Design Optimization of Underground RCC Tanks Governed by Hydrostatic Uplift

*** Paulraj S.**

Abstract

Depth of underground tanks in reinforced concrete used for collection of water or other liquids by gravity is in principle governed by invert level of inlet. Depending on process requirements, supply to the tank could be either through open drains as in the case of settling ponds or through pipes which convey sludge into these tanks. Where freeboard height is relatively more than liquid depth, overall depth of the tank increases considerably as compared to the actual storage capacity required. Owing to this increase in depth below ground level, stability of the tank against uplift turns out to be critical for design if ground water table must be considered up to ground level. The following discussion explores a design alternative which is quite easier, when site conditions do not suit use of traditional under-reamed piles. This concept had been adopted in coal based thermal power plants engineered and executed.

Keywords : Counterweight, freeboard, hydrostatic uplift, liquid storage depth, underground reinforced concrete tanks, water table

I. INTRODUCTION

Elevation of storage tanks with respect to ground level is decided by their functional requirements. Reinforced concrete tanks which are above ground level are supported by framed construction or a mix of wall and column-beam framework. However, open underground tanks founded directly on soil are governed mainly by hydrostatic uplift considerations in design. The deeper the tank, higher is the counterweight required to prevent uplift with adequate margin of safety.

Let us take the cases of two different underground tanks, first, a sludge sump meant to collect sludge from a pre-treatment facility and second, a settling pond meant to collect wash water from a paved stockpile area.

II. DESIGN APPROACH

A. CASE 1

A reinforced concrete open sump, 46m x 22m in plan with 5.5m inner depth below ground level for handling sludge discharged from pre-treatment plant. Inlet level of tank is 3.4m below ground level with a liquid-cum-sludge storage depth of 2.1m. Pressure relief valves are generally not permitted in these tanks to prevent contamination either by ingress or egress.

Design of this tank is to be done according to [1] for empty condition with ground water table right up to ground level with a Factor of Safety (FOS) of 1.2 against uplift (Fig.1).

1) Conventional Design

This requires counterweight for stability against uplift due to upward hydrostatic pressure. Using lean concrete counterweight over raft as the only counteracting force, thickness of lean concrete required is noted below:

Unit weight of water, γ_w : 9.81 kN/cu. m.
Specific weight of PCC, γ_c : 24 kN/cu. m.
Depth of tank including freeboard from ground level (D) : 5.5 m
Thickness of PCC including base slab : T in metres
Reduction factor for unit weight of concrete, r : 0.9

Equating the upward and downward forces with necessary factors for one sq. m. area, i.e

$$\gamma_w (D + T)*1.2 = T* \gamma_c *r,$$

Value of T works out to 6.58 m

For a storage liquid depth of 2.1m, total depth of tank

Manuscript received August 12, 2019; revised August 20, 2019; accepted August 26, 2019. Date of publication November 5, 2019.
* Paulraj S. is Vice President - Civil Design with BGR Energy Systems Limited, 443, Anna Salai, Teynampet, Chennai, Tamilnadu, India - 600018. (email: paulraj2k4@gmail.com)
DOI:10.17010/ijce/2019/v2i2/149068

from ground level to bottom of base works out to 6.58 + 2.1 + 3.4 = 12.08 m, if base slab alone is meant to counter the entire hydrostatic uplift with required factor of safety.

B. Alternative Design

Available freeboard depth of 3.4m is used for providing a counterweight in the form of RC trough of size 7.7 m x 3.5 m x 46.0 m filled with sand without compromising on functionality. Twelve RC columns are introduced from bottom raft to support the central RC trough along the length of the sump at around 6.5m intervals. Transverse framing beams are also added at sump top level connecting outer walls and trough. This arrangement acts as props for outer walls which are to be designed as uncracked sections [2][3]. Base raft projection of 3.1m is kept all along the outer walls to invoke soil weight. Stability against uplift with required factor of safety is achieved using this technique while limiting the raft thickness to 1.1m. Bottom level of raft is also restricted to 6.6m below ground level. Calculations for uplift check are given as follows:

Area of base raft, A : 54.5 * 30.5 = 1662 sq. m.
Hydrostatic upward pressure
at 6.6m below GL, P_u : 9.81*6.6 = 64.8 kN/sq. m.
Maximum uplift at raft bottom : $P_{u*}A$ = 107624 kN
Total downward load = Weight of (RC tank + RC trough + Saturated soil above raft projection)

Weight of RC tank = Volume of concrete * 25 kN/cu.m.
= 2450 * 25 = 61250 kN
Weight of trough
= ((7.7*3.5)*16+(7.7-7)*(3.5-0.55)*(25-16))*46
= 20690 kN
Soil weight on raft projection considering top slope
= (1662-((54.5-7.6)*(30.5-7.6)))*5.6*20 = 65855 kN
Factor of Safety for uplift = (147795)*0.9/107624 = 1.24

Volume of concrete equivalent to sand trough required in conventional design: 20690/(24*0.9) = 958 cu. m. This could be done by lowering the raft below bottom level by 950 mm and filling with lean concrete inside the sump which again has a cascading effect on hydrostatic uplift.

Minimum savings in concrete in the alternative concept with sand trough is around 500 cu. m. over and above the reduction in earthwork excavation and backfilling.

Raft behaves as a structural slab spanning between long walls with hogging moments. RC columns which transfer the counterweight from sand trough help in controlling these hogging moments. Punching effect below columns calls for local thickening of raft parallel to long walls as per Sec 1-1.

This can be compared to traditional use of under-reamed piles as prescribed in Table 1 of IS:2911 (Part-III) [4] considering an example of 300 mm diameter:

Safe uplift load with single bulb, 3.5m long : 8 T
Spacing of piles at 5 times diameter : 1.50 m

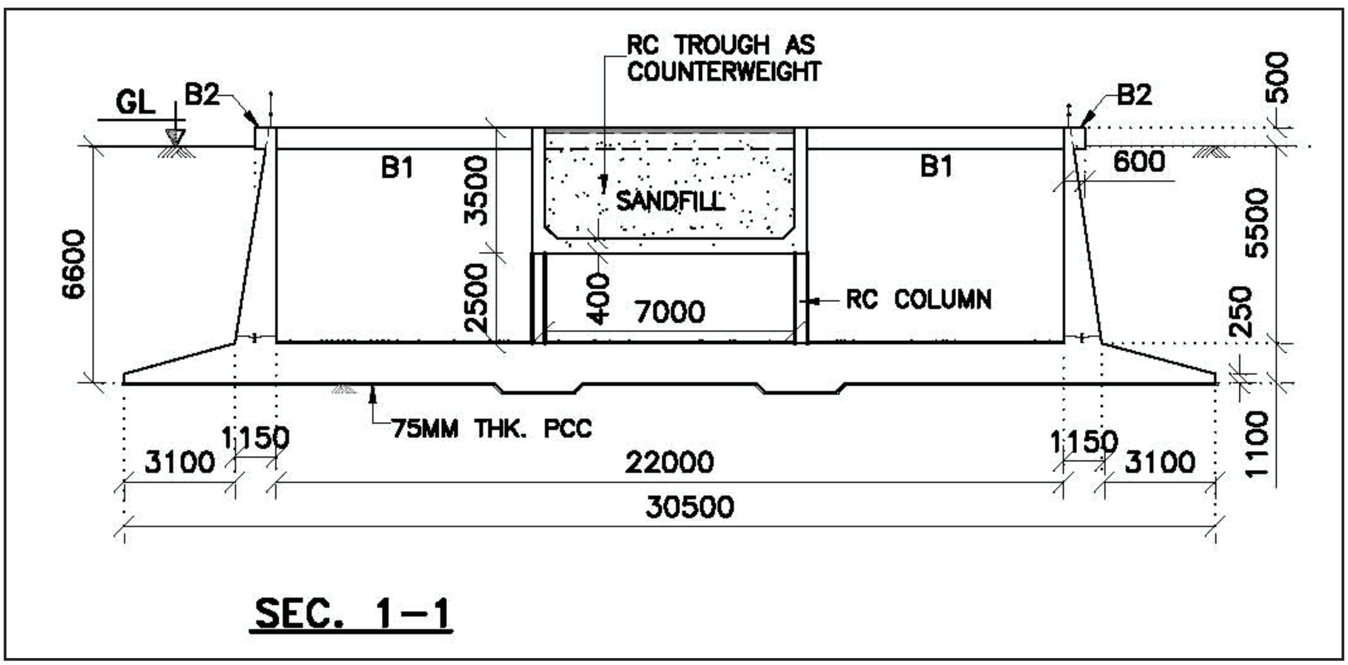

Fig. 1. (a) Cross Section of Sludge Sump

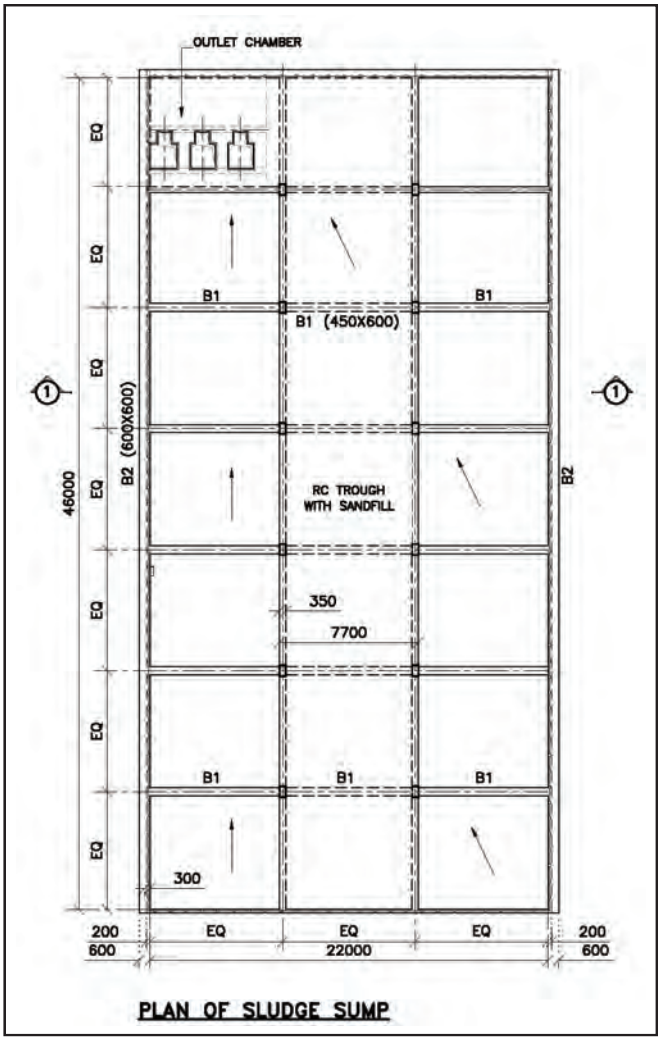

Fig. 1. (b) Plan of Sludge Sump

Tributary area for piles at this spacing : 2.25 sq.m.
Weight of 950 mm PCC = (0.95*2.4*0.9) : 2.05 T/sq.m.
Counterweight required for tributary area : 4.61 T
that is, 3 m long, 300 mm diameter under-reamed piles with single bulb at 1.5 m centres in both directions are required which translates to 450 piles within the sump.

Higher diameter under-reamed piles in the range of 375 and 500 mm spaced at 5 times the diameter both ways would help in reducing the number of piles between 288 and 162 respectively.

B. CASE 2

Settling pond of size 38.8 m x 19.1 m in plan with 3.46 m inner depth below ground level in two equal compartments of 19.3 x 18.7 m each. Each compartment is further partitioned into three chambers with baffle walls of varying heights across the direction of flow. Function of this tank is to receive coal contaminated surface discharge through storm water drains from an open coal stockpile, retain it for a specified duration, and allow coal particles to settle by gravity in these chambers. Water that gets collected in the last chamber is then pumped out for further treatment to comply with environmental norms.

Design of this tank is to be done for empty condition with ground water table right up to ground level with a Factor of Safety (FOS) of 1.15 against uplift.

1) Conventional Design

This requires counterweight for stability against uplift due to upward hydrostatic pressure. Using lean concrete as the only counterweight over raft, calculation for its thickness is noted as follows:

Depth of tank including freeboard
of 2.0 m from ground level (D) : 3.5m
Thickness of PCC including base slab : T in metres
Reduction factor for specific weight of concrete, r : 0.9
Equating the upward and downward forces with necessary factors for one sq.m. area, viz.,
$\gamma_w (D+T)*1.15 = T*\gamma_c*r$,
Value of T works out to 4.19 m.

For a storage liquid depth of 1.5 m, total depth of tank from ground level to bottom of base works out to 4.19 + 1.5 + 2 = 7.69 m if base slab alone is meant to counter the entire hydrostatic uplift with required factor of safety.

2) Alternative Design

Depth of 2 m freeboard available is used to introduce a sand trough over central partition wall above the maximum water level. Without increasing overall depth of the tank, internal baffle walls are raised for the full height with cut-outs at required elevations, for movement of water from one chamber to the other as per functional requirements. Base raft is extended all along outer walls to the required extent to invoke soil weight. With this arrangement, base raft is designed as one-way continuous structural slabs spanning between long walls. Internal long walls in turn, act as deep beams spanning between outer walls, and central sand trough. Central RC trough filled with sand provides the required downward reaction for long walls. Stability against uplift with the required factor of safety is achieved using this technique. Please refer to Fig. 2 & 3 which show this arrangement.
Calculations for uplift check:
Area of base raft, A : 43.4*23.7 = 1029

sq.m.

Hydrostatic upward pressure at 4.11m
i.e. (3.46+0.65) below GL, P_u : 9.81*4.11
= 40.3 kN/sq.m.

Maximum uplift at raft bottom : $P_{u*}A$ = 41471 kN

Total downward load = Weight of (RC tank + Trough + Saturated soil above raft projection + Submerged weight of soil wedge considering 30 degrees to vertical, compatible with soil type)

Weight of RC tank = Volume of concrete * 25 kN/cum
= 1032.8*25 = 25820 kN

Weight of trough
= (18.7*5.9*2.085*25)-(18.7*5.4*1.635*9) = 4265 kN

Soil weight on raft projection
= (1029-(39*19.3))*3.46*20 = 19091 kN

Soil wedge outside raft projection at 30 degrees to vertical
((43.4+1.33)+(23.7+1.33))*2*3.46*2*0.5*10.19
= 4919 kN

Factor of safety for uplift = (54095)*0.9/41471 = 1.17

In both these cases, base slab acts as a structural slab spanning between walls and restraints offered by the sand trough arrangement. Local thickening is done at areas where there is local concentration of stresses to impart the necessary strength.

III. CONCLUSION

As could be seen from the analysis in this paper, alternative method of design adopted is easier and it also saves time in execution as compared to conventional design.

This concept is particularly useful when depth of underground tanks is high owing to a large freeboard and there is enough space available for introducing such counterweights.

However, it would be more appropriate to limit the overall depth of underground tanks below ground level from functional considerations, right at the process design stage.

This could be done by locating the sumps at lower elevations in the layout where freeboard can be

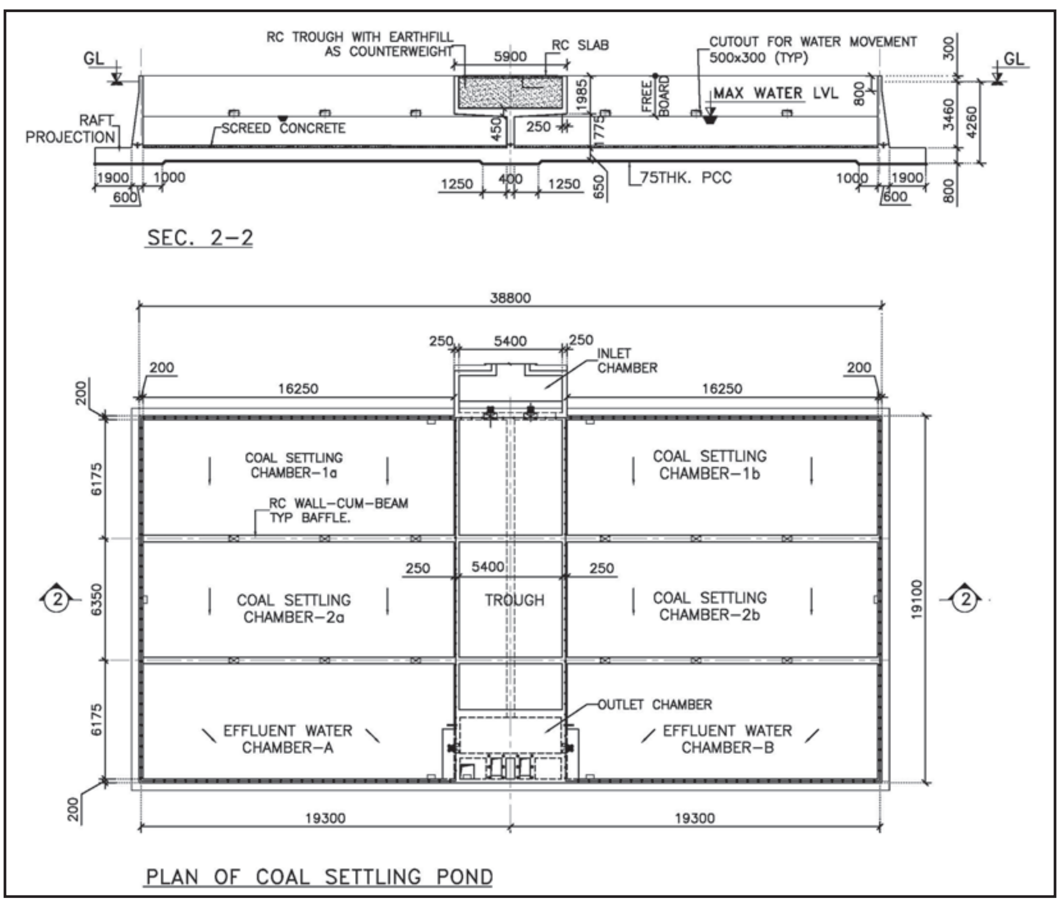

Fig. 2. Plan and Cross Section of Coal Settling Pond

maintained at a minimum, when flow into them is through gravity. Similarly, for a given storage capacity, plan size of underground sumps shall be increased with an eventual reduction in depth.

It should be noted that the alternative using sand trough as counterweight is ideal when traditional method of providing bored cast-in-situ reinforced concrete under-reamed piles is time-consuming for qualitative under-reaming, subsequent evaluation, and validation of capacities through routine pile load tests at deeper elevations.

Also for very loose sandy soil whose N value is less than or equal to 4, as per Clause B-1.5 of IS:2911 (Part-III), safe loads prescribed in Table 1 are to be reduced by 50%. Formation of bulbs in loose sandy soil requires extreme care during execution to ensure that estimated safe loads are achieved. Reference should also be made to [5].

Fig. 3. Coal Settling Pond – As Constructed View

ACKNOWLEDGMENT

The author thanks the opportunity provided by M/s BGR Energy Systems Limited, EPC organization which engineered and executed 2 x 600 MW Turnkey EPC package for M/s Rajasthan Vidyut Utpadan Nigam Limited, Kalisindh, Rajasthan, and 1 x 800 MW Balance of Plant package for M/s Tangedco, North Chennai Thermal Power Project-Stage-3 expansion, Tamil Nadu.

He also places on record his sincere thanks to Structural Engineer Mr. M. Dhandapani, who was instrumental in evolving this concept during the design phase of coal settling pond for Kalisindh project.

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About the Author

Paulraj S. is a Civil and Structural Engineering professional with over three decades of experience in structural design, review, and engineering coordination of industrial projects in sectors like cement, coal based thermal power, and automotives with added experience in direct execution of residential and commercial projects.

Projects engineered cover a range of structures in in-situ, precast & prestressed reinforced concrete and structural steel using Indian, American, British, DIN, and other international codes. He has considerable field experience in design supervision at project sites with a fair knowledge of erection methods. He also has working knowledge in proposal engineering and engineering management.