Freeboard Requirement in Dams

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INDIA

April 2024

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ABBREVIATIONS

ASCE	American Society of Civil Engineers
DPR	Detailed Project Report
E	East
eDF	Electricite De France
EL.	Elevation
FPV	Floating Solar Photovoltaic
FRL	Full Reservoir Level
GFRD	Geomembrane Faced Rockfill Embankment Dam
GoMP	Govt. of Madhya Pradesh
IREP	Integrated Renewable Energy Project
IS	Indian Standard
km	Kilometer
m	meter
MCM	Million Cubic Meter
MDDL	Minimum Drawdown Level
MP	Madhya Pradesh
MW	Mega Watt
MWL	Maximum Water Level
N	North
PSP	Pumped Storage Project
TCE	Tata Consulting Engineers Ltd.
TMC	Thousand Million Cubic Feet
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation

FREEBOARD REQUIREMENT IN DAMS

1.0 INTRODUCTION

India has set a target to reduce the carbon intensity of the nation's economy by less than 45% by the end of the decade, achieve 50 percent cumulative electric power installed by 2030 from renewables, and achieve net-zero carbon emissions by 2070. India aims for 500 GW of renewable energy installed capacity by 2030. In this regard India is accelerating the pumped storage projects, wherein artificial reservoirs are created by construction of dams. CEA has identified the PSP potential in India as 96254 MW. Hence, many artificial reservoirs are likely to be constructed in few years.

For estimation of freeboard in Dams, we use IS 10635-2014: (Reaffirmed 2020) "Freeboard Requirement in Dams- Guidelines". One of the inputs required in estimation of freeboard is the basic wind speed. For the data on basic wind speed with 50 yr return interval, IS 10635 refers to IS 875-part III-2015: "Code of practice for design loads (other than earthquake) for buildings and structures". The freeboard estimated using the wind speed as per IS 875, results in a freeboard of about 6.0 m or above since the side slope of the embankment dam on the reservoir side will be a smooth layer and results in higher wave run up. This note covers the limitations in the IS codes for estimation of freeboard and the optimization of the same using international codes.

2.0 REFERENCES

The IS codes/Guidelines/ international references pertaining to estimation of freeboard used in this document are as below.

i. IS 10635-2014: (Reaffirmed 2020) "Freeboard Requirement in Dams- Guidelines".
ii. IS 875-part III-2015: "Code of practice for design loads (other than earthquake) for buildings and structures".
iii. USACE: Engg. and Design: Coastal Engineering Manual – Part II EM 1110-2-1100 (Part II)30 September 2015)
iv. Guidelines on Freeboard for Dams-2011: Volume-I-Literature Review and case studies"
v. USBR, "Design Standard No. 13, Embankment Dams, chapter-6, Free Board
vi. EurOtop manual on, "Manual of wave overtopping of sea defence and related structures, second edition-2018.

3.0 LIMITATION IN IS CODES

The IS codes utilized while estimating the freeboard and the limitations are:

i. IS 875-part III-2015: “Code of practice for design loads (other than earthquake) for buildings and structures”.

The limitation in adopting the wind speed (gust) while estimating the wave height as per IS 10635-2014: (Reaffirmed 2020).

ii. IS 10635-2014: (Reaffirmed 2020) “Freeboard Requirement in Dams- Guidelines”.

Parapets are normally provided for protection of life of living beings and not to resist the wave forces. Hence it is not considered for calculation of free board. Parapet can be open web type or full solid wall. However when parapet wall is a solid material wall we can design the wall to resist the wave/wind load acting on wall and consider the same for free board requirement.

The limitation of this IS 10635, is that the parapet wall height cannot be considered as part of freeboard. In case of solid RC wall parapet, the wall height can be considered as free board.

In addition, IS 10635-2014: (Reaffirmed 2020) is silent on the effect of freeboard in case the wind direction is not perpendicular to the Dam axis.

The limitations for each of the codes are explained in the following paragraphs.

4.0 IS 875: PART III- 2015

4.1 Limitation of IS 875 wrt Wind Speed

As mentioned earlier, we use IS 10635-2014: (Reaffirmed 2020) “Freeboard Requirement in Dams- Guidelines” for the estimation of freeboard in dams. One of the data required in estimation of freeboard is the basic wind speed. For the wind speed, IS 10635 refers to IS 875-part III-2015: “Code of practice for design loads (other than earthquake) for buildings and structures.” This code indicates the wind speed to be considered for the structural design of buildings. The basic wind speed mentioned in the IS code corresponds to 3 seconds gust wind speed (Refer Clause 6.2).

6.2 BASIC WIND SPEED

Figure 1 gives basic wind speed map of India, as applicable to 10 m height above mean ground level for different zones of the country. Basic wind speed is based on peak gust velocity averaged over a short time interval of about 3 s and corresponds to mean heights above ground level in an open terrain (Category 2). Basic wind speeds presented in Fig. 1 have been

However, the 3-seconds gust wind speed is of insufficient duration to fully develop waves significant wave height. Specifically, the wind speed duration of 3 seconds is insufficient to develop the wave height, which would occur due to the traction of a constant wind at this speed and propagate the wave across the reservoir. This calls for wind speed adjustments appropriate for developing significant waves in the reservoir. The details of correction have been dealt in the following paragraphs.

4.2 Duration Adjustment for Wind Speed

Wind speed adjustments appropriate for developing significant waves in the reservoir is given in the equation below. (Refer - Figure II-2-1-USACE: Engg. and Design: Coastal Engineering Manual – Part II EM 1110-2-1100 (Part II)30 September 2015**)**

For $t \le 3{,}600$: $$\frac{U_t}{U_{3,600}} = 1.277 + 0.296 \tanh\left(0.9 \log_{10}\left(\frac{45}{t}\right)\right) \quad \text{Eqn. 1}$$

For $3{,}600 < t < 36{,}000$: $$\frac{U_t}{U_{3,600}} = -0.15 \log_{10} t + 1.5334 \quad \text{Eqn. 2}$$

where:

t = time (seconds)

U_t = wind speed (mph) at time t (seconds)

$U_{3,600}$ = 1-hour average wind speed (mph)

The minimum duration of time required for the development waves for the defined velocity of wind speed over water surface is calculated from the equation given below.

$$t = 112 \frac{X^{0.67}}{u^{0.34}} \quad \text{Eqn. 3}$$

where:

t = wind duration time (minutes)

X = fetch length (miles)

u = wind velocity (mph)

5.0 IS 10635:2014

5.1 Limitation of IS 10635:2014

The limitations in this code are as below.

i. Wind Direction: Figure-1 of IS 10635: The central fetch line is usually drawn along the predominant wind direction from the dam axis. Wind perpendicular to dam axis will always result in maximum wave height. The code is silent on the correction factor to be applied in case of predominant wind direction is not perpendicular to the dam axis. Hence, the correction need to be applied.

ii. Parapet Wall: Clause 7.2, “1.0 m high solid parapet wall may be provided in all dams on the upstream side, but the same is not to be considered as part of the free board.” Having provided RCC parapet wall all along the upstream side of the embankment dam of length of few kilometers in PSP projects, and not accounting the same for freeboard would be cost ineffective design.

The correction factors followed in international codes have been explained below.

5.2 Correction factor for wind direction as per USBR

The wave heights will be maximum if the predominant wind direction (Refer Wind rose diagram for particular site) is perpendicular to the Dam axis. In case the wind direction is not perpendicular, there is a correction factor applied in USBR, “Design Standard No. 13, Embankment Dams, chapter-6, Free Board”. The correction factor curve is furnished in Figure-1.

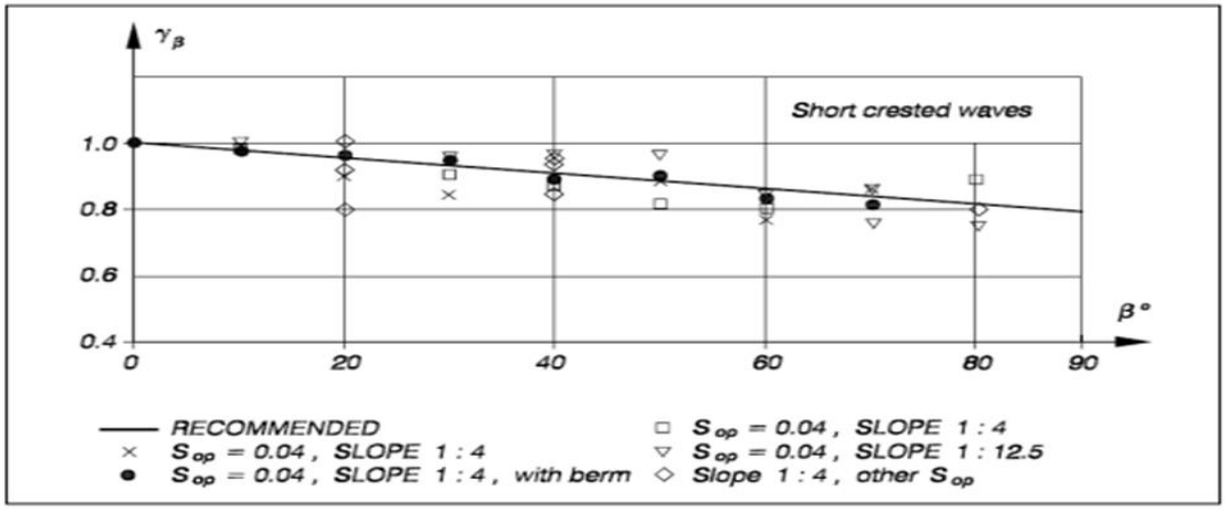

Figure B-4. Influence of angle of incidence, β, and the directional spreading on runup on smooth slopes at Delft Hydraulics [16b].

Figure - 1: Correction factor curve for the wind inclination with the dam axis

β=

5.3 Correction factor for Parapet wall

EurOtop manual on, “Manual of wave overtopping of sea defence and related structures, second edition-2018” has covered the correction factors to be applied to include the parapet wall height as part of free board. This Overtopping Manual gives guidance on analysis and/or prediction of wave overtopping for flood defences attacked by wave action. It is primarily, but not exclusively, intended to assist government, agencies, businesses and specialist advisors & consultants concerned with reducing flood risk. Methods and guidance described in the manual may also be helpful to designers or operators of breakwaters, reclamations, or inland lakes or reservoirs.is helpful to design or operate of breakwaters, reclamations, or inland lakes or reservoirs.

As per EurOtop manual, the parapet wall at the top of dam also affects the wave run up height and correction factor due to the parapet will be calculated from the formula given below,

$$Y_v = \text{Exp}\ (-0.56 \times (h_{wall} / R_c))$$

The slope and parapet wall arrangement are furnished in Figure-2.

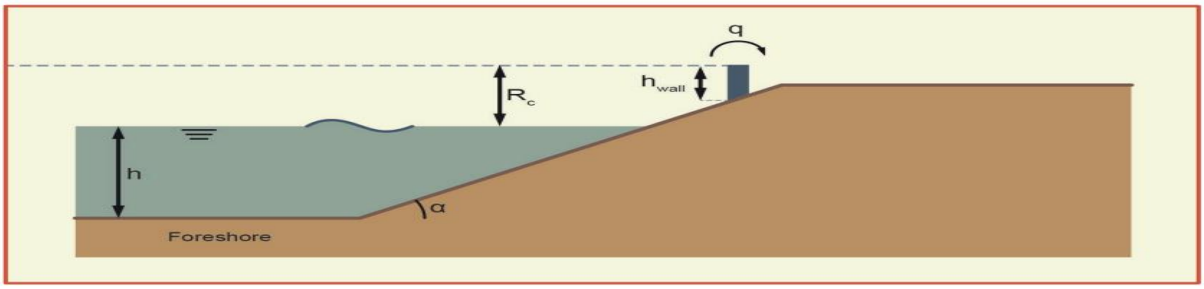

Figure - 2: Arrangement of slope and Parapet wall

6.0 CASE STUDY

Freeboard has been estimated for proposed embankment dam for a Pumped Storage Project in Madhya Pradesh and the details are below.

6.1 Wind Speed Adjustment

The calculation of wind speed adjustment is based on the worked example given in “Guidelines on Freeboard for Dams-2011: Volume-I-Literature Review and case studies” and the step-by-step calculations are as below. For calculation purpose basic wind speed and fetch length is converted into English units.

- The assumed 3 second gust-wind speed in reservoir area is 105.14 mph (47 m/s)
- As we are considering 50-year frequency, the wind speed conversion will be 1 as per Table DCM 2-2 in the “Guidelines on Freeboard for Dams 2011”.

- Adjusting the 105.14 mph, 3-second wind speed to a 1-hour wind speed duration with Eqn. 1.

$$U_3/U_{3600} = 1.51$$

- The resulting 1-hour average wind speed would be 69.66 mph (105.14/1.51)
- As per clause A-1.3 of IS 10635-2014, the wind speed on water surface has been calculated with coefficient derived from the fetch length with wind speed on land.

Table 1 Wind Velocity Relationship from Land to Water
(*Clause* A-1.3)

Effective Fetch, in km (F_e)	1	2	4	6	8	10 and above
Coefficient $Q(V/W)$	1.1	1.16	1.24	1.27	1.30	1.31

Source: IS 10635-2014: Freeboard Requirement in Dams – Guidelines

The effective fetch for the upper reservoir is 1.67 km and the corresponding coefficient is 1.134. Wind speed over the water surface is estimated to be 79 mph.

- The central fetch is 1.32 miles (2125 m). For this 79.0-mph wind speed, the minimum duration time from Eqn. 3 is 30.5 minutes (1833 seconds).
- Adjust the 1-hour 79 mph wind speed to 30.5 minutes duration using Eqn. 1 since it is less than 3600 seconds.

$$U_{1833}/U_{3600} = 1.012$$

- The resulting 30.5-minute average wind speed would be 79.9 mph or 36.0 m/s (79*1.012) and the same will be used for the freeboard determination. The detailed calculation of wind speed adjustment is furnished in Table below.

Table - 1: Wind Speed: Duration correction

Sl. No	Computed Item		Remarks
1.	Central fetch length	2125 m	
2.	Central fetch length (X)	1.32 miles	
3.	Basic Wind Speed (50-yr return period-IS 875)	**47 m/s**	3 second gust-wind speed
4.	Basic Wind Speed (50-year return period)	105.14 mph	3 second gust-wind speed
5.	3-second wind speed to a 1-hour wind speed duration (U3/U3600)	1.51	Eqn-1
6.	1-hour average wind speed = (4) / (5)	69.66 mph	**31.14 m/s**
7.	Over water wind speed (u) = (6) * 1.134	79 mph	35.31 m/s
8.	Minimum Duration of wind speed	30.5 minutes	Eqn-3
9.	Minimum Duration of wind speed (t) = (8) * 60	1833 seconds	
10.	1833-second wind speed to a 1-hour wind	1.012	Eqn-1 (t<3600)

Sl. No	Computed Item		Remarks
	speed duration (U_{1833}/U_{3600})		
11.	Over water wind speed = (7) * (10)	79.9 mph	
12.	Over water wind speed	36 m/s	

From the above it is seen that the 50-year basic wind speed and the corrected wind speed for appropriate wind duration are 47 m/s and 31.14 m/s respectively (about 30% reduction in windspeed).

6.2 Freeboard Calculation

Freeboard has been estimated considering the adjusted wind speed using IS: 10635-2014.

Table - 2: Freeboard Calculation for Embankment dam

S.No	Description	Units	Freeboard Without Wind Speed Correction	Freeboard With Wind Speed Correction
1.	Central Fetch (F)	km	2.13	2.13
2.	Effective Fetch (Fe)	km	1.67	1.67
3.	3 second gust Wind Velocity over land (U)	m/s	**47.00**	47.00
4.	Wind speed accounting correction for wind duration	m/s	-	**31.14**
5.	Coefficient for conversion of wind speed over water	m/s	1.134	1.134
6.	Wind velocity over water (V)	m/s	53.30	36.00
7.	Significant wave height (Hs)	m	1.71	1.131
8.	Wave Period (Ts)	s	4.08	3.43
9.	Wavelength (Ls)	m	25.97	18.39
10.	Design Wave height (Ho) in m	m	2.86	1.89
11.	Wave steepness (Ho/Ls)		0.11	0.10
12.	Relative run-up (R/Ho)		2.36	2.36
13.	Run Up (R)	m	6.76	4.46
14.	Coeff. for roughness		1.00	1.00
15.	Designed ‘Ra’ considering type of surface	m	6.76	4.46
16.	Average depth (D)	m	23.70	23.70
17.	Wind setup	m	0.053	0.024
18.	Freeboard Required	m	6.90	4.50

From the above it is seen that the estimated freeboard without and with wind speed correction is 6.90 m and 4.50 m respectively. It is noted that with wind speed correction, the freeboard reduces to about 35%. Considering the embankment height of more than 25 m and a length of about 6.0 km, significant reduction in the rockfill requirement, construction time and cost is expected (Refer Figure 3). Considering the PSP potential in India of about 96254 MW (as per CEA) the cost saving is expected to be about Rs. **9526** Crores. In light of the above, it would be prudent to revise the IS code 10635:2014 to include the windspeed correction.

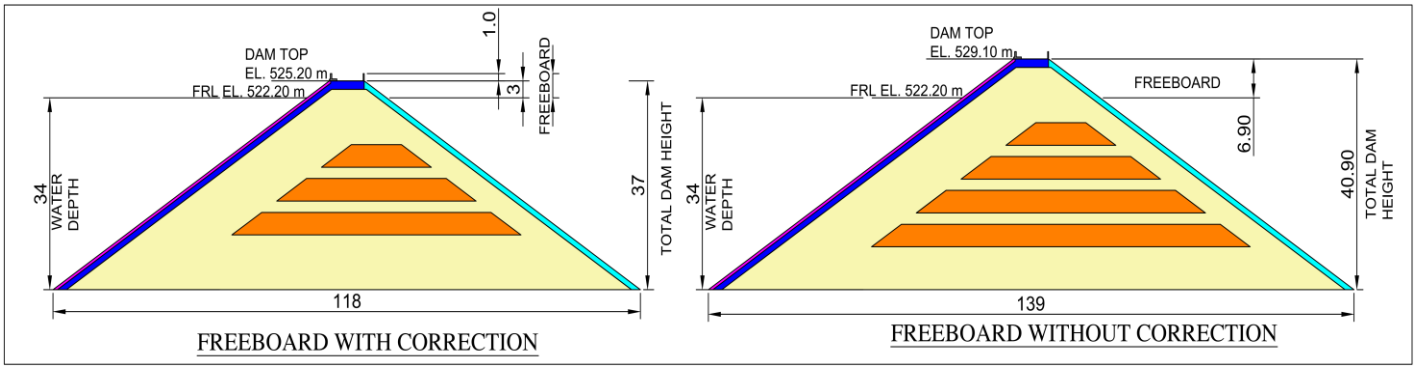

Figure - 3 : Comparison of Embankment dam with and without corrections

The angle of inclination between perpendicular of dam axis with central fetch is 1^{o} and the same is furnished in Figure-4. The correction factor considered from the curve is 1.

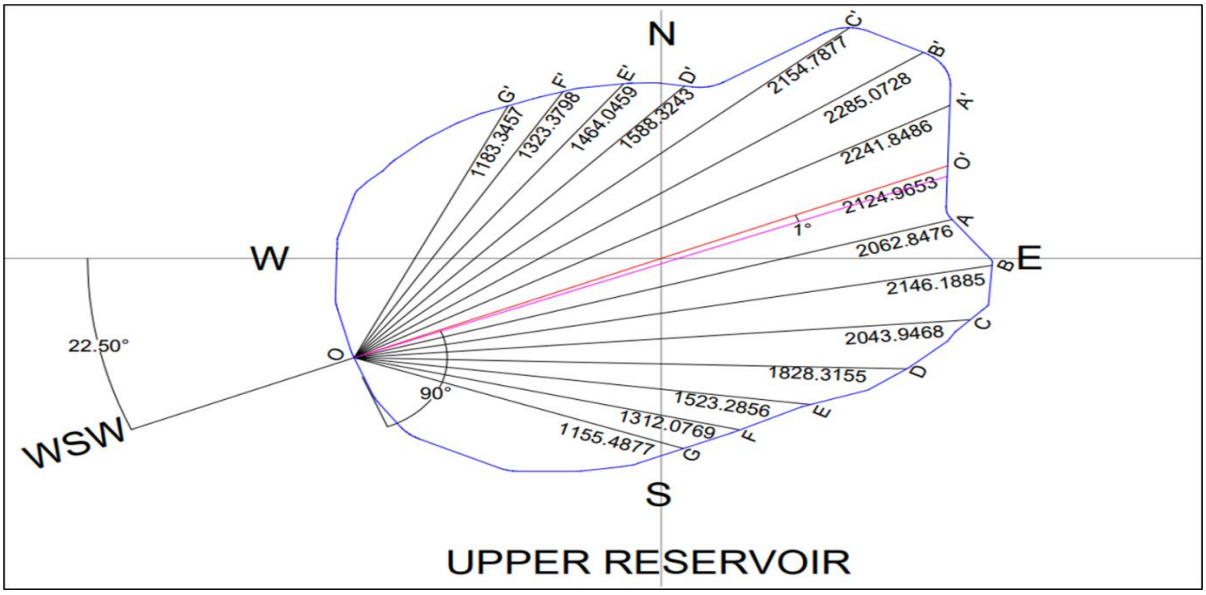

Figure - 4: The Angle of Inclination between perpendicular of dam axis with central fetch

The correction factor is calculated and summarized below:

Table - 3: Correction for Freeboard

Sl.No.	Description		Remarks
1.	Freeboard with wind speed reduction	4.50 m	Refer Table-2
2.	Correction factor based on Wind direction	1.00	Refer Clause-5.2
3.	Correction factor based on parapet wall	0.87	exp (-0.56 x (1.0/4.0)) = 0.87
4.	Freeboard = (1x 2x3)	3.91 m	
5.	Say	**4.0 m**	

6.3 Summary of the Freeboard Calculation

The summary of freeboard calculation with and without applying the relevant correction factors for the case under study is furnished in Table-4. It is noted that there will be a reduction of Dam height is substantial and is about 3.1 m by applying all the corrections including the wind speed correction. Incorporating the corrections as indicated in this note results in the following:

i. Reduction of Dam height by 3.1m
ii. Reduction in Base width of the Dam by about 21 m,
iii. Reduction in Land acquisition about 12.6 Hectares
iv. Reduction in construction material by about 4.04 MCM and
v. Reduction in construction time
vi. Overall capital cost reduction of about Rs. 200 Crores excluding the advantage of reduction in construction time and land acquisition.

- Benefits : Estimated freeboard without and with all corrections above is 6.90m and 3 m respectively. Applying the corrections as indicated in this note results in the following:
  i. Reduction of Dam height by 3.1 m
  ii. Reduction in Base width of the Dam by about 21 m,
  iii. Reduction in Land acquisition about 12.6 Hectares
  iv. Reduction in construction material by about 4.04 MCM and
  v. Reduction in construction time
  vi. Overall cost reduction of about Rs. 200 Crores excluding the advantage of reduction in construction time and land acquisition.
- Considering the embankment height of more than 25 m and a length of about 6.0 km, significant reduction in the rockfill requirement, construction time and cost is expected with all the corrections indicated above. Considering the PSP potential of about 96254 MW (as per CEA) in India the cost saving would be about Rs. **9500** Crores. In light of the above, it would be prudent to revise the IS code 10635:2014 to include all the above corrections.

Table - 4: Freeboard Comparison

S.No	Description	Freeboard Without Wind Speed Correction	Freeboard With Wind Speed and other corrections
1.	Freeboard Required	6.90 m	4.50 m
2.	Correction factor based on Wind direction	-	1.00
3.	Correction factor based on parapet wall	-	0.87
4.	Freeboard Required	6.90 m	3.91 m
5.	Freeboard Considered	6.90 m	4.00 m
6.	Height of Embankment above FRL	6.90 m	3.00 m
7.	Height of parapet considered in Freeboard	-	1.00 m
8.	Reduction in Height of Dam	BASE	**3.9 m** (6.9-3.0)

7.0 CONCLUDING REMARKS

The following corrections need to be applied while estimating the free board requirement for the Embankment Dams for Pumped Storage Projects.

- Due to more importance given by GOI on renewable energy production, many PSP projects are proposed to be built. These projects demand to construct large water reservoirs for storage of water and use for power generation. Length of reservoirs are in several thousand meters. Any reduction in height of bund will result is huge savings in construction cost to tune of several hundred crores. Considering the national interest in resources and sustainable growth/ decarbonization aspects, there is need to revise the IS 10635.
- Wind Speed Correction: The wind speed mentioned in IS 875 PART III- 2015 pertains to 3 second gust wind. However, the 3-seconds gust wind speed is of insufficient duration to fully develop waves significant wave height. Specifically, the wind speed duration of 3 seconds is insufficient to develop the wave height, which would occur due to the traction of a constant wind at this speed and propagate the wave across the reservoir. This calls for wind speed adjustments appropriate for developing significant waves in the reservoir. The correction factor as mentioned in USACE guideline: Engg. and Design: Coastal Engineering Manual – Part II EM 1110-2-1100 (Part II)30 September 2015 has been referred.

  The estimated freeboard without and with wind speed correction is 6.90 m and 4.50 m respectively. Considering the wind speed correction, the freeboard reduces to about 35%.

- Wind Direction Correction: IS 10635 – 2014, Figure- 1: Computation of Effective Fetch, the wind direction is perpendicular to the Dam axis. Effect of freeboard in case the wind direction is not perpendicular to Dam axis is not covered in the code. The correction factor as mentioned in USBR, “Design Standard No. 13, Embankment Dams, chapter-6, Free Board” can be utilized.
- Parapet Wall Correction : IS 10635 – 2014, Clause 7.2, “1.0 m high solid parapet wall may be provided in all dams on the upstream side, but the same is not to be considered as part of the free board.” Having provided RCC parapet wall all along the upstream side of the embankment dam of length of few kilometers in PSP projects, and not accounting the same for freeboard would be a cost ineffective design. The considerations as per EurOtop Manual, “Manual of wave overtopping of sea defence and related structures, second edition-2018” can be referred. This Overtopping Manual gives guidance on analysis and/or prediction of wave overtopping for flood defences attacked by wave action. It is primarily, but not exclusively, intended to assist government, agencies, businesses and specialist advisors & consultants concerned with reducing flood risk. Methods and guidance described in the manual may also be helpful to designers or operators of breakwaters, reclamations, or inland lakes or reservoirs. Structural design of wall with adequate base length shall be arrived considering bearing resistance of soil under over topping RC wall moment. This also needs to be addressed in the IS code.

Our opinion is to include above aspects in the code appropriately for optimization without affecting safety & integrity of the dam structure.