas.The analysis of results that have been obtained can be used to establish the following equation to estimate the minimum vertical stress $Pv(min.)$ with a high acceptable limit of a correlation coefficient.

$$Pv_{(min.)} = -0.0048\, H^2 + 1.391\, H - 19.148 \quad [9]$$

The values and behavior of vertical normal stress $Pv\ (max)$ are shown in Figure (10) which clarified that as H increases the $Pv\ (max.)$ increases and no effect of tailwater has been found. The values of $PV(max.)$ vary through a range 250 – 1800 Kpas.,

$$Pv_{(max.)} = 19.831\, H - 17.925 \quad [10]$$

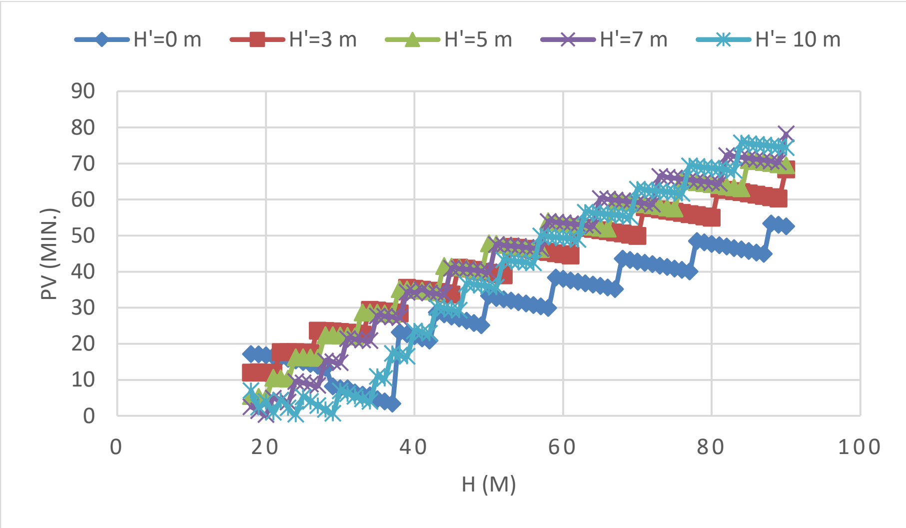

Figure 9: Variation of Pv(min.) with H for different tailwater H'

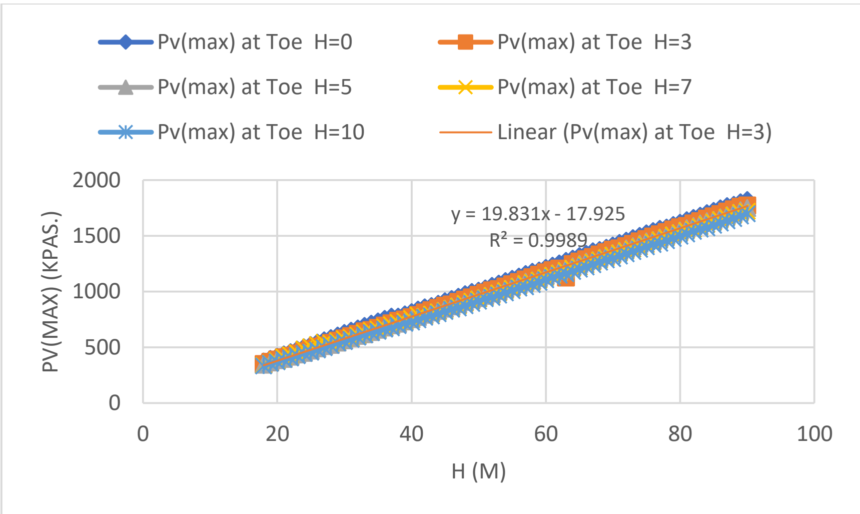

Figure 10: Variation of Pv(max.) with H for different tailwater H'

The variation of principal stresses σ with the head of water in the reservoir (H) can be seen in figures (11) and (12). For both σ (U/S) and $\sigma\ (D/S)$, the values are increases as H increase. The values started from about zero up to around 55 Kpas. The variation of $\sigma\ (U/S)$ showed some fluctuations and was influenced to some extent by the tailwater depth values as shown in figure (11). The approximate values of $\sigma\ (U/S)$ can be estimated by the following equation:

$$\sigma_{U/S} = -0.004\ H^2 + 1.2155\ H - 23.104 \qquad [11]$$

Figure (12) illustrates that the values of σ (D/S) changed smoothly and no effect of tailwater depths has been indicated on the values or behavior. The values of σ (D/S) has ranged from 500 up to 3000 Kpas.

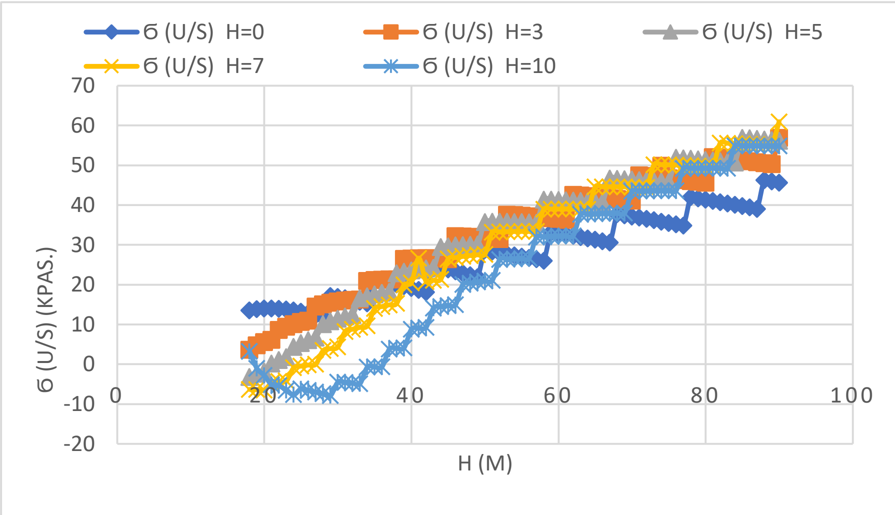

Figure 11: Variation of U/S Principal stress with H for different tailwater H’

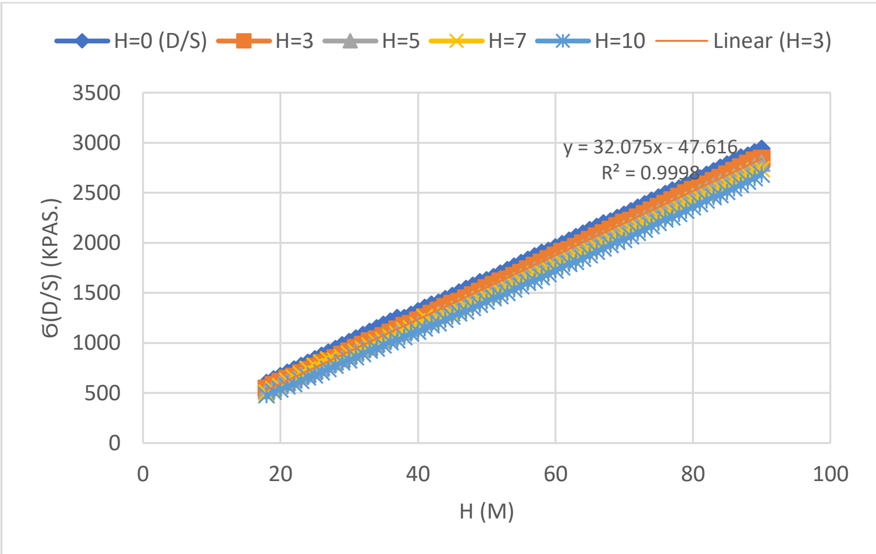

Figure 12: Variation of U/S Principal stress with H for different tailwater H’

3.5 Comparison with Previous Studies

In the dam sections that have been considered in the current study, the gallery which is used to reduce the effects of uplift pressures is provided beside the existence of different values of tailwater depth. The results obtained were compared with a case that has no gallery and without tailwater (Ahmed, 2016). The comparison indicates that the existence of the gallery and tailwater causes a reduction in additional parts required for the safe dam section to be around 25 % of the values used in the case of dam sections without gallery and tailwater. Whereas, no significant difference was indicated for the behavior and values of eccentricity that has been found for these two cases under comparison

4. Summary and Conclusions

Dams are considered one of the most prominent infrastructure facilities that strongly contribute to providing and controlling water needs. Several iterations with a wide range of water head values starting from 20m to 90 m with an increment of 1 m were performed to analyze the stability of the full dam cases until the safety state is reached.

All the stresses computed were within acceptable limits and proven safe, stage by stage adding parts to the base.

The following are the main conclusions:

1. As H and H' increase, the additional part B' is increased accordingly. The safe additional part B' can be estimated for each value of H and H' by using the corresponding equations which have been obtained by results regression. The equations mostly produce approximate and reasonable results required for additional part values indication which are useful for saving design time and effort.
2. The safe eccentricity values (e) are uniformly increased as H increases, and no significant effect of tailwater depth has been found on the values of (e).
3. the safety factor due to overturning is increases as (H) increased up to H=40 m, beyond which, the safety factor is invariant. The results indicated that the overturning safety has inversely proportional with the tailwater depths. The results show that there is no obvious effect of H and on safety factors due to sliding.
4. for operation head (H), the Pv (max.) and Pv (min.) increase as H increases, and no significant effect of tailwater H' has been seen on their values.
5. for different operations head (H), the upstream principle stress σ(U/S) and the downstream principal σ(D/S) are increases when the value of the height of water (H) increases. The results showed also that a significant effect of tailwater (H') exists on values the σ(U/S) in which.
6. The comparison indicates that the presence of the gallery and tailwater leads to a reduction in the additional sections required for a safe dam section so that it is about 25% of the values used in the case of dam sections without gallery and tailwater. Where there was no significant difference in the behavior and deviation values that were found for these two compared cases

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