Assiut Barrage, to rehabilitate or to rebuild

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SYNOPSIS. Assiut barrage, 400 km upstream of Cairo, is the last barrage downstream of the High Aswan Dam (HAD) before the Nile reaches Cairo. It was built between 1898 and 1902 in order to divert Nile river flows to the Ibrahimia canal. The barrage was remodelled extensively between 1934 and 1938, increasing the annual discharge to the Ibrahimia canal which, in its present form, has a length of about 350 km and irrigates an area of 690,000 ha.

The barrage was designed as an arched viaduct founded on a mass concrete floor, with a 16 m wide lock positioned on the extreme left bank. The overall length of the structure is 820 m with a water-way capable of discharging 14,000 m^3/s provided by 110 individual openings of 5 m width. Each opening contains a double leaf vertical lift roller gate designed for a maximum head difference of 4.2 m.

This paper describes the results and conclusions of a feasibility study carried out by Mott MacDonald in association with CES Salzgitter, Fichtner and Inros Lackner, all of Germany, and Hamza Associates of Egypt, to investigate the present structural and operational conditions at the barrage and to outline options for the future. The principal conclusion of this feasibility phase, completed in December 2005, was a recommendation to construct a new barrage downstream of the existing one rather than rehabilitating the existing barrage.

A HISTORY OF THE BARRAGE

Original Construction, 1898-1902

The Ibrahimia canal was excavated in 1873 to serve the cultivated area on the left bank of the Nile as far as Giza to the north, and Fayum to the West. When the river was high, during the annual Nile flood in August and September, the canal easily supplied enough water to satisfy the requirements of its command area. However, during the earlier summer months it was often difficult to pass all of the water which could be allocated to the canal, due to low river levels at Assiut.

Towards the end of the 19th century proposals were put forward for a large storage reservoir at Aswan. The additional water supplies that would be made available to the Ibrahimia canal during the summer months as a result of the reservoir's construction made the need for a barrage at Assiut more of a necessity.

The original plans for the dam at Aswan and the barrage at Assiut were the responsibility of the Director-General of Reservoirs, Mr William Willcocks (later Sir William Willcocks). The Egyptian Government then appointed Sir Benjamin Baker (a past president of the Institution of Civil Engineers in London) as their Consulting Engineer on the project and he made considerable modifications to the original Willcocks' designs. In February 1898 Messrs John Aird & Co. were appointed by the Ministry of Public Works as the Contractor for both the dam at Aswan and the barrage works (which included a head regulator on the Ibrahimia canal) at Assiut.

The location of the barrage appears to have been determined on the basis of three primary requirements:

- The need to be downstream of the Ibrahimia canal offtake
- The provision of suitable foundation conditions
- A position which simplified construction operations

The second criteria proved to be non-critical since no changes were identified in possible barrage foundation conditions throughout the river reach under investigation. However, both the first and third requirements were met at a position some 400 m downstream of the Ibrahimia offtake. Here a seasonally revealed sand island covered the western (left) third of the river channel (Leliavsky, 1934) affording improved river diversion and cofferdam construction possibilities. It may be noted that the sedimentation now prevalent along the left side of the river immediately upstream of the existing barrage may be a result of the river's natural inclinations towards silt and sand deposition at this location.

At Assiut construction began in June 1898, and was completed in March 1902, one year in advance of the contract period. The total cost of the works at Assiut, including the head regulator, was 921,772 Pounds Sterling (Stephens, 1904) (one-quarter of the expenditure on the earlier Delta Barrage).

The barrage was designed as an arched viaduct founded on a concrete floor, with a 16 m wide lock positioned on the extreme left bank. The barrage floor was 26.5 m in width and 3 m thick, the lower 0.9 m of which was cement concrete, the rest being rubble masonry set in 4:1 cement mortar. Cast iron sheet piles, extending 4 m below the underside of the barrage floor, were installed along the upstream and downstream edges of the foundation slab. The riverbed was protected for 20 m beyond both lines of sheet piles, giving an overall structure width of 66.5 m. The overall length of the structure was 820.2 m between abutment faces with a water-way provided by 111 openings of 5 m each. Each water-way, or vent, had a maximum height of 10.7 m to the springing of the arches. The vents were divided into groups of nine by 12 abutment piers each 4 m thick. The intermediate piers were 2 m thick. The upstream faces of all the piers were vertical, with the downstream faces inclined at approximately 6.6V:1H. The barrage roadway was 4.5 m wide, between parapets.

The Ibrahimia head regulator structure was of similar design to the barrage except having only nine 5 m wide sluices, and a 9 m wide lock.

Interim Remedial Measures

The barrage's primary purpose was to ensure adequate irrigation supplies to Middle Egypt during the early summer, as such it was not intended to be used during the annual Nile flood. The original 1902 design assumed that all gates would be fully raised to allow the flood to pass unheeded.

It is reported that in 1902, the first year after completion of the barrage, the annual Nile flood was very low and exceptionally late. All through August the river levels remained stubbornly low, leading to the potentially catastrophic loss of a significant portion of Egypt's crops going unirrigated. On August 15th Sir A. L. Webb, Director General of Reservoirs (he had succeeded Mr W J Wilson in the post upon the latter's death in August 1900, who in turn had succeeded Mr Willcocks in 1898), travelled to Assiut, and on arrival decided to utilise the barrage gates to raise the Nile level upstream of the barrage by some 1.50 m. This was a risky decision but it was crowned with success. The resulting irrigation of the crops was estimated at the time to have saved Egypt 600,000 Pounds Sterling. Leliavsky (1934a) records that this is an instance unique in the field of irrigation engineering, where a structure repays two-thirds of its capital costs within a few months of completion.

While a 1.50 m head drop across the structure was significantly less than the design head, the potential for downstream erosion as a result of the decision to partially close the gates was significant. This is because the required energy dissipation (proportional to head and discharge) at the barrage was much greater than envisaged in the design. To his credit Sir A. L. Webb was well aware of the risks he was taking. He arranged for soundings to be taken on a weekly basis to gauge the extent of downstream erosion and about 4,000 m^3 of rubble was eventually dumped to replace areas of damaged pitching.

The need for partial gate closure during the rising or falling flood period became a regular occurrence. Design curves for allowable head against river discharge were developed and modified throughout the 1920's, however scour remained a serious problem. In 1912 rubble was used to fill "an exceptionally deep scour hole" on the eastern side of the barrage and between 1920 and 1925 an average of 2,600 m^3 of stone was placed annually downstream of the barrage to control the erosion. During the 1926 flood 6,650 m^3 of rubble was placed.

In 1927 it was decided that a more permanent solution was required and so concrete blocks (1.5m x 1.0m x 0.7m) were prepared and placed downstream of the barrage by divers. 1,772 blocks were placed in 1927, 849 in 1928, 1,523 in 1929, and 2,041 in 1930 making a total of 5,685.

Remodelling, 1934-1938

The need for a more permanent solution to the problem of downstream erosion was evident and work began on finding an answer in the early 1930's.

Consulting Engineers Coode, Wilson, Mitchell and Vaughan-Lee were appointed to design remedial works to the barrage to enable the structure to be operated in the manner that was needed. The opportunity was also taken to further increase the level of the river upstream of the barrage to facilitate required increases in Ibrahimia canal flows.

On the 9th October 1934 Messrs John Cochrane & Sons Ltd were appointed by the Egyptian Government to carry out the remodelling works (Bostok 1940). These were completed on the 14th July 1938, 3 months ahead of the contract date, at a cost of 1,115,979 Egyptian Pounds[1]

The principal aspects of the remodelling works were stated to be as follows:

- New sluice gates and operating machines installed
- New lift bridges provided over the lock

[1] One Egyptian Pound was equivalent to approximately £1 0s 6d

- Extensions to both sides of the existing barrage floor (14.5m u/s, 19m d/s)
- Cement grout injected under the barrage floor extensions
- Flexible concrete block aprons added to both sides of the new barrage floor
- Three rows of sheet piling added parallel to the barrage: 3.5m deep steel sheet piles along the u/s edge of new floor. 6.5m deep interlocking r/c piles under the new upstream floor. 2.5m deep steel sheet piles along the d/s edge of the new floor
- New raised granite weirs, concrete sills and floors added on top of the existing floor
- Barrage piers and arches lengthened on the d/s side
- Roadway widened to 8m and resurfaced
- East wall of lock widened and strengthened (resulting in filling in of vent No. 1)
- Barrage lock gates overhauled and the bottom bearings renewed

Figure 1 shows a general view of the barrage as it stands today.

Figure 1: Assiut Barrage, View from Upstream

Figure 2 shows the design cross section for the remodelled barrage. Except for grouting works in the mid 1980's and replacement of the lock gates in the 1970’s, no further major works have been carried out at the barrage since 1938.

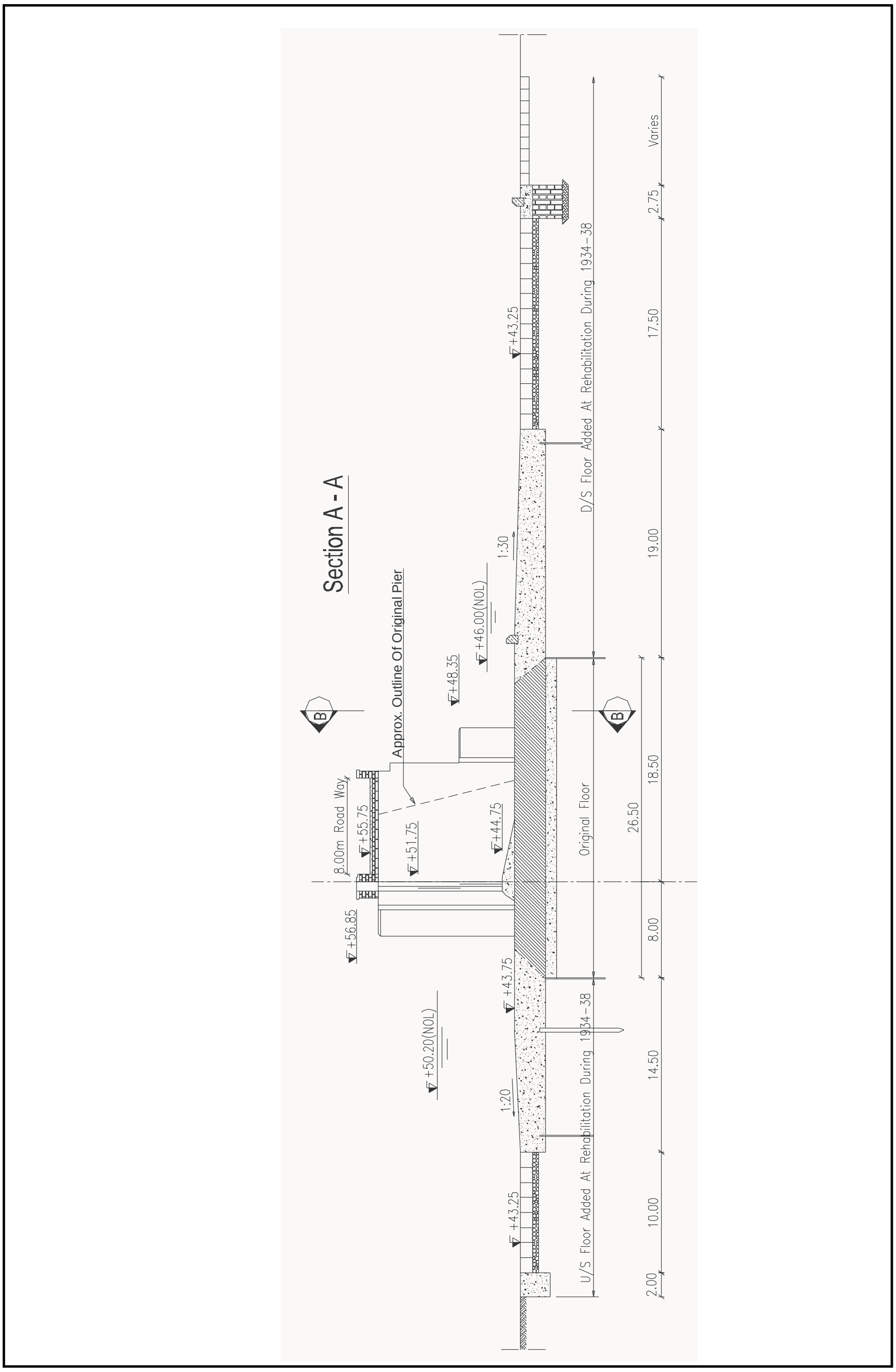

Figure 2: Assiut Barrage Design Cross Section, 1938

CONDITION SURVEYS

The Barrage Superstructure

The feasibility study commenced with a detailed condition survey of the barrage. In all, four different survey methods were adopted:

1. Walk-over visual inspections of the barrage and head regulator superstructures;
2. De-watering of four barrage vents behind newly procured stoplogs and detailed inspection in the dry;
3. Underwater diver surveys conducted within the barrage vents and both upstream and downstream of the barrage;
4. On-site investigations and laboratory analyses of samples. These included drilling works, lugeon testing and measuring, sampling and testing of steelwork.

The key conclusions of these extensive studies were that:

- Apart from some abrasion damage from shipping and trash clearing barges both the barrage and head regulator civil structures are in a generally good condition. There are no signs of structural distress, excessive cracking or settlement.
- Some high Lugeon values were observed, especially in the head regulator structure. This indicated that an extensive grouting exercise is required to ensure future structural integrity.
- Apart from some of the lock equipment, which has been relatively recently replaced, all hydro-mechanical equipment at the site is considered to have reached the end of its useful service life. Rehabilitation of the existing equipment is not economically feasible and full replacement is recommended.

Scour Erosion

Annual bathymetric surveys at the site revealed that an unusually deep (8m in 2004 reduced to 6m in 2005) scour hole had developed in the centre of the river between 50m and 100m downstream of the barrage structure. In addition, overall scour appeared to be developing at a faster rate than was recorded between 1991 and 1997. This is most likely a result of increased river flow in the period from 1997.

There is no direct evidence that the barrage is in imminent danger from excessive downstream scour erosion, however, the client was advised to consider the need for a stone infilling exercise on the downstream side of the barrage in the near future. Such an operation should secure scour protection at the barrage until the planned rehabilitation or new barrage works commence.

Conclusions from the Condition Survey

The overall condition of the barrage and head regulator structures is considered to be sufficient for a rehabilitated barrage solution to be a technically viable alternative.

FUTURE BARRAGE OPERATING STRATEGY

The client defined a complex future operating strategy for the new or rehabilitated barrage. The key changes from the existing strategy being an increase in the maximum allowable head across the barrage, from 4.2 m to 7 m, and a rise in the maximum upstream water level from around 50.5 m asl to 51.6 m asl.

These changes allowed the client significantly more operational flexibility at the barrage for irrigation purposes while also providing enhanced head for a proposed low-head hydropower plant at the site. On the negative side, increased upstream water levels will result in a commensurate rise in the surrounding groundwater table and the increased head will result in more severe structural and energy dissipation conditions at the barrage.

Although the hydropower plant, groundwater modelling and assessment of the resulting environmental and sociological mitigation needs did form a key element of the feasibility study, they are not reported in this short paper.

THE REHABILITATED BARRAGE SCHEME

The design work for the rehabilitated barrage scheme was undertaken with the aim to provide a robust design, suitable for the future barrage operating strategy envisaged by the client and with a design life commensurate with that of a new barrage.

This latter requirement became the driving force behind key decisions such as whether to patch and mend the less damaged aspects of the hydro-mechanical equipment, or to go for wholesale replacement. In the majority of cases the replacement option won through.

The following elements apply to the rehabilitation alternative:

Barrage Rehabilitation. The barrage superstructure is considered to be in a good condition. Minor rehabilitation works are proposed, primarily to the upstream pier nosings and vent soffits. The hydro-mechanical equipment is

70 years old and has reached the end of its useful service life. A complete replacement of these items is required.

New Barrage Navigation Lock. The construction is needed of a new 120m x 17m navigation lock on the left side of the river, immediately to the East (riverward side) of the existing lock. This location will require the demolition of some 9 barrage vents. Constructing the new lock on the landward side would have resulted in difficult land acquisition issues and the demolition of a number of houses and hotels.

Rehabilitation of the Existing Barrage Navigation Lock. The existing 80m x 16m lock will be fully rehabilitated, though its overall dimensions will remain unchanged. In the future the lock could be used to allow passage of vessels with a shallow draft throughout the year and for large cruise ships during the summer (deep water) months. It would also offer the possibility of continued navigation during maintenance of the new lock.

Downstream Weir. A concrete weir is to be constructed immediately downstream of the barrage apron slab. The purpose of the structure is to expressly limit future head differentials across the barrage to those already experienced (4.2m).

In addition to the above, there is also a need for consideration of a hydropower plant. It is proposed to position the HPP on the right side of the river, approximately 150m downstream of the existing barrage. Optimisation studies showed a clear preference for a 32 MW plant with four, 8MW bulb turbine sets.

THE NEW BARRAGE SCHEME

The design of the new barrage at Assiut commenced with an extensive qualitative assessment of thirteen potential sites, ranging from a location some 3.5 km upstream of the existing barrage, to a position some 2.5 km downstream. The limiting factors on the location were the need to construct a separate link canal once the new barrage position extended upstream of the Ibrahimia Canal, and the extensive remedial works to lower groundwater levels in a dense urban environment once the barrage location is downstream of the existing structure. The finally accepted position was between 200 m and 300 m downstream of the existing barrage.

Although the global position of the new barrage has been determined, key decisions regarding the location of the new lock are yet to be finalised by the client. As a result there remain four alternative arrangements of the key scheme components: spillway, HPP and new lock. These are described in Table 1 below.

Table 1. Description of New Barrage Scheme Layouts

Scheme	New barrage	HPP	Sluiceway	Barrage Lock	Road crossing
Alternative 1	200m d/s	Yes Right	Yes Right	Left inline	2-lanes on new and 2-lanes on existing barrage
Alternative 2	200m d/s	Yes Centre	Yes Centre	Left inline	2-lanes on new and 2-lanes on existing barrage
Alternative 3a	300m d/s	Yes Right	Yes Right	Right d/s	4-lanes on new barrage
Alternative 3b	200m d/s	Yes Right	Yes Right	Right d/s	4-lanes on new barrage

Alternatives 1 and 2 have the barrage new lock structure located on the left side of the river, adjacent and immediately East of the existing lock. The layout of the locks is essentially identical to that proposed for the rehabilitated barrage scheme. For alternatives 3a and 3b the lock is positioned on the right side, downstream of the existing barrage. Upon conclusion of the works, therefore, all schemes offer a new (120m x 17m) navigation lock in addition to a refurbished (80m x 16m) existing navigation lock.

The advantages of moving the new lock to the right side of the river lie primarily with ease of construction - all three major scheme components: HPP, sluiceway and lock, can be constructed within a single construction pit. The main disadvantage is the need to use the right channel around the downstream Bani Murr island for navigation purposes. This channel is narrower and deeper than the current navigation channel on the left, and it is likely to exhibit high surface velocities in the future because of the proximity of the new HPP immediately upstream.

In all cases the sluiceway and hydropower structures are located adjacent to each other. Separating them is considered to cause unnecessary complication both during construction and for future operation. Two locations have been examined for these structures: adjacent to the right bank and in the centre of the river. The former alternative offers ease of access to the structures both during construction and also during operation. On the negative side are the less than ideal hydraulic approach conditions to the HPP and the potential for increased erosion downstream of the barrage along the right channel of Bani Murr island. A more central location for the HPP/sluiceway improves both the approach conditions and the downstream flow split around the island. However, construction is more complex (there is no direct access to land) and there is limited room available around the structures for maintenance and operational needs.

Consideration has also been given to future road traffic requirements and for each new barrage alternative a possible scheme for providing a second 2-lane road crossing has been developed.

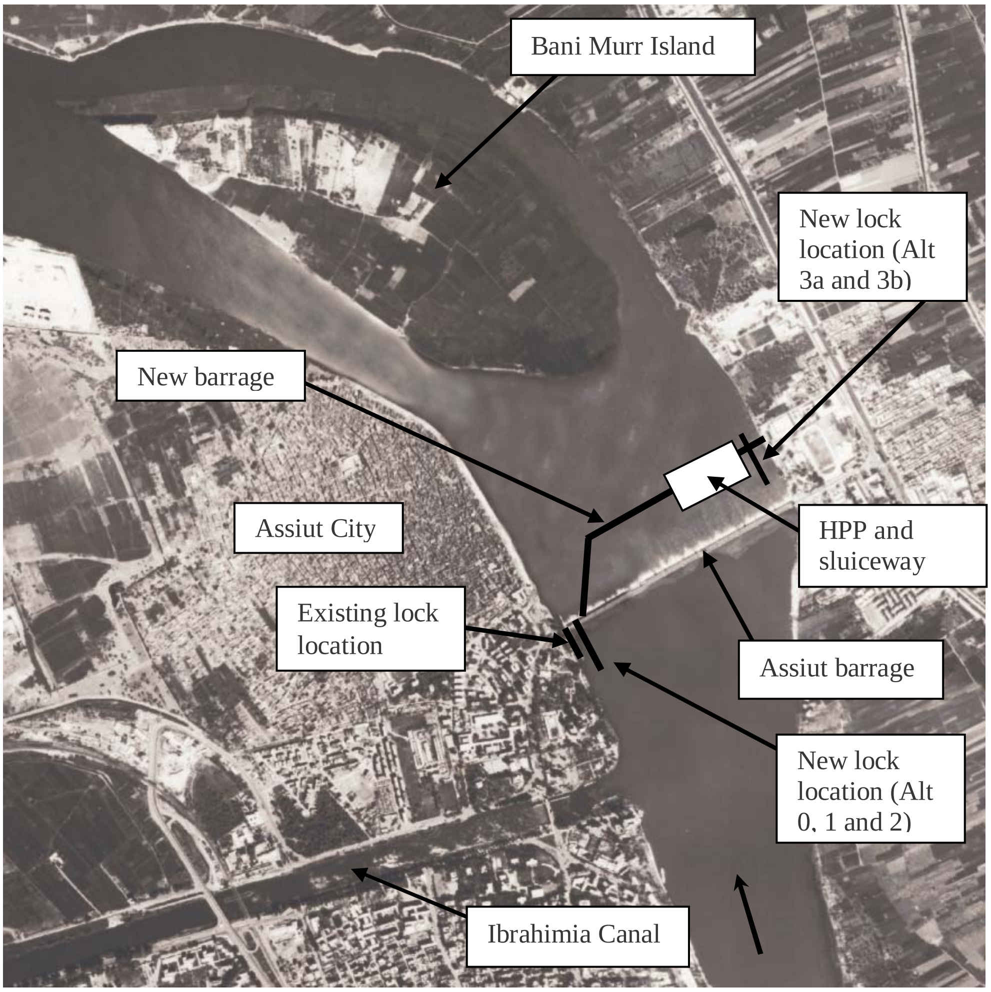

Figure 3. Assiut Barrage from the air

INVESTMENT COSTS

Detailed cost estimates for the rehabilitated and new barrage alternatives have been prepared. These are presented in Table 2 below.

Table 2. Summary of Scheme Investment Costs

Scheme	Total Investment Cost (Million Euro)		Cost of HPP component (Million Euro)
	With HPP	Without HPP	
Alternative 0	255.5	141.3	114.2
Alternative 1	284.6	175.5	109.1
Alternative 2	283.1	171.6	111.5
Alternative 3a	279.5	173.2	106.3
Alternative 3b	277.9	172.8	105.1

CONCLUSIONS

The cost of the rehabilitation scheme (Alternative 0) is some 8-12% cheaper than the new barrage alternatives. However, the cost of the hydropower element of the scheme is some 2-9% more expensive.

Of the new barrage options, those with the new lock on the right side of the river (Alternatives 3a and 3b) are found to be around 2% cheaper than the two left bank alternatives. This is primarily due to the reduced temporary works costs associated with combining the three key scheme components: HPP, sluiceway and new lock; into a single construction pit. There remain concerns regarding the suitability of the downstream right channel around Bani Murr island for lock traffic. Until this issue is resolved in the forthcoming physical hydraulic modelling, the concept of a lock on the right side of the river cannot be confirmed.

If the future of Assiut Barrage is to solely provide continued irrigation supplies for the Ibrahimia Canal then the rehabilitated barrage alternative without HPP is seen as the most appropriate way forward. However, the Client's vision is to see the barrage as a multi-purpose structure with a combined irrigation and power generating function. With this in mind the recommended future direction for Assiut is as a new structure, to be positioned between 200 and 300m downstream of the existing barrage.

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