

**COFFERDAM CONSTRUCTION AND DEWATERING  
TAUNSA BARRAGE REHABILITATION PROJECT**

Muhammad Nadeem, PhD, PE



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## Abstract

Cofferdams are temporary structures instrumental to meeting big challenges like the rehabilitation of Taunsa barrage which was made possible only through constructing so many of these. A simple structure was designed and constructed successfully in the mighty Indus River. To safeguard against piping, sheet piles were installed along most of the length of the Cofferdams. The experience of installing sheet piles in cofferdam was not available in the country. The contractor was able to bring whatever limited experience was available together in one team and satisfactorily completed the job as per plan.

As the project scope was demanding, requiring round the clock working to meet the targets, the chances of failure were high. Risk mitigation approach was used to identify possible risks involved in the construction of the project including the cofferdams and all the risks were addressed through a series of risk minimizing measures to provide safe and reliable working setup like adding extra plant and equipment, stock piling of materials, etc.

Dewatering operation is normally carried out in two steps. In the first step, the construction area enclosed inside the cofferdams was unwatered through surface pumping and then a groundwater pumping system consisting of shallow wells was installed to lower the water table to the desired level for construction of the permanent works of the project in the river bed. Subsequently, pumps were installed and operated till the target water levels were achieved.

This paper presents the experience of the contractor in the design and construction of the cofferdams along with installation, operation and maintenance of dewatering system used for the construction of permanent structures of “Taunsa Barrage Emergency Rehabilitation and Modernization Project”.

## 1.0 Introduction

Taunsa Barrage is located on Indus River which is a gigantic river of the Indus valley. The valley is a flat alluvial fan formed by Indus and its tributaries. There are five main tributaries irrigating the fertile lands of Punjab and Sind provinces. The irrigation system has all the rivers interconnected through a series of link canals that facilitate inter-basin transfers. Water for irrigation is diverted from the rivers through a series of barrages (diversion weirs) releasing water into main canals and subsequently to a vast irrigation network of distributaries and minor channels.

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The development of the irrigation system started in the nineteenth century and a number of the existing barrages were constructed. There is a major initiative from the Government of Pakistan to rehabilitate the century old infrastructure. One of these was Taunsa barrage constructed in 1958 and presently feeding four main canals; two on the right and two on the left bank. The barrage has 65 bays/gates each 60ft wide and separated by 7ft thick piers. Total width of the structure is 4,346ft and it has a design capacity to pass a flood of 1,000,000 cusecs; the historic maximum flood observed on the river Indus at this location in 1929. Sufficient experience with respect to operation and maintenance of the barrage exists in the country.

The structure had a maximum recorded flood of around 760,000 cusecs soon after its completion. Subsequently, more projects were added upstream of the barrage including a very large reservoir at Tarbela, the annual peak flood has been gradually reduced to around 650,000 cusecs, generally occurs during summer monsoon season (July-Sept). The area of barrage location is also influenced by the Western disturbances during winter months with a historic peak of 300,000 cusecs.

## 2.0 The Rehabilitation Project

The Rehabilitation Works planned in the project were executed in the year 2005-2008 and were supervised by the Punjab Barrages Consultants (the Engineer) and Punjab Irrigation Department (the Employer). The project was funded by the World Bank (IBRD). The rehabilitation work was divided into mechanical and civil works and executed through three major contracts.

The civil works contract was awarded to Descon Engineering Limited (DEL) in Joint Venture with China Gazooba Corporation (CGGC) under international competitive bidding. The project was originally planned for construction in three low flow periods (Oct to June). No work was allowed in the monsoon period inside the river (Jul to Sep) each year, when maximum flows were expected and the whole Barrage width was made available to pass the floods.

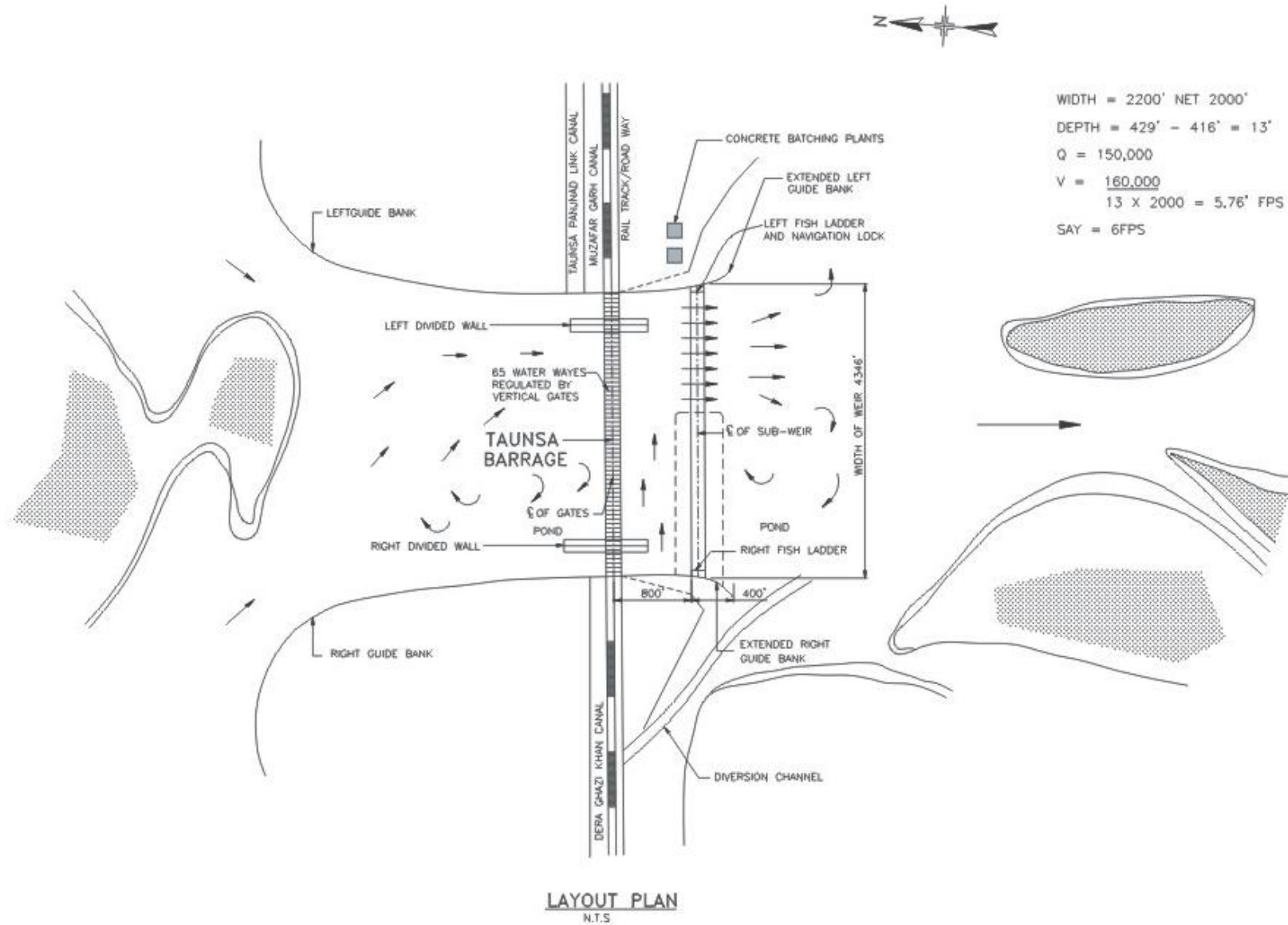
The main structure of the barrage was kept in operation to supply water for irrigation during construction of the subweir which was carried out in the drier part of a year i.e. Oct to Jun. For this reason, the subweir was located at a distance of 925ft downstream of the existing barrage such that silt load from the left and right pockets of the barrage can be released downstream (See Figure 1).

The contractor (DEL-CGGC JV) planned the construction of the whole project in two years; each year one half of the weir was to be completed along with half the bays of the old barrage to be rehabilitated. The rehabilitation work comprised replacing old weaker concrete from the chute and stilling basin floor. For this purpose cofferdams (CDs) were constructed in one half of the barrage length on the upstream and downstream of the construction site.

A typical layout of the cofferdams constructed each year for the construction of subweir is shown in Figure 2. The other half of the barrage was left open to pass the river discharge; with a much greater capacity than the maximum observed flood of 300,000 cusecs for the non- monsoon period i.e. from Oct to Jun. No activity was planned inside the river channel during monsoon flood season i.e. from Jul to Sep.

## Taunsa Barrage (downstream face)





*Figure 1: Flow Through Barrage*

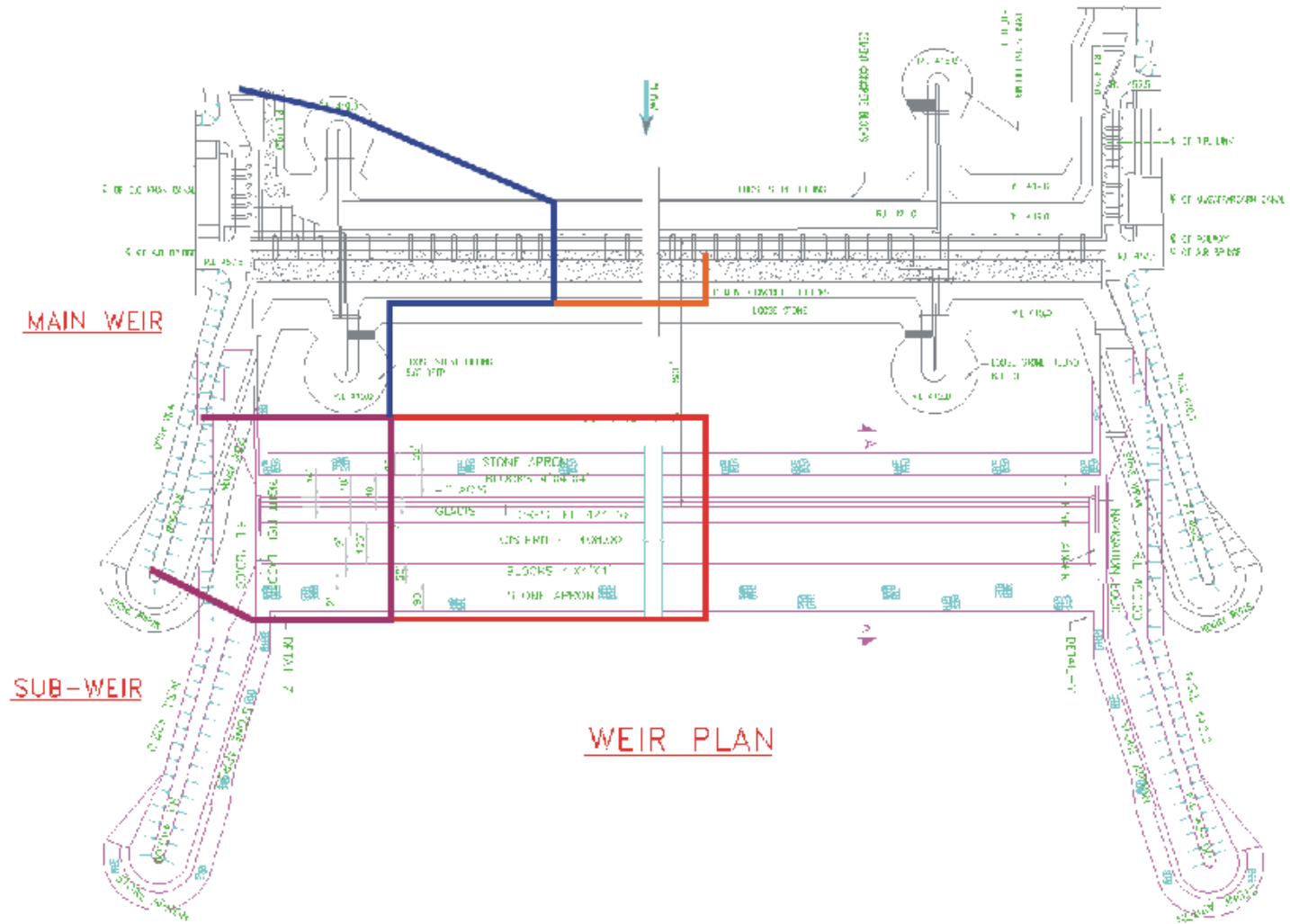


Figure 2: Layout of Taunsa Barrage

<b>FLOW PATTERN THROUGH THE BARRAGE (cusecs)</b>		
<b>Months</b>	<b>Avg</b>	<b>Max</b>
JAN-APR	25000	50000
MAY	50000	100000
JUNE-AUG	150000	>612000
SEP	50000	100000
OCT-DEC	25000	50000
based on discharge data for the last 3 years		

Winter flows in the main river were regulated through Tarbela Reservoir. However, some of the smaller western streams could generate floods during the winter and spring season at the barrage site which might disturb the construction activity. In order to safeguard against these floods, the historic maximum flow of 300,000 cusecs for the spring season was used to estimate the height of cofferdams. The capacity of half the barrage and the available river channel downstream was much more than the required capacity for historic flood. Hence, it was ensured that adequate factor of safety was available for the diversion channel and the height of the cofferdams.

The flow in the river was monitored continuously in order to safeguard the activities of the project. Similarly, the water levels upstream and downstream of the barrage were continuously observed and maintained to feed the irrigation channels off taking from the barrage. To ensure safety of the existing structure, all the construction activities were planned such that head across the barrage remains within 15 ft whereas the design head across the barrage is 24 ft.

As noted earlier, the height of the coffer dams was determined by estimating the maximum flood level caused by the winter freshets.

The sub weir was the major cost component of the project and was estimated to be around Rs 3.0 Billion and the cost of the temporary works for care and handling of water was estimated as Rs 700 Million.

A detailed procurement plan for the required materials and equipment was prepared to ensure that the materials are available at the site at the right time. Other important tools and scaffoldings required for the project were planned to be supplied in abundant quantity to avoid any undue delay in the construction activity.

### **3.0 Cofferdam Design Criteria**

Cofferdams are temporary structures therefore rigorous design and construction techniques are not strictly followed to provide safety against extreme operating conditions. Normally these structures are designed and constructed fit for purpose with major emphasis on the time available for construction and factors of safety are relatively low when compared to permanent structures.

The preferred design of the cofferdams used in Taunsa were of a hybrid type structure in which two materials were used for different purposes along with sheet piles to provide effective seepage cutoff and to improve the overall stability of the structure. Salient Features of the CD section are:

1. Stone fill is provided to break the erosive action of the flowing river
2. Earthfill is provided for a water tight section minimizing the water flow across CD body.
3. Sheet Piles were installed to cut seepage rate across the earthfill and improve its stability.

The stone size is governed by the velocity of flow expected in the river. Corresponding to river Indus, a design velocity of 8-10 fps was used to compute the stone size. The stone size used in the construction was >100 lb weight with one face cut to minimize the rolling of stone under its own weight. When water starts flowing along the cofferdam, it tends to undermine the stone by removing sand from underneath the stone. The stone launches itself to curtail further removal and provides stability to the bed.

The other integral part of the cofferdam is the earthfill which was provided to hold the water from flowing across the cofferdam. The earthfill used was fine grained soil (mainly clayey silt) with sufficiently low permeability value of  $10^{-3}$  to  $10^{-4}$  cm/s that can hold the water from flowing across the cofferdam. The stability of the embankment was ensured through providing a slope flatter than the angle of repose of the soil. It was flatter than 1V:2H (27°). The earthfill slopes formed underwater achieved much flatter gradient as compared to dry conditions.

In order to ensure safety of the work area inside the cofferdam enclosures including life and property, sufficient pumping capacity should be provided to ensure safe working under worst scenario. The permeability of the strata is highly variable and can affect the seepage rate by the order of 10. Therefore, using a higher value will ensure that sufficient pumping capacity is available at the time of construction.

The availability of materials need to be ensured with respect to quantity and close proximity was an important criterion for the selection of materials.

Mostly, construction of the cofferdams had to be carried out in flowing water; the dumped material settles under its own weight. Moreover, due to the dumping machines moving on top the materials quickly reach a fairly compacted state. The support provided to the heavy machines on the crest of the CDs showed that the material was compacted sufficiently to cater for the heavy loads and any horizontal force on the cofferdam by flowing water.

### **3.1 Soil Tests / Bore logs for the design of Cofferdams**

Ample data was provided by the consultants in the tender documents about the substrata in the form of bore logs and soil tests. These were compiled in Volume IV of the Tender Documents prepared by Punjab Barrages consultants; and were used for designing the cofferdams. The substrata in the area comprises primarily medium to fine sand.

Some initial laboratory tests were also carried out on the earthfill materials being transported to the site by suppliers primarily for determining the silt and clay content of the soil, angle of repose, gradation curves, etc.

### **3.2 Soil Classification of Cofferdam Borrow Materials**

The soil type identified in design for the earthfill of the cofferdam was Clayey silt which was available in the surrounding area in ample quantities. The soil gradation was about 98% passing #200 sieve. The gradation for soil finer than #200 sieve cannot be determined by the standard sieve analyses. The material remained the same for all types of cofferdams. The borrow areas of the materials were specified to the supplier by establishing their suitability through laboratory testing at site.

The base width of the earthfill embankment was kept wide enough in order not to allow the phreatic line to appear on the d/s face. This was primarily done to minimize the chances of movement of fines or piping through the embankment. This condition became redundant for most of the CDs due to installation of sheet piles.

### **4.0 Quality Control Procedures**

No specific quality control measures were specified for construction of the cofferdam as these were built most of the time under water. The movement of machinery on top of the cofferdam is an indicator that the cofferdams were sufficiently compact and stable. No compaction tests were carried out; however, day and night vigilance to avoid failure through overtopping and piping was a prerequisite due to high risk of failure of life and property being protected by CDs.

### **5.0 Construction Methodology and Compaction**

The construction of cofferdam in flowing water was carried out by means of heavy machinery like dozers, dump trucks and excavators. The weight of such machinery ranges from 10 to 15 tons moving freely on top of the newly constructed embankment. The stone dump was constructed in advance of the earthfill embankment which was constructed in its shadow. The dumper dumped the stone in reverse on top of the embankment and dozers moved it across the flowing water. The water washes away some stone and some was left behind at the toe of the embankment. The earthfill material was also dumped from the top as it settles down under the load of machinery.

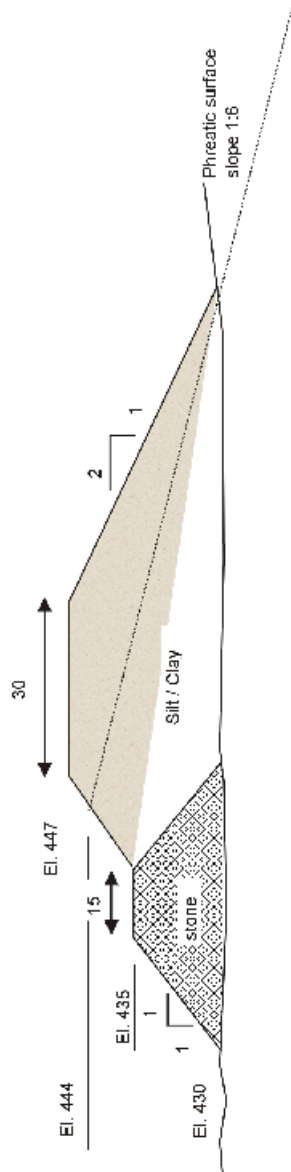
Normally, the working space and the time available for construction governs the level of compaction achieved therefore highly variable behavior can be expected from the embankment section. High vigilance is thus required for monitoring the cofferdams day and night. Regular maintenance of the cofferdams was also needed in the form of placement of materials at the point of observed settlement to ensure that the required freeboard is not eroded and the cofferdams perform the function they are built for i.e., to provide safe working conditions.

As the construction moves near the centre of the river channel the velocities kept on increasing and so is the scour at the nose of the cofferdams thus requiring more materials to achieve the planned progress. The scour depths observed below the water levels during construction were at times more than 20 ft.

**DESIGN OF U/S COFFER DAMS**

**DATA:**

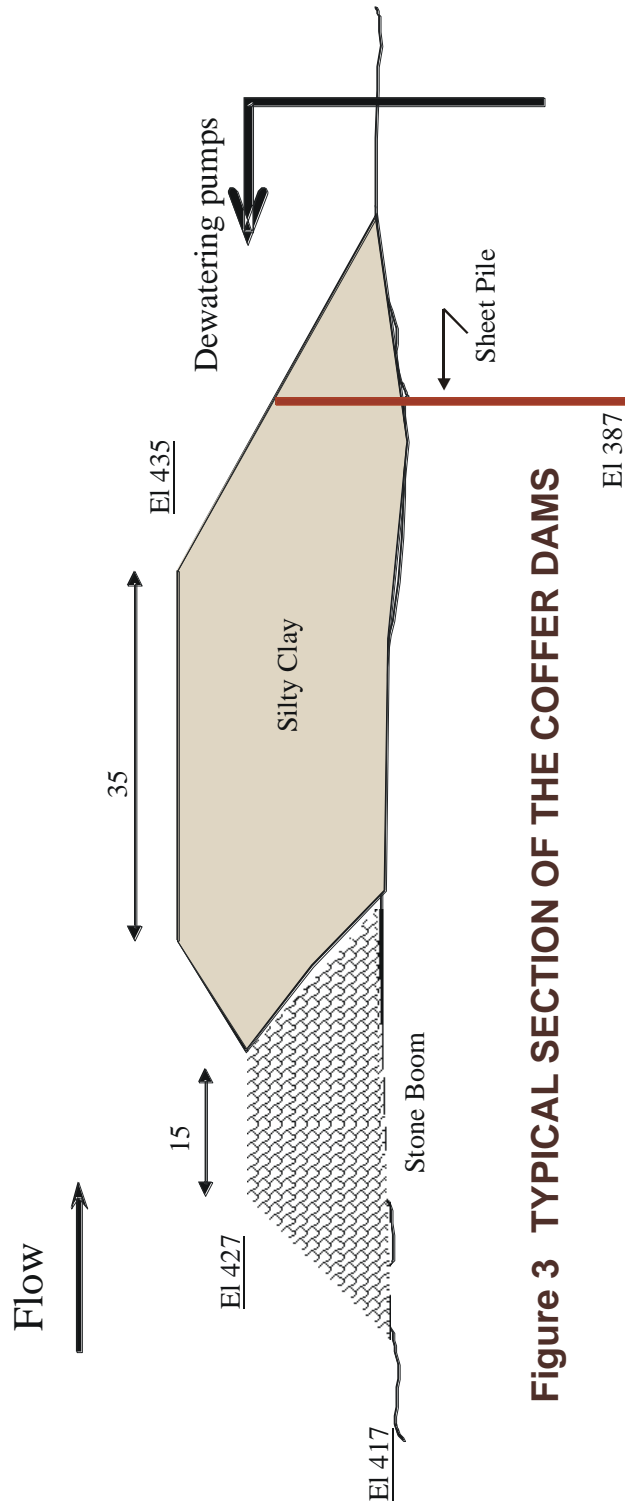
Water Level = 444  
 Top of the Cofferdam = 447  
 Ground level = 432 average



**HORIZONTAL FORCE**

P= gh      873.6 PSF  
 FH      2.73 TONS/FT  
 Weight of material =  
     earthfill      75600  
     stone

Construction of cofferdams is a critical activity for the construction of the project in the flowing river. It required large volumes of the materials like stone and earthfill at site which was dumped in the river on the upstream and downstream for construction of the subweir and also for the repairs of other structures inside the river khadir. Typical Section of the cofferdams is shown in Figure 3.



**Figure 3 TYPICAL SECTION OF THE COFFER DAMS**

The construction of cofferdams was a continuous round the clock operation to maintain a stable progress inside the river and only uninterrupted supply of materials made the operation successful. For this purpose stock piles of materials like stone and earthfill were maintained at site and supplemented by direct supplies from the quarries during construction.

The quarries for stone were located at approx. 50-60 km distance from the site; therefore it was more critical to maintain the volume of stone anticipated to be used in the cofferdams with sufficient cushion to avoid any delay in the supply due to non availability of the material. Careful planning was required to achieve the targets as very limited time was available for the construction of each cofferdam. This activity was the most critical in the time plan as no other activity could have been carried out until the cofferdams complete. The rate of dumping required for such construction was around 20-25 dumps in one hour to keep it moving forward at the required phase. Quantity of materials estimated for the coffer dams is as follows:

<b>Quantities of Material used for construction of cofferdams in Phase I</b>			
1.	Earth Filling	=	11.46 M cft ( 324,394 m <sup>3</sup> )
2.	Stone	=	100,000 cft (3000 m <sup>3</sup> )
3.	Sheet Piles	Area	= 224,000 sft
		Depth	= 35-40 ft
4.	Sand Bags	=	60,000 No.

## 6.0 Maintenance of Cofferdams

Regular maintenance of the cofferdams was carried out to ensure that these perform according to plan and working conditions inside the enclosures bounded by the cofferdams providing safe working conditions. Intermittent settlements were observed at different locations for which regular placement of materials was required on the crest of CDs in order to maintain sufficient freeboard and replenishment of stone to protect these from excessive erosion at the toe due to flowing water.

## 7.0 Dewatering

Dewatering was also a major operation subsequent to the construction of the coffer dams. The pumping effort required in the project was immense and needed detailed planning in order to lower and maintain the required water levels in the work enclosures bounded by the cofferdams. Dewatering the enclosures required surface water removal and lowering of the subsurface water levels. The operation required installation of a large number of tubewells along with pumps and screens in the substrata, according to water level required for concreting in different parts of the compound.

Dewatering in the subweir area was the most demanding and critical to construction work. Detailed seepage analyses were carried out on a typical X-section of the sub weir along with substrata and u/s and d/s cofferdams (see Figure 4).



The seepage modeling was done using software SEEP/W to analyze the impact of sheet piles and overall stability of the cofferdam section. The model used for the analyses is shown in Figure 5. Flow net analyses generated by the model are presented in Figure 6. The flow nets showed that the sheet piles are useful in cutting down the seepage by about 35% of its original value.

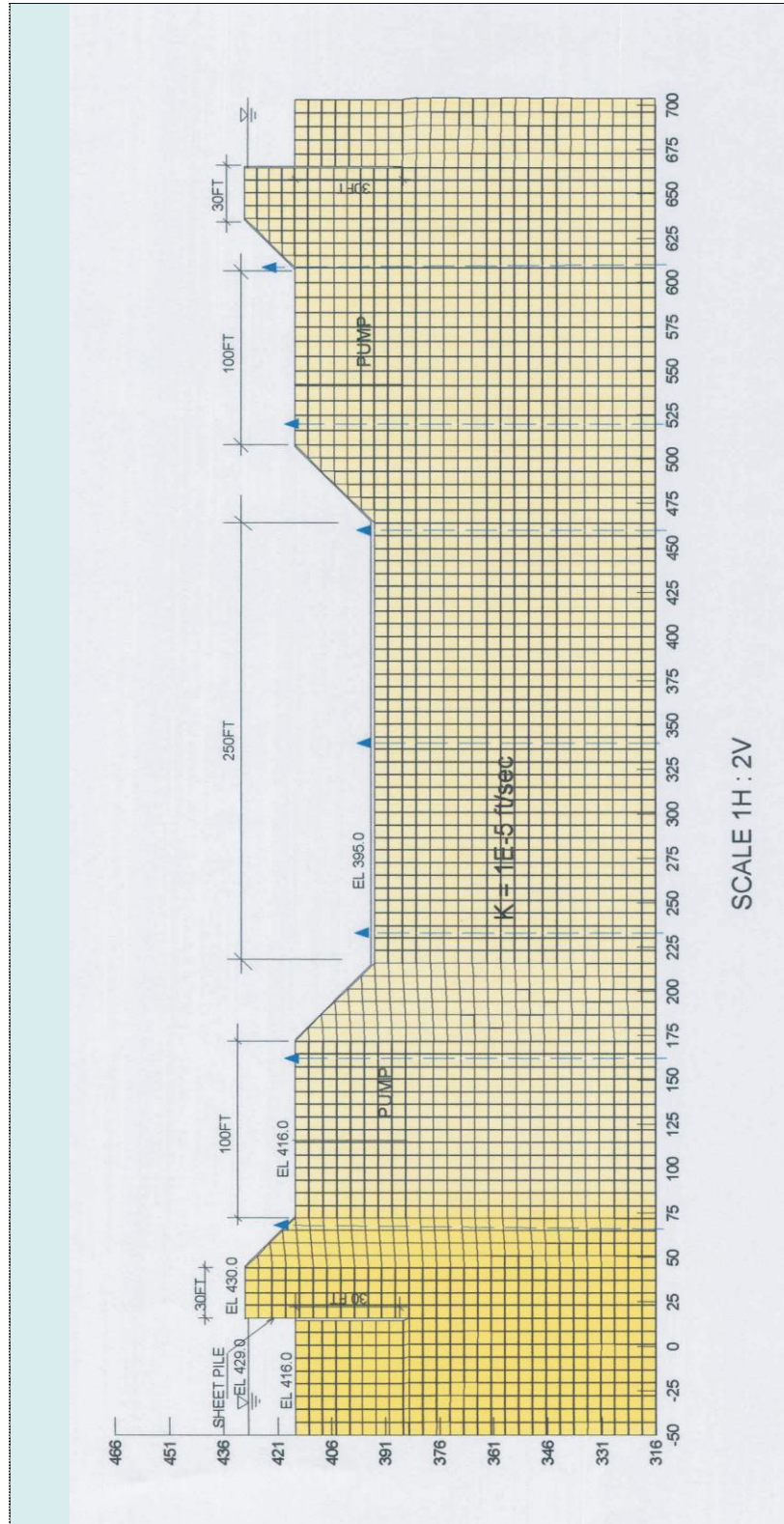
The quality of results of the model depends on the parameters used for the analyses like the permeability of the soil strata, boundary conditions, etc. However, once a realistic model is available, sensitivity analyses may be carried out to study the impact of different parameters. The decision to install a sheet pile in the cofferdams was primarily based on the results of the model showing that the seepage quantity may be reduced by 30-35% in addition to improved stability and reduced risk of piping.

In addition to supply of pumps to control the surface and subsurface water levels, a stable and reliable electricity supply was needed to maintain a continuous day and night operation of the pumps. For this purpose, ten new generator sets were installed with sufficient capacity to operate the pumps in a reliable manner. In addition to the main generator, additional standby units were provided at the site to minimize the risk of failure.

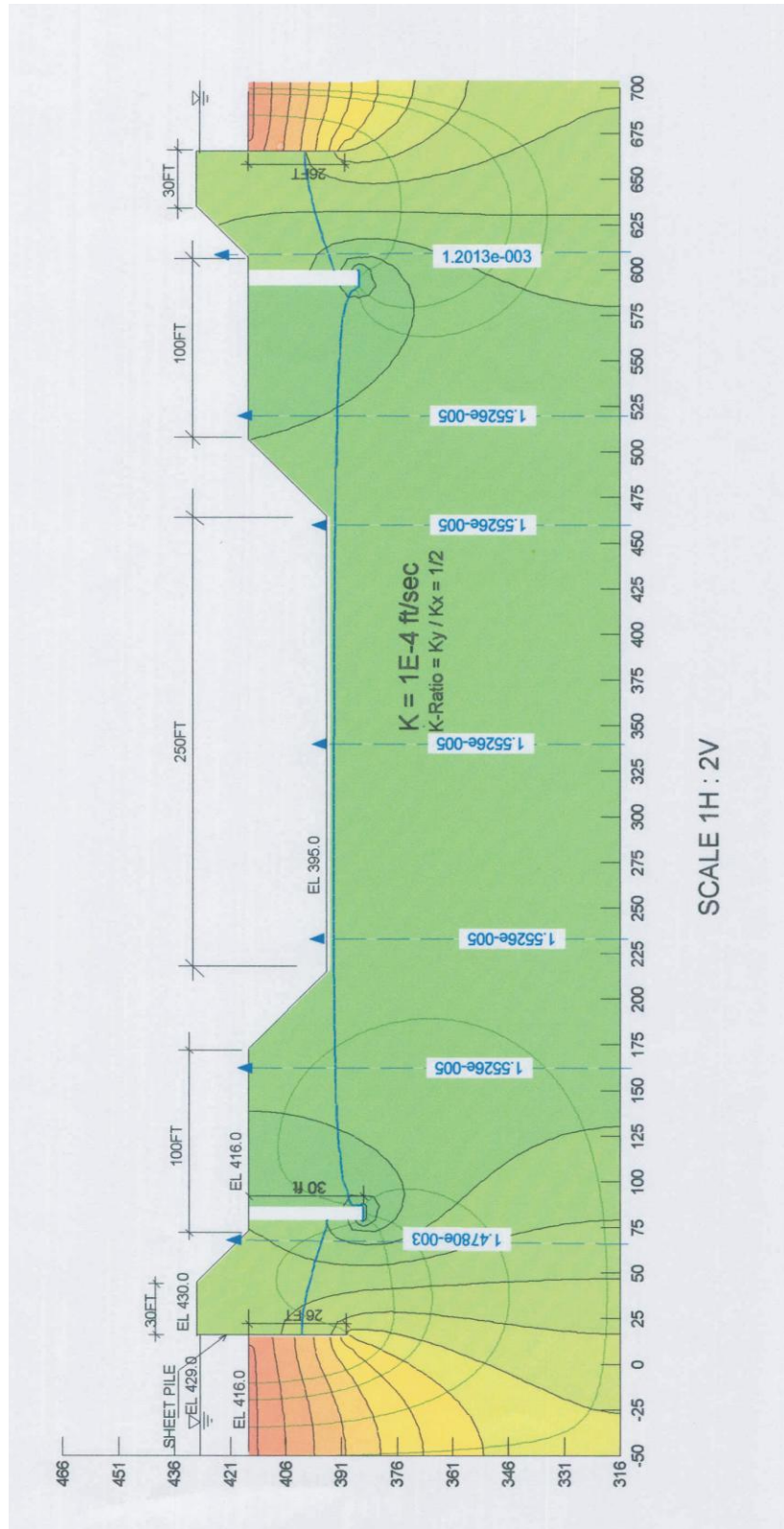
Initially, it was planned to construct one single enclosure for the construction of sub weir. However, after subsequent discussions and analyses of the flow conditions across the barrage it was necessary to construct four enclosures of 700 ft width each instead of one single enclosure of 2800ft length. This subdivision resulted in an early start of construction of subweir as well as rational phasing of the effort of dewatering for each enclosure in a separate well defined sequence.

It was estimated that each enclosure of 700 ft will require 50-60 wells in order to lower the water table to the required levels. Availability of pumps and generators were critical to achieve the dewatering of the site for construction, therefore, extra capacity was provided to ensure continuity of operation. Following number of pumps were made available at site:

	PUMP TYPE	CAPACITY	NO OF PUMPS		TOTAL CAPACITY
			Estimated	Provided	cs
		cs			
1.	Submersible pumps	0.5		60	30
		1.0	120	128	128
2.	Centrifugal pumps	0.5	68	90	45
		1.0		7	7
3.	Mud pumps	2.0	8	5	10
	Total		196	290	220



**Figure 5:** FE Model used for Design of Cofferdams at Taunsa Barrage Project

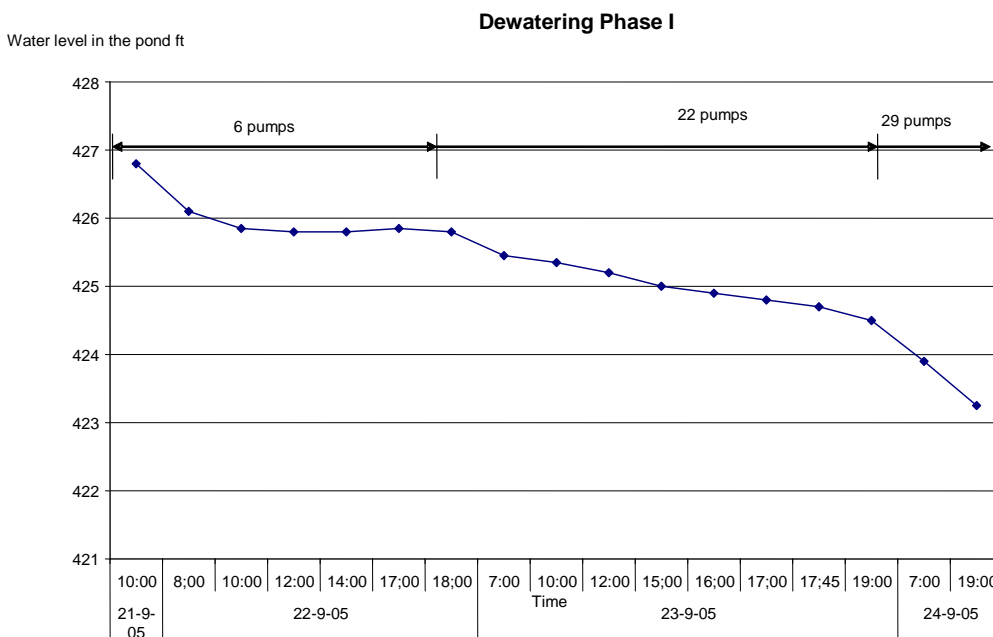


**Figure 6:** FE Model results used for Design of Cofferdams at Taunsa Barrage Project

The total generation capacity required for the pumps in the sub weir area was more than 3 MW for which 8 generator sets of 375 KVA were provided. For every two generators required for dewatering, a standby generator was also provided to ensure uninterrupted power supply for dewatering operation.

Disposal of pumped water to the surrounding river was another major task needing detailed planning. During the initial phase flexible fire hose pipes were used to dispose the water. However, too many fire hoses in the construction site was difficult to handle, subsequently specially designed disposal mains of steel and flexible hose pipes were used to stream line the site. The service road requirement on the cofferdam necessitated the use of steel pipes embedded in the cofferdam crest. The pumped water disposal point had to be clear of the coffer dam toe to safeguard against erosion of the cofferdams.

The following Figure shows the rate of dewatering in a 700 ft wide cofferdam compound and its response to different pumping capacities. The data was collected at regular interval during the initial phases of the project. Most of the pumps had 1 cusec capacity. This data was used to optimize the pump sizes and locations.



### 8.0 Performance of Design

A total length of 12 km length of CDs was constructed during the project with only one failure event. The failure occurred during the second year of the project in an upstream cofferdam which resulted in an alarming situation with respect to water running quickly towards the downstream site overtopping some of the cofferdams.

A number of unusual factors contributed to the failure:

- the dams were constructed in a hurry and could not have sufficient time to consolidate.
- the soil was dry and water level was raised at a much quicker pace than recommended by the barrage operators.
- the failure occurred at the deepest point ie where the head across was maximum due to piping in the subsoil which triggered the failure. Subsequently, no access was available for the machines to recover the failure.

There are strict guidelines for the barrage operators on how to operate the barrage especially raising and reducing water levels on the upstream side. A quicker action might result in breaching of bunds as a result of sloughing or slope failures.

The failure was recovered quickly through emergency closure of the breached section. The section was rebuilt again with the help of heavy machinery in a couple of days. A length of about 250 ft was reconstructed to recover from failure. It also provided access to the remaining part of the cofferdams which were in very bad condition due to piping through the dam body which primarily occurred due to dry soil conditions inside the embankment.

The closure of the cofferdam constructed under river flow is very demanding especially when the opening between the two ends is reduced to less than 100 ft. The progress becomes very slow and some times may become negative due to the increasing head across the closure section. This is primarily due to a very high velocity of flow through the remaining section. Even big boulders do not stay in position under these conditions. Therefore, some special efforts in terms of size of stones may be used such as gabions or large concrete blocks which can be a good option to provide stability against the high velocity in the closure section. Both the options were used in the closure sections.

The other good option to achieve a closure is through the help of the barrage operators. If they can raise the water level on the downstream side by operating the barrage gates it can tremendously reduce the effort at the closure section at Taunsa.

## 9.0 Conclusions

Cofferdams are temporary structures, however safety considerations need to be emphasized from planning to construction through careful choice of materials and round the clock vigilance. The construction team should be briefed regularly for the importance of the structure and possible after effects of failure.

The design used for the project was found to be sufficient and reliable provided that the following precautions are taken:

- 24 hr vigilance to monitor any settlement;

- Gradual variation in water levels in the reservoir area;
- Head across does not exceed design conditions;
- Plasticity index of around 15 for the soil used for earthen embankment.

Seepage flow analyses helped in estimating required pumping capacity sufficient to dewater two enclosures simultaneously along with the dewatering of barrage area for rehabilitation works.

Failure of the CD hampered the confidence level of the team and labour working in the area. To build confidence and to ensure the safety of the cofferdams after recovery from the failure the cofferdams were further strengthened by installing a berm on the back of the embankment fill and a line of sheet piles at some places.

A set of Photographs taken during construction are included at the end of paper to show the stages and extents of the Cofferdams. The titles of the photos are self explanatory and a couple of photographs are included to show the conditions at each stage.

The sheet piles used in the project were found to be very useful in reducing the effort of dewatering by about 35% and adding stability and reliability of the cofferdams by cutting down the chances of piping in a very conducive environment.

## PICTORIAL OF COFFER DAM



Start of coffer dam



Dump truck unloading stone at the nose of the cofferdam



Cofferdams completed in parallel at the front and back of the enclosure



Cofferdams - Sheet Piling in progress



Cofferdams – unwatering of enclosure



Cofferdams - Subweir dewatering wells installed with simultaneous excavation in progress



Sheet Piling in the cofferdams with simultaneous dewatering



Sub-weir Construction in progress