# TECHNO-ECONOMIC ASSESSMENT STUDY FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

## PHASE II: PROJECT DEFINITION OPTIONS

## Volume 3: Engineering and Design

## Chapter 3: Alternatives design

## Appendix 6 - Freeboard due to waves

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| | | | | | |
|---|---|---|---|---|---|
| C | 13/08/2014 | Final-August 2014 | OCL | LBO | LBO |
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| A | 16/07/2013 | First Emission | OCL | NSA | NSA |

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# 1 INTRODUCTION

This note presents calculations that led to freeboard estimation to protect the dam against waves.

Freeboard is a safety measure to take into account the difference between theoretical maximum water level of still water and the one that is increased by waves and wind tide effects.

# 2 REFERENCES

[1] Freeboard criteria and guidelines for computing freeboard allowances for storage dams, USBR, 1992.

[2] Rogun HPP completion report, Hydrometeorological conditions, n°1861-2-2-2, Hydroproject Institute, 2009.

[3] Bankable feasibility study for Stage 1 construction completion, Vol3D “Hydrology”, Lahmeyer International, January 2006.

# 3 DEFINITIONS AND HYPOTHESIS

## 3.1 Fetch

Fetch length is the horizontal distance of open water surface over which the wind blows. In the past, the use of the greatest straight line distance over open water in waves’ computations had resulted in calculating wave heights that were too high, since the amount of adjoining open water having shorter but significant fetches influences the waves.

In [1], it is stated that “the recommended procedure for estimating the fetch over an inland reservoir having an irregularly shaped shoreline consists of constructing nine radials from he point of interest at 3° intervals and extending these radials until they first intersect the shoreline again on the opposite side of the reservoir. The length of each radial is measured and arithmetically averaged. […] This calculation should be performed for several directions (of the central radial) approaching the dam, including the direction where the central radial is normal to the dam axis and also the direction where 24° total spread results in the longest possible set of radials.

For each fetch calculated, the angle of the central radial with respect to a line normal to the dam’s axis should be determined. This angle will be used later to adjust the wave height considering that the wave may approach the dam from a less severe direction. “

Therefore, the fetch have been calculated on Rogun reservoir for the 3 alternatives according to the presented method. The next figure illustrates the method and highlights the main radials in the case of Rogun. The next table shows the results.

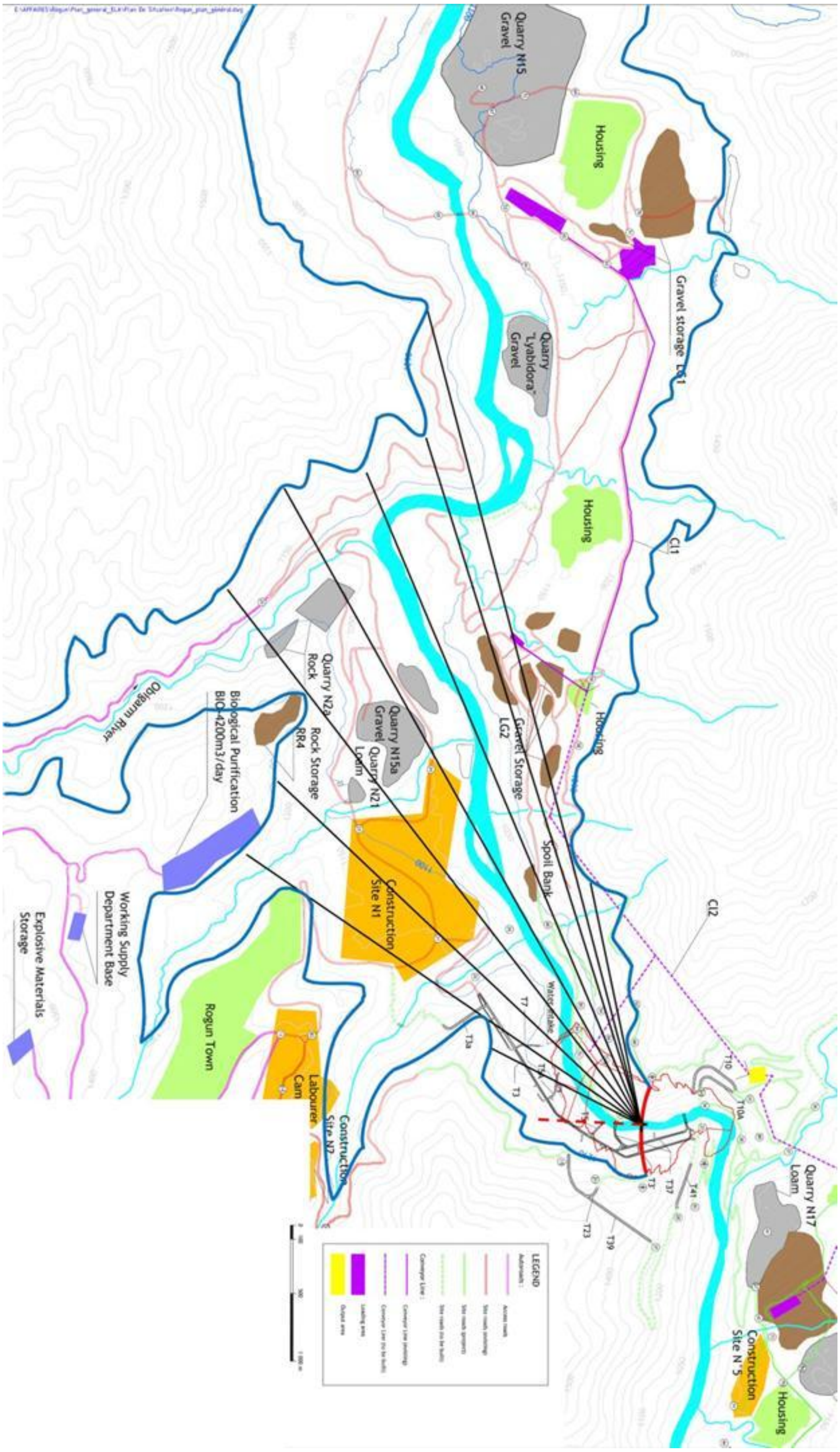


**Figure 3.1 : Fetch calculation - FSL = 1290 masl**

| Wind direction (°) | Fetch (km) |
|---|---|

| | FSL = 1290 masl | FSL = 1255 masl | FSL = 1220 masl |
|---|---|---|---|
| **0** | 0.389 | 0.347 | 0.306 |
| **3** | 0.608 | 0.558 | 0.508 |
| **6** | 1.266 | 1.208 | 1.149 |
| **9** | 1.882 | 1.816 | 1.749 |
| **12** | 2.467 | 2.392 | 2.317 |
| **15** | 3.021 | 2.946 | 2.871 |
| **18** | 3.567 | 3.492 | 3.417 |
| **21** | 4.104 | 4.029 | 3.954 |
| **24** | 4.622 | 4.547 | 4.472 |
| **27** | 4.978 | 4.903 | 4.828 |
| **30** | 5.188 | 5.113 | 5.038 |
| **33** | 4.960 | 4.885 | 4.810 |
| **36** | 4.761 | 4.686 | 4.611 |
| **39** | 4.572 | 4.497 | 4.422 |
| **42** | 4.367 | 4.292 | 4.217 |
| **45** | 4.172 | 4.097 | 4.022 |
| **48** | 3.732 | 3.657 | 3.582 |
| **51** | 3.296 | 3.221 | 3.146 |
| **54** | 2.876 | 2.801 | 2.726 |
| **57** | 2.581 | 2.506 | 2.431 |
| **60** | 2.287 | 2.212 | 2.137 |
| **63** | 2.004 | 1.929 | 1.854 |
| **66** | 1.733 | 1.658 | 1.583 |
| **69** | 1.461 | 1.386 | 1.311 |
| **72** | 1.173 | 1.098 | 1.023 |
| **75** | 1.121 | 1.046 | 0.971 |
| **78** | 1.079 | 1.004 | 0.929 |
| **81** | 1.041 | 0.966 | 0.891 |
| **84** | 1.003 | 0.928 | 0.853 |
| **87** | 0.961 | 0.886 | 0.811 |
| **90 (normal to the dam axis)** | 0.909 | 0.834 | 0.759 |
| **93** | 0.859 | 0.784 | 0.709 |
| **96** | 0.805 | 0.730 | 0.655 |
| **99** | 0.759 | 0.684 | 0.609 |
| **102** | 0.724 | 0.649 | 0.574 |
| **105** | 0.684 | 0.609 | 0.534 |
| **108** | 0.640 | 0.565 | 0.490 |
| **111** | 0.589 | 0.514 | 0.439 |
| **114** | 0.538 | 0.463 | 0.388 |
| **117** | 0.496 | 0.421 | 0.346 |
| **120** | 0.464 | 0.389 | 0.314 |
| **123** | 0.439 | 0.364 | 0.289 |
| **126** | 0.418 | 0.343 | 0.268 |
| **129** | 0.400 | 0.325 | 0.250 |
| **132** | 0.385 | 0.310 | 0.235 |
| **135** | 0.372 | 0.297 | 0.222 |
| **138** | 0.366 | 0.291 | 0.216 |
| **141** | 0.363 | 0.288 | 0.213 |
| **144** | 0.361 | 0.286 | 0.211 |
| **147** | 0.360 | 0.285 | 0.210 |
| **150** | 0.360 | 0.285 | 0.210 |
| **153** | 0.360 | 0.285 | 0.210 |
| **156** | 0.360 | 0.285 | 0.210 |
| **159** | 0.360 | 0.285 | 0.210 |

| | | | |
|---|---|---|---|
| **162** | 0.360 | 0.285 | 0.210 |
| **165** | 0.360 | 0.285 | 0.210 |
| **168** | 0.360 | 0.285 | 0.210 |
| **171** | 0.320 | 0.245 | 0.170 |
| **174** | 0.280 | 0.205 | 0.130 |
| **177** | 0.240 | 0.165 | 0.090 |
| **180** | 0.200 | 0.125 | 0.050 |
| **147** | 0.360 | 0.347 | 0.306 |
| **150** | 0.360 | 0.558 | 0.508 |
| **153** | 0.360 | 1.208 | 1.149 |
| **156** | 0.360 | 1.816 | 1.749 |
| **159** | 0.360 | 2.392 | 2.317 |
| **162** | 0.360 | 2.946 | 2.871 |
| **165** | 0.360 | 3.492 | 3.417 |
| **168** | 0.360 | 4.029 | 3.954 |
| **171** | 0.320 | 4.547 | 4.472 |
| **174** | 0.280 | 4.903 | 4.828 |
| **177** | 0.240 | 5.113 | 5.038 |
| **180** | 0.200 | 4.885 | 4.810 |

**Table 3.1: Fetch calculation for every wind direction - FSL = 1290 masl**

## 3.2 Wind velocity

Information on wind velocity has been found in reference [2] and [3] and comes from data recorded at meteorological stations of Garm, Komsomolabad and Obigarm.

Both average monthly and annual wind speed are presented ion the next table.

| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XI | An. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Garm (Rogun site) | 3.6 | 3.5 | 3.1 | 2.3 | 1.9 | 2.0 | 1.9 | 2.1 | 2.2 | 1.8 | 2.8 | 3.2 | 2.5 |
| Komsomolabad | 1.5 | 1.6 | 1.8 | 1.9 | 1.4 | 1.6 | 1.6 | 1.5 | 1.6 | 1.4 | 1.7 | 1.6 | 1.6 |
| Obigarm | 0.6 | 0.6 | 0.8 | 1.2 | 1.1 | 1.0 | 1.3 | 1.6 | 1.6 | 1.2 | 0.8 | 0.5 | 1.0 |

**Table 3.2 : Monthly wind velocity (m/s)**

Calculated wind speed likely to occur on several time periods are presented in the next table.

| Meteorological station | Wind speed (m/s) possible once every | | | | |
|---|---|---|---|---|---|
| | 1 year | 5 years | 10 years | 15 years | 20 years |
| Garm | 18 | 22 | 24 | 25 | 26 |
| Komsomolabad | 12 | 14 | 15 | 16 | 17 |
| Obigarm | 18 | 25 | 28 | 30 | 32 |

**Table 3.3 : Design wind velocity (m/s)**

Knowing those data, the two types of wind considered in the design criteria are precised: a strong has a velocity of 18 m/s and an extreme wind has a velocity of 32 m/s.

### 3.3 Waves height

Wind-generated waves in large bodies of water are not uniform in height but consist of spectra of waves with various heights. A well-defined relationship exists between the significant wave height ($H_s$) and the heights of the other waves in the spectrum. From this relationship, it can be seen that $H_s$ represents the average height of the highest one-third of the waves in a given spectrum. Likewise, the average wave height of the highest 10 percent of the waves in a given spectrum is $1.27H_s$ and the average wave height of the highest 1 percent of the waves in a given spectrum would be approximately $1.67H_s$.

With a crest and slope adequacy protected against erosion (concrete sidewalk and asphalt road for instance), the wave height of the highest 10 per cent of the waves should be used to compute run-up and freeboard ie 1.27 $H_s$.

## 4 CALCULATION

The methodology to calculate the total elevation E reached on the dam compared to the still water level is first based on the evaluation of the significant wave height $H_s$. The inputs are the fetch and the wind characteristics.

Then, the run-up R on the dam will be calculated with respect to the design wave height $H_d$. It will take into account several parameters of the dam as the roughness, the porosity, the slope and the type of dam.

The wind tide (setup S) shall also be taken into account as an additional effect to the wave impacting on the dam.

Freeboard is defined as the wind tide (S) plus the run-up (R).

### 4.1 Wave height

The significant wave height $H_s$ is defined as being the average of the height of the one-third highest waves.

In the USBR wave prediction, the significant height computations are based on the hypothesis of deep water. In the table below is reminded the classification according to the length of waves $L_w$ and the depth of the reservoir d:

| Classification | $d/L_w$ |
|---|---|
| deep water | >1/2 |
| transitional | 1/25 to 1/2 |
| shallow water | <1/25 |

Table 4: Deep water hypothesis

In deep water :

$$H_s = 5.112.10^{-4} \times U_A \times F_{eff}^{1/2} \qquad T_w = 6.238.10^{-2} \times (U_A \times F_{eff})^{1/3} \text{ and } \qquad L_w = \frac{gT_w^{\ 2}}{2\pi}$$

With Fetch defined part 3.1 and:

- $U_A$ — Wind factor defined as follows: $U_A$= 0.71×($V_w$)$^{1.23}$
- $V_w$ — Wind velocity 10 meters above water surface (18 or 32 m/s according to part 3.2).

Calculated design wave heights (1.27.$H_s$) are as following:

| Dam alternatives | $H_{dn}$ (strong wind) | $H_{du}$ (extreme wind) |
|---|---|---|
| FSL = 1290 masl | 1.15 m | 2.36 m |
| FSL = 1255masl | 1.15 m | 2.34 m |
| FSL = 1220 masl | 1.14 m | 2.32 m |

## 4.2 Angular approach of the waves

Waves heights for waves computed for fetches (or wind direction) that are not normal to the dam axis should be reduced according to a factor derived on next figure. The angular spread is the angle between the central radial of the effective fetch calculation and the axis normal to the dam axis. The reduction factor noted $C_a$ is then multiplied to the wave heights.

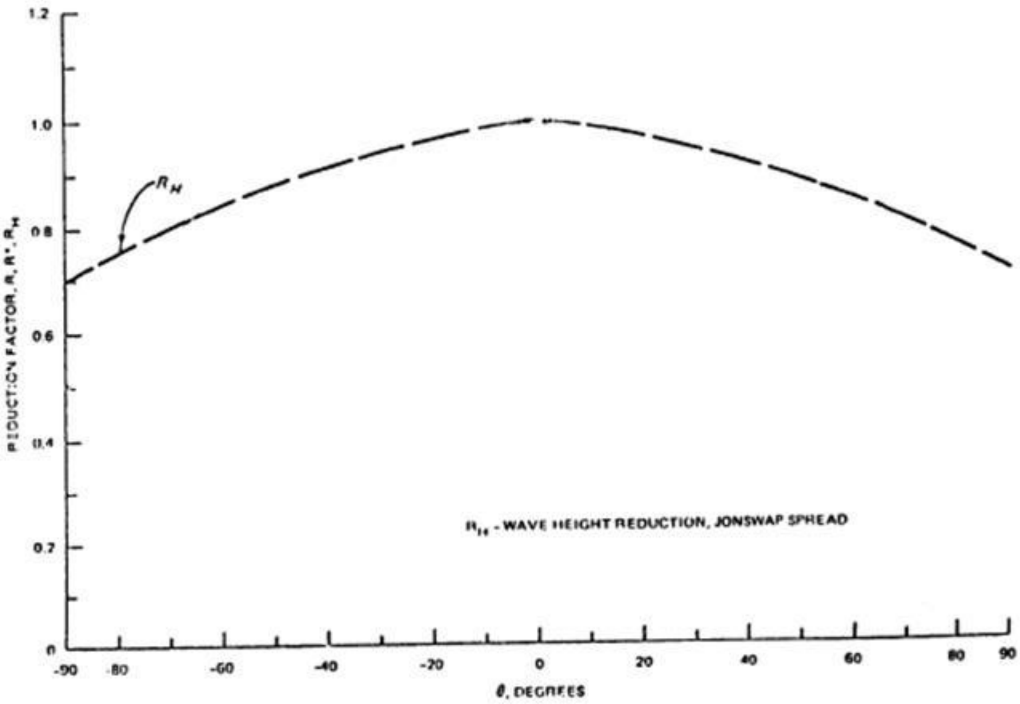


**Figure 4.1: Wave height reduction due to angular approach**

## 4.3 Run-up calculation

The waves running up on the upstream face of a dam may increase or decrease the necessary freeboard in function of the following parameters that will be studied hereby:

- The upstream slope of the dam,
- The roughness and porosity,
- The angular spread of the waves compared to the normal to the dam axis.

The significant wave heights $H_{sn}$ and $H_{su}$ shall be corrected according to the related coefficients to determine the run-up.

On a vertical dam, the kinetic energy of the waves is directly converted into potential energy causing surging waves. Then, the maximum vertical height attained is increased.

For slopes of embankment slopes equals or steeper than 5H/1V, the wave will ultimately break on the embankment and run up the slope to a height governed by the angle of the slope, the roughness and the permeability of the embankment surface and the wave characteristics. On an embankment with a rip rap surface, the run up is given by:

$$R = \frac{H}{0.4 + \sqrt{\frac{H}{L}} cotan\theta}$$

Where H is the wave height, L is the wave length and θ is the angle of the dam face from the horizontal.

The calculated run-ups are presented in the next table.

| | Run-up for strong wind | Run-up for extreme wind |
|---|---|---|
| FSL = 1290 masl | 0.99 m | 1.88 m |
| FSL = 1255 masl | 0.98 m | 1.86 m |
| FSL = 1220 masl | 0.98 m | 1.85 m |

**Table 4.1 : Calculated Run-up**

## 4.4 Wind tide calculation

Wind tide is the piling up of water at the leeward end of an enclosed body of water, as a result of the horizontal stress on the water exerted by the wind. The magnitude of wind tide can be expressed by the following Zuider Zee formula presented below:

$$S = \frac{{V_w}^2 \cdot F}{4850 \cdot D}$$

With parameters as defined part 3.1, and D the average depth of the reservoir along the fetch line. D is taken equal to 2/3 of maximum water depth.

The calculated wind tides are presented in the next table.

| | Tide for strong wind | Tide for extreme wind |
|---|---|---|
| FSL = 1290 masl | 0.002 m | 0.005 m |
| FSL = 1255 masl | 0.003 m | 0.004 m |
| FSL = 1220 masl | 0.003 m | 0.005 m |

**Table 4.2 : Calculated wind tide**

# 5 RESULTS

**The freeboard agaisnt waves are the following:**

| | Strong wing (18 m/s) | Extreme wind (32 m/s) |
|---|---|---|
| FSL=1290 masl | 0.99 | 1.88 |
| FSL=1255 masl | 0.99 | 1.87 |
| FSl=1220 masl | 0.98 | 1.85 |