The Journal of Engineering Research (TJER), Vol. 13, No. 2 (2016) 124-136

An Investigation of Excessive Seepage from the Al-Fulaij Recharge Dam, Oman

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Received 22 July 2013; Accepted 8 December 2015

Abstract: The Al-Fulaij recharge dam is located on the Al Batinah coast in Oman and was constructed in 1992. The dam is about 3.3 km long and 7.7 m high with a storage capacity of 3.7 million cubic meters of water. It is an earthfill dam with silty, sandy gravel fill in the embankment. Excessive seepage of between 5,000–12,500 m^3/day was observed during floods in 1993, and several sinkholes were noticed close to the upstream toe. Remedial work consisting of an upstream blanket and a cut-off trench wall was performed in 2000. However, these remedial measures failed and almost the same seepage was noticed again during the impoundment. This paper investigates possible causes of the seepage using a finite element model. The input data for the model were collected from site investigations and field records during the construction and monitoring of the dam. The study reveals that the most probable cause of the excessive seepage is the presence of a permeable soil layer underneath the dam due to the dissolution of the gypsum material.

Keywords: Cut-off walls, Earthfill dam, Recharge dam, Remedial measures, Seepage.

التحقيق في التسرب الزائد من سد الفليج للتغذية الجوفية، عمان

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الملخص: يقع سد الفليج للتغذية الجوفية على ساحل الباطنة في سلطنة عمان وشيد في عام ١٩٩٢م. ويبلغ طول السد حوالي ٣,٣ كم مع ارتفاع ٧,٧ م بسعة تخزينية قدرها ٣,٧ مليون متر مكعب من المياه. وهو سد مليء بالطّمي مع حصى ترابية عند الحافة. وقد لوحظ تسرب زائد يتراوح ما بين ٥٠٠٠ إلى ١٢٥٠٠ متر مكعب في اليوم خلال فيضانات عام ١٩٩٣، مع عدة مجاري تم رؤيتها بشكل ملحوظ على مقربة من مقدمة المنبع. وقد تم تنفيذ عمل علاجي يتكون من إنشاء غطاء عازل للمنبع وجدار خندقي قاطع في عام ٢٠٠٠م. ومع ذلك، فشلت هذه التدابير العلاجية وتقريبا تم ملاحظة نفس كمية التسرب مرة أخرى خلال حجز السد للمياه. وتبحث هذه الورقة الأسباب المحتملة للتسرب باستخدام نموذج العنصر المحدود. وقد تم تجميع بيانات التغذية المدخلة للنموذج من خلال تحقيقات الموقع والسجلات الميدانية خلال بناء ورصد السد. وتكشف الدراسة أن السبب الأكثر احتمالا للتسرب الزائد هو وجود طبقة تربة قابلة للاختراق تحت السد بسبب انحلال مادة الجبس.

الكلمات المفتاحية: غطاء عازل للمياه، جدار قاطع، سد ترابي، سد للتغذية الجوفية، تدابير علاجية، تسرب.

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1. Introduction

All earth and rock-fill dams are subject to seepage through the embankment, foundation, and abutments. Many case studies of dams with seepage through their foundations have been reported in the literature (Leonards 1987; Piqueras *et. al*. 2012; Richards and Reddy 2007; Unal *et. al*. 2008). Seepage through the foundation is the main cause of failure of many dams (Leonards 1987; Richard and William 1985; Richards and Reddy 2007; Zhang and Chen 2006). One of the factors contributing to seepage through the foundation is the presence of soluble materials such as gypsum (Piquerase *et. al*. 2012), because gypsum has a tendency to dissolve as a result of water impoundment and create seepage paths. A well-known example is the failure of the St. Francis Dam in 1928 due to the dissolution of the conglomerate with gypsum in the left abutment (Yilmaz 2001). This paper presents an investigation of the possible causes of excessive seepage in the Al-Fulaij Dam and its remedial works. The computer program SEEP/W (GEO-Slope, 2009) was used in the analysis.

2. Background

2.1 *The Al-Fulaij Dam*

Oman has an arid climate, and the main source of fresh water is rain as there are no rivers or lakes in Oman. However, there are many seasonal streams where rain water flows in huge quantities for a short period of time. These streams discharge their water either in the sea or inland. To reserve these enormous quantities of water, the government started building recharge dams to retain water and store it for a certain period of time (usually for a maximum of two weeks) in order to recharge the underground water aquifers. More than 30 recharge dams have been constructed in Oman (Ministry of Regional Municipalities and Water Resources (MRMWR Files, 1998-2010), and most are earth and rock fill dams.

The Al-Fulaij Dam is located in the Barka-Rumays area of the Al Batinah coast, about 40 km west of Muscat, Oman (Fig. 1).

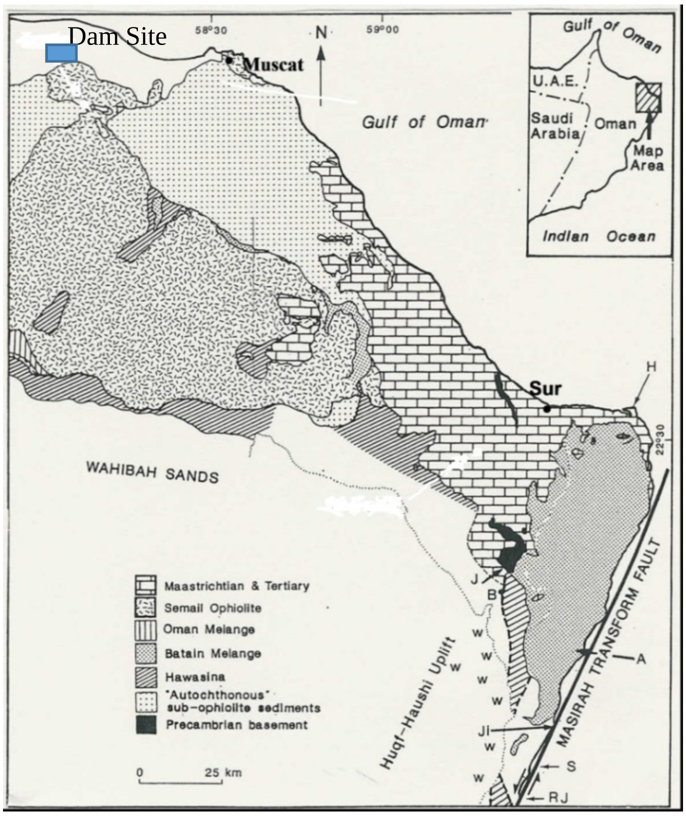


Figure 1. Location of Al-Fulaij dam (From Geological map of NE Oman, Glennie *et al*. 1974 and Shackleton *et al*. 1990**).**

Table 1. Main features of the dam.

Main dam	
Total length	3346 m
Crest elevation	65.55 m above sea level (asl)
Max. height	7.70 m
Upstream slope (v:h)	1:2
Downstream slope (v:h)	1:2.7
Spillway	
Type	Gabion mattress
Length	1150 m
Crest elevation	64.00 m above sea level (asl)
Max. height	6.15 m
Upstream slope (v:h)	1:2
Downstream slope (v:h)	1:4
Outlet conduits	
Type	Ductile iron pipe, No. 2, Dia. 80 cm
Reservoir	
Capacity	3.7 million cubic meters
Catchment	117 km^2

The dam aims to enhance the groundwater level in the Barka-Rumays area by retaining the water from seasonal streams that otherwise would be lost to the sea. Construction of the dam was completed in September 1992 (MRMWR Files, 1998-2010). During floods in 1993, significant seepage was observed downstream of the dam, and several sinkholes were noticed close to the upstream toe. The amount of seepage was between 5,000–12,500 m^3/day (Binnie Partners Overseas Ltd. 2001) when the reservoir was full. Remedial work was performed in 2000 consisting of an upstream blanket 10 meters wide and 0.6 meters thick of silty sandy gravel with 35% fines and a 2.5 m wide cut-off trench that was deep enough to reach the hard strata (limestone). The cut-off trench was filled with the same material as the blanket. However, these remedial measures failed for many reasons, and almost the same seepage was noticed again during the impoundment (Binnie Partners Overseas Ltd. 2001).

The main features of the dam are listed in Table 1. The dam is about 3.3 km long and 7.7 m high. The upstream slope of the dam is protected by rip rap whereas the downstream slope is protected with a 20 cm thick-layer of gravel. The total storage capacity of the reservoir is 3.7 million cubic meters. The dam has a spillway to discharge water freely during floods when the water quantities are beyond the dam storage capacity. The spillway is 1.15 km long with a maximum height of 6.15 meters. The upstream slope of the spillway is protected with rip rap whereas the downstream slope of the spillway is protected by a 30 cm layer of gabion mattresses.

The earthfill dam's embankment is made of a silty, sandy gravel fill with a maximum particle size of about 100 mm. The maximum dry density and optimum moisture content of the embankment fill as determined by the modified proctor compaction test varied from 2.15–2.20 g/cm^3 and 6.1–6.9%, respectively. *In situ* density tests by the sand cone method gave degrees of compaction of 100%. One test carried out on the embankment fill material in a fixed-wall permeameter gave a coefficient of hydraulic conductivity (k) equal to 3.24 x 10^{-7} m/sec (Electowatt-Ekono 2006).

2.2 *Geology and Subsurface Conditions*

Two site investigations were carried out at the dam site: one during the feasibility study in 1989 and the second in 2006 (Electrowatt-Ekono 2006). The two site investigations consisted of 11 boreholes and 19 test pits. According to the investigations in 1989 and 2006, the subsurface profile at the dam site consists of tertiary rocks, belonging to the Jufnayn Formation and is overlain by shallow Quaternary deposits. The Jufnayn Formation comprises marl and limestone with a regional dip of 15–30° to the northwest. The Quaternary deposits consist of recent alluvial deposits and conglomerate. The alluvium may reach a thickness of up to about three meters. It is composed of evaporate-rich (gypsum and halite), loose to medium dense, silty fine to coarse gravel with cobbles and boulders. The conglomerate extends below the alluvial deposits. The depth to the conglomerate layer in trial pits varied generally between 0.5–3 meters.

The gypsum material was encountered in many trial pits (Fig. 2). Table 2 shows, by weight, the gypsum content of some samples taken from different depths of the trial pits. The gypsum content varies by up to 28% and generally increases with depth.

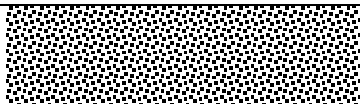
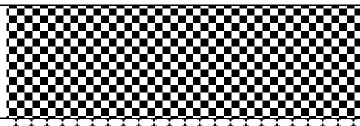
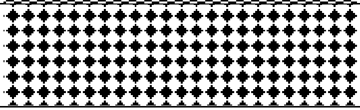
Depth (m)	Visual Description	Symbol
0.0 to 0.3	Soft light brown silty CLAY	
0.3 to 1.5	Medium dense brown silty clayey SAND with gravel and cobbles	
1.0 to 1.7	Weak grey CONGLOMERATE with gypsum, highly weathered	

Figure 2. Gypsum concentration in trial pit No. 8 (Swissboring, 2006).

Table 2. Gypsum content in some sample taken from the dam site (Electrowatt-Ekono, 2006).

Trial Pits No.	Chainage (m)	Depth (m)	Gypsum Content %
2	0+500	0.20-0.50	8.12
		1.0-1.50	3.76
1	0+750	0.20-0.50	0.58
		0.20-0.50	0.17
3	1+900	0.50-1.0	0.11
		1.0-2.0	0.09
4	1+900	1.0-1.20	0.05
5	2+230	0.50-1.0	2.54
		2.0	6.58
6	2+500	0.20-0.50	0.28
		0.50-1.0	0.26
8	2+900	0.20-0.50	26.25
		1.0	22.64
		0.20-0.50	1.05
7	2+900	0.50-1.0	5.76
		1.90	13.33
		0.80-1.0	2.0
Trial Trench 1	2+230	1.20-1.70	27.76
		1.30-1.70	23.93
		0.0-0.50	0.58
Trial Trench 2	2+500	1.0-1.20	5.16
		1.0-1.50	17.05

2.3 *Hydraulic Conductivity*

The site investigation in 2006 (Swissboring, 2006) included 14 packer tests (ASTM D4630, 2008) (Table 3). The hydraulic conductivity was found to generally be low and variable. In the top four meters (*i.e.* the layer of alluvial and conglomerate materials), the hydraulic conductivity was 10^{-5} m/sec. Below this depth (*i.e.* the limestone layer), the hydraulic conductivity varied from as low as 10^{-9} to 10^{-5} m/sec.

2.4 The Seepage Problem

During floods, significant seepage has been observed at many points downstream of the dam (Fig. 3). As a result of the gypsum occurrence, numerous sinkholes, probably a few hundred within the reservoir basin just upstream of the dam, were formed. They are mostly circular but sometimes elongated, sinuous and channel–like (Fig. 4). Typically the sinkholes are 0.4–0.6 m in diameter with a depression of about 0.2 m deep, with the occasional sinkhole measuring 0.3–0.4 m deep (Binnie Partners Overseas Ltd. 2001).

Table 3. Measured hydraulic conductivity using packer test (Electrowatt-Ekono, 2006).

Test No.	Borehole No.	Chainage (m)	Depth of section Tested (m)	Hydraulic conductivity (m/s)
1	1	0+750	10.00-13.50	$1.78x10^{-8}$
2	2	2+230	9.00-13.00	$1.83x10^{-5}$
3	3	2+500	10.00-14.00	$2.53x10^{-8}$
4	4	0+750	1.50-2.80	$8.79x10^{-5}$
5	5	0+750	7.00-10.00	$2.67x10^{-9}$
6	6	2+230	3.80-5.00	$9.23x10^{-8}$
7	7	2+500	3.80-5.00	$<1x10^{-9}$
8	8	2+500	3.00-8.00	$3.13x10^{-6}$
9	9	2+230	4.00-8.00	$<1x10^{-9}$
10	6	2+230	1.00-2.30	$3.32x10^{-5}$
11	7	2+500	1.00-2.00	$1.96x10^{-5}$
12	2	2+230	7.00-8.00	$9.81x10^{-6}$
13	3	2+500	8.50-9.50	$3.30x10^{-7}$
14	TP-5	2+230	0.80-1.80	$1.24x10^{-5}$

Figure 3. Seepage from the dam.

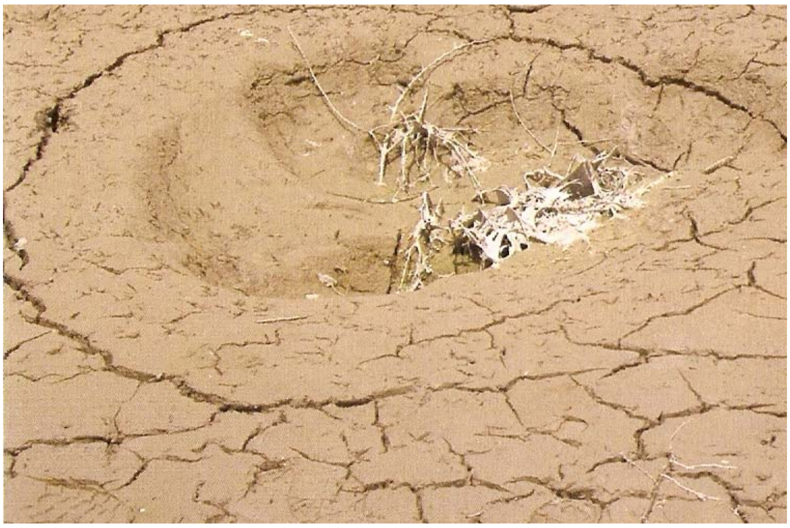


Figure 4. A sinkhole in reservoir area about 40 m from the dam heel.

Figure 5. Crack in the crest of the dam at chainage 2+700.

A crack in the crest of dam embankment about 5–7 m long and 80–100 cm deep running parallel to the dam axis was also noticed at about chainage 2 + 700 (Fig. 5). The formation of this crack may have been due to some settlement in the foundation caused by gypsum leaching from the foundation.

The dam has over spilled at least three times; the latest overspill was due to Cyclone Gonu in June 2007.

3. Investigation of the Seepage in the Dam

The most probable causes of excessive seepage in the Al-Fulaij Recharge Dam were evaluated based on the available information and data from previous site investigations and the inspection of the dam during the impoundment. The possible causes of the seepage in this dam were thus attributed to the site geology, dam design, and material used for dam construction and are listed here (Fig. 6).

- The presence of a permeable soil layer beneath the dam as a result of gypsum material dissolution and the insufficient depth of the key trench.

- Seepage through the dam body because of the segregated layers of fill.

- Seepage through the limestone or the hard strata as a result of cavities, faults, or open joints.

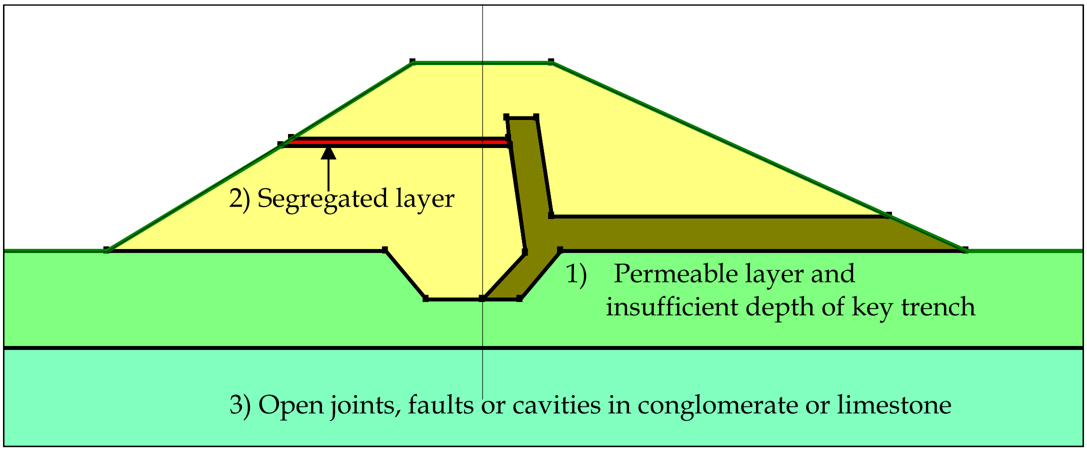


Figure 6. Possible causes of seepage.

Table 4. The gap between the cutoff wall and the hard strata (Electrowatt-Ekono, 2006).

Cross section	Chainage (m) (Start – End)	Average gap between foundation and hard strata (m)
1	400 - 450	0.18
2	525 - 575	0.8
3	675 - 700	0.8
4	725 - 800	0.88
5	925 - 975	0.34
6	1100 - 1325	1.55
7	1375 - 1500	1.31
8	1550 - 1600	1.05
9	1750 - 1850	1.02
10	1950 - 2075	1.50
11	2250 - 2300	0.03
12	2325 - 2375	0.39
13	2425 - 2475	0.46
14	2500 - 2700	0.94
15	2725 - 2900	1.54

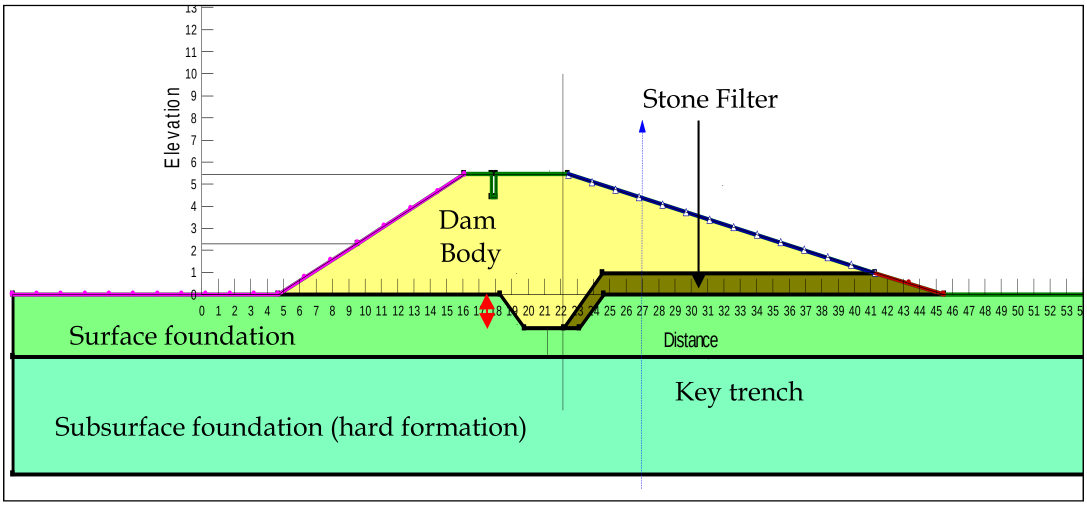


Figure 7. Design case of the dam as modeled in the program (SEEP/W 2007).

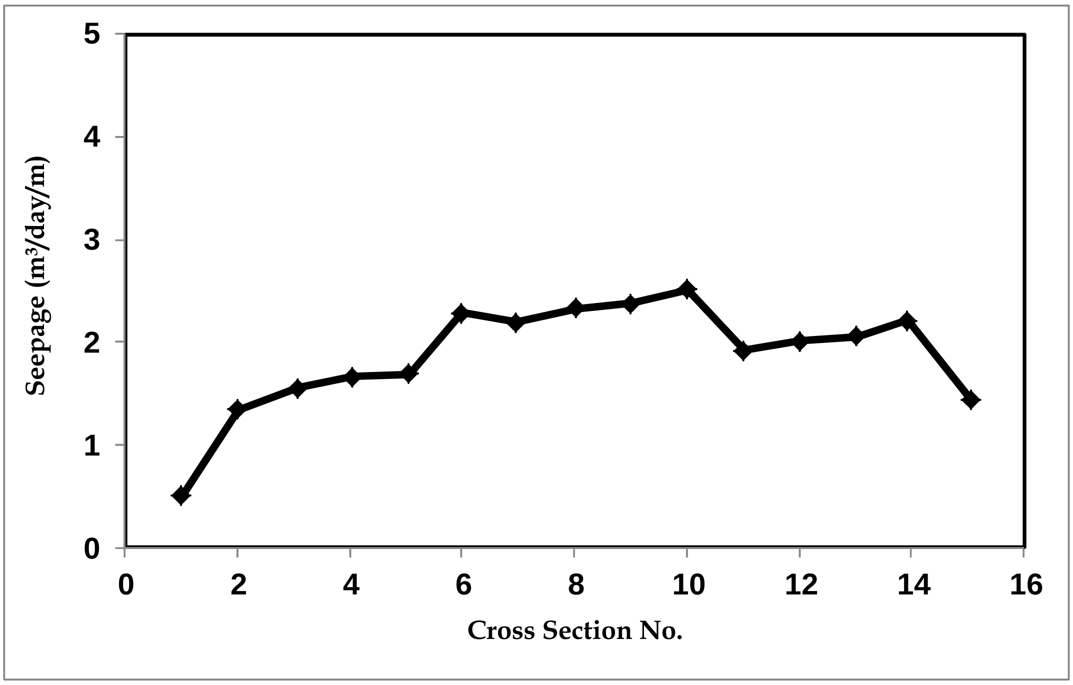


Figure 8. The seepage modeling results of the design case of Al-Fulaij dam.

The first cause is valid since all of the site investigations showed the presence of gypsum in the foundation of the dam. Furthermore, according to the design, the foundation of the dam was not extended to the hard formation (*i.e.* the limestone) in some places. A second cause may be related to the dam's construction since the silty sandy gravel used, if not mixed properly, will lead to seepage problems. However, if such a case had existed, then the seepage would have been noticed directly after the water impoundment, but it was not noticed. Additionally, the water which seeps from the dam reservoir takes about two to three days to appear downstream.

The third cause is not valid because many permeability tests were carried out during the site investigation in 2006 in the hard strata or the bedrock underneath the dam foundation. The coefficient of permeability obtained from the packer tests in these materials was found to vary from less than 10^{-9} m/s to 10^{-5} m/s (Table 3). Since the first potential cause, the presence of a permeable soil layer beneath the dam as a result of gypsum material dissolution and insufficient depth of the key trench, is the only plausible solution, it is considered for further study in the following sections.

3.1 Modeling to Determine the Most Possible Causes of Excessive Seepage

The dam was modeled using the 2009 seepage modeling program SEEP/W2007 (GEO-Slope International Ltd. Calgary, Alberta, Canada). SEEP/W2007 is a finite element software used for analyzing groundwater seepage and excess pore-water pressure dissipation problems. As a first step to model the dam, the locations along the dam where the key trench was not extended to the hard strata were identified. The effect of the gypsum material was introduced later in the analysis. Table 4 shows the gap between the key trench and the hard strata at 15 cross sections along the dam.

To show the effect of the presence of the permeable layer underneath the dam on the seepage quantity, the problem was modeled according to the design case and the actual case. The design case represents the dam without the causes of the seepage problem. This means that the presence of the gypsum material at the site was not considered since it was not evaluated properly during the design stage; hence, the values of the hydraulic conductivity (k) of the different material are as shown in Table 5, and the case is shown schematically in Fig. 7.

Table 5. Materials properties obtained during feasibility study (MRMWR Files (1998-2010)).

No.	Material	k (m/s)
1	Dam body (silty sand with gravel)	$3.24\text{x}10^{-7}$
2	Surface foundation (silty sandy gravel)	$3.40\text{x}10^{-5}$
3	Subsurface foundation (Limestone)	$9.10\text{x}10^{-6}$
4	Stone Filter (fine)	$1.00\text{x}10^{-3}$

The seepage modeling results of this case (Fig. 8) show that the seepage quantities of the design case range from 0.50–2.450 m^3/day/m (total seepage 1250 to 6125 m^3/day). During the impoundment, 5,000–12,500 m^3/day of seepage was noticed per day. Based on this, trials were carried between 5,000 and 12,500 m^3/day out using the modeling program to find out the corresponding k-value of the foundation material. The trials were conducted using the average cross section of the dam where the water head is 4.05 meters and the thickness of the permeable layer underneath the dam is 0.85 meters. A total seepage figure of 8,750 m^3/day was used in the analysis. This equates to a seepage amount of 3.5 m^3/day/meter for a 2,500 meter long dam.

After conducting the trials, the average k-value was estimated at 1.00 x 10^{-4} m/s (Fig. 9). It is clear that the average foundation permeability was higher than the one obtained during the feasibility study. This is because the leaching process of gypsum material as a result of water flowing underneath the dam created voids within the dam's soil structure.

In this section, the actual case was simulated using the revised permeability value of the foundation material. The results that were obtained from the modeling of this case along with the design case are presented in Fig. 10. As can be seen, the seepage quantities of the actual case ranged from 0.85–5 m^3/day/meter with a total amount of seepage between 2,125–12,500 m^3/day), which is about double the seepage for the design case.

4. Remedial Measures

As mentioned before, the previous remedial measures did not work and almost the same amount of seepage was noticed. Two methods of remedial measures are considered in the current study: the installation of a grouting curtain at the foundation of the dam and the use of a geomembrane at the upstream face of the dam anchored to the upstream cutoff.

Grouting is one of the most popular techniques to reduce the seepage amounts from storage dams. Grouts such as clay, cement, bentonite or bentonite-cement can be successfully grouted in a formation having a permeability of more than 10^{-3} cm/second (Shroff and Shan 1993). One of the remedial measures suggested is to carry out grouting under the dam foundation (Fig. 11). A permeability value of less than 10^{-6} m/second can be expected at the foundation after applying the grouting (Shroff and Shan 1993). A six-meter deep hole is recommended with 1.5-meter spacing between the holes on the first round. More holes between them can be added as a second round depending on the results achieved during the grouting execution. The grouting was modelled in the program as a

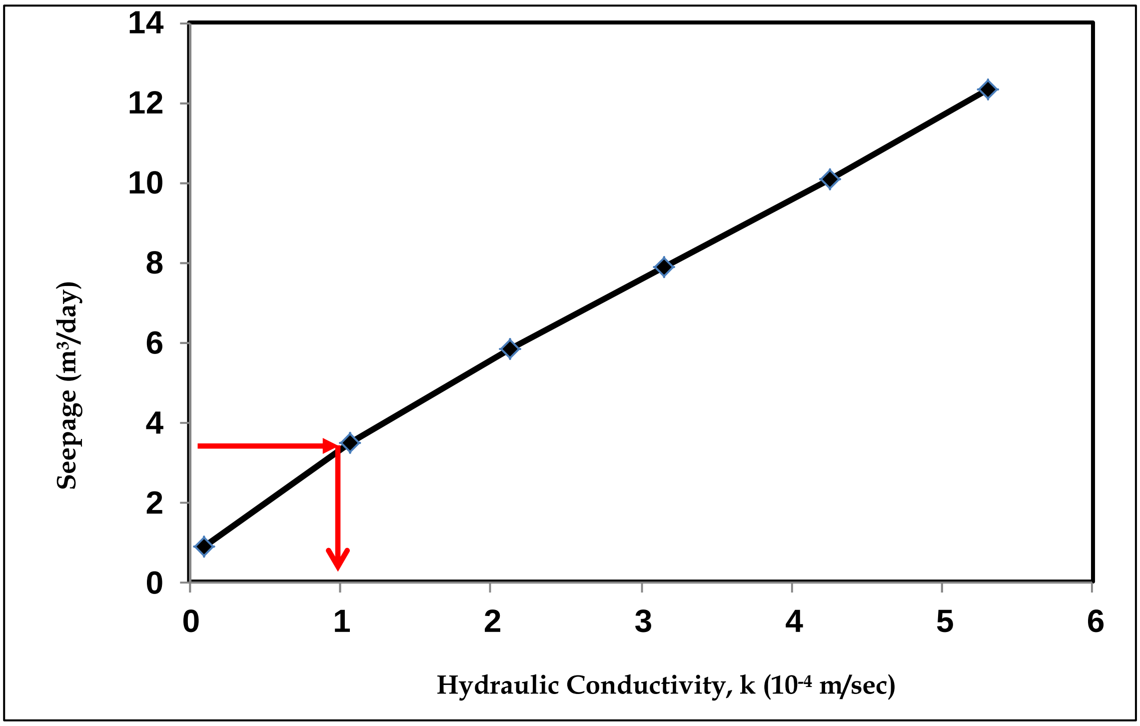


Figure 9. Trails to obtain the revised k-value of the foundation material.

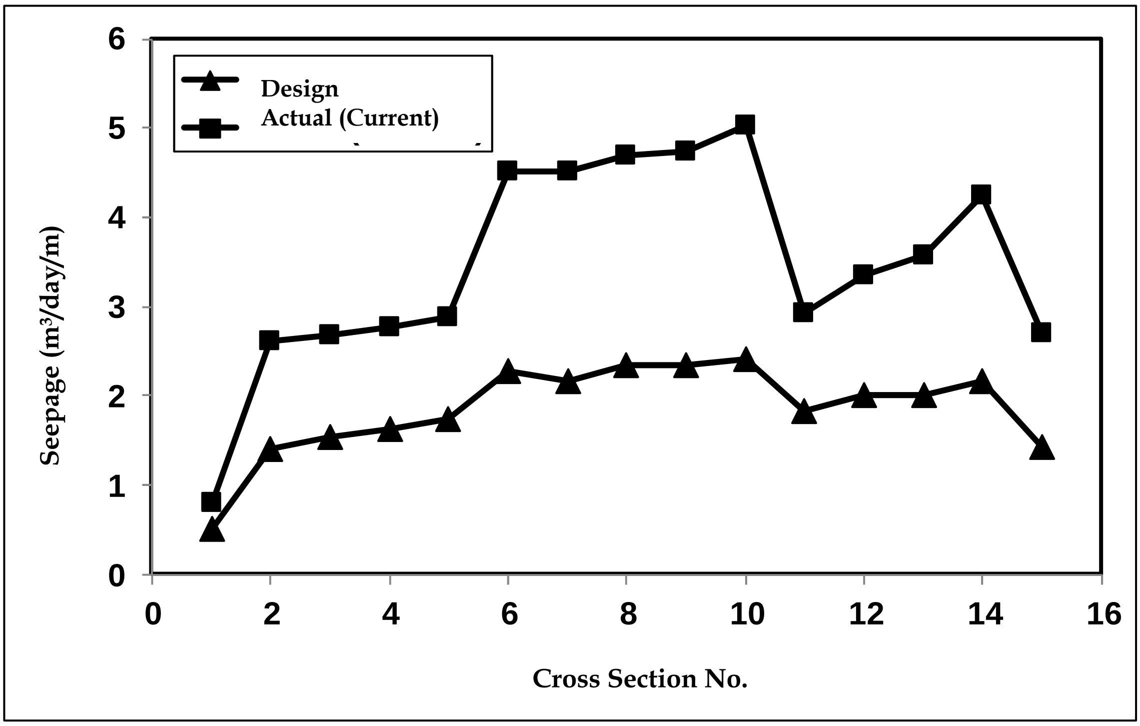


Figure 10. The seepage modeling results of the design and actual cases.

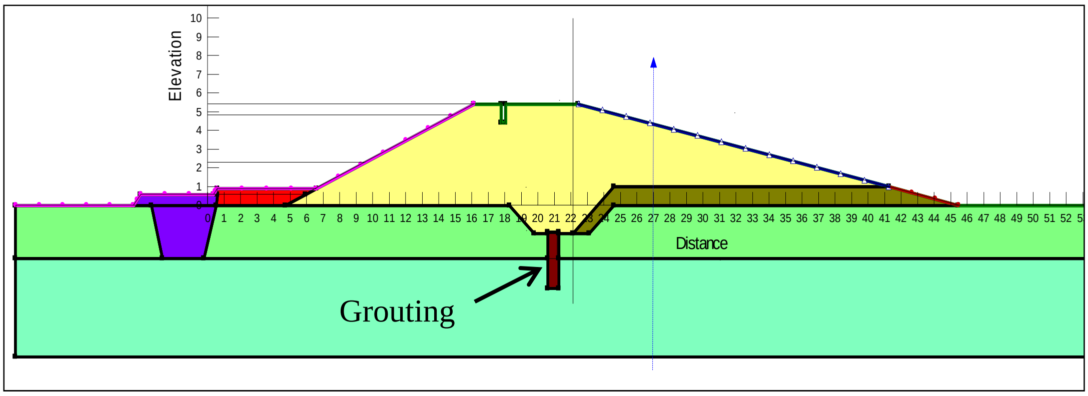


Figure 11. Grouting at the dam foundation as modeled in the program.

cutoff wall as shown in Fig. 11. The results of the dam modeling with the grouting curtain along with the current case are shown in Fig. 13, which demonstrates that the seepage quantities after applying the grouting range from 0.5–2.6 m^3/day/meter (500–2,600 liters/day/m) whereas the seepage quantities of the current case range from 0.85–5 m^3/day/meter (850–5,000 liters/day/meter). This shows 41–48% expected decrease in the seepage quantities. It is very important to mention here that grouting also has the advantage of improving the stability of the dam which is achieved by making the foundation denser since it will replace the materials which were washed away and prevent any depression or settlement of the dam foundation.

A geomembrane can also be used to control seepage by inserting sheets of this material on the upstream face of the dam and extending it down to be anchored in the limestone (Fig. 12).

The figure shows the seepage profile of the dam when using the geomembrane. The value of hydraulic conductivity (k) used in the program for the geomembrane was 10^{-9} m/second. As can be seen from Fig. 13, the seepage quantities after installing the geomembrane range from 0.4–1.8 m^3/day/m (400–1,800 liters/day/meter) whereas the seepage quantities of the current case range from 0.85–5 m^3/day/m (850–5,000 liters/day/meter). This shows an expected decrease in the seepage quantities between 53–64%. This means that technically using the geomembrane is the best way to solve the seepage problem. However, from a financial point of view, this solution would be very costly because the installation process is very expensive and requires special techniques and care. The need to remove all the riprap and provide a smooth layer as well as supports will increase the total cost. Al-Hashmi (2010) presented a cost estimate for the two remedial options.

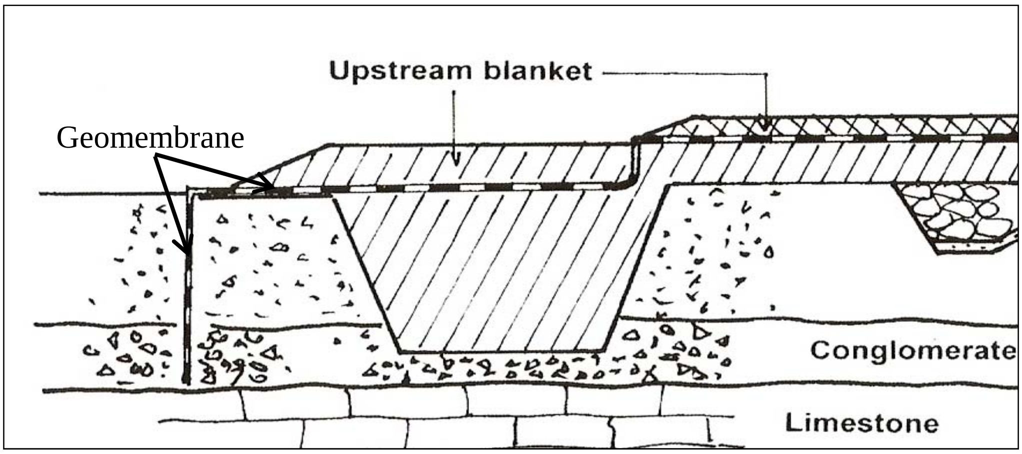


Figure 12. Dam with geomembrane.

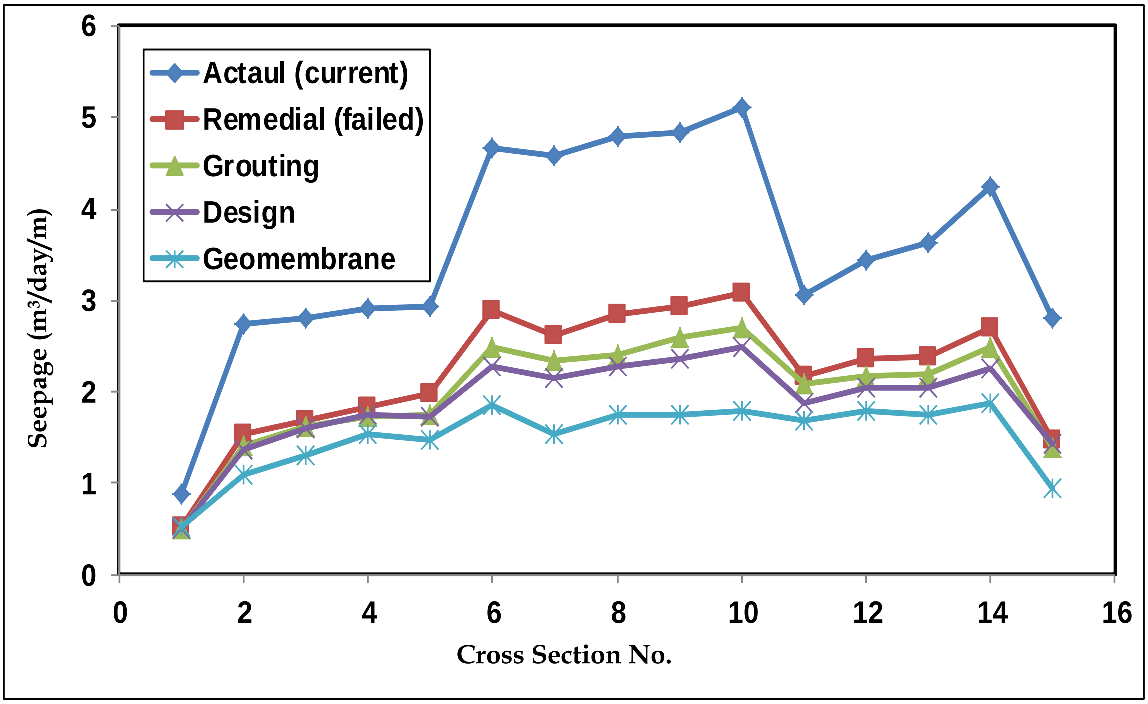


Figure 13. Seepage quantities profile of all cases.

5. Conclusion

The objective of the current study was to investigate possible causes for excessive seepage at the Al-Fulaij Recharge Dam and to suggest remedial measures. A finite element program (SEEP W 2007) was used to simulate the dam's seepage, considering the most probable causes and suggested remedial measures. The most possible causes of seepage at Al-Fulaij Dam are the presence of permeable alluvium deposits and conglomerates with cavities that formed due to the dissolution of the gypsum material and the insufficient depth of the dam key, which constitutes the dam's foundation. As a result of alluvium deposits and the dam key's insufficient depth, the seepage quantities increased to about double the expected amounts. There was also a sign of settlement that had taken place because of gypsum leaching from the dam's foundation. Two methods were proposed to control the seepage and were modelled by the program to validate their efficiency. The first method is the installation of a geomembrane at the upstream face of the dam. The second method is the installation of grout at the foundation of the dam. It is expected that using a geomembrane would reduce the current seepage by about 53–64% while installing grout at the dam foundation would reduce the seepage by about 41–48%. Grouting is the best option although a geomembrane would give better results as the total process of installation of the geomembrane is costly and needs special care as well a protection from sunlight and vandalism. Grouting is more suitable and also has the advantage of enhancing the dam stability by filling the voids and cavities which were created by gypsum leaching.

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