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Stability Evaluation of Rabigh Concrete Gravity Dam

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Abstract. Concrete gravity dams are constructed for holding big volume of water for various uses, and their stability is vital to ensure its benefits. Rabigh dam (RD) is the third important dam in Saudi Arabi, located in the eastern side of the Red Sea, and intended to protect Rabigh city and the adjacent industrial complex and recharging the groundwater. Its length is 380 m, 71 m high with a huge reservoir of 220 million m3. A gravity dam is subjected to two external hydraulic forces in addition to the force of the submerge silt. Those external forces are opposed by the dam self-weight (Wt). The acting forces introduce compressive and tensile stresses on dam body that need to be checked for the concrete limits for those stresses. The main objective of this study is to reevaluate the dam stability in static and pseudo-static conditions in view of global warming. Several recent research warned of an expected increase of rainwater and flood frequency due to global warming, which will raise the destabilizing forces while the dam weight (Wt.) is the same. The stability was tested for three types of failure: overturning, sliding and the induced stresses in the dam body. It turns out that the obtained factor of safety (Fs) is within expectable values for all tested conditions.

Keywords: global warming, Rabigh dam, Saudi Arabia, Dam stability analysis.

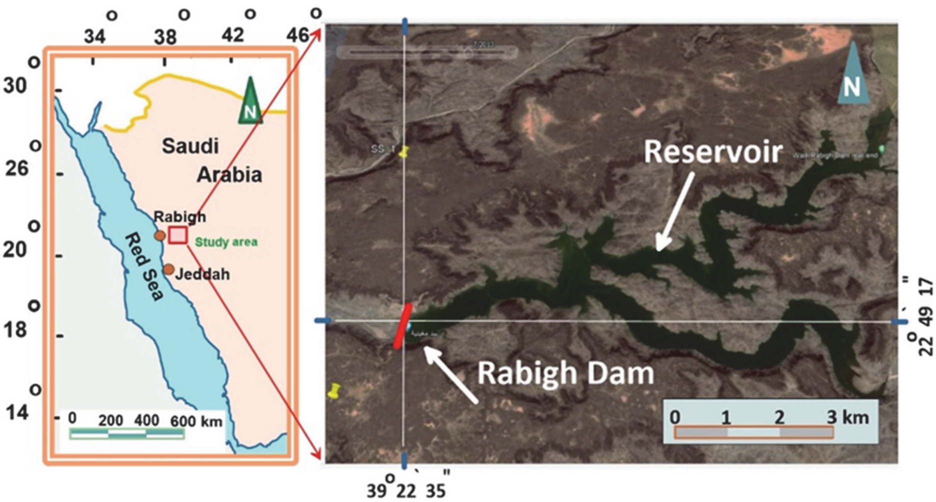
1. Introduction

Most areas of Saudi Arabia lie within subtropical zone of high pressure which has a dominant influence on its climate (Sen, 1983). The climate is greatly affected by different air masses, which blow from the Indian Ocean and the Mediterranean Sea. The climate is dominated by continental features characterized by long hot and almost totally dry summers, and short cool winter seasons with little rainfall making the region one of the driest countries in the world. The study area is not an exception, the climatic condition is influenced by the topography of the catchment area and the nearby Red Sea. The temperature in the dam site ranges from 47° in summertime to almost 1° in winter with an average of 27° (Bindagjii, 1978). The total monthly evaporation is 32.5 cm, and the humidity varies from 19% to 46%. The maximum wind speed is 73 km/hr. from north or west direction during wintertime and from southeast in summer.

Rain areal distribution in the study area is highly influenced by the local topography, where rain increases at higher elevations and the humid air as approaching the Red Sea. Rainy periods extend from October to the end of May resulting from moist air masses. The wettest month is January (16.6 mm) and the driest month is July (0.1 mm). The mean annual rainfall within Rabigh basin ranges from 40 mm close to the dam to 140 mm upstream, with an average of 98 mm.

Rabigh is known as a historical port city along the Red Sea shoreline, located 140 km north of Jeddah (Figure 1). The area is generally flat, having an average width of 25 km and covered with different types of soil followed eastward by mountains. The coastal area is dissected by Rabigh Wadi that is running east-west through the western rim of the Arabian Shield toward the city. The rainfall is in winter (December to February), ranging from 50 to 100 mm, the scarcity of rain and high temperature restricted the area vegetation to scattered desert shrubs and few natural oases along the wadi course.

The city expands rapidly with time to reach a population of more than 100,000 (2013 census). In the past few years, a major refinery in addition to petrochemical facilities were constructed in the area (Petro Rabigh). Rabigh and the surrounding industrial complex cover an area of about 7,000 km2, that enables the area in general to produce and market refined hydrocarbon and petrochemicals materials. Such huge investment must be protected from flood hazards. This was managed in the past by a large-size concrete gravity dam and appropriate channels that prove their efficiency during several flood events.



(Figure 1). The location of Rabigh city and its dam.

One of the oldest studies is an engineering geological and hydrogeological map for Rabigh area carried out by Laurent et al. (1973) at a scale of 1:10,000. This map shows local relief, water table contours, and the contacts between four soil units. Several geologic and hydrogeologic investigations have been conducted within and around Rabigh city. The previous works included geological studies, geological map and explanatory notes compiled by Ramsay (1986), hydrology, and hydrogeology investigations (El-Hames, 2011), watersheds analysis (Shi, 2014; and Zaigham, 2017), soil characteristics (Abdelrahman, 2020), expansive soil (Hakami and El-Sayed, 2019), groundwater quality and associated health risk (Rajmohan, 2021), environmental impact of landfill on groundwater (Al-Arifi, 2013); Al Alahmadi et al., 2019; and Rajmohan et al., 2021). Desert floods were studied in some detail by El-Khatib (1980) and Zaigham et al. (2015). They showed that precipitation has short duration, sudden, violent, very intense and produce flash flood within short time. An extensive hydrological and geotechnical investigation was carried out by the Ministry of Water and Agriculture (MWA) (1987) in Wadi Rabigh. The aim is to build, in 2009, a large-scale gravity dam for flood protection. Although it performed safely in the past but it must be tested for the changing conditions of global warming. Gravity dams are designed to oppose various forces especially for the overturning movement and dam sliding. Ajayakumar et al. (2015) studied hundreds of dams and explained their importance in regulating water flow and that cannot be achieved without ensuring the dam safety. Jayendra (2019) studied gravity dam stability resting on and surrounded by soil media using finite element analysis. Dams may fail also due to excessive internal stresses. The compressive stresses as generated from the hydrostatic external pressure (water lateral force) and internal load (uplift) may reach a level that is more than the allowable limit for concrete (Novak et al, 2007). Zeng et al. 2015 conducted a study using finite element method and concluded that the tensile stress concentration appeared at the heel and toe of dam.

The aims of this study are to:

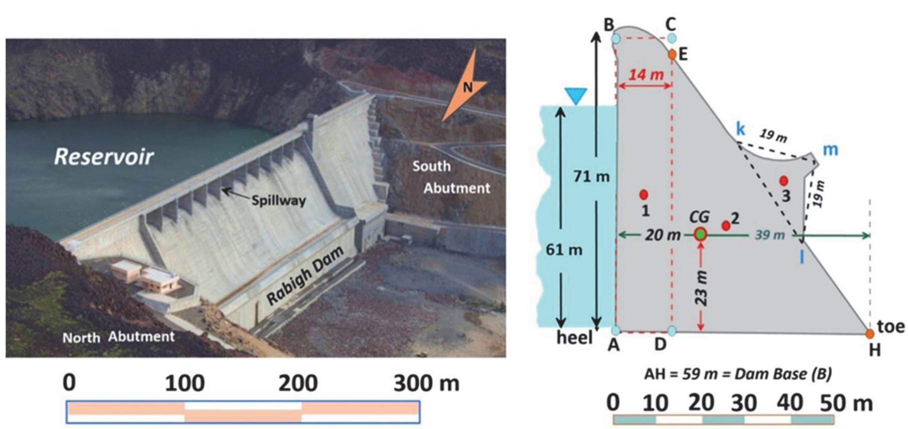
- Estimate the increase in Rabigh area flood runoff (m3/s) since 2009-2011 and compare that with any changes in the original runoff due to Global warming.
- Calculate the dam stability to the maximum water level of 61 m for static and pseudo-static conditions,
- Estimate the maximum reservoir volume and spillway capacity due to the expected changes.

2. Dam description

In the past few years, Rabigh city suffered from several devastating floods. A large-size gravity dam was built in 2009. The reservoir capacity behind the dam is one of the largest in the Kingdom of Saudi Arabia, 220 million m3 that accommodate the drained rainwater from a huge catchment area of 3,456 km2. The dead load is at water level of 40 m, and the maximum level is 61 m beyond which the water will reach the spillway.

The dam is the main flood protection in the area, situated 35 km on the edge of the mountains to the east. The dam site coordinates are 39° 22' 33" E and 22° 49' 18" N. It is an extensive body of reinforced concrete having a cross-sectional area of 2,535 m2, forming a triangular- shape with some modifications. The dam centroid is located at a vertical distance of 23 m above the dam base, and a horizontal distance of 20 m from the heel (Figure 2). The dam upstream face is vertical with a height of 71 m, and slightly inclined (0.75 to 1) on the downstream side (Figure 2). The dam length 380 m that stretched along the wadi, the width of its crest is 5 m and freeboard is 1.25 m. The spillway is composed of 12 separated units, 14 m wide each giving a total width of 168 m, which provides a large capability to handle a peak inflow of 9,543 m3/sec. The dam has two outlet structures that are 1 m2 in cross section, and a concrete foundation 59 m wide and 4 m thick.

The dam reserves huge quantities of water, 220 million m3, intended to control floods in Wadi Rabigh basin and contributes, at the same time, in recharging the aquifer underneath. The dam reservoir is composed of two large branches, each 15 km long, joined at a point 6 km before they reach the dam (Figure 1).

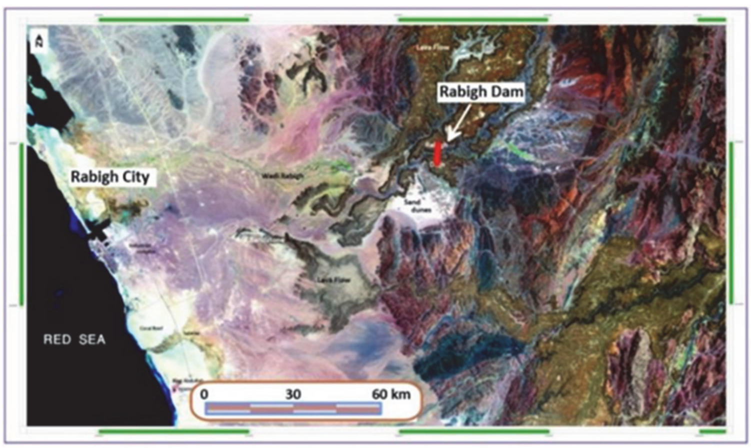


(Figure 2). Rabigh gravity dam (left), and dam cross-section (right).

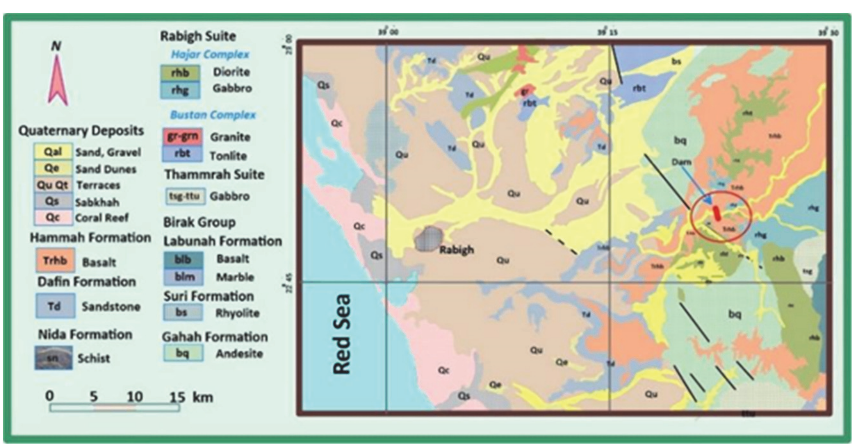
3. Geomorphology and Geology

The study area is a small portion of Rabigh Quadrangle (sheet 22D) (Ramsay, 1986). The area can be grouped into three geomorphological parts; flat terrain along the Res Sea followed by mountains of different elevations and covered in part by Recent basalt (Harat) (Figure 3). Recent deposits are rather simple, but rock types are complicated. Rabigh city occupies a flat low-lying coastal plain that is covered in part by Quaternary deposits as sabkhah (sand, clay, and gypsum deposits, Qs); alluvial terraces and talus fans (Qu); eolian sand (sand dunes and sand sheets, Qe); alluvium (sand and gravel in wadis, Qal); and coral reef (Qc) (Figure 4).

The coastal plain is generally succeeded eastward by various and complicated types of rocks that extend from the Precambrian to Tertiary (Figure 4). The older rocks are of three types: igneous rocks (granite, granodiorite, diorite, tonalite, and gabbro), metamorphic rocks (Schist, marble, and quartzite), and sedimentary rocks (sandstone, shale, and limestone). These rocks are of different ages. The Recent rocks are mainly consisting of olivine basalt flows. The basement rocks in the dam site are light-color granite, quartz diorite and gneiss. These rocks are frequently intruded in some parts by dolerite and andesite dykes. Basement rocks are covered by sheet-like flows of columnar basalt forming a general flat topography in the dam site and catchment area.



(Figure 3). Satellite image showing Rabigh city and Rabigh Wadi.



(Figure 4). Geological map of the study area (Simplified after Ramsay, 1986).

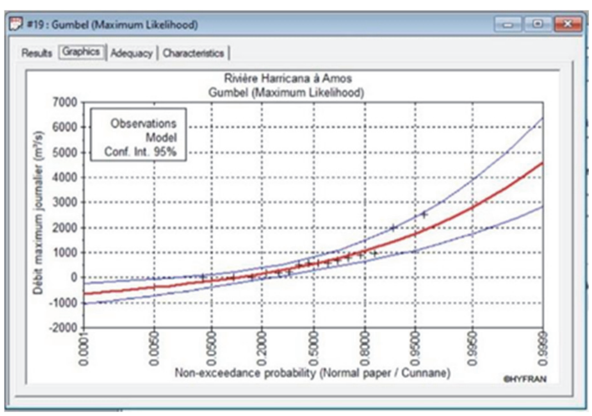
The rock formations that constitute the reservoir area are practically impervious and there exists no problem of water leakage. Rock weathering is moderate at the slopes of the reservoir area. The existing discontinuities are mainly joints that are widely spaced (60-200 cm) with tight aperture in the range of 0.1 mm. The trend of the dam axis is N3.5°E, while the strike of the major joint set is 30° with respect to the dam axis. The joints are dipping in a direction of 85° toward the upstream with an angle of 60°. The water table within the basin ranges from 40 m close to the dam to 130 m at higher elevations. The rock quality in the dam abutments is sheared by a major fault, in some localities, rock material can be easily removed by a geological hammer. Rocks become much stronger only few hundred meters up or down stream. The joint spacing is wide and the rock quality designation (RQD) for granite is 93 % and 95 % for diorite. The basement rocks permeability is very low, ranges from 3×10-5 to 5×10-6 cm/sec. The rock mass rating (RMR) for both granite and diorite are good. The soil thickness is about 15 m, composed of sand mixed with gravel and silt.

4. Materials and Methodology

The applied research methodology utilized several tools, methods, and techniques to ensure accurate results to achieve the desired objectives. The performance of Rabigh dam since 2009 was in line with what it was intended for. The prime change is the expected increase in the peak discharge due to global warming. The conditions to be checked for the dam static and pseudo-static stability are:

- dam overturning,
- dam sliding,
- the magnitude of induced stresses (either tension or compression)

Floods in Rabigh area occur in winter and spring, the measured events during the period from 1970 to 1985 varies from 140 (in 1978) to 2,500 m3/sec (in 1985) (MWA, 1987). Based on this flood record Hyfran software was implemented to estimate peak discharge (Q) with various return periods in Rabigh area, the Q-value for 100 years return period is 2,490 m3/sec (Figure 5).



(Figure 5). The estimated peak discharge for 100 return period in Rabigh.

5. Static Dam Stability

Dam stability is based on thorough regulations established individually by the Bureau of Reclamation (USBR, 1976), the U.S. Federal Energy Regulatory Commission (FERC) and the U.S. Army Corps of Engineers (USACE, 2005). Their engineering processes follow the limit equilibrium analysis. Dam's stability depends on the balance between its weight (as a stabilizing force), and the external forces that may cause the dam displacement. Gravity dams' stability can be analyzed by several methods the most common are:

(1) the trial load twist method where the dam horizontal elements behave as beam that will transfer the water pressure acting upon it to the abutments by beam action.

(2) the slab analogy method which is simply a plane that is supported partially by few hanging beams and all are hanging totally from both sides by the rock abutments.

(3) the gravity method which might be graphical or analytical and the dam is assumed to transfer their weight to the ground by cantilever action provided that the rock foundation is strong. It is used for both conditions: reservoir full or empty.

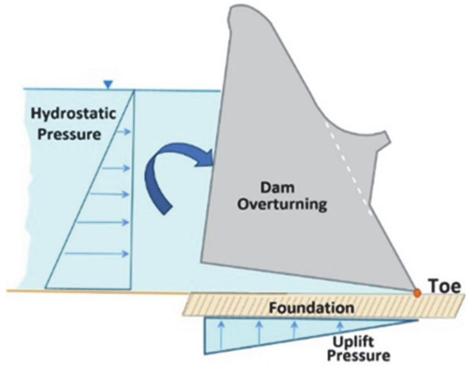
This research is based on the last method for its simplicity and commonly applied. The dam, under consideration, is divided into vertical sections having a unit length, each section behaves as vertical cantilever independent of each other. Three external forces are acting on each dam section:

- horizontal hydrostatic force (Pw)
- silt horizontal force (Ps)
- vertical water uplift (Pu) underneath the dam base

The external forces induce internal stresses inside the dam body. Those forces are opposed by the dam self-weight (Wt). Dam failure might be in the form of overtopping, sliding or concrete crushing. The degree of dam stability is represented by the factor of safety (Fs) which is simply a numerical balance of the positive forces that are stabilizing and negative forces that cause dam failure. The acceptable Fs-value for static condition is 1,25 to 1.5 (de Vallejo and Ferrer, 2011).

5.1 Dam Overturning

One form of failure is the dam rotation around the dam toe (overturning). The basic concept of the failure mode is that the forces create a moment around the toe of the dam which leads to a clockwise rotation of the structure (Figure 6). Overturning a gravity dam of a significant size is an unlikely mode according to Novak et.al. (2007), but most gravity dams are evaluated for possible rotation. Therefore, it is necessary to take the moment of each external force around the toe provided that the lever arm of each force from the toe is known. The moment of the forces (Pw, Ps, and Pu) that might cause movement is considered negative (M-ve) and the stabilizing force (Wt) is positive (M+ve). The algebraic sum of negative moments must be compared with the positive one.



(Figure 6). Dam overturning.

b. Hydrostatic Force

The water stored in the reservoir creates horizontal forces (Pw) on the upstream side of the dam that gradually increase with water depth (h). The resultant of the water pressure on the dam face is acting at a height of h/3, this height is also equal to the moment arm. Pw-value is giving by the Equation:

$$Pw = 0.5\ \gamma w\ h2 \qquad \text{Eq. 1}$$

Where; γw = water density (1.0 t/m3), h = the desired water level in the reservoir.

During a strong storm, flood water will increase the water level in the reservoir beyond the dead load (40 m), the maximum level is 61 m, higher water level will flow through the spillway. Implementing Eq. 1, the forces of the lateral pressure is 1,860 t/m/, in favor of rotating the dam clockwise and considered negative moments. The moment arm is 20.3 m (61/3), and the resulting moment is – 37. 8×103.

c. Uplift Force

Part of dam operation is to keep water in the reservoir continuously to a level of 40 m, this water head is enough to cause water to percolate under the dam through soil pores and/or rock joints and cracks. As water seeps towards the toe, a vertical pressure (Pu) at the dam base (B) is created and extending from the dam heel to the toe.

The width of dam base (B) equals 59 m, the numerical Pu-value can be calculated by:

$$Pu = 0.5\ \gamma w\ B\ h \qquad \text{Eq. 2}$$

According to Eq. 2 the uplift pressure for the maximum water level (61 m) is 1,800 t/m\. The moment arm is 2(B/3) =39.3 m. The negative uplift moments is 70.74×103.

d. Sedimentation Force

During the flow of torrent water, soil mixture and various sizes of rock fragments are carried toward the reservoir. Silt is accumulated with time at the reservoir bottom along the upstream face of the dam which exerting additional horizontal pressure on the dam. The Ministry of Agricultural and Water (MAW, 1987) assumes that the expected dam operational life is 50 years starting from 2009. MWA performed a hydrological study to measure the suspended sediments at the flow in 14 dams gaging stations in 1984 and 1985 (Table 1). Based on this record, the expected sediment yield in Wadi Rabigh is 465 m3/year/km2 of the catchment area using Fleming formula (MAW, 1987). Since the size of the catchment area is 3,456 km2, then the annual total sediment yields to dam reservoir is 1,607,040 m3/year. Assuming a dam life expectancy of 50 years (starting from 2009), the maximum silt volume settled in the year 2059 is 80.35 million m3. The silt pressure (Ps) is:

$$Ps = 0.5\ \gamma silt\ (hs)2\ ka \qquad \text{Eq. 3}$$

Where; γsilt is the silt submerge density, hs is silt height behind the dam, ka is the silt coefficient of active earth pressure that can be estimated by:

$$ka = [1-\sin\varphi\ ]/[\ 1+\sin\varphi] \qquad \text{Eq. 4}$$

where φ is the silt friction angle.

Implementing the above estimations for the worst case, MWA calculated the maximum silt height hs behind the dam to be 53 m. The measured silt density is 1.4 t/m3, the friction angle is 33° and the active earth pressure (ka) is 0.29. Silt exerts pressure on the dam that increases linearly. Using Eq. 3 and Eq. 4, the maximum Ps on the dam is 570 t/m/. The moment arm of Ps is 17.66, and the silt negative moment is 10.1×103.

The overall dam stability is a balance between the positive and negative moments. The total maximum negative moments is 118.6×103 for water level 61 m. These forces are trying to overturn the dam around the toe, the dam movement is resisted by the moment of the dam self-weight (+250.3×103). The Fs is 2.1. Therefore, the dam is stable (Table 2).

5.2 Dam Sliding

The dam is more liable to horizontal forces (Hf) such as hydrostatic and sediment load. Dam sliding may take place if the total horizontal forces (Hf) are more than the combined effect of the dam weight (Vf) and the friction between the concrete and the rocks (μ) acting in the same direction. Sliding (or shear failure) may be initiated along a horizontal plane in the foundation, and the factor of safety (Fs) is:

$$F_s = \frac{\mu V_f}{H_f} \qquad \textit{Eq. 5}$$

Where μ is the coefficient of friction between the concrete and the rock foundation

(0.65 to 0.75, average=0.70)

The original dam weight (6,417 t/m/,Vf) is reduced by the uplift force (1,800) so that the effective weight is 4,617. The total horizontal forces (hydrostatic and silt sedimentation, Hf) is 2,430 t/m/ for water level 61 m. Appling Eq. 5 gives a satisfactory factor of safety of 1.3.

(Table 1). The measured suspended sediments in 14 stations in Saudi Arabia (MWA, 1987).

Station ID	Date	Discharge (m^3/sec)	Sediment (t/day)
B-405	Jan 26, 1985	2.5-11.3	4,610
	Apr 4-13, 1985		39,284
	May 5, 1985		11,190
SA-425	Apr 4-28, 1985	3.3-110	368,500
	May 12-31, 1985		12,921
	Jun 11-1, 1985		1,960
	July 3-4, 1985		3,080

Station ID	Date	Discharge (m^3/sec)	Sediment (t/day)
SA-421	Sep 1-17, 1985	3.6-4.0	7,430
	Feb 15-16, 1985	2.0	3,130
	Apr 23-24, 1985	43	101,000
SA-423	Sep 10-19, 1984	1.0-10.3	67,962
	Apr 4-28, 1985	1.6-228	1,720,500
	May 1, 1985	1.6	2,010
J-418	Nov 25-26 1984	16.3	49,410
	Dec 19-20, 1984	7.4	22,600
	Jan 27, 1985	1.9	2,030
	Apr 12-14, 1985	15.4	41,660

(Table 2). The balance between the positive and negative moments.

	Value (t/m/)	Moment		Total moments ($\times 10^3$)	
		Arm from toe (m)	Value × 10^3	Positive	Negative
Dam self-weight	6,417	39.0	+250.263	250.263	118.6
Water pressure	1,860	20.3	- 37,758		
Uplift pressure	1800	39.3	- 70.74		
Silt pressure	570.0	17.70	-10.07		
			F_s	2.1	

5.3 Dam Induced Stresses

The external forces cause induced internal stresses, compression (σ) and tensile (τ) within the dam body, both may contribute to dam failure. The dam's effective force is 4,617 t and the total horizontal forces is 2,430 t. Their resultant (R), using Pythagorean theorem is 5,217 t. The R-value intersects the dam base at point k, and make an angle (Θ) with the vertical (Figure 7). Simple trigonometry helps to estimate jk and Θ values:

- The value of the angle Θ can be evaluated as follow:

  cosine Θ = (effective vertical force) / [resultant force]

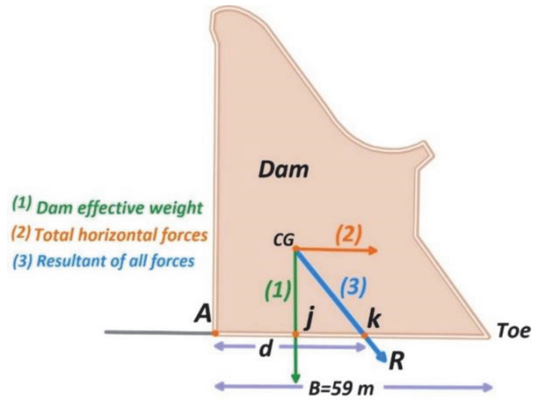
  = (4,617)/[5,217] = 0.8850

- Θ-value can be estimated by taking arccosine (0. 8850), then Θ=27.7 degrees.
- the vertical distance from the centroid to the base is 23 m (Figure 2 and 7), the value of jk is:

  jk = 23 (tan Θ) = 23(0.5250) = 12.1 m

The R-value induces internal stresses that may exceed the allowable stresses limit for concrete. The maximum τ-value occur at heel mostly during reservoir empty condition, the maximum σ-value concentrated at the toe when the reservoir is full. Referring to Figure 7, jk = 12.1 m, Ak = d = 32.1 m, hence eccentricity (e) is (Novak et al., 2007):

$$e = d - [0.5 (B)] = 2.6 \text{ m} \qquad \text{Eq. 6}$$



(Figure 7). The location of the force's resultant in Rabigh dam.

The compressive (σ) and tensile stresses (τ) acting on the RD toe can be calculated from Equations 7 and 8 as follow:

$$\sigma = \frac{W_t}{B}\left(1 + \frac{6e}{B}\right) \qquad Eq.\ 7$$

$$\tau = \frac{W_t}{B}\left(1 - \frac{6e}{B}\right) \qquad Eq.\ 8$$

The calculated σ and τ acting on the RD toe and heel are 98.6 t/m/ and 57.6 t/m/ respectively. The concrete gravity dams are usually designed in such a way that no significant tension is developed anywhere in the structure. As a rule, when R cross the gravity dam base at the middle-one-third, there is no significant tension force (τ) (Novak et al., 2007), the location of the resultant intersection with the dam base is within the mid-third distance. According to MAW (1987), the maximum permissible tensile stress for high Rabigh dam is taken as 100 to 133 t/m/, and the allowable compressive stress for concrete varies from 800 to 1050 t/m/. Therefore, the internal stresses which may develop in the dam body is much less than the allowable limits. The toe and heel are of great importance in the design. However, the stress is still less than the strength of dam concrete.

6. Pseudo-static Dam Stability

Earthquake is the ground shaking caused by seismic waves from sudden energy release in the inner Earth crust. Tectonically, Saudi Arabia is part of the Arabian Plate (25-30 million years). The majority of earthquakes in the Arabian Peninsula are concentrated along three major belts (Al Hadad, 1992):

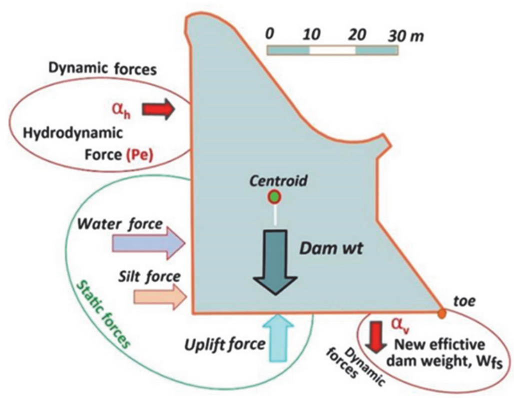
- Zagros fold belt that extends about 1500 km in a northwesterly direction from Oman through west Iran and northeast Iraq to Turkey.
- The second belt extends from the northern tip of the Red Sea in a northeasterly direction through the Gulf of Aqaba, Dead Sea, Lebanon, Syria, and terminates in southern Turkey.
- The third belt expands from the central Red Sea region south to Afar and then east through the Gulf of Aden.

The study area occurs in the third belt and no seismicity was recorded in the interior of the Arabian Peninsula which suggests little internal deformation (Al Hadad, 1992).

Ground movement due to tectonic activities is considered an extreme condition for dam stability and may create ruptures of faults that may lead to dam failure. Ground acceleration is taken as a measure of ground shaking, it is expressed as a fraction of the acceleration due to gravity (αg), where α is the seismic coefficient Earthquake activities in the vicinity of Rabigh (1998– 2010) is characterized by small magnitude (Mw ≤ 3.8). Ashour and Abdel-Rahman (1994) suggested an α-value of 0.05 for the coastal area close to Rabigh, Al Hadad et al. (1992) recommend 0.075g, while Osman (2012) estimated the α-value to range from 0.08g to 0.099g. An α-value of 0.1 will be used for the study area as a design value, which is also recommended by the Saudi Building Code (SBC 301).

A quick estimation of the role of earthquake on dam stability is known as pseudo-static. It is a simplified approach that allows accelerations to be expressed in terms of horizontal and vertical seismic coefficients, αh and αv, multiplied by gravitational acceleration, g. In this manner, the seismic effect characterized by inertia forces is considered in theoretical analysis.

The acceleration of seismic waves resolved into horizontal (α_h) and vertical (α_v) ground accelerations. Estimating the dam pseudo-static stability follows the same procedure used for static condition, except two additional destabilizing forces are added due to both αv and αh (Figure 8). The factor of safety (F_s) is expected to be lower than the one obtained for static case. A factor of safety of 1.1 or more is accepted for extreme cases (de Vallejo and Ferrer, 2011).



(Figure 8). The static and pseudo-static forces acting on the dam.

The calculation was performed according to Zanger formula. The degree of dam pseudo-static stability in this study assumed the worst cases for dam overturning, sliding and induced stresses as follow:

- The vertical acceleration (αv) vibrates under the dam and may either acts downward or upward. Upward movement pushes the foundation much closer to the dam and the effective weight of the dam will increase. The downward vibration moves the foundation away from the dam and the effective dam weight is reduced. The αv downward movement case is more conservative and will be taken in the analysis.
- The horizontal one (αh) creates a quick and temporary dam oscillation in the up-stream and down-stream directions.

Regardless of direction, the Peak Ground Acceleration (α=0.1) will be used in the analysis to calculate the inertia force (IF) due to the dam movement and the hydrodynamic force (Hf) in the reservoir.

6.1 The effect of vertical acceleration

The vertical acceleration (αv) that is assumed to be 0.1 will reduce the density of concrete, and water by a certain amount (r):

$$r=(\alpha v /g) = (0.1/9.81)=0.01 \qquad \text{Eq. 9}$$

where

g is gravity acceleration (9.81),

The original dam weight is 6,417 t/m′, it was reduced in the static analysis into 4,617 t/m′ due to the uplift force. The seismic vertical acceleration will reduce further the pervious effective weight into (Table 3):

$$Wtfs= 4,617 (1-0.01) = 4,571 \ t/m' \qquad \text{Eq. 10}$$

In addition, a reduction of water density is expected due to seismicity (γws) to be:

$$\gamma ws=1.0-[0.01x1] = 0.99 \ t/m3 \qquad \text{Eq. 11}$$

6.2 The effect of horizontal acceleration

The horizontal acceleration (αh) will produce two forces;

- Horizontal Inertia (Pem) of the dam, that is assumed
  to act in the upstream direction and cause water movement
- Hydrodynamic force (Pe) pushing in the downstream direction.

the amount of the horizontal inertia (Pem) is (Zanger, 1950):

$$Pem = (\alpha_v) \ Wt = (0.1) \ 4,571 = 457 \ t/m' \qquad \text{Eq. 12}$$

The Pem-value produce the hydrodynamic force (Pe), its magnitude can be calculated by (Zanger, 1950):

$$Pe = (0.67) \ Ce \ \alpha h \ \gamma ws \ H2 \qquad \text{Eq. 13}$$

$$= (0.67) \ 0.82 \ (0.1) \ (0.99) \ (61)2= 202 \ t/m'$$

where:

Ce is a coefficient = 0.82

H maximum water elevation in the reservoir, 61 m.

αh the design horizontal acceleration, 0.1 (Table 3).

(Table 3). Summary of the values of the additional seismic forces.

	α_v	α_h
Seismic force	W_{fs}= 4,571	---------
	---------	P_{em}=457 t/m′
	------	P_e=202 t/m′

6.3 Dam overturning

In case of an earthquake, the possibility of dam overturning is due to both the static plus the hydrodynamic forces (Pe). The moment-arm of Pe equals to (2/5) h, using the maximum water level of 61 m the moment caused by Pe is quite high (Zanger, 1950):

$$\text{Pemom} = \text{Pe}\,[(2/5)\,61] \qquad \text{Eq. 14}$$

$$= 4{,}929 \text{ t/m}'$$

The negative moment due to seismicity (Pemom) is 4,929, this amount should be added to the negative moments of the static analysis which is 118.6x103 t/m′ (Table 2), the overall moment will reach a value of:

$$\Sigma \text{ negative moments} = 118.6 \text{ x}103 + 4{,}929 = 123.5 \text{ x}103 \text{ t/m}'$$

On the other hand, dam effective weight in case of an earthquake is 4,571 and the dam moment arm is 39 m, hence the positive moment is:

$$\Sigma \text{ positive moments} = 4{,}571\text{x}39 = 178.3\text{x}103 \text{ t/m}'$$

$$\text{Fs} = [178.3] / (123.5) = 1.44, \text{ then}$$

the dam is stable.

6.4 Dam Sliding

The vertical acceleration (αv) is assumed to be in the downward direction, the following consequences are expected:

- the dam weight was reduced to 4,571, this represents the vertical force (Vf),
- with the static horizontal force (2,430) remains the same, the new horizontal force is added (Pe=202), the total (Hf) becomes 2,632 t,
- the coefficient of friction between the concrete and the rocks is 0.7.

The obtained factor of safety (Fs) against sliding using Eq-5 is:

$$\text{Fs} = [\mu(\text{Vf})] / \text{Hf}$$

$$= [0.7\,(4{,}571)] / (2{,}632) = 1.2$$

6.5 Induced Stresses

The equations used to calculated the induced internal stresses in the pseudo-static case are Eq. 7 and Eq. 8. Because more external forces, in earthquake case, are acting on the dam, it is expected that the values of the internal stresses are higher.

Seismicity decreases the effective dam weight into 4,571 t/m′(section 6.1). The additional pseudo-static horizontal force (Pe) is 202 (section 6.2), if it is added to the static horizontal forces then it becomes 2,632 t/m′. Based on the vertical and horizontal forces the resultant (R) is 5,274 t/m′ using Pythagorean theorem. Simple trigonometry revealed that the angle (Θ) between the resultant (R) and the vertical force is 30o, The resultant (R) cross the dam base at point k, and value of jk in Figure 7 is:

$$jk = 23\ (\tan 30) = 13.3$$

where 23 m is the vertical distance of the centroid from the dam base (Figure 1).

In order to implement Eq. 7 and Eq. 8, the following values are needed:

- dam base (B)= 59 m,
- Aj= 20 m (Figure 1)
- jk = 13.3 m
- then Ak = Aj + jk = 33.3 m = d (Figure 7),
- e = d – [0.5(B)]= 3.8

Then the values of σ (Eq. 5.5) and τ (Eq. 5.6) are:

$$\sigma = (wt/B)\ \{1+(6e/B)\}$$
$$= (4{,}571/59)\ \{1+(6(3.8))/59)\}$$
$$= 108\ t/m/$$
$$\tau = (wt/B)\ \{1-(6e/B)\} = 47.3\ t/m/$$

Again, the internal stresses which may develop in the dam body is much less than the allowable limits (section 5-3).

7- Sensitivity Analysis of Dam Stability

The dam factor of safety against movement can be commonly improved by enlarging the dam size and/or reduce the water seepage under the dam as follows:

1. The upstream face of Rabigh dam is vertical, if it was inclined by a certain angle, the dam weight will increase, and the dam centroid (CG) will move toward the upstream direction. This movement increases the dam's moment arm making the dam more stable.
2. With an inclined upstream face, part of the reservoir water that is directly above the dam inclined upstream face will contribute to dam stabilization against dam overturning and sliding.
3. The previous stability calculation shows that the uplift force contributes a tangible reduction in dam weight. It has also increased the negative moment due to its high value and the relatively long moment arm, about 66% of the dam foundation width (B).

   The uplift value is a function of water level (h) in the reservoir and the width (B) of the dam foundation. The h-value can be changed as desired during dam operation, but the B-value will be fixed. The factor of safety (Fs) was used to quantify the balance between the dam weight and the acting forces in static and pseudo-static conditions. The stability calculation was carried out in which the uplift value was lowered by 20% sequence, giving the following results:

- in overturning failure mode, the dam weight is the same. The relationship between the reduction of uplift percent (Ur) and the improvement in the factor of safety can be expressed by the equation:

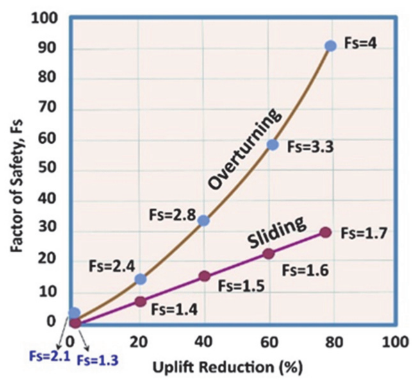
$$Fs=0.0002\ (Ur)2+0.01\ (Ur)+2.11$$

The minimum rise in the Fs-value is 14% and the highest value is 90% (Figure 9 and Table 4),

- in dam sliding, the dam effective weight is improving, and no changes in the horizontal forces. The Fs-value increases linearly according to the equation (Figure 9 and Table 5):

$$Fs=0.005\ (Ur)+1.3$$

The uplift pressure can be practically reduced with a cutoff wall or injecting grouting through soil underneath the dam or both.



(Figure 9). The relationship between the Fs and the uplift reduction.

(Table 4). The percentage rise in the factor of safety (Fs) as uplift is lowered in overturning failure.

Uplift decrease		Moment X 10^3	Total vertical force, X 10^3	Total horizontal force, X 10^3	Factor of safety	
%	value				value	% rise
0	1,800	70.74	250	118.6	2.1	0
20	1,440	56.6	,,	104.5	2.4	14
40	1,080	42.4	,,	90.3	2.8	33
60	720	23.3	,,	76.2	3.3	57
80	360	14.1	,,	62	4.0	90

(Table 5). The improvement in the factor of safety (Fs) in case of sliding failure as uplift is lowered in.

Uplift decrease		Moment X 10^3	Improvement in dam effective weight	Factor of safety	
%	value			value	% rise
0	1,800	70.74	4,617	1.3	0
20	1,440	56.6	4,977	1.4	8
40	1,080	42.4	5,337	1.5	15
60	720	23.3	5,697	1.6	23
80	360	14.1	6,057	1.7	30

8. Waves dynamic Force

Waves are generated with certain height (hv) in the reservoir as wind is blowing over the water surface. The effect of water waves is also considered here only to prevent water splashing over the dam crest. The hv-value depends on the following factors:

- wind speed (Sw),
- the blowing duration (Dr), and
- wave fetch (ftc)

  (the straight distance of water surface over which wind blow to reach the dam).

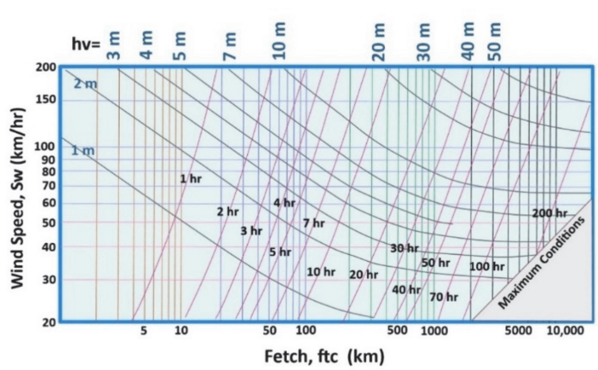
Wave dynamic pressure is generated when a wave hits the face of the dam. It is a force that is seldom accounted for when designing a dam due to its small magnitude and random occurrences (Novak et al., 2007). The importance of the expected hv-value is usually to compare it with the design dam freeboard to assure that water is not able to splash over the dam crest. Free board is the vertical distance between the top of the dam and the maximum water level.

The maximum Sw in the study area is 70 km/hr, the fitch is approximated as 10 km, and the Dr is assumed to be 1 hour. Figure 10 shows the relationship between Sw, ftc, and hv. In Figure 10, the hv-value can be estimated as 1.4 m, hence water waves will overtop the dam crest since the dam designed freeboard is 1.25 m.

9-Global Warming

The present climate change affects both the temperature and rainfall (Prein, et al., 2016; Mily et al., 2002). Increasing global temperatures cause water to evaporate in larger amounts and rain amounts and intensity increases and become more frequent in the coming years. Climate scientists predict that this shift will lead to more floods since vegetation and soil will not be able to absorb the excess water. Therefore, this puts more static pressure on Rabigh dams. To be on the safe side, the stability of Rabigh dam and the capacity of both the reservoir and spillway must be re-evaluated.

Global warming is likely to increase the future rainfall and the flood frequency and peak discharge (Q). The expected percentage increase in flood magnitude, as reported by several researcher, range from 27 to 40 % by several researcher (Al Zawad, 2009; Almazroui, 2017; Youssef, 2016). In this study, the estimated Q-value having a 100-return period was 2,490 m3/sec (Figure 10), that peak discharge was hypothetically increased by 20, 30, 40, 50 and 60 % (Table 6).

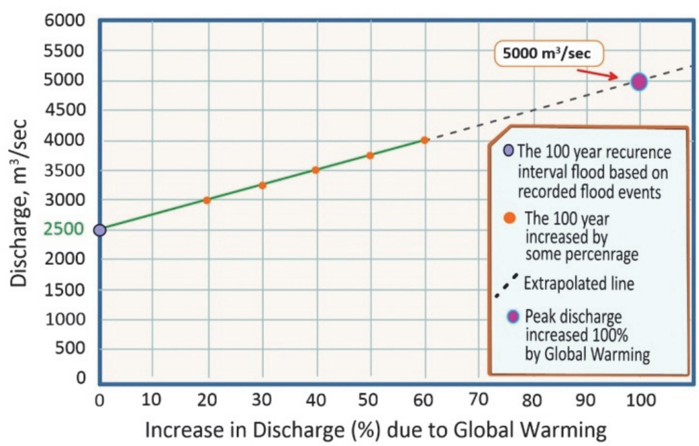


(Figure 10). The relationship among Sw, ftc, and hv (after Rhan, 1986).

(Table 6). The possible increase in peak discharge due to global warming.

Increase in Q-value (%)	Q-value (m^3/sec)
0	2,490
20	2,988
30	3,237
40	3,486
50	3,735
60	3,984

A simple linear relationship was derived between the percentage increase (as an independent factor) and the resulting Q-value (Figure 11). It can be seen that a 100 % increase in the flood magnitude (Q=2,490 m3/sec) due to global warming gives a new Q of 4980 m3/sec. In the same time the spillway was designed with a capacity of 9,543 m3/sec. Therefore, the maximum Q due to maximum expectation of global warming will not be able to exceed the spillway capacity and the Fs is 1.91.



(Figure 11). The estimated flood magnitude with an increase of 100 % due to global warming.

9. Conclusions

The weight of Rabigh concrete dam is huge, 5,731 tons per unit length. The spillway capacity is very large (9,543 m3/sec), much higher than the designed peak discharge (2,490 m3/sec). Overturning and sliding stability are the common failure modes for gravity dams. Rabigh gravity dam was built in 1987 and has been stable since then. It is more likely that global warming may increase the peak discharge and add more pressure to the extent that the dam stability is endangered. The present peak discharge was hypothetically increased by 100% to a value of 5000 m3/sec, so as to reach the spillway level. It is clear that with a higher water level the factor of safety decreases. As a summary the following points can be concluded:

1. The maximum peak discharge due to maximum expectation of global warming will not be able to exceed the spillway capacity.
2. The dam stability was evaluated for static and pseudo-static conditions, assuming the a maximum water level of 61 m. The calculated safety factor for two types of dam failure: overturning and sliding are 2.1 and 1.44 respectively.

3. The dam is also stable against sliding. The dam weight played a major part, the resisting forces, the Fs-values for the two cases are 1.3 and 1.2 respectively.
4. The obtained Fs-values for the static and pseudo-static conditions for the two types of failure are acceptable, but closer to the lower limits.
5. As the condition changes from static to pseudo-static, the factor of safety in overturning is more sensitive than sliding. The reduction in Fs-value in dam overturning is about 30%, while the reduction in Fs-value is 7% for sliding.
6. The change of dam condition from static to pseudo-static increases the value of dam eccentricity (e). As a result, the induced compression stress (σ) increases, while the tensile stress (τ).
7. The above results indicate the importance of the dam shape (cross section) increases, which in turn affects the length of moment arms for the different forces. In addition, the uplift force played a major role in the Fs-values by reducing the original dam weight.

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تقييم ثبات سد رابغ الخرساني

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المستخلص. يتم انشاء السدود الخرسانية لحجز كميات كبيرة من مياه السيول لأغراض متعددة، وتقييم ثبات السد جزء اساسي لضمان فائدتها. ويعد سد رابغ الوقع في الجزء الغربي من المملكة ثالث سد من حيث الأهمية حيث يوفر وسيلة حماية لمدينة رابغ والمنطقة الصناعية حولها، ويزيد معدل تغذية المياه الجوفية. يبلغ طول السد ٣٨٠ وارتفاعه ٧١ مترا وخزان مياه وسيع يبلغ ٢٢٠ متر مكعب. ويتعرض السد لضغوط محركة جانبية تتمثل بماء الخزان ودفع الطمي وقوة الطفو أسفل السد، ويتم مقاومة القوى المحركة بوزن جسم السد. وتولد الضغوط الجانبية ضغوط مختزنة في جسم السد يجب تقديرها والتأكد انها ضمن المسموح به حسب تصميم السد. يهدف هذا البحث إعادة تقدير درجة ثبات السد المتأثر بالتغير المناخي تحت تأثير القوى الساكنة والزلزالية، ويحذر عدد من الأبحاث الحديثة من زيادة متوقعة في تكرار السيول وتنامي كمياتها، الامر الذي سيصعد من زيادة القوى المحركة للسد. واعيد تقييم ثبات السد في ثلاث حالات للانهيار هي انقلاب السد وانزلاقه وانهيار جسمه الخرساني من زيادة الضغوط المختزنة. واتضح ان السد ثابت في كل تلك الظروف بمعامل امان ضمن المسموح به.

الكلمات المفتاحية: الاحتباس الحراري، سد رابغ، المملكة العربية السعودية، تحليل ثبات السدود.