# Remedial measures to control seepage problems in the Kafrein dam, Jordan

Osama K. Nusier · Ahmed Shlash Alawneh · Abdallah I. Husein Malkawi

**Abstract** The Kafrein dam, 480 m long and 30 m high, is located on the Wadi Kafrein, a few kilometres from the active Jordan Valley fault. The Jordan Valley Authority proposed raising the crest of the existing dam by approximately 7 m and extending the length of the embankment to 554 m, in order to increase its storage capacity by 6 million $m^3$ to a total of 8.5 million $m^3$. The paper discusses the likelihood that existing seepage problems will be exacerbated when the dam is raised and proposes some remedial actions to increase the safety of the dam and minimise both the amount of seepage and any adverse effects.

**Résumé** Le barrage en terre de Kafrein, de 480 de longueur et 30 m de hauteur, est situé sur l'oued Kafrein, à quelques kilomètres de la faille active de la vallée du Jourdain. La Jordan Valley Authority a proposé de surélever la crête du barrage d'environ 7 m et de rallonger le remblai de 554 m, afin d'augmenter la capacité de stockage de 6 à 8,5 millions de $m^3$. L'article examine la possibilité d'une aggravation des fuites existantes et propose des mesures correctives pour améliorer la sûreté du barrage, diminuer les fuites et atténuer tout effet négatif.

**Keywords** Seepage · Dam · Remediation action · Dam safety · Control

**Mots clés** Fuites · Barrage en terre · Mesures correctives · Sûreté de barrage en terre · Contrôle

Received: 28 December 2000 / Accepted: 13 May 2001
Published online: 1 November 2001
© Springer-Verlag 2001

O.K. Nusier (✉) · A.S. Alawneh · A.I.H. Malkawi
Jordan University of Science and Technology,
P.O. Box 3030, Irbid 21110, Jordan
e-mail: nosama@just.edu.jo
Fax: +962-2-295018

## Introduction

Dams are the most common and efficient means of ensuring the value of every drop of water available in arid regions suffering a water scarcity or limited water resources. Jordan suffers considerably from this problem, yet a dam project is not a perfect solution and problems may arise both during and after its construction. Most of these problems will be related to the geological, hydrological and/or geotechnical conditions at the dam site.

Wilson and Marsal (1979) indicated that despite the uniqueness of every individual project, the most common causes of dams being breached are overtopping, the internal erosion of fine-grained soils from either the embankment itself, its foundation and/or the abutments and the stability problems resulting from excessive pore pressures and the hydraulic gradients. There may also be a danger associated with the probable maximum flood (PMF) and/or a seismic threat. Clevenger (1974) estimated that 10% of all dam failures were caused by foundation seepage. He also noted that seepage through the foundation of a dam is an indicator of a risk of failure, although this cannot be determined with a high level of certainty. Leonards (1987) reported that of four failures studied, those at Baldwin Hills, Teton and Malpasset had all been caused by complex seepage problems involving the dam and foundation contacts. Muniram and Gobin (1995) studied the effect of seepage-induced slope failures of sand bars in the Grand Canyon. A simple model based on seepage parallel to the slope in an infinite, homogeneous, cohesionless soil was used to determine the limiting stable seepage slope which they concluded becomes a predefined failure plane. Sand deposited above this seepage slope will fail along the predefined plane from gravitational forces, high pore pressure and seepage forces. Even if a dam is stable as regards other possible failure scenarios, seepage control remains a very important consideration.

The Kafrein dam is located on the Wadi Kafrein, a few kilometres from the active Jordan Valley fault (Fig. 1). The existing dam embankment is 480 m long, with a maximum height of 30 m. It is founded on alluvial deposits extending to depths of up to 50 m. No specific cut-off works were constructed in the dam foundation, but a limited grout curtain was placed in the left abutment, including the spillway location. The Jordan Valley Authority is proposing to raise the crest of the existing Kafrein dam by approximately 7 m and extend the length of the embankment to 554 m, in order to increase its storage capacity by 6 million $m^3$ ($Mm^3$) to a total of 8.5 $Mm^3$.

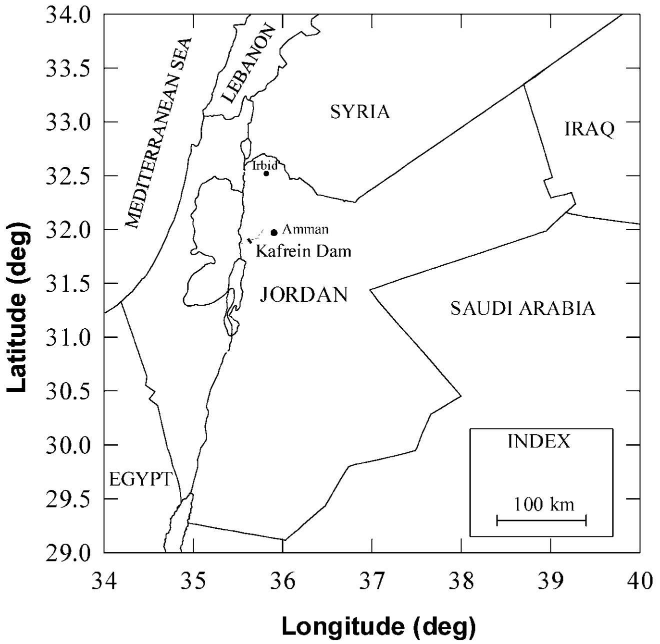
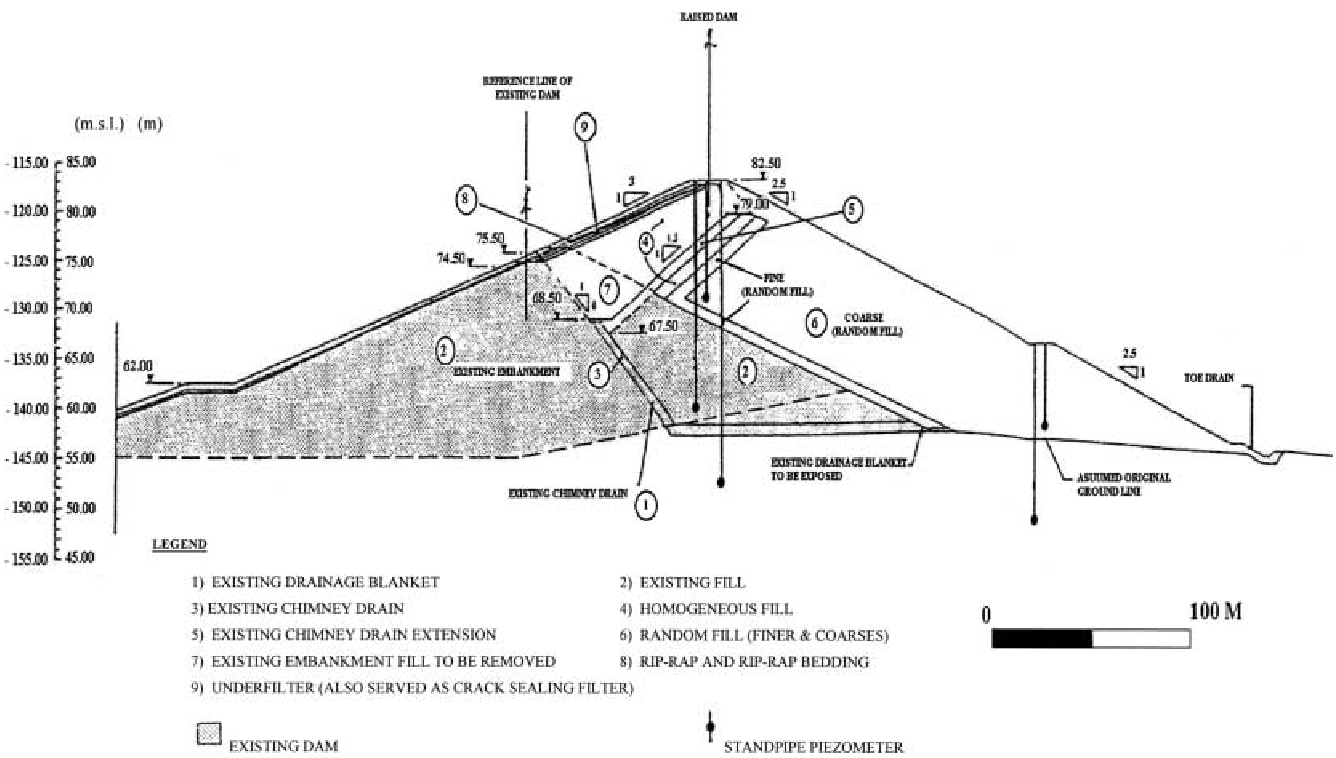



**Fig. 1**
Location of the Kafrein dam, Jordan

**Fig. 2**
Cross section through the Kafrein dam




Seepage occurs in almost every dam and the Kafrein dam (Fig. 1) is no exception. The quantity of seepage collected at a retention pool (Batous) about 1.5 km downstream is expected to rise to about 700 l/s once the reservoir has reached its full capacity.

This paper discusses the general background of the Kafrein dam project and the evidence of developing seepage-related problems in relation to the geological and geotechnical properties. From the conclusions drawn, remedial actions to reduce the seepage are recommended.

## General background

In order to overcome the current and future deficit in water used mainly to irrigate the Kafrein area and the farms in its vicinity in the fertile Jordan Valley, the raising of the Kafrein dam is one of many projects that have been carried out recently in Jordan. The dam is located on the Wadi Kafrein. The topography of the area consists of deep-sided valleys providing an annual inflow to the reservoir of about 11 $Mm^3$.

The dam was built in 1968 with a storage capacity of 4.5 $Mm^3$. It is basically a homogeneous earthfill dam some 30 m high and 480 m long, constructed of a compacted clayey core protected by a compacted rock fill on both sides (Fig. 2). To overcome the problem of sediment deposition, probably in the order of 2.5 $Mm^3$ and to meet the ongoing demand for agricultural water in the Kafrein area, it was proposed to increase the height of the dam by 7 m to provide an additional 6 mcm of storage.

**Table 1**
Nomenclature of Upper Cretaceous strata

| Period | Epoch | Age | Group | Rock unit | Formation | Lithology |
|---|---|---|---|---|---|---|
| Recent | | | | | | Alluvium |
| Cretaceous | Late | Campanian | Belqa | B2 | Amman | Chalk and marls |
| | | Santonian/Coniacian | | B1 | Ghudran | |
| | | Turonian | Ajlun | A7 | Wadi Es-Sir | Massive limestone |
| | | | | A6, A5 | Shueib | Marl and chalky marl |
| | | | | A4 | El-Hummar | Dolomitic limestone |
| | | | | A3 | Fuhais | Yellow and green marl |
| | | Cenomanian | | A2, A1 | Na'ur | Limestone and marly limestone |
| | Early | | Kurnub Sandstone | | | |

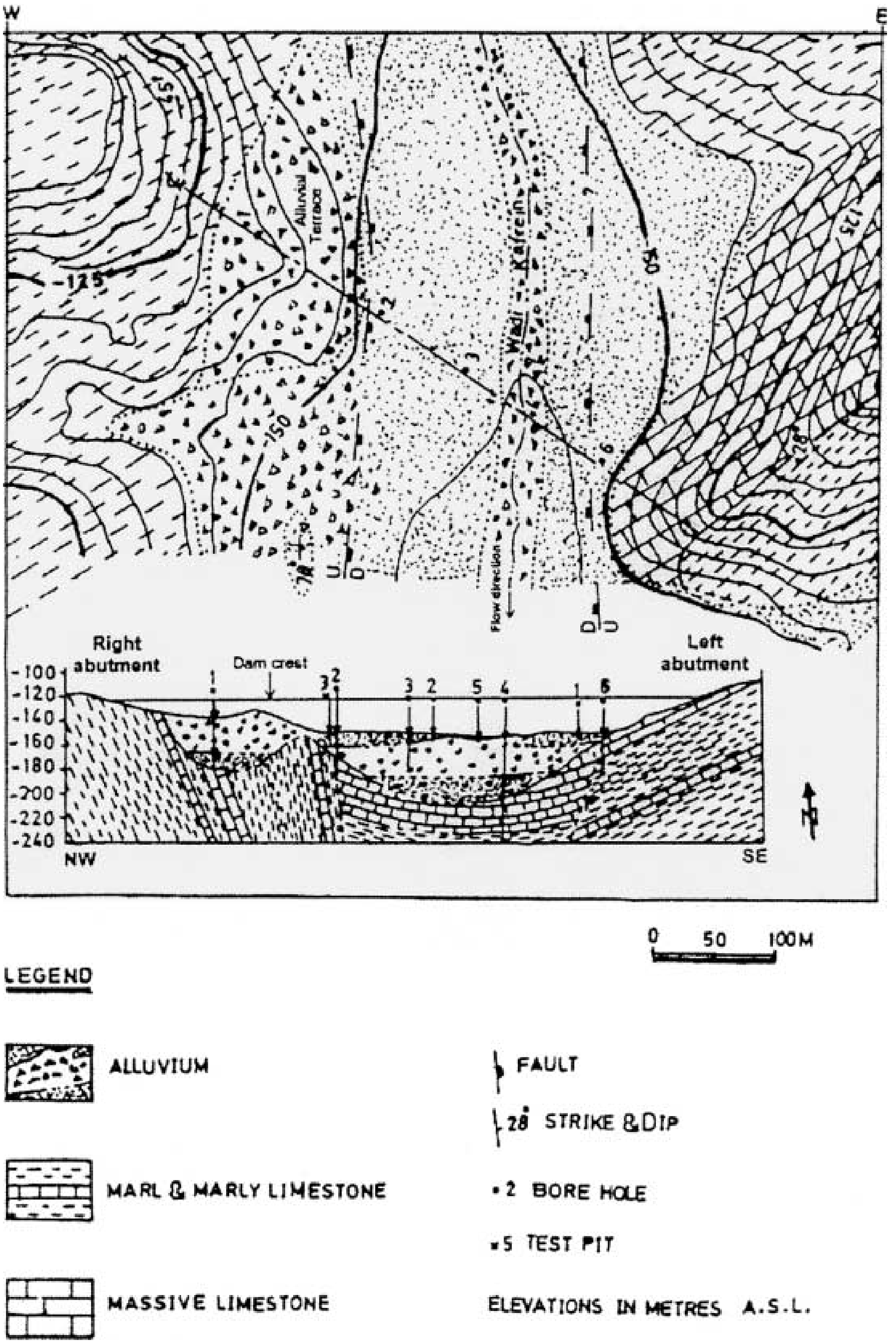



**Fig. 3**
Geological map and section with borehole locations

## Regional geology

To determine the geology of the Kafrein reservoir and dam site, five boreholes and four trial pits were undertaken (Table 1). According to the Water Resources Authority study (1965) of east Jordan, which included the Wadi Kafrein, there are four rock units in the area: the Kurnub Sandstone Group, the Ajlun Group (A1–A7), the Belqa Group (B1–B2) and recent deposits of talus, alluvial soils, uncemented alluvial gravel and partially cemented alluvial gravel. The Lower Cretaceous Kurnub Sandstone Group occurs on the eastern and western parts of the Wadi Kafrein and consists of varicoloured, friable sandstone interbedded with siltstone, claystone, claystone and shale, with upper horizons of dark grey or green silty clays. The overlying Ajlun Group (lower part of the Upper Cretaceous) is dominated by a carbonate sequence. It can be divided into seven subdivisions (A1–A7). The lowest part, the Na'ur Formation (A1, A2), is composed predominantly of marl and clay intercalated with marly limestone, limestone, chert and dolomites and is found in the western part of the Wadi Kafrein. This is overlain by the limestone marl sequences of El-Hummar, Shueib and Wadi Es-Sir (A4, A5–A6 and A7), which, at the eastern part of the Wadi Kafrein, have chalky marl intercalations. Overlying these deposits are the recent talus, alluvial soils, uncemented alluvial gravels and partially cemented alluvial gravels forming the valley floor.

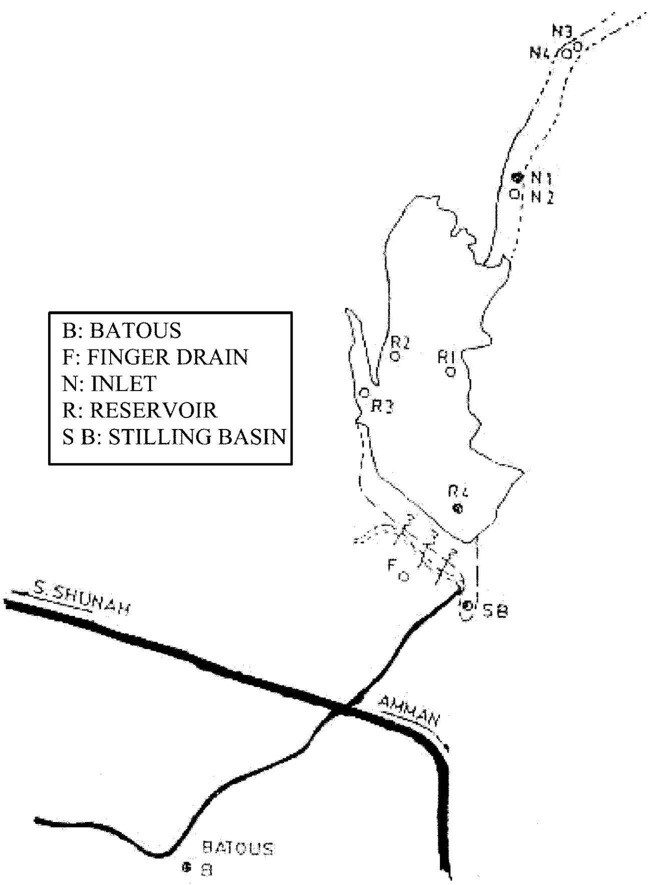



**Fig. 4**
Sampling locations

**Table 2**
Results of chemical analyses (in ppm). For locations see text

| Date of sampling | 4/3/96 | | 14/4/96 | | 21/5/96 | | | | 24/7/96 | | | | 19/8/96 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | 30 | | 33 | | 39 | | | | 40 | | | | 41 | | | |
| Monthly rainfall (mm) | 67.2 | | 6.7 | | 0 | | | | 0 | | | | 0 | | | |
| Reservoir water level (m) | 66.61 | | 68.42 | | 67.8 | | | | 66.06 | | | | 64.65 | | | |
| Location | R | SB | R | SB | N | R | SB | B | N | R | SB | B | N | R | SB | B |
| Anions | | | | | | | | | | | | | | | | |
| Cl | 99.4 | 117.2 | 68 | 113.6 | 126 | 88.7 | 95.8 | 99.4 | 126 | 131.4 | 106.5 | 133.2 | 124.3 | 127.8 | 120.7 | 120.7 |
| $SO_4^{2-}$ | 76.8 | 110.4 | 48 | 82 | 69.6 | 19.2 | 48 | 43.2 | - | - | - | - | 62.4 | 76.8 | 57.6 | 96 |
| $HCO_3$ | 219.6 | 146.4 | 207.4 | 250 | 244 | 219.6 | 293 | 293 | 231.8 | 134.2 | 201.8 | 170.8 | 195.2 | 170.8 | 207.4 | 158.6 |
| $PO_4^{3-}$[a] | - | - | 0.3 | 0.4 | - | - | - | - | 52.3 | 34.8 | 53.9 | 45.9 | - | - | - | - |
| Σ Anions | 395.8 | 374 | 323.4 | 445.6 | 439.6 | 327.5 | 436.8 | 435.6 | 357.8 | 265.6 | 308.3 | 304 | 381.9 | 375.4 | 389.7 | 375.3 |
| Difference with respect to reservoir (%) | - | 5.8 | - | 37.6 | 85 | - | 83.8 | 82.3 | 40.4 | - | 16 | 14.5 | 1.7 | - | 3.8 | 0 |
| Cations | | | | | | | | | | | | | | | | |
| Na | 41.2 | 54.2 | 36.6 | 55.4 | 71.7 | 55.6 | 64.4 | 62.8 | 94.7 | 61.41 | 55.6 | 59.8 | 83.7 | 78.4 | 70.6 | 75.7 |
| K | 7.82 | 13.7 | 4.7 | 5.4 | 7.9 | 5.4 | 5.6 | 6.14 | 8 | 7.43 | 5.47 | 7 | 10.2 | 9.8 | 7 | 9.8 |
| $Ca^{2+}$ | 80 | 74 | 62 | 80 | 43 | 24 | 44.5 | 47 | 66 | 62 | 100 | 72 | 58 | 38 | 54 | 50 |
| $Mg^{2+}$ | 24.4 | 19.5 | 17.1 | 31.7 | 43.6 | 28.7 | 40.7 | 41.5 | 31.1 | 23.2 | 21.3 | 23.2 | 31.7 | 29.3 | 26.8 | 28.1 |
| Σ Cations | 153.4 | 161.4 | 120.4 | 172.5 | 166.2 | 113.7 | 155.2 | 156.9 | 199.8 | 154.04 | 182.4 | 162 | 183.7 | 155.5 | 158.4 | 163.6 |
| Difference with respect to reservoir (%) | - | 5.2 | - | 43.29 | 46.2 | - | 36.5 | 38 | 29.7 | - | 18.4 | 5.2 | 18.1 | - | 1.9 | 5.2 |

[a]Affected by agricultural activity upstream

## Structural geology

The main structural features dominating the area are two major faults with several minor folds. The dam is built on three structural features; a north–south-trending syncline bounded by two north–south faults. These major structures and several minor features have resulted in near-vertical bedding in the vicinity of the site. In addition, joints and fractures occur in the limestone, which would be anticipated to result in water loss.

## Geology of the dam site

The boreholes drilled along the dam axis (BHs 1, 2, 3, 4 and 6) indicated 60 m of alluvial deposits comprising poorly sorted silty clay, sandy gravels with occasional lenses of boulders or silty sands with varying degrees of cementation (Fig. 3). Two channels have been eroded into the bedrock. The main one, between the two faults, is approximately 60 m deep, while the depth of the second, beneath an alluvial terrace at the right abutment, is unknown but at least 36 m.

The bedrock is dominantly the limestone, marlstone and dolomites of the Fuhais Formation (A3) and the massive crystalline limestone of the El-Hummar Formation (A4). In the area of the right abutment, however, the Na'ur Formation is present, dipping steeply to the northeast and of varying thickness. The El-Hummar Formation is the bedrock material at the left abutment, dipping to the northwest and characteristically coarse to medium grained and well jointed. This unit is underlain by the well-jointed fine-grained limestone, marly limestone and marlstones of the Fuhais Formation (A3) although the El-Hummar Formation is probably the bedrock of the main valley floor.

## Reservoir geology

The reservoir area consists of alluvial deposits and bedrock. The alluvial deposits are characterised by poorly sorted, partially cemented gravels and pebble beds, which merge with limestone and marl talus at the edges of the valley floor. Due to the variation in the cement content of the material in the reservoir area the permeability of these materials also varies. At the edge of the reservoir area, high-permeability silty clay was observed.

The limestone and marly limestone beds of the Na'ur Formation (A1, A2) occur on the eastern limb of the north–south-trending anticline, steeply dipping and disturbed by cross faulting in the upper reservoir area and by the major north–south fault along the edge of the valley. To the northwest of the reservoir the permeable Kurnub Sandstone is exposed in the core of the anticline at a depth of approximately 50 m. To the east of the reservoir area the A4, A7, B1 and B2 units are found, together with limestone and marlstones which are partially disturbed by minor folds and faults.

On the valley floor the bedrock consists of massive limestone, marl and marly limestone, in a synclinal fold created by two north–south faults. These faults generally mark the boundary between the alluvium and the bedrock.

## Seepage study programme

The study programme was initiated in order to monitor the behaviour of the dam in general and specifically the seepage, and included piezometer readings, relief wells and readings of the reservoir levels, measurement of the volume of water collected at Batous and determination of the water quality at various locations (Fig. 4). Examples of these data are presented in Tables 2, 3 and 4.

In addition to the very clear visual evidence of water coming out of rather than through the spillway or the outlet pipes from the dam, a sudden increase in the quantity of water collected at Batous was noted as the reservoir level reached an elevation of –69 m. The most obvious evidence of developing seepage problems is that a seepage outflow increases disproportionately to the rise in water level, or with time when the water level is generally consistent. A further indication may be provided by the

**Table 3**
Results of trace element analyses (in ppm). For locations see text

| Date of test | 4/3/96 | | 14/4/96 | | 21/5/96 | | | | 24/7/96 | | | | 19/8/96 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | 30 | | 33 | | 39 | | | | 40 | | | | 41 | | | |
| Monthly rainfall (mm) | 67.267.2 | | 6.7 | | 0 | | | | 0 | | | | 0 | | | |
| Reservoir water level (m) | 66.61 | | 68.42 | | 67.8 | | | | 66.06 | | | | 64.65 | | | |
| Location | R | SB | R | SB | N | R | SB | B | N | R | SB | B | N | R | SB | B |
| Boron | – | – | 0.27 | 0.35 | 0.26 | 0.18 | 0.27 | 0.22 | 0.2 | 0.15 | 0.13 | 0.08 | 0.2 | 0.22 | 0.22 | 0.25 |
| $Cu^{2+}$ | – | – | 0.03 | 0.036 | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.04 | 0.02 | 0.04 | 0.03 |
| $Mn^{2+}$ | – | – | 0.011 | 0.013 | 0.01 | <0.01 | 0.02 | 0.02 | <0.015 | 0.015 | 0.01 | <0.01 | <0.01 | 0.01 | 0.01 | 0.02 |
| $Fe^{2+}$ | – | – | 0.06 | 0.069 | 0.07 | 0.03 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.035 | 0.03 | 0.01 | 0.03 | 0.05 |
| $Zn^{2+}$ | – | – | 0.036 | 0.033 | 0.01 | 0.01 | 0.02 | 0.01 | 0.025 | 0.025 | 0.035 | 0.025 | <0.01 | <0.01 | <0.01 | 0.02 |
| $NO_3^{2-}$ | – | – | 7.15 | 6.58 | 4.83 | 5.13 | 5.6 | 5.0 | 3.45 | 0.97 | 4.38 | 1.99 | 3.29 | 0.43 | 4.04 | 0.82 |

**Table 4**
Water quality results. For locations see text

| Date of test | 4/3/96 | | 14/4/96 | | 21/5/96 | | | | 24/7/96 | | | | 19/8/96 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | 30 | | 33 | | 39 | | | | 40 | | | | 41 | | | |
| Monthly rainfall (mm) | 67.2 | | 6.7 | | 0 | | | | 0 | | | | 0 | | | |
| Reservoir water level (m) | 66.61 | | 68.42 | | 67.8 | | | | 66.06 | | | | 64.65 | | | |
| Location | R | SB | R | SB | N | R | SB | B | N | R | SB | B | N | R | SB | B |
| $EC_w$ (mmhos/cm) | 0.80 | 0.83 | 0.68 | 0.92 | 0.92 | 0.61 | 0.85 | 0.86 | 1.05 | 0.80 | 0.92 | 0.95 | 0.93 | 0.80 | 0.82 | 0.82 |
| Difference of $EC_w$ with respect to reservoir (%) | – | 3.75 | – | 35.2 | 50 | – | 39.4 | 40.9 | 31.3 | – | 15 | 18.8 | 16.2 | – | 2.5 | 2.5 |
| TDS (ppm) | 512 | 531 | 435 | 588 | 586 | 390 | 544 | 550 | 675 | 512 | 589 | 544 | 595 | 512 | 525 | 525 |
| Difference of TDS with respect to reservoir (%) | – | 3.71 | – | 35.2 | 50.3 | – | 39.5 | 41.0 | 31.8 | – | 15.0 | 6.3 | 16.2 | – | 2.5 | 2.5 |
| pH | 8.54 | 8.58 | 7.93 | 7.22 | 8.10 | 9.04 | 7.55 | 7.96 | 8.40 | 8.90 | 7.60 | 8.6 | 8.6 | 8.84 | 7.93 | 8.54 |
| Difference of pH with respect to reservoir (%) | – | 0.5 | – | 9 | 10.4 | – | 16.5 | 12 | 5.56 | | 14.6 | 3.3 | 2.7 | – | 10.3 | 3.4 |

interpretation of the chemical analysis of water samples collected from various fixed locations, as shown in Fig. 4. The locus of the seepage threat and field evidence of any developing seepage problem at the Kafrein dam were considered in three categories as shown in Table 5. From this table it is clear that seepage would be anticipated from the foundation and abutments or reservoir sides away from the dam and may be through sinkholes and solution channels.

## Chemical analysis

Another approach to addressing the problem is to analyse chemical test results on water samples collected at various times from significant locations (Fig. 4), namely the inlet (N), the reservoir (R), the stilling basin well (SB) and the seepage ponds (B). The locations of these sampling points are detailed in Tables 2, 3 and 4 which also provide a summary of the results. The following general trends are noted:

1. Total dissolved solids (TDS) in Batous and the stilling basin well are more than in the reservoir.
2. pH in Batous and the stilling basin well is less than in the reservoir.
3. $NO_3$ and $PO_4$ levels depend on the agricultural season, whether or not fertilizers are being used by the farms located both upstream and downstream and the type of fertilizer used.
4. Ca increases in Batous and the stilling basin well due to dilation as water seeps through the limestone and dolostone of units A3, A4, A7 and A1–2.
5. Trace elements are almost the same in all the locations. Bearing in mind experimental errors, this may indicate the same source of water for all the samples – probably the reservoir.

## Conditions leading to seepage problems

Broadly speaking, there are three major factors that are likely to lead to seepage problems: design defects, construction shortcomings and unfavourable geology not properly taken into consideration (see Table 5). In the case of the Kafrein dam, significant factors include the absence of cut-off walls, the presence of high-permeability material in the foundations and the absence of an upstream blanket. In addition, in some areas, the stored water is directly in contact with permeable strata and open joints/minor faults are present in the abutments or in their vicinity. When this information is included in Table 5, it is clear that the locus of seepage is likely to be through the foundation, abutments or reservoir sides and through sinkholes and solution channels in the vicinity of the dam.

**Table 5**
Field evidence of developing seepage and likely causes

| Locus of seepage | Evidence from the field |
|---|---|
| Through foundation below embankment | Seepage egress at or downstream of embankment toe. Foundation piezometer levels rise downstream of core. Toe drain flow increases and fines appear in discharge. Pool water loss increases with time |
| Through abutments or reservoir sides away from dam | Flow increases in streams draining away from perimeter of reservoir. Pool water loss increases disproportionally with pool rise |
| Through sinkholes and solution channels | Sudden pool water losses after stable pool operations. Sudden development of boils, springs or ground loss in downstream exposures |
| Stage-setting factors in developing seepage | |
| **Locus of seepage** | **Field conditions that lead to problem** |
| Through foundation below embankment | Absence of or inadequate foundation cut-off. Foundation strata include pervious and highly aniso tropic members, dipping downstream. Absence of upstream blanket, pool directly in contact with previous strata |
| Through abutments or reservoir sides away from dam | Absence of blanketing on reservoir sides. Geology around reservoir provides favourable attitude for flow from pool |
| Through sinkholes and solution channels | Typical limestone solution features in reservoir area. Inept or inadequate investigation fails to define extent of solution problem. Long-term seepage pressure washes soil from solution channels |

**Table 6**
Drainage remedial procedures and barriers against seepage at the Kafrein dam

| | |
|---|---|
| Drainage remedial procedure | |
| Through foundation below embankment | Install relief wells, deep ditch drains or pervious blanket downstream of toe of embankment. Attend to proper filter arrangements, particularly in natural strata. Examine and purge toe drain lines through cleanout risers or discharge lines |
| Through abutments or reservoir sides away from dam | Locate supplementary drain lines, properly filtered, where seepages have appeared |
| Through sinkholes and solution channels | Add pervious blanket or reverse filter above downstream boils or spring |
| Barriers against seepage | |
| Through foundation below embankment | Cut-off grouting by joint filling or permeation may need to be positioned more centrally beneath maximum overburden |
| Through abutments or reservoir sides away from dam | Extend an upstream blanket to cover uncovered alluvial material at edge of upstream. Periodical grouting for selected sensitive points at both abutments. Cut-off wall |
| Through sinkholes and solution channels | Void-filling grouting with bulking materials placed as far upstream as practical |

## Remedial action

As shown in Table 6, the most appropriate remedial actions are the installation of drainage measures and barriers which would minimise the risk of piping, cracking or increased pore-water pressure. The main purpose would be to reduce pore-water pressures downstream of the core. Table 6 also suggests that more relief wells should be installed with deep ditch drains and the grout curtain extended at particular locations, especially where open joints were observed in the abutments. However, in the case of the Kafrein dam where there was a pool collecting all the seepage water, this should be properly maintained such that the seepage water could at least be used – provided of course that the ongoing seepage did not compromise the safety of the dam. Quality control and redundancy are essential elements in any proper monitoring programme.

Another practical option for the Kafrein dam might be to extend a cover blanket upstream over the exposed alluvial material and to undertake periodical grouting at sensitive points on both abutments where there is clear evidence of joints. Probably the most effective solution would be to construct a cut-off wall, but it is likely that a more practical option would be to enhance the drainage downstream by increasing the number and depth of the relief wells and improving the capacity and efficiency of the Batous seepage collection point.

## Discussion and conclusions

Based on the available geological, geotechnical and hydrological information as well as site observations and visual inspections, the case study of the Kafrein dam can be summarised as follows: the dam is constructed in unfavourable geology. In addition, the design did not take proper account of the presence of alluvial material under the foundation or include a cut-off wall. As a consequence, seepage is observable which varies with changes in the reservoir level and shows a marked increased when the water level is at –69 m (Table 5).

Chemical analysis of water samples supports the visual and monitoring data that seepage is occurring. In addition, the exposed high-permeability material upstream of the

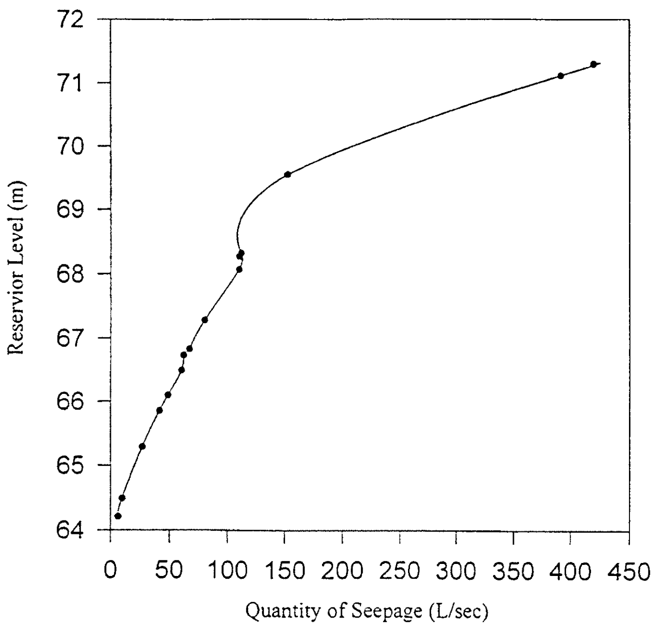



**Fig. 5**
Variation of seepage water with reservoir level

dam, the presence of an eroded channel and open joints at the right and left abutments, and the presence of many minor faults are all conducive to the development of seepage problems.

The quantity of seepage is expected to rise to about 700 l/s when the reservoir is completely filled and it is known that seepage increases sharply as the reservoir level reaches an elevation of –69 m (see Fig. 5). Most of the water seeping from the dam passes through the alluvial foundation material, although the exposed high-permeability material in the upstream area, the open joints and channel in the right abutments as well as the numerous minor faults also provide water pathways.

It is clear, therefore, that some remedial action is required, as suggested in Table 6. The most practical options would be to construct an upstream blanket, to improve the capacity of the downstream relief wells and blanket and to enhance the efficiency and capacity of the Batous collecting station. Periodical grouting in the most likely seepage areas would also be desirable; acoustic emissions is a promising method of identifying the location of active seepage and/or embankment deformation.

Although the use of slurry trenches and cut-off walls would normally be an option, this was likely to be an expensive solution and in the case of the Kafrein dam was unlikely to be feasible.

**Acknowlegements** The authors gratefully acknowledge the co-operation of Maher Iskander, assistant to the Secretary General of the Jordan Valley Authority, and his staff, Jafar Ababneth, Ome Al-Hatamleh and Wajih Haboush.

## References


Clevenger WA (1974) When is foundation seepage unsafe? In: Proc Conf on Inspection, Maintenance and Rehabilitation of Old Dams, ASCE, New York

Leonards GA (1987) Proceedings of the International Workshop on Dam Failures, Purdue University. Elsevier, Amsterdam

Muniram B, Gobin R (1995) Seepage-induced slope failure on sandbars in Grand Canyon. J Geotech Eng ASCE 121(8)

Water Resources Authority (1965) Geology of east of Jordan. Final Rep. Water Resources Authority, Amman

Wilson SD, Marsal RJ (1979) Current trends in design and construction of embankment dams. Prepared for Geotechnical Division, ASCE, New York