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Hydraulic and Structural Design of Navigational Locks

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Abstract

Navigation lock is a structure in the waterway provided to create a safe navigation passage between two water pools which are not at the same level. The reason for difference in water levels can be natural such as tidal variations or can be manmade such as construction of dam or barrage across the river. The main components of Navigation lock comprise of approach channels, lock pit, filling/emptying arrangement. Design of lock depends on lockage time, water level variations, Lock capacity requirements, design vessel size. filling/emptying system shall be designed to work under gravity flow without any pumping requirements. Filling/emptying system is chosen to get appropriate filling/emptying time. The optimum time for filling and emptying is generally kept between 8.0-10.0 minutes. The size of filling culverts are so computed to attain the optimum time for filling/emptying. Every lock is unique in terms of its geology, location, size, requirements and water level differences. Here typical design aspects of a navigational Lock in inland waterway have been described.

Keywords: Hydraulic; Structural design; Navigational locks

Abbreviations: C: Cohesion; cm: Centimetre; D/S: Downstream; DSWL: Downstream water level; EL: Elevation; FOS: Factor of Safety; HFL: High Flood Level; IS: Indian Standard; KN: Kilo Newton; kN/m^3: Kilo Newton per meter cube; KNm: Kilo Newton meter; Kpa: Kilo Pascal; LWL: Low Water Level; m: Meter; m/s: Meter per Second; Max: Maximum; Min: Minimum; mm: Millimetre; MWL: Maximum Water level; PCC: Plain Cement Concrete; RCC: Reinforced Cement Concrete; SBC: Safe Bearing Capacity; U/S: Upstream; USWL: Upstream water level; WL: Water Level

Introduction

Navigation lock is a structure in the waterway provided to create a safe navigation passage between two water pools at different levels. Typical arrangement of navigational lock is shown in Figure 1 [1].

The reason for difference in water levels can be manmade such as construction of dam or barrage across the river, creating difference in water level up-stream and down-stream or difference in water level between the pond up-stream of the barrage and in the canal off taking from the pond through the head regulator or because of natural reasons such as tidal variations where Locks may be required at entrances to wet docks which require a constant water level for docking.

The size of navigation lock (i.e. length breadth and depth) depends greatly on the size and draft of design vessel, traffic projections and difference in water levels. The depth of the lock is dependent on various factors such as the water level difference upstream and downstream, the draft of the design vessel, size of inlet/outlet openings and quantity of incoming silt etc. The dimensions should be kept optimum, to insure adequate locking capacity and appropriate operating time. Every lock is unique in terms of its geology, location, size, requirements and water level differences. In this paper, typical design aspects of a navigational Lock in inland waterway have been described [2].

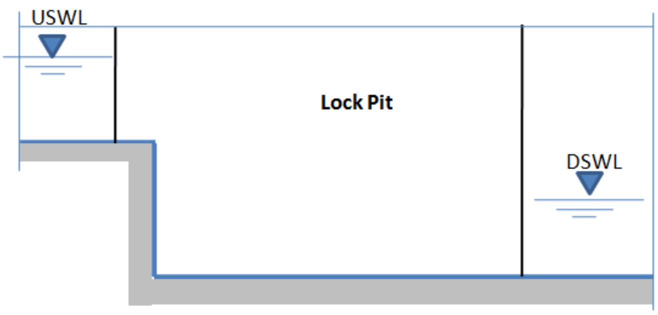

Figure 1: Typical arrangement of navigational lock.

Materials and Methods

Main components of navigation lock

The main components of Navigation lock comprise of approach channels lock Pit, filling/emptying culverts and operating gates [3]. There are various alternatives for all of these main components and based on the location and site specific requirements one has to choose the best appropriate option. For our case various alternatives considered before finalizing the main components are described below:

Approach channel: The location/orientation of the lock should be kept in a way that the maneuvering vessel can enter/exit the lock pit travelling in a straight line without taking any turn. Moreover there should be appropriate space for waiting vessels near the approach channels. Approach channels are retaining structures and based on the height it can be designed as cantilever retaining wall, counter fort retaining wall or gravity retaining wall. So ease of construction the retaining walls of approach channel shall preferably be of the similar type as the retaining walls of the lock pit. Typical arrangement and cross section of retaining wall for approach channel is shown in Figure 2.

Lock pit: The Lock pit itself can be a monolith "U" shaped structure or it may comprise of retaining walls and base slab. In our case the Lock pit consists of retaining wall and base slab. Typical cross section of Lock pit is shown in Figure 3.

Further retaining wall can be designed in various ways depending

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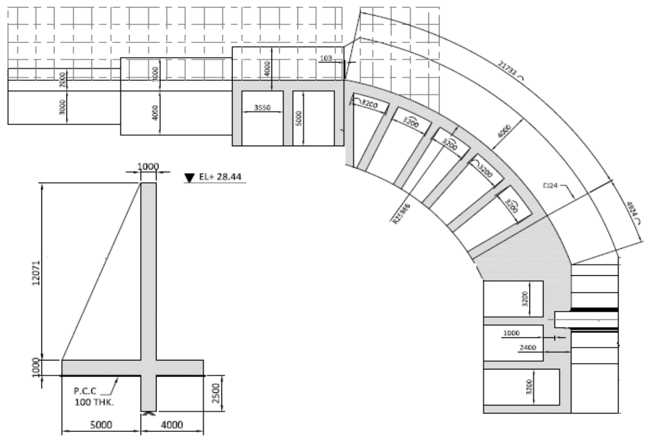

Figure 2: Typical arrangement and cross section of retaining wall for approach channel (in mm).

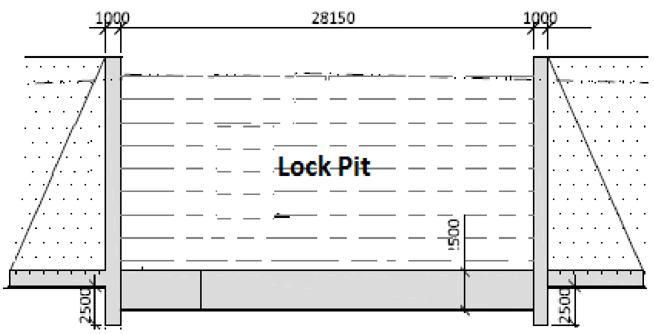

Figure 3: Typical cross section of Lock pit (in mm).

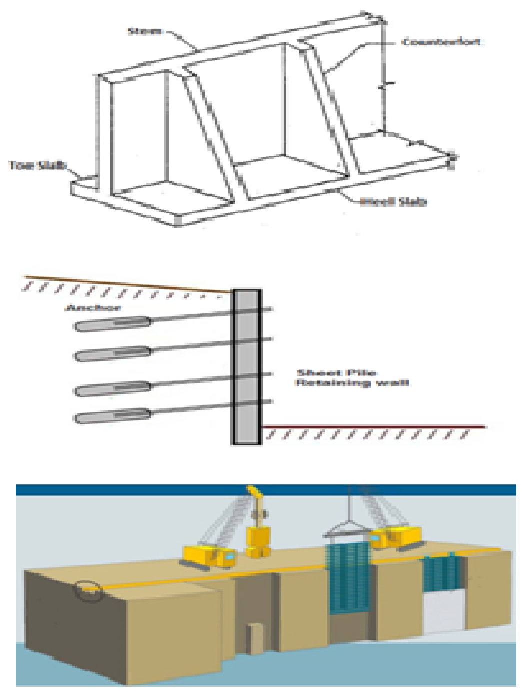

Figure 4: Typical sections of these retaining walls.

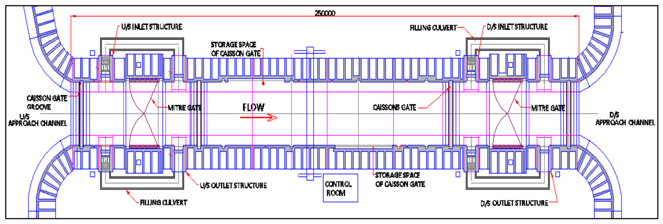

Figure 5: General arrangement plan of navigational lock.

on the depth of lock. Three types of retaining walls i.e. counter fort retaining wall, anchored diaphragm retaining wall and diaphragm wall without anchors have been studied. Typical sections of these retaining walls are shown in Figures 4 and 5 [4].

The counter fort retaining walls have been proposed because of following advantages:

- No special equipment is required for constructing these type of retaining walls, whereas other options need specialized machinery.
- It is easier to construct the counter-fort retaining wall as compared to other types of walls.
- It is cheapest among all of the above options (Case specific).

In case of the navigation lock, the retaining wall of lock is having number of niches (caisson gate storage niche, floating mooring/bollard niche and safety rung ladder niche). The construction of these niches is very difficult in a diaphragm wall whereas, it is easier to do so in a counter-fort retaining wall.

Filling/emptying arrangement: Filling/emptying system is chosen to get appropriate filling/emptying time. As per manual on design of locks, intake and discharging systems, Netherlands, the optimum time for filling and emptying is 8 to 10 minutes. For computing the size of culverts, scenarios with maximum water levels both in upstream and downstream channels, minimum water levels both in upstream and downstream channels, and minimum water level in upstream channel and maximum water level at downstream channel have been considered. The scenario giving maximum size of inlet/outlet has been adopted.

Considering time of 8 minutes for maximum filling/emptying the lock (for the worst condition) the size of the intake has been computed and two openings of size 4.0 m (Width) × 2.0 m (Height) one on each side for filling/emptying have been proposed.

One operation comprises passage of the vessels from upstream to downstreamor from downstream to upstream followed by the passage of waiting vessels in opposite direction. The total time for one way comprises the time taken in opening/closing of gates, filling/emptying of lock chamber, travel time of vessel through the lock. As the scenario of extreme water levels does last only for a couple of hours (Our case being of a river where highest lowest water levels do not occur every year and also, they remain for a few hours if at all such an event takes place). Therefore, we have considered average water levels for calculation of emptying/filling time, though safety aspects are taken for extreme conditions. As per manual on design of locks, intake and discharging systems, Netherlands, the optimum time should be about 30-45 minutes.

The details of time taken in movement of vessels through navigation lock (operation time) are given in Tables 1 and 2 below:

Thus, one-way movement of the vessels is in 38 minutes. If it is followed by movement in reverse direction, time taken is 23 minutes. This is the case for average water levels if worst condition happens the total time of operation will increase by approximately 10 minutes.

Operating gates: Operating gates are very important component of lock, as without efficient gates no lock can work effectively. Four types of main operating Gates i.e. Conventional Mitre Gates, Suspended Mitre Gates, Sliding Caisson Gates and Rolling Gates with integrated filling/emptying system suitable for our requirements have been studied. Various types of Main operating gates are shown in Figures 6-9.

All these gates are widely used worldwide for example Mire gates has been used in Three Gorges Locks- China (Completed in 2009), Floating caisson gates has been used in Deurganckdock lock– Belgium. Based on the project specific conditions it is required to choose appropriate option.

Normal Scenario, average water levels both upstream and downstream (water level in lock equal to D/S level and downstream Mitre gate considered open)	
Activity	**Time (minutes)**
Downstream Mitre gate closing	5
Upstream radial gate opening	2
Lock Filling upto WL in upstream channel	3
Opening upstream Mitre gate and upstream radial gate closing	5
Travel time (into the lock)	5
Upstream Mitre gate closing and D/S radial gate opening	5
Lock Emptying to WL in D/S channel	3
Opening downstream Mitre gate and downstream radial gate closing	5
Travel time (Out of lock)	5
Total	38

Table 1: Navigation lock (operation time) vessel movement upstream to downstream.

Normal Scenario, average water levels both upstream and downstream (water level in lock equal to downstream level and downstream Mitre gate considered open)	
Activity	**Time (minutes)**
Travel time	5
Downstream Mitre gate closing and upstream radial gate opening	5
Lock Filling upto WL in upstream channel	3
Opening upstream Mitre gate and upstream radial gate Closing	5
Travel time	5
Total	23

Table 2: Navigation lock (operation time) vessel movement downstream to upstream following the upstream to downstream movement.

Figure 6: Mitre gate.

Figure 7: Sliding caisson gate.

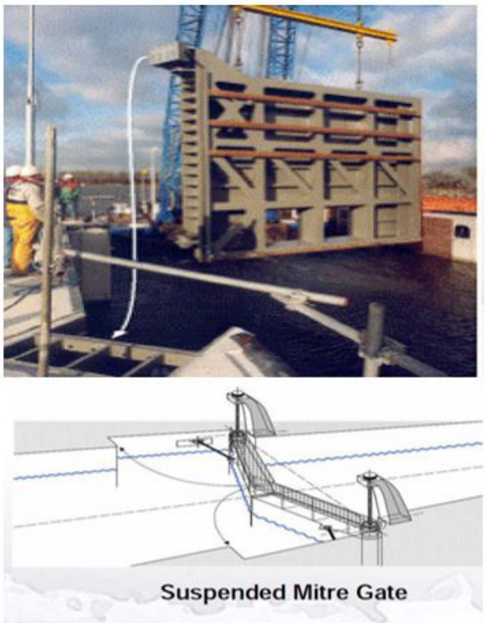

Figure 8: Suspended mitre gate.

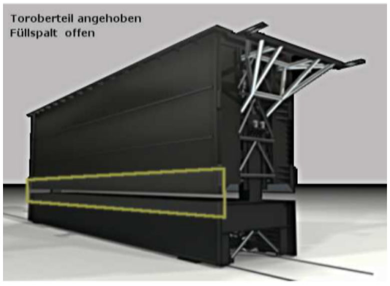

Figure 9: Rolling gates with integrated filling/emptying system.

The Mitre gates have been proposed because of following advantages:

- Filling culverts can be constructed on both the sides of Mitre gate unlike sliding gates, thereby resulting in reduced filling time with same size inlet/feeder channel. Even if filling culverts are also constructed on other side of the lock, the length of the culvert on the bank on which arrangement for putting the groove for the gate to slide in is made will

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be about 30 m. Alternatively, culverts can be on one side only which will require larger culvert and bigger and heavier gate. It will take longer to operate.

- Easy construction, as sliding gate requires construction of recession for the gate in open position.
- Land requirement for the Lock is less as compared to sliding gates.
- Mitre gates are widely in use and have been recently used in the Three Gorges locks (the largest locks in the world) [5].
- In this case, the river carries a heavy sediment load as evident from heavy siltation in approach channel. This may choke the sliding mechanism and will require elaborated cleaning arrangement.

Engineering of Civil Works

Counter fort retaining wall

Considering various advantages of counter fort retaining wall in our case it is proposed to adopt as a retaining structure. The counter fort retaining wall has been designed to take care of the earth pressure along with earthquake forces.

Typical cross section at lock pit showing counter fort retaining wall has been shown in Figure 10.

The stability analysis of the structure has been carried out considering the maximum depth of the retaining wall. The details are as given below:

Assumptions

For the stability analysis of retaining wall, the following assumptions have been made

a) The backfill soil is saturated and the density of backfill soil is 21 KN/m^3.

b) The backfill soil has been considered as cohesion-less.

c) The surcharge of 1.2 m has been considered on top of backfill. This is in accordance with IRC 6-2000.

d) Angle of repose of backfill soil considered is 25°.

e) Safe bearing capacity of foundation soil is 500 KN/m^2.

f) Density of reinforced cement concrete=25 KN/m^3

g) Cohesion of soil strata at base=1.2 Kpa

Design loads

The retaining wall has been designed for the following loads:

a) Dead load (self-weight of structure).

b) Static earth pressure.

c) Dynamic increment in earth pressure due to earthquake.

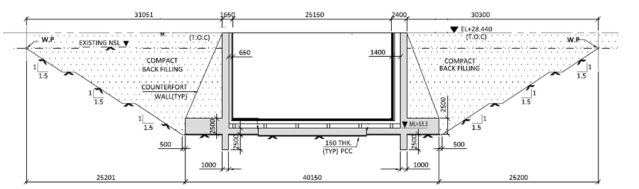

Figure 10: Typical cross section at lock pit showing counter fort retaining wall (in mm).

Minimum factor of safety	Normal	Seismic
Sliding	1.5	1.2
Overturning	2	1.5
Base pressure	<500 KN/m^2	<750 KN/m^2

Table 3: Requirements of factors of safety.

Stability Check	FOS (Normal case)	FOS (Seismic case)	Remarks
Overturning	2	1.6	Safe
Sliding	1.99	1.55	Safe
Base pressure	Max. 230.29 KN/m^2	Max. 398.53 KN/m^2	Safe
	Min. 133.91 KN/m^2	Min. -0.9 KN/m^2	Safe

Table 4: Results of stability analysis.

d) Earthquake forces (horizontal and vertical inertia forces).

Stability check

Condition: Stability of the retaining wall is checked for the following condition

- Lock is empty
- Maximum water level, upstream at H.F.L.
- Backfill soil is saturated
- Stability is checked for the following conditions:

a) Overturning: Safety against overturning is checked about the point of rotation at the bottom end of toe of retaining wall in the horizontal direction.

$$\text{Factor of Safety}\,(FOS) = \frac{\text{Restoring} \quad \text{Moments}}{\text{Overturning Moments}}$$

b) Sliding: Factor of Safety $(\text{FOS}) = \dfrac{\text{Resisting forces}}{\text{Sliding} \quad \text{forces}}$

c) Foundation base pressure: $Base\,\text{Pr}\,essure = \dfrac{W}{b.L}[1 \pm \dfrac{6.e}{L}]$

Where,

b: Foundation base width (m)

L: Foundation base length (m)

e: Eccentricity of load

W: Algebraic sum of the vertical forces

Factors of safety: The factor of safety must be more than those given in Table 3 below.

Results of stability analysis: The results of stability analysis are given below in Table 4. Thus, our design meets relevant safety requirements.

Inlet/outlet structures

The project envisages construction of four feeder culverts, two at upstream and two at downstream. The water shall be carried through culvert system planned on both sides of the lock for filling/emptying of the lock. Typical arrangement of inlet and outlet structures is shown in Figure 11.

The inlet/outlet system comprises of an inlet structure at one end and outlet structure at another end.

General arrangement

The centre line of inlet/outlet is located approximately 40 m of the Mitre gate axis both upstream and downstream.

The inlet is provided with bell mouth opening for efficient flow. The invert level at tunnel inlet is kept at EL. 14.8 m at upstream and at EL 13.0 m at downstream to meet the depth requirements based on water levels upstream and downstream. The invert level is kept so as to ensure that sufficient depth of water is available above the invert. The top level of inlet is kept based on maximum water levels and natural terrain levels. The inlet is provided with a radial gate as main operating gate which is required to be opened/closed for locking operations. On the upstream of the radial gate, a bulkhead gate is provided for inspection and maintenance of Radial gate and its embedded parts.

Outlet is provided with only bulkhead vertical gate which can be operated for isolating the tunnel for maintenance of Radial gate at Inlet. The whole filling/emptying system can be isolated by operating the gates at inlet and outlet. The stability of both Inlet and Outlet structures has been checked separately considering the following scenarios:

a) Lock chamber is empty, i.e. during maintenance of the lock.

b) Lock chamber is fully filled but no backfilling along the structure, i.e. testing condition.

c) Safe bearing capacity at founding level=500 KN/m^2 (Assumed)

d) Density of Reinforced cement concrete=25 KN/m^3

e) Density of Plain cement concrete=24 kN/m^3

f) Saturated density of Soil=21 KN/m^3

g) Density of water=10 KN/m^3

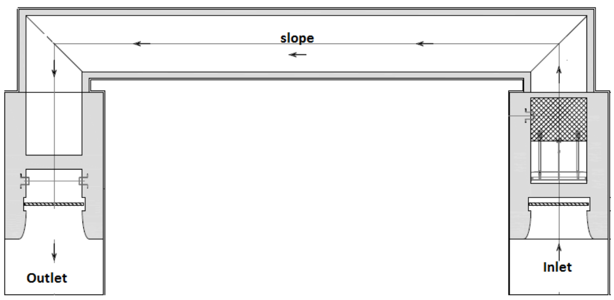

Figure 11: Typical arrangement of inlet and outlet structures.

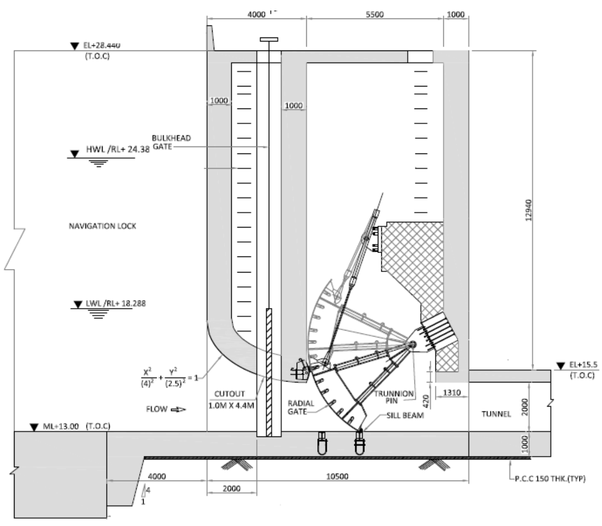

Figure 12: Typical cross-section at inlet (in mm).

h) The soil mass of the foundation of the structure in capable of supporting the loads transmitted within an acceptable stress range.

i) The structure is made up of a material that is homogeneous, isotropic, and sufficiently strong to carry the applied loads below the elastic limit to the foundation.

j) The stability of the inlet structure is checked for the conditions when emergency gate is closed and service gate is open.

k) Live load is not considered in the stability analysis as it would add to the stability of the structure.

l) The stability analysis of inlet/outlet has been carried out considering the following forces:

- Dead weight
- Seismic load
- Lateral water pressure
- Uplift pressure
- Weight of water
- Earth pressure

Stability analysis

The stability of the inlet/outlet structure is checked in the lateral directions along the flow. Typical cross-section at Inlet is shown in Figure 12.

In the stability analysis, safety is checked against the following:

a) Overturning: Safety against overturning is checked about the point of rotation at the bottom end of toe of inlet structure in the horizontal direction.

$$\text{Factor of Safety } (FOS) = \frac{\text{Restoring Moments}}{\text{Overturning Moments}}$$

b) Sliding: $\text{Factor of Safety (FOS)} = \frac{\text{Resisting forces}}{\text{Sliding forces}}$

c) Foundation base Pressure: $Base\,Pressure = \frac{W}{b.L}[1 \pm \frac{6.e}{L}]$

Where,

b: Foundation base width (m)

L: Foundation base length (m)

e: Eccentricity of load

W: Algebraic sum of the vertical forces

Factors of safety: As per relevant IS codes, factor of safety must be more than those given in Table 5 below.

Results

Results-stability analysis of inlet structure

The results of stability analysis carried out are given below (Cases 1 and 2).

Case 1: Lock considered as empty, i.e. maintenance condition–Results of stability analysis of inlet structure.

Stability Check	FOS (Normal case)	FOS (Seismic case)	Remarks
Overturning	2.04	1.5	Safe

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Sliding	1.87	1.21	Safe
Base Pressure (kN/m²)	Max. 158.43	Max. 259.14	Safe
	Min. 119.51	Min. 18.04	Safe

Case 2: Lock considered fully filled but no backfilling along the structure, i.e. testing condition-Results of stability analysis of inlet structure.

Stability Check	FOS (Normal case)	FOS (Seismic case)	Remarks
Overturning	2.5	1.92	Safe
Sliding	2.16	1.4	Safe
Base Pressure (kN/m²)	Max. 332.09	Max. 438.78	Safe
	Min. 110.94	Min. 10.83	Safe

Results-stability analysis of outlet structure

Typical cross-section at Outlet is shown in Figure 13. The results of stability analysis carried are given below (Cases 3 and 4).

Case 3: Lock considered as empty, i.e. maintenance condition-Results of stability analysis of outlet structure.

Stability Check	FOS (Normal case)	FOS (Seismic case)	Remarks
Overturning	2.27	1.65	Safe
Sliding	1.88	1.65	Safe
Base Pressure (kN/m²)	Max. 206.64	Max. 299.66	Safe
	Min. 118.68	Min. 34.82	Safe

Case 4: Lock considered fully filled but no backfilling along the structure, i.e. testing condition- Results of stability analysis of outlet structure.

Stability Check	FOS (Normal case)	FOS (Seismic case)	Remarks
Overturning	2.2	1.9	Safe
Sliding	2.21	1.69	Safe
Base Pressure (kN/m²)	Max. 184.56	Max. 193.47	Safe
	Min. 93.58	Min. 66.56	Safe

Base slab

The sub-surface flow of water plays an important role for the stability of structure. The base slab gets destabilized due to uplift pressure and provision of sufficient floor thickness/tension piles prevents the failure against uplift pressure. Typical arrangement of Tension Piles at Base slab is shown in Figure 14.

Uplift pressure at the base, or below the foundation, is taken care of by providing 2 m thick base slab and 900 mm diameter cast *in-situ* 15 m deep tension piles. The base slab has been designed to act as Pile cap. The pile shall be capable of sustaining a load of not less than 3 times the specified working load for piles in tension, before ultimate failure and as may be determined by calculation.

Minimum factor of safety	Normal	Seismic
Sliding	1.5	1.2
Overturning	2	1.5
Base Pressure(KN/m²)	<500 KN/m²	<750 KN/m²

Table 5: Requirements of factors of safety.

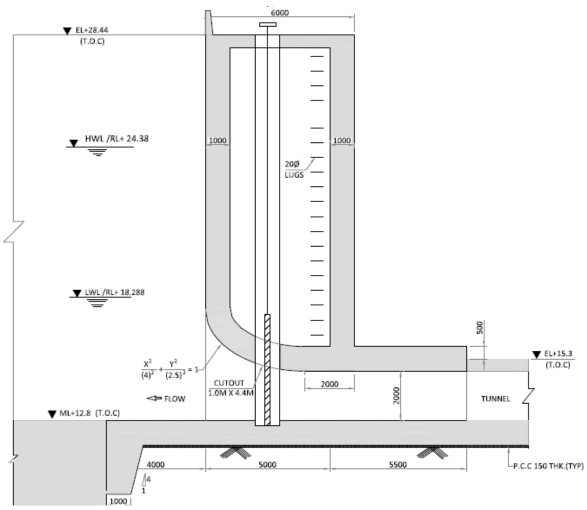

Figure 13: Typical cross-section at outlet (in mm).

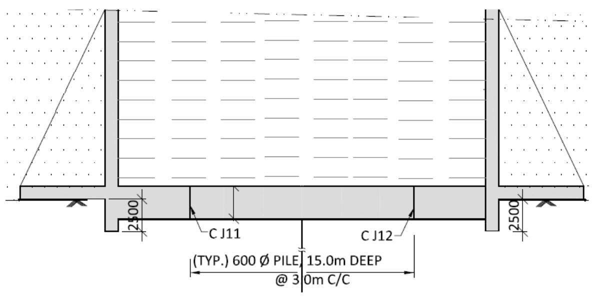

Figure 14: Typical arrangement of tension piles at base slab (in mm).

Load	FOS
Skin friction on tension piles	(SF)=3.0
Lateral load	(SF)=2.0

Table 6: Safety factors geotechnical working load capacities of the piles.

Adopted factors of safety

The following safety factors are used to establish the safe geotechnical working load capacities of the piles given in Table 6 below.

Discussion

Engineering of hydro-mechanical works

Mitre Gates are proposed one at upstream and another at downstream of the lock to facilitate opening and closing operation. Double leaf hinged type Mitre gates are proposed in the new lock. Differential water head considering maximum water level on the upstream side and other side empty shall be considered for design. The gate shall be operated through electro-hydraulic system.

Two numbers floating type of Caisson Gates are proposed for replacement/repair/maintenance of Mitre Gate. Gates will be installed vertically at both end of the lock for stopping water flow from upstream and downstream of lock chamber only when Mitre gates are to be repaired. The sinking and raising operation of the gate shall be carried out through suitable valve arrangement without requiring any external assistance.

Four numbers Radial gates are proposed, 2 numbers at upstream and 2 numbers at downstream at both side of lock for filling and emptying of the lock chamber. The Radial gates should be designed for the differential water head considering maximum water level on upstream side and other side considering empty. The gate shall be operated through electro-hydraulic system. The control system shall be PLC based.

For repair of Radial gates, there will be eight numbers bulkhead gates at the inlet and outlet for all feeder culverts. The Bulk Head gates should be designed for the differential water head considering maximum water level on one side and other side considered empty. The bulkhead gate shall be operated by electrically operated rope drum hoists.

Conclusion

The main components of Navigation lock comprise of approach channels, lock Pit, filling/emptying arrangement and operating gates. Based on the location and locking requirements all of these components should be adopted. Approach channel should provide straight entry/ exit to the locking vessels and it should also ensure that an adequate waiting area is available for waiting vessel. Locking pit consists of the retaining structure and base slab. The type of both these structures should be finalized based on the available construction mechanism, ease of construction and overall economy of the system. Filling/emptying system is chosen to get appropriate filling/emptying time, without the requirement of pumping. The face of the culvert at inlet and outlet shall be smoothened so as to provide smooth entry to the flow and minimize disturbance to the vessel in the lock pit. Operating gates shall be chosen based on the requirement for locking time requirement of the space and reliability in operation. Considering all these factors along with the site conditions and the river morphological characteristics the navigation lock has been designed as latest “state of art” technology.

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