State of Colorado
Department of Natural Resources
Division of Water Resources
Office of the State Engineer
Dam Safety

GUIDELINES FOR USE OF THE FREEBOARD & RIPRAP WIND & WAVE ANALYSIS (FRWWA) SPREADSHEET DESIGN TOOL

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Section 1. Introduction & References

1.1 The DSB's FRWWA spreadsheet facilitates freeboard and riprap sizing analysis in accordance with USBR Design Standards 13, Chapter 6 *Freeboard* (Sept 2012) and Chapter 7 *Riprap Slope Protection* (May 2014): https://www.usbr.gov/tsc/techreferences/designstandards-datacollectionguides/designstandards.html

1.2 Rules and Regulations for Dam Safety and Dam Construction (2020), Rule 7.4.2.2 Freeboard Design provides the following design criteria:

Type of Freeboard	Rule 7.4.2.2 Criteria
Normal	Normal water surface + wave runup & setup from 100 mph wind velocity. Minimum 3 feet.
Residual	Maximum water surface (during IDF) + wave runup & setup from a wind velocity exceeded 10% of the time*. Minimum 1 foot.

* Rule 7.4.2.2.2 incorrectly states "10 percent AEP wind". 10% AEP (annual exceedance probability) would result in an extreme wind on top of the maximum water surface, which is not the design intent. USBR PFARA wind data are hourly and the intent is a typical wind that would occur during an average 10-hour period, meaning 10% hourly exceedance probability (P_{wh}) (ref: DS 13 Ch. 6, pg. 6-5)

1.3 Rule 7.4.2.8.1 Rock Riprap. Rock riprap shall be well-graded, durable, sized to withstand design wave action, and shall be placed on a well-graded pervious sand and/or gravel bedding or acceptable geotextile fabric that is filter compatible with the underlying embankment zone.

Section 2. Key Definitions

2.1 Wave & Wind Analysis (ref: USBR DS 13 Chapter 6, Appendix A):

2.1.1 Runup: the movement of water up a structure on the breaking of a wave. The runup is the vertical height that the wave reaches above the stillwater level.

2.1.2 Setup: Wind setup is the vertical rise in the stillwater level on the leeward side of a water body due to wind stresses on the surface of the water.

2.2 Riprap & Bedding (ref: USBR DS 13, Chapter 7):

2.2.1 Tolerable damage limit: Level of damage where a considerable amount of riprap displacement has occurred, but no bedding material has been lost and no embankment material has been pulled through the bedding or riprap layers. Periodic maintenance of the riprap is expected, and planning for this may include constructing stockpiles of riprap near the dam and arranging for the resources needed to place the material.

2.2.2 Zero damage level: Condition where no damage occurs to the riprap layer, and very little, if any, movement of the riprap occurs.

2.2.3 No erosion: Design of the bedding material to be filter compatible with the riprap according to Reclamations "no erosion" filter criteria, which renders erosion of the bedding through the riprap to be more unlikely.

2.2.4 Some erosion: Design of the bedding material to allow some erosion of the underlying material through the riprap.

Section 3. Wind Data & Statistics

3.1 The USBR's Probabilistic Freeboard and Riprap Analysis (PFARA) program can be used to create hourly wind probability curves for use with freeboard and riprap design in accordance with DS13 Ch 6 & Ch 7. A copy of the program, readme file, and supporting data files are on the Colorado Dam Safety Branch (DSB) website under *Guidance Documents->Freeboard & Riprap Wind & Wave Analysis Resources*.

3.2 Also included on the DSB website:

- A map and Station ID list of PFARA wind station in Colorado and neighboring states
- Summary tables of PFARA hourly wind speed (P_{wh}) and 50YR & 100YR Non-exceedance wind speeds (P_{NEL}) for each PFARA wind station in Colorado over a range of different fetch lengths. If applicable to your site, use these as an alternative to running PFARA.

3.3 There are a limited number of PFARA wind stations (14 in Colorado). Stations should be representative of the dam/reservoir-of-interest -- meaning similar elevation, terrain, meteorology and vegetation (ref: Ch 6, App. B).

3.3.1 Compare PFARA wind station locations with dam/reservoir location on the 80m Wind Speed Map (pdf format) in order to see if the sites have similar wind climates

3.3.2 If there is not a directly comparable PFARA to the reservoir site, use the nearest PFARA wind station data and then scale PFARA wind speed results by the following ratio:

$$\frac{(80m\ wind\ speed\ at\ reservoir)}{(80m\ wind\ speed\ at\ PFARA\ station)}$$

To facilitate scaling, a GeoTIFF (which can be loaded into ArcMap) of the 80m wind speed dataset for Colorado is on the DSB website.

3.4 Tips for running PFARA:

- See the README.TXT file in the PFARA directory on the Dam Safety Branch Website.
- You must EXIT the program and re-open it between multiple runs. Otherwise the program appears to continue to accumulate the data and returns different results given the same input parameters.
- PFARA wind data are adjusted from over-land to over-water wind speeds per Ch. 6 App. B (see *Site specific wind data analysis* discussion below)
- PFARA wind statistics have an associated duration, which is based on the minimum duration required to generate the maximum wave height (t_{min} from Ch 6, App. B, Eq. 1), which is a function of reservoir fetch and the over-water wind speed of interest.

3.5 For Site Specific wind data analysis see the discussion in Section 6 below.

Section 4. General Design Considerations

4.1 Freeboard Wind & Wave Analysis (ref: USBR DS 13, Chapter 6):

4.1.1 Chapter 6 design procedure should prevent wave overtopping of a nature that would cause dam failure, but not necessarily total prevention of splash-over by occasional waves

4.1.2 Chapter 6 only addresses freeboard due to wind and wave considerations. Other considerations such as inflow design flood routing and seismic deformation need to be considered separately. Potential for spillway misoperation or debris blockage may be other considerations.

4.1.3 Chapter 6 states wave runup and setup should be included in hydrologic risk analysis. For DSB purposes, this implies that Hydrologic Hazard Analysis (see Colorado Dam Safety Rule 7.2) overtopping dam breach analysis may be done based on the IDF maximum water surface and volume, assuming incipient dam overtopping of residual freeboard based on associated wave runup and setup (i.e., it is not necessary to route a flood larger than the IDF to simulate overtopping of the residual freeboard).

4.1.4 Risk Factors for existing dams (Ref: DS 13 Chapter 6, Section 6.3.2):

- Low areas of crest will concentrate wave action and erosion
- Transverse cracking can lead to embankment erosion below the dam crest
- Erodibility of downstream slope and dam crest (paved crest, vegetation cover, soil PI)
- Consider history of wave overtopping events and damage
- A fragility curve can be developed to evaluate the likelihood of dam failure given wave runup + setup in a potential failure modes analysis (PFMA) framework (Ch. 6 Figure 6.3.2.1-1 shows an example fragility curve)

4.1.5 Deep water assumption by USBR is a simplifying assumption. It may not be valid for many state-regulated dams, but deep-water assumptions are generally conservative.

4.1.6 For the 100 mph wind speed wave runup + setup, DS 13 Ch. 6, Fig. 6.2.2-1 may be used per the USBR. However, the DSB notes that Ch. 6 App. B runup + setup calculations (per DSB FRWWA spreadsheet) are different (see graphs below). Because the App. B calculations are more conservative in the range of typical fetches for most state-regulated dams (<2 miles) our recommendation is to use the spreadsheet.

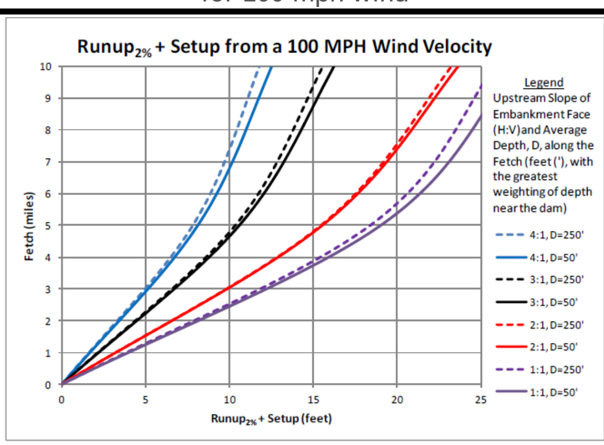
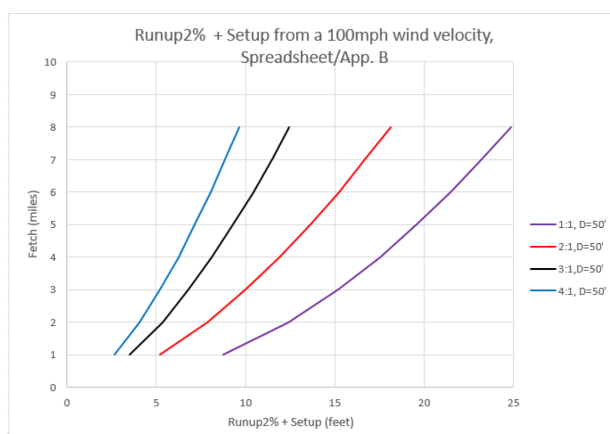
<table>
<tr><th>USBR DS 13 Ch. 6 Figure 6.2.2-1
for 100 mph wind</th><th>DSB FRWWA Spreadsheet Results
for 100 mph wind</th></tr>
<tr><td>

Figure 6.2.2-1. Runup$_{2\%}$ + setup from a 100-mi/h sustained wind velocity on a surface protected by riprap.</td>
<td>
</td></tr>
</table>

4.2 Riprap Sizing (ref: USBR DS 13, Chapter 7):

4.2.1 Chapter 7 riprap sizing equations may not be conservative for short wave periods (T<3s), such as may be calculated for small reservoirs (see Ch. 7, pg. 7-7)

4.2.2 Chapter 7 provides guidance on vertical extents of riprap relative to typical reservoir water levels (Ch. 7, pg. Section 7.2.3), embankment slope (Section 7.2.4) and rock quality and shape (Section 7.2.5)

4.2.3 Chapter 7 riprap sizing is based on forces from wave action and gravity, but other considerations may include potential for ice or debris damage, extreme freeze-thaw conditions, riprap availability, etc. (Section 7.2.6 & 7.3.1).

4.3 Bedding Requirements (ref: USBR DS 13, Chapter 7):

4.3.1 The bedding material should be designed to meet three primary criteria:

- It must not be so broadly graded as to be susceptible to internal instability;
- It must be coarse enough to prevent it from eroding through the riprap; and
- It must be fine enough to retain the underlying embankment material.

4.3.2 Chapter 7 provides step-wise guidance to design a bedding material to meet the above criteria. However, it is dependent on the selected riprap gradation(s) from the previous section and the gradation of the underlying embankment material. As such, there are several steps that require engineering judgement such that both DSB and USBR criteria are met.

- When underlying embankment material is very fine-grained a single bedding material would need to be very broadly graded in order to comply with each of the bedding filter criteria stated above (i.e., bedding not eroding through riprap and embankment not eroding through the bedding). Ch. 7, Section 7.3.7.1 gives guidance on internal stability to prevent the selected bedding material from being too broadly graded.
- Ch. 7, Section 7.3.7.2 gives guidance to keep the bedding material from eroding through the riprap.
- Ch. 7, Section 7.3.7.3 gives guidance to ensure the bedding material gradation is fine enough to provide retention of the embankment material beneath it.

Section 5. FRWWA Spreadsheet Use

The Colorado Dam Safety Branch's FRWWA spreadsheet can be downloaded from the Dam Safety Branch Website. The spreadsheet filename contains the date of the latest spreadsheet revision (ex. *Freeboard&Riprap-Wind&Wave-Analysis (FRWWA) spreadsheet_2020-06-03.xlsx*). It may periodically be updated.

The spreadsheet contains three worksheets: One for freeboard (wave runup & setup), a second for riprap sizing, and a third for riprap bedding design. Following are brief user notes for each worksheet.

Worksheet *DS13 Ch6 App B R+S calculations*:

- This worksheet facilitates wave runup and setup calculations following equations in USBR DS 13 Chapter 6, Appendix B. User entry cells have a bold border. Locked spreadsheet calculations are shown in red (note: Current version of the spreadsheet is not protected).
- User entry: average reservoir depth (D), over-water wind speed (VMPH), fetch (F), upstream slope (_H:1V), Upstream Slope Material (riprap or concrete *from drop down list*), gamma-b, gamma-h, and gamma-beta
- User entry fields have units, definitions, and Ch. 6 table references in the spreadsheet

Worksheet DS 13 Ch7 riprap sizing:

- This worksheet facilitates riprap sizing calculations following equations in USBR DS 13 Ch. 7. User entry cells have a bold border. Locked spreadsheet calculations are shown in red.
- User entry: 100-YR 90% non-exceedance wind speed, fetch (F), specific gravity of riprap rock (Gs), upstream slope (_H:1V), and selected permissible damage (see next bullet).
- Riprap W50 is calculated based on user-selected damage tolerance, from a drop down menu (tolerable damage or zero damage -- see **Key Definitions** above). USBR recommendation is *tolerable damage* when minimum 90% $P_{NE100YR}$ is used.
- Next the calculated W_{50} is compared to USBR recommended minimum and maximum for their dams (see Ch. 7 pg. 7-18). NOTE: minimum 160 lb W_{50} recommended for USBR dams may govern for smaller state-regulated dams. Our recommendation is to consider this minimum in light of riprap availability and cost. The *calculated* W_{50} may be used as an acceptable alternative.

Worksheet DS 13 Ch7 bedding:

- This worksheet facilitates design of riprap bedding material to meet the criteria stated in USBR DS 13 Ch. 7. User entry cells generally have a bold border (except for embankment gradation entry). Locked spreadsheet calculations are shown in red.
- User entry: Embankment gradation(s), Selected Constant for "No erosion" or "Some Erosion" in equation (13), graphically selected D_{85} and D_{15} values, and the Candidate Bedding gradation(s).

Section 6. Guidance on Site-Specific Wind Data Analysis

6.1 Sources for possible wind datasets include:

- NCDC (LCD, ASOS, AWOS), : https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets
- RAWS: https://raws.dri.edu/coF.html
- USBR: https://www.usbr.gov/gp/hydromet/archive_colorado.html
- UAWCD: http://resources.uawcd.com/dcs_siteinfo.php#14C

6.2 USBR DS 13 Chapters 6 and 7 provide the following guidance on wind data and statistical analysis:

6.2.1 Ch 6, App B.3.2: The tables of wind persistence from Battelle [used by PFARA] list the number of occurrences that a given wind velocity has been exceeded for a selected number of consecutive hours. By converting the "number of occurrences" to "number of hours," and dividing by the total number of hours of the period of record, the value P_{wh}, the probability of the wind exceeding a given velocity for a specific number of hours, is derived.

6.2.2 Ch 6, App. B.3.4: The probability of wind exceeding a given velocity (Pwh) for 1, 2, 3, 4, and 5 consecutive hours at the reservoir is plotted for each wind velocity. The data points are plotted on semi-logarithmic paper, and a best fit curve is drawn for each velocity. Each curve represents the probability of the wind exceeding a specific velocity for a selected duration (Pwh) during any wind event.

For the selected duration, it appears PFARA uses:

$$t_{min} = 1.87(F^{0.67}/VMPH^{0.34}) \qquad \text{[Ch. 6, App. B, Eq. 1]}$$

where,
t_{min}=minimum duration req'd to generate maximum wave height (hours)

F = reservoir fetch (miles)
VMPH=over-water wind velocity (mph)

6.2.3 Ch 6, App. B.3.5: Wind data over land must be adjusted to over-water velocity for use in wave setup and runup calculations. Ch. 6 Figure B-2 (shown below) provides a conversion, where U_L=wind speed over land and U_W=wind speed over water.

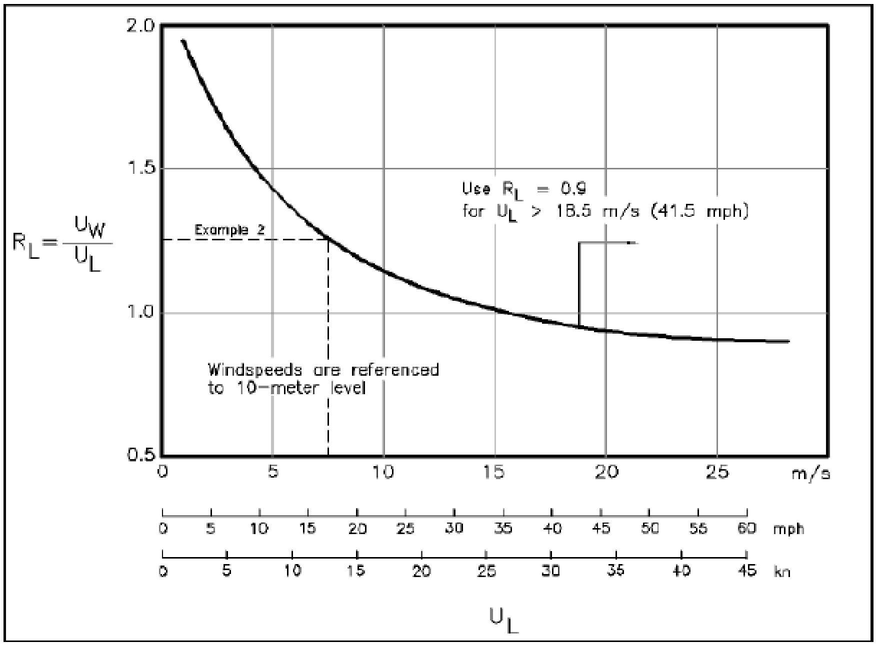


Figure B-2. Ratio of wind speed over water to wind speed over land as a function of wind speed over land [16a].

6.2.4 Ch 7, Section 7.3.3: In the absence of the Battelle wind data or Reclamation's PFARA program, wind data collected hourly from a representative station can be ranked and statistically converted to develop this same relationship … For a selected set of wind velocities (for example, 50, 55, 60, 65, and 70 mi/h), the probability of not being exceeded (non-exceedance probability, P_{NEL}) within a given design time period (L) is computed by equation 3:

$$PNEL = (1 - PWH)^{8760L}$$

Where,
P_{NEL}= probability of non-exceedance over the design time period (L)
P_{WH} = hourly exceedance probability of the design wind event
L= Design time period (years)

6.3 Possible Distributions for Pwh and PNE100YR Estimates:

A simple procedure for computing hourly wind statistics may be to develop an empirical probability distribution. First, rank hourly wind speed data from largest to smallest. The Weibull plotting position formula for empirical exceedance probability is:

$$Pwh(V > vi) = \frac{i}{n+1}$$

Where,
Pwh=exceedance probability for given hourly wind speed xi
V=wind speed random variable
vi=wind speed with rank *i*
i = rank (largest to smallest wind speed)
n= total number of wind speed data points

The 10% hourly exceedance probability wind speed for Rule 7.4.2.2 can be interpolated at Pwh=0.1 Alternatively the Rayleigh distribution can be fit to an hourly wind speed dataset and used to estimate Pwh as follows:

$$Pwh(V > v) = e^{-(\frac{v}{c})^2}$$

Where,
v=wind speed of interest
and the parameter *c* can be estimated as follows:

$$\hat{c} = \sqrt{\frac{1}{2n}\sum_{i=1}^{n} v_i^2}$$

For USBR DS 13 Ch. 7 riprap sizing, non-exceedance probability over a 100-year design life can be calculated for any wind speed with associated Pwh by the following equation:

$$PNE100YR = (1 - Pwh)^{8760*100}$$

Where,
PNE100YR = non-exceedance probability of wind speed associated with Pwh over 100-year design life
Pwh = exceedance probability for a given hourly wind speed

NOTE: The USBR's 100-year 90% non-exceedance probability wind speed (for riprap sizing) would correspond to a wind speed with approximately Pwh 1.1e-5 hourly exceedance probability. Using the Weibull plotting position formula, this would correspond to the maximum wind speed from a 10 year hourly wind speed data set (i.e., 1/(10yr x 8760hr/yr + 1)=1.1e-5). For longer datasets the wind speed at 1.1e-5 Pwh can be interpolated. For shorter datasets the maximum observed hourly wind speed could be used for riprap sizing provided the data set is sufficiently long.