FIELD EVALUATION OF ENGINEERING GEOLOGIC HAZARDS OF AN EMBANKMENT DAM CONSTRUCTED ACROSS A MAJOR, ACTIVE PLATE BOUNDARY, FAULT

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ABSTRACT

The geological structures associated with the site of the 55 million m^3 Karameh embankment dam constructed in the Jordan Valley and the tectonic effects on dam foundation and reservoir margins were reviewed. The dam crosses the strike-slip fault of the Jordan Valley Rift Zone. Trace evidence of the fault indicates a displacement of 8 to 15 m over a rupture length of some 130 km, which probably took place several centuries ago. Earthquakes with Richter magnitudes as great as 7.8 have occurred along the Jordan Valley Fault

Field mapping of geological features during the dam foundation excavation and construction revealed that: a) the most likely location of the Jordan Valley Fault is in the area where the Wadi Mallaha stream crosses the dam axis, b) zones of "en-echelon" type open fissures have been defined in the laminates sub-parallel to the Jordan Valley Fault Zone, c) at the Wadi Mallaha stream bed a parallel zone of faulting and warping of the Lisan formation was identified, and d) the alignment is clearly confirmed by the exposure immediately upstream of the core at Ch 1375. The main wrench fault zone crosses the embankment footprint (upstream to downstream approximately) and reaches the surface around Ch 1375.
Key Words: embankment dam, geology, tectonic structure, active fault, rupture displacement.

INTRODUCTION

In Jordan, for both geological and economic reasons, most of the constructed dams are embankments. In addition, embankment dams are particularly appropriate for construction in earthquake-prone regions because of their ductility and generally lower cost.

The Karameh dam site is located on Wadi Mallaha (creek) which is adjacent to the Jordan River near the town of Karameh, on the eastern side of the Jordan Valley Rift (Fig 1). The construction of the dam started in October 1995 and was finished in September 1997. The embankment consists of a 10 million m^3 of zoned earthfill with a central clay core. The spillway includes a twin pipeline in a tunnel of 5.2 m diameter and 440 m long. The outlet works consist of a pumping station and a twin 1.2 m diameter pipeline to the King Abdullah Canal (Fig. 1). The dam is 41 m high, 800 m wide at its base and has a crest length of 2,200 m. The storage capacity of the dam is 55 million m^3.

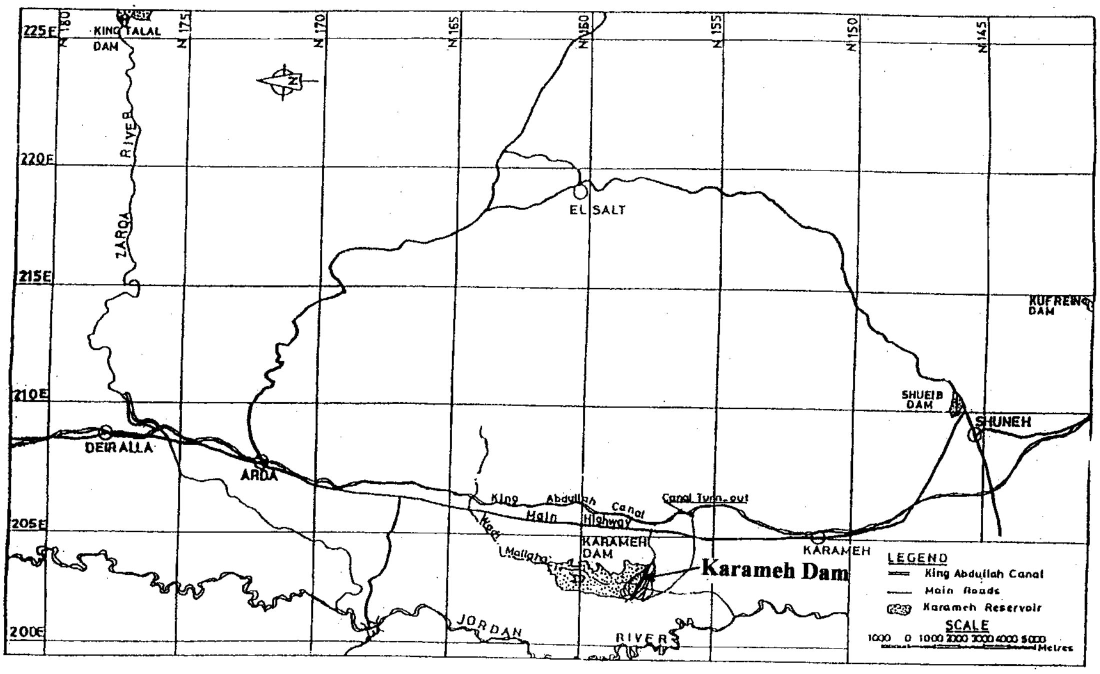

Fig. 1 Detailed Location Plan of Karameh Dam Showing Storage Reservoirs, King Abdullah Canal, Wadi Mallaha and Jordan River.

The geotechnical properties of the in situ foundation materials and the construction materials as well as the presence of the major Jordan Fault make this site complex. As Jordan is an earthquake prone region, the design of Karameh dam needed to take into consideration dynamic loading and such associated hazards as liquefaction and ground surfaced rupture. Sir Alexander Gibb and Partners designed the works on an estimated earthquake magnitude based on the International Committee on Large Dams (ICOLD) (1989) guidelines.

This paper considers the engineering geological hazards of the Karameh embankment dam and critically reviews the dam design, based on data obtained from field studies undertaken prior to and during the construction.

PROJECT DATA

The purpose of the Karameh Dam Project was to provide a reservoir which would store surplus winter flows in the King Abdullah Canal to allow implementation of irrigation at the southern end of the Valley. The reservoir lies below the level of the Canal and is connected to it by means of a twin pipeline system. The pipeline system will be used to fill the reservoir during the winter months and to pump water from the reservoir back into the Canal during the late spring and early autumn.

The scope of the project works is defined in the terms of reference for the design studies as follows (Sir Alexander Gibb and Partners, 1992a):

1) A 45 m high zoned earth fill dam with spillway and draw off structures;
2) A left bank saddle embankment;
3) A grout curtain to control leakage through the right abutment;
4) A twin pipeline system between the Karameh Dam and the King Abdullah Canal, designed both for transfers under gravity into the reservoir and by pumping from the reservoir.

5) A pumping station comprising four electric drive pump/motor units including all support facilities for maintenance and operation.
6) A turn-out structure on the King Abdullah Canal with screens, gates and other facilities for regulation of flows;
7) Diversion of the main access road to the irrigated lands on the left bank ridge and diversion of the main distribution pipes;
8) An access road to the dam and pump station from the main Jordan Valley highway;
9) Diversion of saline inflows away from the reservoir at or close to full storage level.

Fig. 2 gives the main zones of a typical cross-section of Karameh dam.

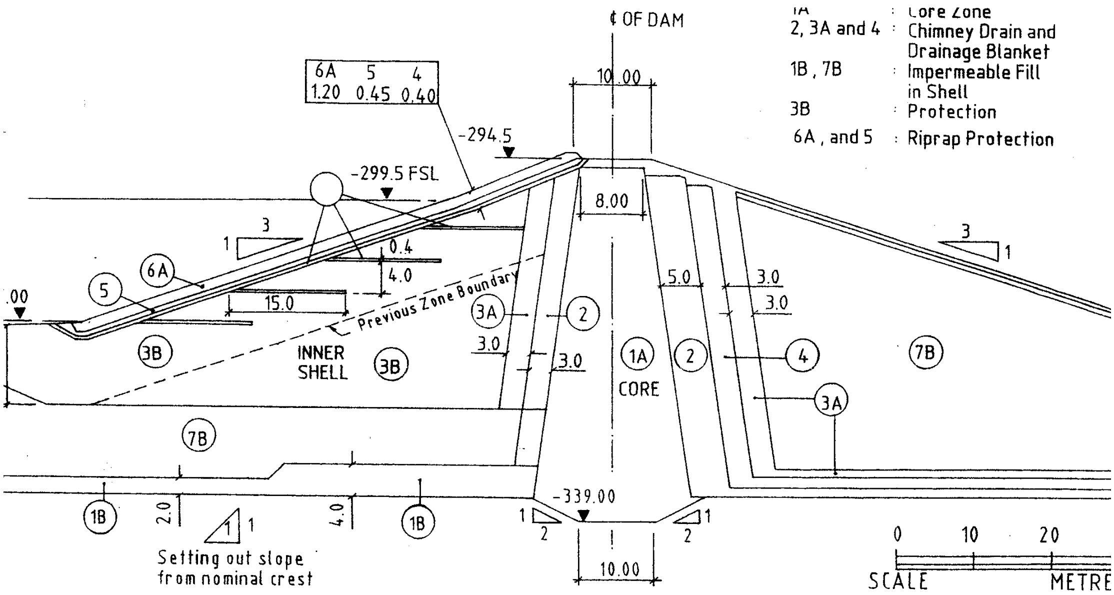

Fig. 2 Main Zones of a Typical Cross-Section of Karameh Dam.

Embankment Construction and Materials

The zoned embankment dam is constructed of the following materials (Fig. 2):

1A, 1B, Middle Clay for the core and impermeable upstream blanket.
2 Filter Sand
2US Upstream crackstopper
3A, 3B, Gravelly sands for downstream drainage blanket and shell
4 Gravel drains including chimney
5 Coarse gravel bedding and berm top protection.
6A, 6I, 6B, 6F Riprap
7B Reworked Upper Laminates for the inner shell
7C Recompacted Mudstone for the downstream outer shell.
8 External upstream impermeable blanket.
9 Toe weighting berm

Filling on all zones was reduced to a known process. Borrow areas were first identified and tested, including an existing quarry on the left bank ridge on the upstream side of the Ghor. Most of the materials placed have been excavated from close to the dam foundation. Construction control and materials testing results for all zones were more than satisfactory, and in particular the unconfined compression test data gave confidence to the undrained shear strengths used in the end of construction stability analysis.

REGIONAL GEOLOGY / ENGINEERING GEOLOGY

The rift valley originated in the Miocene since which a thick sequence of lacustrine deposits and associated evaporites accumulated in the valley. Most of the evaporites were deposited near the centre of the rift valley. A thickness of 3500 m of halite is located beneath the Dead Sea in the area of Lisan Peninsula.

Pliocene and Pleistocene lacustrine deposits underlie the site of the Karameh Dam. Local volcanic activity occurred in the mid-Pleistocene and basaltic lava occurs on the Ghor El-Katar dome.
Four formations are recognized in the Jordan Valley region:
1) Damya Formation;
2) Lisan Formation;
3) Samra Formation (upper Pleistocene), and
4) Ghor El-Katar series from lower and mid Pleistocene.

However only the Samra Formation/deposits and Lisan Formation/deposits are exposed at the site (Fig. 3).
These contain a range of structures including convoluted bedding, jointing and sinkholes.

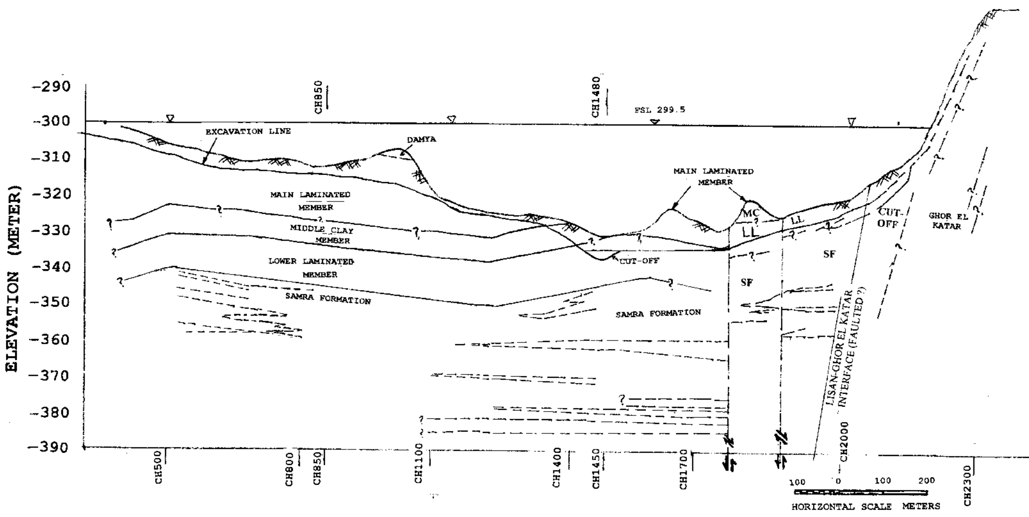

Fig. 3 Geologic Cross Section Along Dam Axis

Tectonic Structure

The main Jordan Valley Rift has caused movement along faults extending the length of the Jordan Valley. Both horizontal and vertical movements in the geological past have determined the present day distribution of the various rock types. Continued subsidence of the Jordan Valley has resulted in the deposition of over 3,500 m of sediments beneath the Dead Sea. Horizontal displacements in excess of 100 km between the western and eastern sides of the rift have been estimated.

Based upon the field mapping, a major fault referred to as the main Jordan Valley Fault, trends approximately north-south and runs at least 75 km from the Dead Sea to Lake Tiberias

(Fig. 4). This fault zone extends beneath the site of the dam and reservoir in the eastern side of the right embankment (Fig. 5). Rather than a single linear fault, this is a major movement zone consisting of a principal fault and numerous secondary faults and fractures. The presence of the extensive faulting at the site is implied by numerous steep-sided gullies possibly formed by the incised drainage.

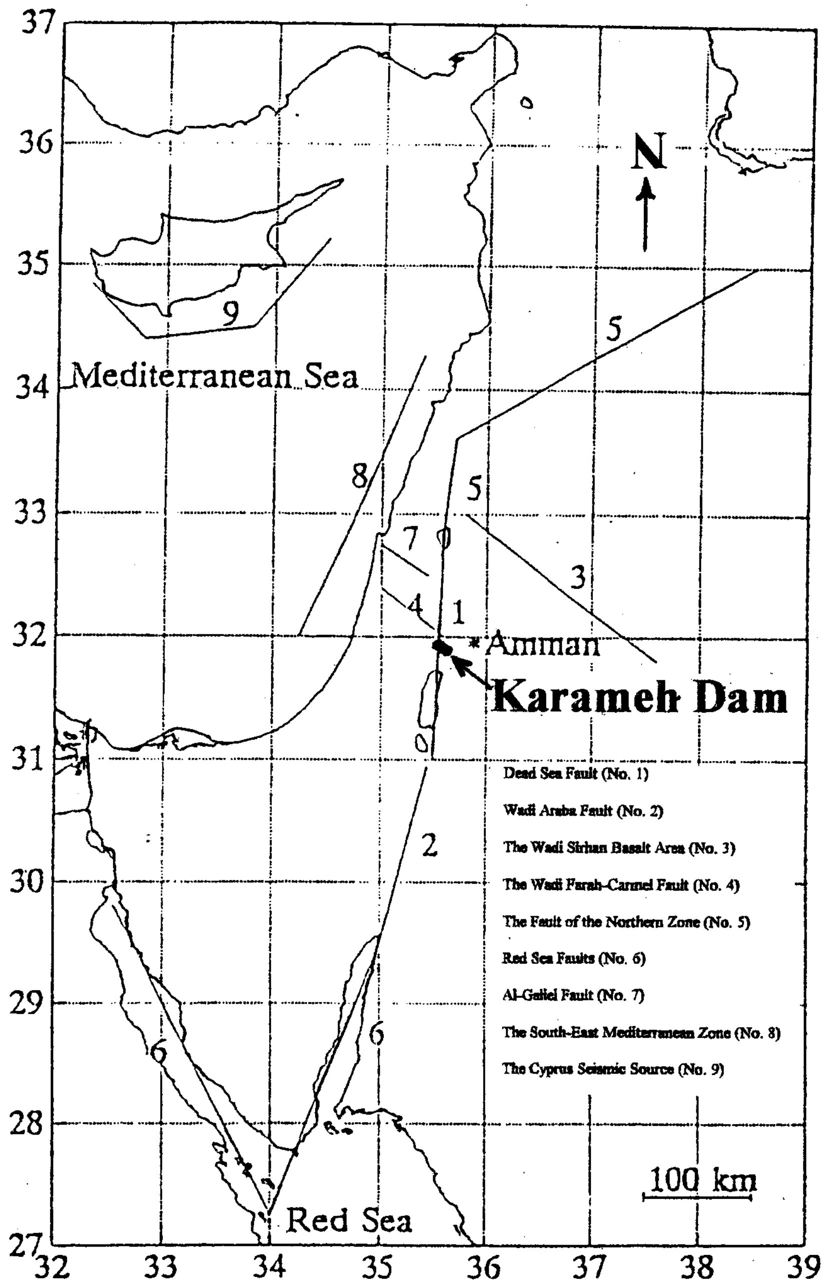

Fig. 4 Tectonic Map of Jordan Showing Location of Major Faults Including Jorda Valley Fault and Dead Sea - Jordan Transform Fault System.

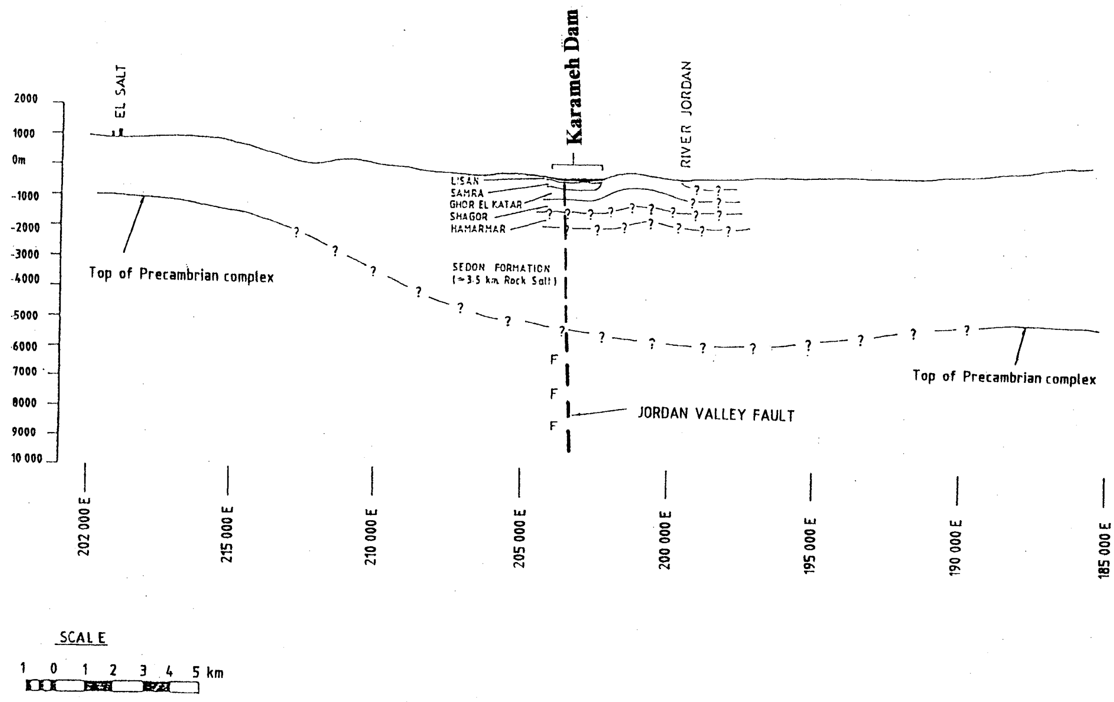

Fig. 5 Geologic Cross Section of the Jordan Valley Looking South Showing the Location of the Karameh Dam and the Geologic Formations Under the Dam (Modified After Sir Alexander Gibb and Partners, 1992a).

The Jordan Valley Fault is well known as a classic strike-slip fault. Along the main Jordan Valley Fault, and specifically at the Karameh dam site, major earthquakes have occurred in the past. The last was the 1927 earthquake, with a surface wave magnitude of 6.5 (Al-Homoud and Amrat, 1998).

The right abutment of the dam is highly fractured while the foundations contain cavities, gypsum and halite. Moreover, geological sections show the existence of continuous layers of loose liquefiable sand (Al-Homoud et al, 1995). The most prominent structural feature in Jordan is the Dead Sea-Jordan Rift System. This transform fault system, more than 1000 km long, links the Zagros-Taurus zone of plate convergence to the north with the Red sea to the south where crustal spreading occurs. The Dead Sea Rift (Jordan Valley Rift) was formed during the Cenozoic break up of the once continuous Arabo-African continent. The plate boundary movement in Jordan was strike-slip with a total left-lateral movement of some 105 km (Sunna, 1994). Some individual faults have a length of over 40 km (Fig. 4).

Faults within the Jordan Valley Rift zone are considered active. The most affected areas are nearest the rift margins. The transition from the rift valley to the raised shoulders of the rift (regional fault-line scarp) occurred through the system of step-faults, flexures, and grabens (Fig. 4). Outside the rift zone, faults are considered inactive (passive) due to an absence of geomorphic features typically associated with active faults.

The Jordan Valley is a linear depression, approximately 10-15 km wide on the south. The width of the valley is controlled by the presence of parallel faults dipping towards the Jordan River to form a graben. The length of the valley is approximately 360 km.

ASSESSMENT OF FOUNDATION GEOLOGY AS EXCAVATION PROGRESSED

Site investigations

The site investigations carried out comprised 74 boreholes totaling 3,145 m of cored and non-cored drilling in the ratio of 2:1. They were supplemented by test pits and trenches, and a 50 m adit. Also Packer and Lefranc permeability tests, and geophysics laboratory tests were carried out. The scope of the investigation and detailed mapping of the complex foundation materials before and during construction is considered to have been essentially adequate and appropriate for the design of an earthfill dam at this extremely difficult site.

Stratigraphy

The stratigraphy is well understood as regards the lithology of the formations, their attitude, lateral variations in thickness and engineering properties, as discussed previously. Construction of the dam progressed well and by October 1995 the bulk of the dam and upstream blanket foundations had been excavated, logged and backfilled. The extent of the completed excavation and logging is shown on the simplified geological map of the dam foundations provided in Fig. 6.

Two 0.3 m thick beds of fine sand in the Ghor at Ch 2022 and 2044 were inspected. After scraping away the softened "weathered" surface, the bands were seen to be extremely dense silty sand and weak silty sandstone into which a penknife could not be pushed. It is considered they do not represent a preferential seepage path under the core and mapping of the core foundations indicates that they are not continuous.

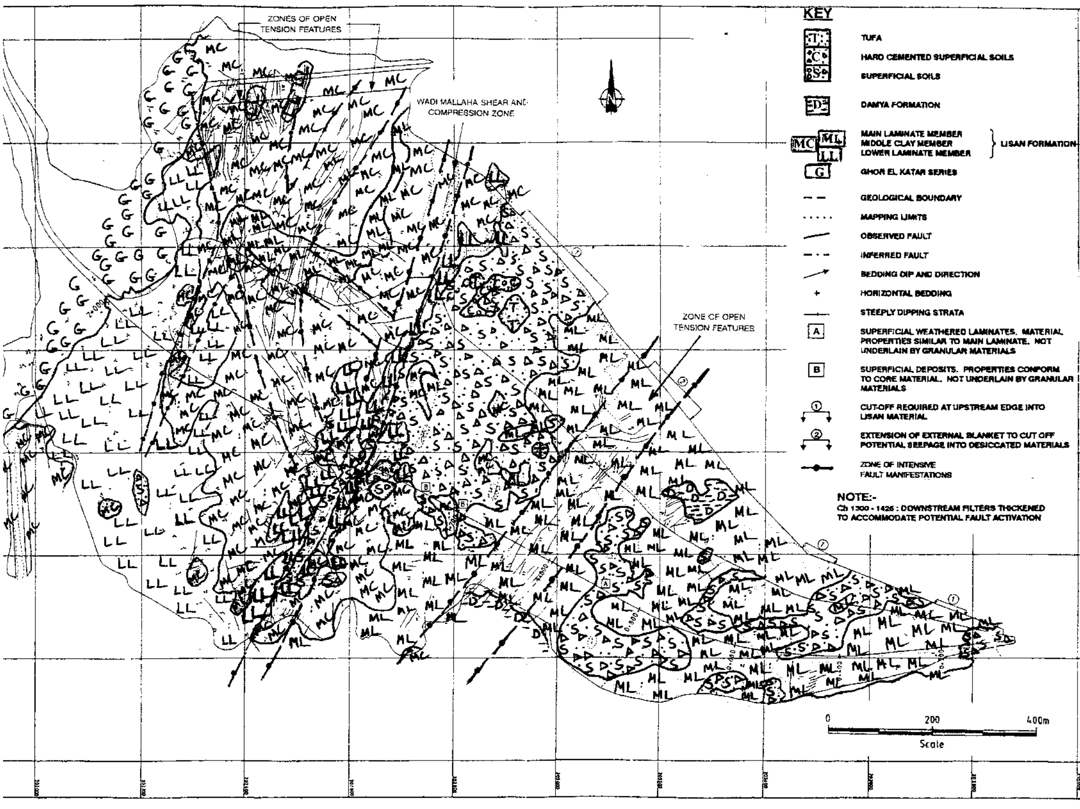

Fig. 6 As Excavated Geology (Sir Alexander Gibb and Partners, 1997).

Geological Interpretation of the Dam Site

As the foundation of the dam was exposed during the dam construction, a detailed geological interpretation of the site was prepared. Fig. 6 gives the geological mapping of the surface outcrop at formation level of the dam footprint including the external blanket area. This simplified geological map is a reduction of a 1:2,000 map. A longitudinal geological section along the dam axis at 1:1,000 was also produced as shown in Fig. 3.

Fig. 6 shows:

1) A geological stratigraphy that closely matches that identified during the site investigations
2) Three main structural features:
    a) A zone of open sub=vertical tension features striking NE/SW, crossing the dam centre line at approximately Ch 1100.
    b) A zone of principal movement along the original line of the Wadi Mallaha - (the Wadi Mallaha Shear Zone) trending NNE/SSW
    c) A shear zone of open sub-vertical features, similar to that at Ch 1100, which strikes N from the dam centre line at approximately Ch 1500 before swinging NE SW as it crosses the approach channel. This zone has a number of subsidiary off-shoots as shown on the map. The zones of open sub-vertical tension features are typically graben type structures, characteristic of extensional tectonics, exhibiting overall total vertical movements of the order of 2 - 4 m but with no indication of any lateral movement. These features were identified during the site investigations at Karameh, prior to construction and the dam was designed to withstand the earth movements likely to create such phenomena.

The Wadi Mallaha Shear Zone represents the zone of principal tectonic movement across the site in that it exhibits compressional deformation probably involving box type folding and en echelon shear of the strata. Although the Wadi Mallaha Shear Zone has an apparent downthrow of less than 5 m towards the west, compression within the zone has resulted in local movements of up to 6 m. It has not been possible to assess the extent of any lateral movement along the zone due to the horizontal nature of the strata at Karameh. As this is the zone of principal deformation, the dam filters have been thickened across it (Ch 1300 and Ch 1425).

These main features are consistent with the surface manifestations of a concave strike-slip feature at depth below a relatively weak sediment cover.

Foundation Excavations on the Right Abutment

Foundation excavations at higher elevations on the right abutment for the upstream blanket have shown increased depths of dry desiccated Main Laminates. These desiccated materials tend to occur on ground above -305 m and close to steep slopes in the original topography hence may provide preferential seepage paths under the blanket. It was therefore recommended that the upstream blanket be extended to ensure that any existing preferential seepage paths were cut off; the exact extent to be assessed following a site survey between Ch 850 and 1000. To assist in determining a suitable foundation level for the blanket in this area, it was recommended that a series of trial pits be excavated in two phases:

1) To assess whether a particular loading level could be identified.
2) Having assessed a likely impounding level, the excavation of a pit near the proposed level in order to carry out an infiltration test in it. The pit would then be extended below the founding level and a similar infiltration test undertaken to assess whether there were real advantages in increasing the depth of the foundation excavation.

It should be noted that the presence of the high permeability desiccated beds at higher elevations had implications for the impounding at Karameh, particularly above - 305 m. It was appreciated a significant volume of water would be required to saturate these sediments which would reduce the rate of reservoir filling at higher elevations. This is demonstrated by the length of time taken for the Wadi Abyad diversion canal to saturate the canal floor near the site offices.

For the high section of the dam Ch 1250 -1950 the foundation was excavated in accordance with the design drawings. Any pockets of disturbed Lisan or river alluvium were removed and the remnants of the desiccated Upper Laminates forming the dominant ridge feature were progressively taken away. The foundation was entirely underlain by Middle Clay or Lower Laminates. A nominal core trench was added beneath the Wadi Mallaha area without encountering any deep erosion channel. In certain areas minor tension cracks required grouting, but they were not continuous features. For the wet core the foundation was maintained in a moist condition and trafficking avoided.

As the cleared foundation area extended upstream of the core, geological mapping was continued but no significant features were added to the pattern already observed. Work on the Ghor/Lisan contact area at the foot of the right abutment exposed an area at the centreline where unexpectedly the Lisan lies beneath Ghor mudstones. At the core trench, this is interpreted as a block of mudstone that has moved downhill on to the Lisan. At the blanket/Ghor overlap, the face appeared to be an infilled concave cliff face of an original Ghor island.

Structure

Prior to commencement of construction, the understanding of the structure was limited due to the steep attitude of the faults, their small throw and their narrow width. Further, all except three of the boreholes were vertical and thus had little chance of intersecting them.

Normal Faults

As stripping and excavation were in progress, a better understanding of the structure was rapidly attained. It was possible to inspect the cut in the Main Laminates at Ch 1000 and see the incidence of normal faults giving rise to horst and graben structures in this zone of extension. Faults strike normal to the dam axis and have a throw of up to 4 m a disturbed zone of up to 200 mm. Their contents include loosened wall material (affected by drag) and material which had fallen in. These contents had a significant permeability and were readily erodible.

Even over the height of the cut, the width of the faults decreased. Normal faults striking roughly E-W were also noted and careful observations were made to determine whether they were displaced by strike-slip faulting. Field studies showed that the normal (tension) faults occurring at Ch. 1000 were open some 20 mm - occasionally 100 mm, - and infilled with fine grained materials. None crossed from one side of the core trench to the other. All were shallow and dealt with during the works. Some 100 m upstream of these faults more occurred under the shoulder of the dam. These persisted to greater depths and were variously treated by injection and slush grouting.

Another cluster of normal faults occurred between Ch. l800 and 2000 under the upstream shoulders. Where shallow they were dug out, while deeper faults were grouted.

Strike-Slip Faults

Information on strike-slip fault locations at the dam site was also important. Based on lineaments identified on satellite photographs, it was inferred that the main Jordan Valley Fault (JVF) crossed the dam site in the Lisan close to the unconformity with the Ghor. The fault is gently deflected (jogs) around the stronger Ghor bedrock. Thus as the eastern side of the fault moves northwards, it causes compression in the Ghor and push-up of this outliner.

During the inspection of cuts leading to the south portal of the tunnel, evidence of crushed and disturbed Ghor with a change of dip and strike was seen. This might reflect the nearby presence of the Jordan Valley Fault, being approximately where this fault was where anticipated. Meanwhile site investigations showed evidence of the existence of a strike-slip fault running along the Mallaha Valley. Outcrops in the Wadi banks are affected by folding and drag - a reflection of compressional forces. The main fault was not conclusively identified - it is possible that several strike-slip faults of engineering significance were found. En-echelon patterns are common with Middle East faults.

A photo-montage of the exposure of compressional folding near to the dam centreline and stream bed of the Mallaha is produced. It shows the manifestation of the Jordan Valley Fault adjacent to the centerline of the dam and the original channel of Wadi Mallaha. The compresssional zone was indicated by folding of the Lower Laminates stratum and recent movement was evidenced by inclusion of granular Wadi Alluvium material within the fold system.

It was thought that the main strike-slip fault would be found running close to the Ghor. Excavations in the Mallaha showed Lisan beds affected by drag, folding and inversion - further evidence of the compressional faulting. Field evidence indicated that strike-slip faulting was only present in the Malahha Valley.

Core trench excavations exposed Lower Laminates from Ch. 1800 to Ch. 2000 m, the structure being seen in a trench some 1.5 m deep. Laminae of aragonite could be seen throughout the length of the trench unaffected by folding or faulting. It is understood that the strata to the east, now covered by fill, were similarly undisturbed. The fieldwork showed no evidence that the main Jordan Valley Fault is located in its previously inferred position close to the Ghor.

Further evidence of compression in the Mallaha Valley was visible. Some 50 m north of the centreline, inversion of the beds was seen, e.g. Lower Laminates resting on Middle Clay. The best exposure was seen at Ch. 1375 near the centreline. Here a narrow vertical zone (10-20 cm) of sheared laminates separated vertically dipping laminates on the west from flat-lying laminates on the east which were affected by drag and truncated at the contact. The mapping also revealed more strike-slip faults - two positively identified and two inferred between Ch. 1320 and 1395. The fault at Ch. 1375 is considered to be the Main Fault.

Some evidence of sub-horizontal variations was detected but careful mapping of the dam foundations from the Ghor eastwards indicated positive evidence of strike-slip faulting in only some 1.5 km in the Lisan in the Mallaha valley. Movement on the faults must also have a vertical component to account for the structures seen.

The downstream filter was thickened by 2 m and the drain by 2 m from Ch. 1300 to 1425 to make the dam more earthquake resistant in the event of reactivation of this fault.

Foundation Excavation on the Ghor

Mapping of conglomerate, sandstone and mudstone bands across the foundation excavation on the Ghor is difficult due to the mixing that occurs as the material is bulldozed down the slope. However, mapping on the Ghor shows that its structure swings from a predominantly easterly dipping sedimentary sequence north of the dam site to a north easterly dipping sequence almost parallel to the dam axis at the dam site itself. It is therefore unlikely that leakage under the dam along sandstone/conglomerate beds will occur, as the structure is such that any leakage would have to flow "up-dip" across the full sequence of mudstones, sandstones and conglomerates. The exception to this is any sandstones/conglomerates that outcrop below top water level, immediately upstream of the core trench and potentially cross the dam axis at a depth.

The implications were that a grouted cut-off below the dam, to prevent leakage through sands and conglomerates in the Ghor, was unlikely to be required. However, the change in dip direction from easterly to north-easterly is considered to be a result of the faulting around the Ghor. Near surface excavations downstream of the core trench showed a highly fractured rock mass, with open fractures.

Geological Record and Foundation Mapping

Extremely detailed examination and logging of the foundations of the embankment were routinely carried out on a daily basis as the excavations proceeded. The programme of mapping was entirely controlled by the excavation programme of the contractor and hence could not be carried out in a systematic manner across the site or be directed to specific areas where there may be indications of features of geological significance. The purpose of the excavation mapping was to obtain information on the following:

1) the material types forming the excavation
2) the general structure of in situ materials
3) the occurrence of specific structural features, such as faults
4) the occurrence of groundwater seepages and springs
5) geological aspects that may adversely affect the suitability of the material as a dam foundation.

The excavation was divided into the main areas shown in Fig. 6.

Fault Manifestations

An important aspect of the routine mapping carried out at Karameh is the field identification of faulting. This was important because of the implications for the design of the dam where faulting occurred. In addition, a more comprehensive understanding of the tectonics assisted in evaluating the severity of earthquakes associated with fault movements and the magnitude of such movements.

An understanding of the regional tectonics was obtained from the work carried out by Tapponnier (1992) and it is known that the Ghor is a "pop up" structure bounded at depth by strikeslip faults. These deep seated faults have been covered by the lake Lisan deposits. Field work was conducted towards understanding how the Lisan sediments respond and deform due to the fault movements at depth.

Direct identification of faulting at the Karameh site was difficult because only rarely are significantly different materials faulted against each other. In only a few cases has it been possible to acurately determine the vertical fault movement that has occurred. To date it has not been possible to identify strike slip movements.

Three Zones where significant faulting has occurred have now been identified. These are shown on Fig. 6:

Bedrock Rupture Hazard

With the designed location of the Karameh Dam on the Jordan Valley Fault, the site is exposed to a displacement hazard arising from an earthquake-generated fault rupture. Depending on the nature of the soils overlying bedrock, a rupture displacement may extend to the surface.

A seismotectonic approach has also been used to identify the magnitude of fault movement along the main Jordan Valley Fault. The trend of this fault is approximately north-south crossing the dam axis close to the right abutment. The most probable location of the fault line is at the Ghor El-Katar to Lisan contact. Based on empirical length-magnitude-displacement relations by Wells and Coppersmith (1994), the calculated horizontal displacement for a M 7.8 earthquake on a 130 km long fault should be 10 m.

However, in the area around the Jordan Valley Fault, the design fault displacement has been estimated by Sir Alexander Gibb and Partners (1992a) to be 6 m and 3 m for horizontal and vertical movements respectively. These values were adopted by them for the design of the dam.

Fault Displacement

According to Sir Alexander Gibb and Partners (1992a), for no failure of the project works, the following criteria were adopted:

Lisan units: maximum movement in any direction = 4.0 m
Ghor el Katar: maximum movement in any direction = 0.3 m

CONCLUSIONS

As a result of field observations of the geology, construction activities and discussions, the following conclusions are reached:

1. At the Karameh dam site, the conditions of the foundation materials (including liquefiable sands) and construction materials, the presence of the major Jordan Valley fault crossing the site, and the hydrogeological conditions of salty artesian aquifers and soluble soils make this project carry high a level of risk.
2. The constructed Karameh dam is situated in the Dead Sea Rift. The primary seismic source contributing to the hazard at the Karameh dam site is the active Jordan Valley fault which extends from the Dead Sea to the Sea of Galilee a distance of 130 km. This fault has an expected maximum earthquake magnitude of 7.8, and passes under the right abutment of the dam.

3. Engineering Geology:

The main conclusions related to Engineering Geology are:

a. The most likely location of the Jordan Valley Fault is in the area where the Wadi Malahha crosses the dam axis and probably it is the significant fault mapped at Ch. 1375.
b. The geologic mapping has defined extensional zones of "en echelon" type open fissures in the laminates sub-parallel to the Jordan Valley Fault Zone. These fractures were treated at the upstream end of the external blanket by a combination of a shallow cut-off trench and slash grouting.
c. With the combination of driving water heads 0 to maximum 10 m, seepage path (1000 m), and most likely gravel permeability (< 1.0 E-5 m/sec, the reservoir leakage

will not be a problem if the gravels did not accept cement grout. The Wadi's cutting up to the grout bench from the reservoir were filled with uncompacted waste excavation materials to cover any gravels cut by these wadi's.

d. The width (3 m) and the composition of the "Crackstopper" has been added to the dam and implemented. The increase in thickness of the downstream filter and drain at the Jordan Fault Zone has also been implemented as has been the extension downward of the filter on the downstream cut surface of the right abutment core trench.
e. Embankment Filters were widened in response to mapped fault system throughout Chainages Ch1300 to 1425 plus 25 m transitions.
f. Local cut-off trenches and or slush grouting were used for treatment of any open Fissures at upstream edge of external blanket. Any open faults, fissures or permeable Wadi infill deposits were cut off along the entire length of the upstream boundary of the external blanket.
g. At the Wadi Mallaha stream bed a parallel zone of faulting and warping of the Lisan was identified, and the alignment is clearly confirmed by the exposure immediately upstream of the core at Ch 1375. The main wrench fault zone crosses the embankment footprint and reaches the surface around Ch 1375. About 125 m length of filter/drain widening was introduced.
h. The wide Ch 1000 faults exposed on the downstream foundation excavation face have been traced onto the core foundation but were thin and discontinuous. Other examples of 3 cm wide open cracks had been seen beyond the Wadi Mallaha towards the upstream limit of the internal blanket.
i. Actual exposures took the form of down-warped laminations at the edge of the finger drain excavation. The compression zone at Ch 1375 forms a significant feature with upturned strata indicated by the laminations whilst at Ch 1000 lies an extension zone. These two in combination with secondary alignments running diagonally upstream on the right side of the Wadi Mallaha provide the mechanism whereby the fault alignment clearly visible on the aerial photos north and south of the embankment site works around the Ghor.
j. The tunnel excavation yielded only 2 l/sec seepage over a 440 m length, confirming the low mass permeability of the Ghor mudstone. Therefore it was recommended to eliminate the optional centerline of dam grout curtain.

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