The Libyan Great Man-Made River Project Phase I
Paper 6. Storage reservoirs: design and construction

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This Paper describes the design and construction of the storage reservoirs built as part of Phase I of the Great Man-Made River Project in Libya. Three reservoirs have been built to provide capacity for operational and storage purposes. The Paper concentrates on the geomembrane linings and describes the embankments and hydraulic structures. Commissioning and performance are also covered.

Introduction
Between 1986 and 1991, three reservoirs were built to provide capacity for operational and storage purposes. Locations are shown in Fig. 1. Ajdabiya Reservoir, at the bifurcation of the pipelines towards Benghazi and Sirt, provides buffer storage, a break of pressure and enables mixing of water from the different wellfields. The main function of the Benghazi and Sirt End Reservoirs is to provide storage to balance the varying seasonal demands for irrigation.

Design criteria
2. All three reservoirs are off-line so that supply can be maintained when a reservoir is taken out of service. The locations were chosen to suit the hydraulics of the conveyance pipeline, thus maximum operating levels were chosen such that the pipelines deliver the first stage flow under gravity. This also placed a constraint on the bottom operating level at Ajdabiya. At the end reservoirs, the entire outflow supply is to be pumped, so no constraint was placed on bottom operating levels. These were chosen to allow gravity drainage from the reservoir floors.
3. The design criterion for seepage was set to limit any losses to an amount similar to the avoidable loss caused by evaporation. A study had demonstrated that the value of loss due to evaporation did not justify the cost of covering the reservoirs.
4. Normal standards for embankment stability were adopted, with the additional requirement that where internal linings were provided, the embankment would be stable even if the lining became ineffective.
5. The reservoirs were designed for a maximum credible earthquake and an operating basis earthquake, with a return period of one thousand years.
6. A safety control programme for reservoirs required that designs and construction should be carried out under a qualified Engineer of Record who, under UK legislation, has responsibilities similar to the Construction Engineer.

Main dimensions
7. All three reservoirs comprise circular earth embankments with geomembrane lining. The capacities and dimensions are given in Table 1.

Geological influences on design
Ajdabiya Reservoir
8. A plan and typical cross-section of the 10 m high embankment dam are shown in Fig. 2.
9. The geology over the area of the site was fairly uniform. Below the surface layer of silty windblown sand, which was generally less than 1 m thick and which was completely stripped, the next stratum, comprising caliche and caprock, was of 3.3 m average thickness and extremely variable. Medium dense layers of soil alternated with irregular bands of hard caprock. Selective excavation was therefore carried out to achieve uniformity and to minimize differential settlements. The next underlying stratum consisted of dense clayey silty sand with cementation. Its permeability was uniformly of the order of $4 \times 10^{-6}$ m/s, and therefore an unlined reservoir would have had an unacceptably high water loss.
10. In relation to potential losses through the floor of the reservoir, seepage losses through the perimeter embankment would be minor, but the additional criterion for an embankment is that it must be safe against piping. No suitable core material was available and it was decided to carry the floor membrane up the inner slope of the embankment.

Benghazi End Reservoir
11. A plan and cross-section of the embankment are shown in Fig. 3. The superficial layer of hard clay of low plasticity was removed from the foundation. Within the reservoir the upper layers of the limestone were indurated and had
to be blasted. The lower limestone was friable calcarenite, and the contractor selected this material for forming the embankment. Although the specification allowed for a zoned embankment with larger material in the outer shell, it proved difficult to produce a well-graded material with larger block sizes, and the embankment was, in effect, homogeneous. The high plasticity Al Faidiyah clay is remarkably unfissured although over-consolidated, and it was found over a large area in the regional site investigation. This clay was drilled to 35 m and the base was not found. It was determined that this layer was sufficiently impermeable to remove the need for an artificial bottom lining. The slope lining was tied into the clay in a cut-off trench. The clay surface proved to have a uniform level around the 3 km perimeter.

12. A shallow perched water-table sits on top of the clay which had a moisture content just below its plastic limit. This clay has swelling properties, and it was predicted that heave would result from a reduction of stress although over a very long timescale.

Table 1. Capacities and dimensions of three reservoirs

<table>
<thead>
<tr>
<th>Reservoir characteristics</th>
<th>Unit</th>
<th>Ajdabiya</th>
<th>Benghazi</th>
<th>Sirt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>MCM</td>
<td>4.0</td>
<td>4.7</td>
<td>6.8</td>
</tr>
<tr>
<td>Diameter (crest centre)</td>
<td>m</td>
<td>930.2</td>
<td>962.0</td>
<td>887.66</td>
</tr>
<tr>
<td>Maximum operating level</td>
<td>mAMSL</td>
<td>98.4</td>
<td>63.5</td>
<td>49.5</td>
</tr>
<tr>
<td>Minimum operating level</td>
<td>mAMSL</td>
<td>91.9</td>
<td>56.5</td>
<td>37.0</td>
</tr>
<tr>
<td>Operating range</td>
<td>m</td>
<td>6.5</td>
<td>7.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Ground elevation (average)</td>
<td>mAMSL</td>
<td>94.5</td>
<td>60.0</td>
<td>45.0</td>
</tr>
<tr>
<td>Volume of excavation</td>
<td>MCM</td>
<td>2.9</td>
<td>2.8</td>
<td>5.6</td>
</tr>
<tr>
<td>Volume of fill</td>
<td>MCM</td>
<td>2.2</td>
<td>0.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Sirt End Reservoir

13. A plan and cross-section of the embankment at Sirt End Reservoir are shown in Fig. 4. After aeolian materials had been removed to expose dense fluvio-aeolian silty clay which was not susceptible to collapse settlement, the embankment was founded just above the caliche layer. The caliche varied from nodular cemented soil to strong crystalline limestone caprock up to 1 m thick. Clay of low plasticity
was used to form the bulk of the embankment. The groundwater table is 45 m deep—just above sea level.

Lining

**General**

14. At Ajdabiya, the pervious nature of the foundation material has resulted in a high hydraulic gradient across the lining of the reservoir floor. Four main types of lining were considered:

1. natural soils of low permeability
2. artificial geomembrane
3. concrete slabs
4. asphaltic concrete slab.

15. It was concluded that concrete slabs did not meet the central requirement that the lining must be unquestionably effective and durable under the construction, operating and climatic conditions pertaining at Ajdabiya. With regard to the natural soil lining, it would have been impossibly difficult with the type of material readily available to place the large volume required in accordance with the necessarily stringent specification so as to achieve a uniform, crack-free impermeable lining.

16. It became a choice between asphaltic concrete and artificial membrane, and the latter was felt to have practical advantages in construction. The size and simplicity of the circular Ajdabiya Reservoir permitted the adoption of volume production for laying, jointing, testing and burial techniques, thus ensuring a lining of consistently high quality. Production of a satisfactory specification for the geomembrane and its installation had its difficulties, but a very useful starting point was *Guideline 108* produced in July 1983 by the International Commission on Irrigation and Drainage (ICID) as a draft for discussion.

17. The choice of geomembrane for Ajdabiya Reservoir narrowed down to two technically satisfactory offers, namely a 2.5 mm or 2 mm thick high density polyethylene (HDPE) membrane, and a 1.5 mm thick modified ethylene copolymerized bitumen (ECB) membrane.

18. The final selection of a modified ECB
membrane (Carbofol), supplied by Niederberg-Chemie. was made on commercial grounds.

19. For the end reservoirs, the choice of geomembrane which had to comply with the same specification as used at Ajdabiya, was left with the contractors. Both contractors selected Carbofol. Its track record at Ajdabiya was undoubtedly influential, and commercial considerations were also taken into account.

Lining details

20. A typical detail of the floor lining at Ajdabiya Reservoir is shown in Fig. 5. From top to bottom, the lining system comprises

(a) 0.3 m of medium gravel produced by crushing caprock; this protects the invert from disturbance at times of shallow water and acts as a strong layer to spread the loading from plant
(b) 0.5 m of stone-free silty sand, the function of which is to prevent physical damage to the membrane; it was placed as a single layer pushed forward as the membrane was laid and jointed
(c) the geomembrane
(d) 0.6 m of clayey silty sand, the top 0.2 of which is stone-free; this 0.6 m thick compacted layer functions as a reserve or back-up lining to reduce seepage losses at any break in the geomembrane
(e) the compacted formation after stripping and the selected removal of caprock.

21. The construction of the reservoir floor was carried out in four successive quadrants. At the only two locations where the floor lining is penetrated by concrete structures, i.e. at the inlet and outlet culvert units, careful attention to detail and choice of materials ensures long-term watertightness of the joint between the geomembrane and the concrete.

22. The lining of the upstream slope of the embankment was somewhat different from the floor and comprised the following layers

(a) precast concrete blocks as wave protection (described below)
(b) 0.25 m of gravel (crushed caprock)
(c) 0.25 m of selected clean sand filter
(d) the geomembrane
(e) 0.4 m of selected clean sand filter
(f) embankment shell of random fill comprising silty sand with gravel or rock fragments up to 500 mm.

23. The top of the geomembrane was anchored at the dam crest by being buried in a shallow trench filled with stone-free silty sand. However, the specified coefficient of friction for the geomembrane should ensure that it is not subjected to down-the-slope tension.

24. At the end reservoirs, the lining details were similar to Ajdabiya. Penetration of the lining was avoided by constructing the inlet chute on top of the lining. Attachments had to be made to the top of the inlet chute, and to the spillway chute, requiring careful detailing.

Underdrains

25. It was considered necessary to provide adequate drainage under the sloping geomembrane on the embankments, so that if a significant leak did occur, uplift pressure could not cause widespread failure during drawdown.

26. At Ajdabiya, natural non-carbonate materials were preferred to man-made felts or geotextiles in order to guarantee long-term drainage capacity and to contribute to a thick layer of granular fill on the embankment surface, thereby eliminating stability problems with shallow slip circles. The available silica sand was therefore used.

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Fig. 5. Ajdabiya; floor lining detail

<table>
<thead>
<tr>
<th>Reservoir floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium gravel from crushed caprock</td>
</tr>
<tr>
<td>Stone-free silty clay</td>
</tr>
<tr>
<td>Geomembrane liner</td>
</tr>
<tr>
<td>Stone-free clayey silty sand</td>
</tr>
<tr>
<td>Clayey silty sand</td>
</tr>
<tr>
<td>Caliche with remnants of caprock removed</td>
</tr>
</tbody>
</table>
27. At Ajdabiya, a soakaway drain, with overflow pipes to cover malfunctioning of the soakaway, has been provided to remove seepage flows from the underdrainage without compromising the function of the embankment as a back-up watertight system. The soakaway, details of which are shown in Fig. 2, takes the form of a distributor drain, with its invert below caprock level, running around the perimeter of the reservoir floor, with overflow pipes leading to the downstream toe of the dam at 100 m intervals. These pipes provide a very useful secondary function as leakage monitors.

28. At the end reservoirs, the foundation permeability is lower so that downward drainage could not remove water fast enough; the topography did not allow radial drains around the periphery. The solution was to provide a perforated pipe around the inner toe, with a single outlet to the spillway channel. A uPVC plastic pipe is laid in a gravel surround at both reservoirs.

Slope protection

29. At Ajdabiya, the preferred option of using rip-rap for slope protection on the inner face of the embankment was abandoned owing to the lack of suitable rock in the area. The only potential source of durable rock was the local caprock which would furnish only slabby pieces of inadequate size. Several alternatives were considered, but interlocking precast concrete armouring blocks were selected on the grounds of durability, compatibility with the lining design and availability of materials.

30. The precast armouring blocks were laid on the slope in panels approximately 11.5 m wide by 8.5 high, separated by circumferential and radial in-situ concrete beams and with a larger toe beam and a blockwork perimeter road at the foot of the slope to resist the tendency for downhill creep (see Fig. 6). The size of concrete blocks was chosen to be small enough to allow hand placing. Each block was 500 mm x 200 mm x 175 mm thick and weighed 43 kg, and was keyed into the four adjacent blocks by a tongue and groove joint. A relief slot on the side of each block allows water to flow through the layer of blocks while the underlying fine gravel filter material is retained.

31. For the end reservoirs, sources of caprock thick enough to provide rip-rap with a median size of 350 mm were identified during the geotechnical investigations (see Fig. 7). The rip-rap had to be placed with great care to avoid damage to the membrane, and because the maximum size was equal to the thickness of the layer, it was important to have a good grading with interlock.

Hydraulic structures
Ajdabiya Reservoir

32. The main inlet/outlet structure and spillway lie outside the reservoir perimeter in order to minimize interference with the

Fig. 6. Ajdabiya: inner slope protection
embankment and lining. The main features of these concrete structures are shown in Fig. 8. In Fig. 9, the inlet/outlet works are shown in operation, with the reservoir behind.

33. The flows arriving at and leaving Ajdabiya cannot be controlled locally but are controlled at the upstream and downstream ends of the conveyance pipeline, hundreds of kilometres away. This posed interesting problems for the hydraulic design of the inlet/outlet structure where the levels of the weirs on the inlet shafts, the weir between the inlet and outlet chambers, and the crest of the spillway had to be mutually compatible over a wide range of conditions of flow and water levels in the reservoir. The hydraulic design had also to cover the case when the reservoir was being bypassed, i.e. when either, or both, of the culvert sluice gates was closed.

Fig. 7. Sirt End Reservoir: rip-rap

Fig. 8. Ajdabiya: inlet/outlet works
34. The main inlet/outlet structure is a 20 m high reinforced-concrete box surrounded on three sides by an earth embankment for access to the top of the structure. One wall of the structure consists of a concrete gravity weir spillway capable of safely discharging the maximum possible inflow from the twin 4 m diameter conveyance pipelines.

35. The gated inlet and outlet culverts to and from the reservoir are reinforced concrete boxes passing under the embankment and extended under the reservoir floor. The outsides of the culvert walls are tapered to ensure long-term intimate contact with the surrounding backfill.

End reservoirs

36. At Sirt and Benghazi, the primary inlet structures comprise submerged discharge valves in well structures flowing to baffled inlet chutes. At both reservoirs, overflow spillways with baffled chutes have sufficient capacity to carry the maximum possible inflow. The outlet works consist of rectangular openings in the reservoir floor leading to reinforced concrete culverts under the embankment. In the outlet valve chambers, the bypass pipelines tee on to the outlet pipes from which the future pump stations will distribute the water.

Drawdown

37. Provision is made in each case for emptying the reservoir through a drawdown valve upstream of the main outlet control. As there are no wadis nearby, emptying of the reservoirs will result in flooding of the land. At Ajdabiya, the land is unoccupied. At Sirt, however, the land is to be farmed and, if it were necessary to empty the whole reservoir, water would flood into the outskirts of Sirt town. In order to prevent this, a small bund has been built to increase the storage capacity of a natural depression. At Benghazi, all the water in the reservoir can be spilled into a natural depression.

Construction

Ajdabiya Reservoir

38. Construction of the perimeter embankment was carried out using conventional hauling, spreading and compaction plant.

39. As much as possible of the excavated material was used as fill, but for a combination of topographical and hydraulic reasons, it was impossible to balance cut-and-fill. Surplus material was removed to spoil tips nearby.

40. Construction was generally carried out quadrant by quadrant, and floor excavation provided material for the adjacent embankment.

41. After completion of the general excavation, the inlet/outlet culvert trench was dug across the reservoir floor, and the reinforced concrete box culvert was cast in alternate bays each 7.5 m long (See Fig. 10); only after the culvert had been completed and backfilled could the final floor fill and lining be placed, working in quadrants.

42. The stone-free clayey silty sand layer under the geomembrane was spread and compacted just ahead of membrane laying. As soon as the geomembrane joints had been welded and tested, the membrane was covered by the upper stone-free layer pushed forward from the previously completed area. At no time were vehicles allowed on to the unprotected geomembrane.

43. On the inside face of the embankment, the sloping sand layers above and below the geomembrane were compacted by means of vibrating rollers working up and down the slope and restrained by wire ropes attached to a bulldozer on the crest. No horizontal joints were permitted on the sloping geomembrane.

44. The 1.5 mm thick geomembrane was delivered to site in rolls approximately 6 m
wide and 60 m long. In the middle of the day, the high ambient temperatures caused the laid-out sheets to wrinkle, and it was found that jointing, testing and covering were best carried out in the early evening when the wrinkles had disappeared. Sheets had also to be weighted in windy weather. Apart from this, the whole operation of laying, jointing and covering the geomembrane went smoothly and was completed in 12 months as planned (Fig. 11).

45. The 870 000 concrete revetment blocks were cast locally and laid by hand at a rate of 3000 per day.

End reservoirs

46. At Sirt, the discovery of man-made caverns in the reservoir floor and embankment foundations gave rise to some concern. Eventually, 13 caverns were found. In one case, two caverns were connected by a 50 m long tunnel. This type of cavern, normally hollowed out directly under the caprock layer, is common in
Libya. They are used for living in cooler conditions, for storage, as cisterns (see Figs 12 and 13) and as burial chambers. Although some of these caverns are ancient, they have been constructed and used up to relatively modern times. The archeologists gave permission for them to be destroyed in the reservoir. The problem was to ensure that no such caverns existed under the reservoir embankment. Various geophysical methods were considered for identifying them, but these did not give complete confidence. Instead, reliance was put on the detailed inspection of the foundation for entrances. As caverns with dead ends up to 12 m from an entrance had been found, the possibility that a cavern extended under the embankment from an entrance outside the outer toe had to be considered. Various possible configurations were analysed and it was concluded that caverns were unlikely to collapse under embankment loading, and, if they did so, this would not result in the lowering of the crest to below the maximum operating level. The last cavern was found as the temporary access ramp to the inside of the reservoir was being removed; this was within the cut slope of the inner slope where the embankment was only 5 m high. It was backfilled with concrete.

47. As water for construction purposes is an expensive item in Libya, the feasibility of using sea water to moisture condition soil before compaction was investigated. A literature study failed to produce any evidence that this had been done before. A concern was that some of the soils both at Sirt and Benghazi had shown high sodium content in the dissolved solids during the site investigations. If this were the case, the embankment fill could be liable to dispersion, and an increase in sodium ions from sea water could worsen this tendency. A series of pinhole tests was carried out using sea-water conditioned soils, and these all proved non-dispersive.

48. At Sirt End Reservoir, all the fill was compacted using sea water. At Benghazi End Reservoir, continuous seepage of water from the perched groundwater table into the cut-off excavation provided most of the compaction water, supplemented when necessary by a local brackish well.

49. At the end reservoirs, construction of the lining followed the procedures at Ajdabiya. At Benghazi End Reservoir, the seepage at the top of the Al Faidiyah clay meant that the backfilling of the cut-off trench had to be completed rapidly to avoid uplift of the membrane (see Fig. 14). When the last section of lining was installed to complete the circle, a special drain pipe was installed, which was grouted after backfilling.

**Water quality**

50. Under full development, the retention period in the reservoirs is relatively short if the whole flow is passed through them (only just over one day at Ajdabiya). The reservoirs were designed as circular in plan, and inlets and outlets were placed on opposite sides to eliminate stagnant areas.

51. However, as more data on well water quality were obtained, it became clear that there would be sufficient nutrients in the water to sustain algal growth. To minimize the treatment requirements for municipal and industrial users, their water is to be taken directly from the conveyance pipeline or reservoir bypasses. At Ajdabiya, covering of the entire reservoir with a floating plastic sheet has been con-
sidered. The inlet/outlet works will be enclosed. At the end reservoirs, the through flow will be less than originally expected, thus increasing the retention times. A computer study showed that stagnant areas could result where algae could proliferate. The designs have therefore been modified to incorporate jetting pipes in order to cause continuous circulation of the water throughout the reservoirs. Two pipes run from the inlet wells down either side of the inlet spillway and are controlled by submerged valves. The outlets were sited at an optimum position for circulation as determined by the computer model.

Commissioning and performance

Ajdabiya: concrete block wave protection

52. Before the reservoir was filled, i.e. when daily cyclic temperature changes were greatest, problems were experienced with downhill movement of some panels of precast blocks, particularly in the area where the angle of the panels facing the sun produced the largest temperature fluctuations. Forces induced by temperature changes were sufficient to overcome the normal frictional resistance to sliding between the blocks and the underlying gravel layer, and some of the in-situ, radial beams between the panels showed signs of distress as a result of being 'hung-up'. The rate of movement reduced during the second year of exposure as the whole revetment began to lock together in an arching action.

53. The problem of hang-up was resolved by cutting the radial beams free at their junction with the in-situ concrete parapet, and making a new detail at the top of the slope.

Since the filling of the reservoir, no further problems have been detected and the wave protection is performing satisfactorily.

Leakage monitoring

54. The importance of the integrity of the geomembrane lining on the reservoir floor at Ajdabiya led to the decision to try out a novel method of leakage detection there, after the use of a grid of conventional piezometer tips had been ruled out in such a situation.

55. The detection system consisted of a number of flat sensor cables placed 100 m apart in a set pattern immediately below the geomembrane. Each sensor cable consisted of two nickel-plated copper conductors set in porous PTFE insulation and protected by a braided fibre sleeve. These cables were connected to detector units on the embankment, and portable locator units were then to be used to locate a leak on any of the sensor lines.

56. Unfortunately, this type of apparatus appears to be too sensitive for this application and it was found that moisture was being detected before filling, the most likely cause being the presence of condensation on the underside of the geomembrane. On the basis of other observations, however, as stated below, the membranes appear to be entirely effective.

Lining performance

57. All reservoirs were tested during a hold-full period, during which the water level was monitored and evaporation readings were taken in a standard evaporation pan. The water loss is plotted against mean monthly evaporation for all reservoirs in Fig. 15. As the ratio of