

Wave surcharge on long narrow reservoirs- a reality check

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SYNOPSIS. Safety reviews carried out for Scottish and Southern Energy had initially identified five hydroelectric dams where the wave surcharge allowance required was significantly greater than the wave freeboard available. These initial reviews suggested that significant dam heightening, of up to 3 m in one case, would be required to provide adequate wave freeboard.

The dams in question impound long narrow lochs, up to 26 km in length. Basic wave generation formulae suggest that the full length of the loch is available for wave generation resulting in very large significant wave heights. A reality check on this simplified approach was required. Wave analysis methods from the maritime sector were used to model wave generation on the reservoirs. To reduce survey costs old and new technologies were combined by turning 100 year old bathymetric survey into a digital bathymetric model of the loch beds. The modelling output confirmed that significant engineering judgement is required to assess the influence of loch shape on wave generation to determine an appropriate fetch length.

INTRODUCTION

As part of Scottish and Southern Energy's ongoing safety assessments of its stock of dams a series of initial assessments had been carried out to check the freeboard of its dams. One such assessment of wave surcharge had identified four hydroelectric dams in the Highlands with potentially significant freeboard deficits of up to 3 m. Such a large deficit was a concern both in terms of dam safety and the potentially high cost of improvement works. In order to develop a programme of improvements it was considered that a review was required to confirm the need and scale of the works. This paper describes the detailed wave surcharge assessment carried out at the four dams: Lairg dam on Loch Shin, Fannich, Glascarnoch

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and Loch Mhor. A fifth dam, Little Loch Shin, was also included following concerns over wave surcharge following a Statutory Inspection.

The purpose of the detailed assessment was to check the initial assessment, review current wave surcharge literature and determine whether site specific conditions influence the applicability of the initial estimates. Where dams were still found to have a freeboard deficit a risk analysis was to be carried out and measures to reduce the risk of damage or failure proposed.

ISSUES TO BE CONSIDERED

Wave Height Prediction

Up to the late 1940's wave height prediction for fetches under 23 miles was carried out using Stevenson's formula:

$$H_w = 1.5F^{0.5} + 2.5 - F^{0.25}$$

where H_w is the wave height from crest to trough (in feet), and F is the fetch in nautical miles. Research in the United States during the 1950s and early 1960s led to the publication in 1962 of what has come to be known as the SMB/Saville method. This is the method used in the 1978 edition of Floods and Reservoir Safety (FRS). The equations can be expressed as:

$$\hat{H} = 0.0026(\hat{F})^{0.47} \text{ and } \hat{T}_m = 0.46(\hat{F})^{0.28}$$

$$\text{where } \hat{H} = \frac{gH_s}{U^2}, \hat{T}_m = \frac{gT_m}{U}, \hat{F} = \frac{gF}{U^2}$$

Saville et al found that using a simple fetch length along the wind direction overestimated wave heights where the fetch width was small compared with the fetch length (i.e. in long narrow reservoirs). After assessing a number of different methods to adjust the fetch length the concept of an effective fetch was developed, familiar to users of the FRS 1978 edition, where the length of radials is measured over a range from 45 degrees either side of a central radial and then their component in the central radial direction is summed to give:

$$F = \frac{\sum x_i \cos \alpha_i}{\sum \cos \alpha_i}$$

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In the early 1970's a wave measurement programme was carried out in the North Sea as part of the Joint North Sea Wave Project (JONSWAP). The following equations were developed from this work:

$$\hat{H} = 0.00178(\hat{F})^{0.5} \text{ and } \hat{T}_p = 0.352(\hat{F})^{0.3}$$

Donelan introduced the concept that the fetch length should be measured along the wave direction rather than the wind direction, thus the wind speed used should be the component of the wind speed acting in the wave direction. This became known as the Donelan/Jonswap method and is that used in the latest edition of FRS (1996).

Preference for the use of this method over the SMB/Saville method in FRS appears to be at least partly due to work by HR Wallingford in the late 1980s and in the 1990s comparing wave prediction methods against actual wind and wave measurements at Megget and Glascarnoch reservoirs (Owen, 1987 and Owen and Steele 1988). The work showed that none of the methods gave particularly good agreement with observed data for all wind speeds and directions. It did show that the SMB/Saville methods underestimated wave heights at long narrow reservoirs like Glascarnoch (length to width ratio of 13.5), while giving a good match at shorter reservoirs like Megget (length to width ratio of 7). The Donelan/Jonswap method gave a better match to observed data at Glascarnoch, though over-estimated wave heights at Megget. The conclusion from this work was that the Donelan/Jonswap method should be used in preference to the SMB/Saville method as it was conservative.

Fetch length for irregular shaped reservoirs

At two of the five dams (Lairg Dam and Fannich Dam) the large freeboard deficit could be accounted for by the long fetch length used for estimating the wave surcharge.

Lairg Dam lies at the southern end of Loch Shin. Loch Shin has a total length along its longitudinal axis of around 27km and thus has potentially a very long fetch length. However it is relatively narrow with its width varying between 650m and 2000m. The current edition of Floods and Reservoir Safety (1996) introduced the concept that wind may change direction as it passes down steep sided gently curved reservoir such that changes in direction of the longitudinal axis of a reservoir (up to about 50 degrees) should be ignored when determining fetch length. This advice appears based on information in Herbert et al (1995) and Yarde, Banyard and Allsop (1996). It should be noted that the advice is based on anecdotal

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evidence rather than observed data. The implications of applying this “bent fetch” approach to Loch Shin is significant increasing the fetch by a factor of 10 from about 3km to nearly 30km. As a consequence the estimated significant wave height is large.

A similar situation occurs at Fannich Dam which has a curved “banana shaped” reservoir, with a total length along the central axis of around 12km but a width of only between 600m and 1400m.

A key issue was therefore whether waves would propagate along such long narrow curved reservoirs.



Figure 1. Loch Shin – fetch along longitudinal reservoir axis

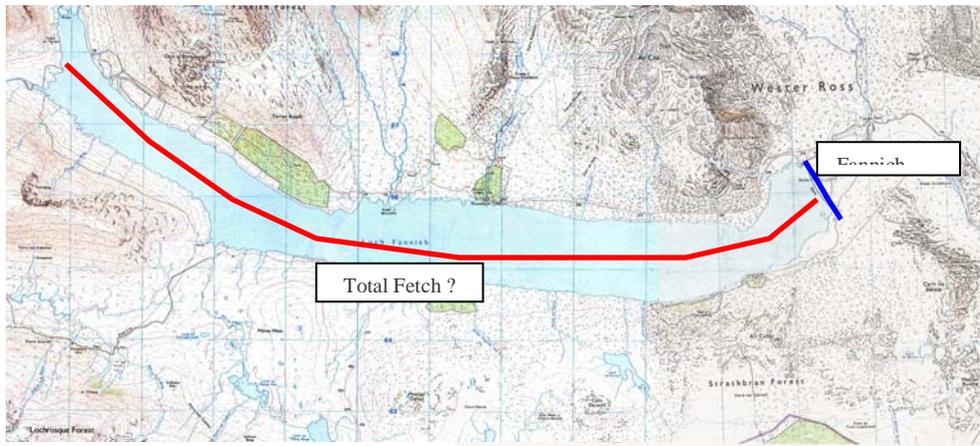


Figure 2. Fannich reservoir - fetch along longitudinal reservoir axis

Wave run-up and overtopping

FRS (1996) uses the concept of a wave surcharge to determine dam freeboard but acknowledges the approach has limitations. These include that it does not cater for composite dam sections, such as an embankment with a wave wall, also no estimation is made of the quantity of water overtopping. It suggests the use of a numerical approach to assess in detail wave carry over and surcharge at existing dams, giving the example of the program SWALLOW, developed by HR Wallingford. SWALLOW uses the method developed by Owen for wave overtopping of sloping embankments: Design of seawalls allowing for wave overtopping (1980). In the early 1990s the method was expanded to cover vertical walls and recurved wave return walls (Herbert, 1993 and Owen and Steele, 1993), however SWALLOW was not updated to cover these wall types. Further research in the 1990s refined the formulae used in Owen (1980). The methods for different types of seawall were brought together in a single volume by the publication by the Environment Agency of Wave Overtopping of Seawalls Design and Assessment Manual (Besley, 1999). This is currently the reference that covers the widest range of embankment types. The methods were developed from series of model tests, some backed up with observed data.

Yarde, Banyard and Allsop (1996) compared the run-up method with the overtopping method and found it to be conservative compared with the overtopping method. They justified the adoption of the overtopping method as a logical and better supported approach, consistent with other practice and easily understood.

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The overtopping method should only be used within the range of application covered by the model testing. Where conditions exist that are outside those modelled then modelling of particular conditions is required. This can be using physical models but also numerical techniques are coming to the fore e.g. AMAZON, a 2D wave modelling software developed by Manchester Metropolitan University's Centre for Mathematical Modelling and Flow Analysis (CMMFA). Research on assessing wave overtopping in coastal conditions is ongoing and includes the development of a European overtopping Manual. Some of this research will be applicable to reservoir conditions.

Tolerable overtopping discharges

The overtopping method described above estimates the mean and peak overtopping discharges. To determine a wave freeboard a safe or allowable overtopping discharge needs to be assigned to a dam. This will depend on the type of construction of the dam and the type of access required along the crest. Criteria for safe overtopping discharges were investigated by Simm (1991) and Franco et al (1994). Criteria are summarised in Yarde, Banyard and Allsop (1996) and the Environment Agency's Wave Overtopping of Seawalls Design and Assessment Manual (1999). These safe allowable overtopping discharges primarily relate to sea defence type embankments and therefore may need some consideration if applied to dams.

Some of the dams that were assessed were rockfill which may be able to withstand higher volumes of overtopping without damage than conventional sea defence embankments. However research on flow over rockfill dams has primarily concentrated on two areas: breaching due to overtopping and the use of rockfill spillways as a low cost alternative to concrete structures. However research tends to concentrate on steady uniform flow and could not be directly applied directly to wave overtopping.

Wind Setup

Wind setup (also called wind tide) is the rise in stillwater level caused by wind stress on the surface of a body of water. USBR (1981) and USACE (1997) both present the same estimation method, which in SI unit is:

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

It is not mentioned in FRS (1996), probably because reservoirs in the UK are generally relatively small so the effect is considered insignificant. The

magnitude of wind set up was verified to confirm that this assumption held true for the long reservoirs being considered.

Wind funnelling

Some of the dams being analysed were at the end of steep sided valleys where wind funnelling may be an influence. Derivation of a design wind speed takes account of the effect of altitude on wind speed but does not generally take account of the effect of topography. The effect, wind funnelling, is more usually associated with building design for the determination of wind loadings.

Information on wind funnelling along valleys is sparse in building codes. BRE Digest 346 (1989) gives a method for calculating the effect on winds of valleys perpendicular to the wind direction. However for winds parallel to the valley axis it states “wind blowing along the axis of a valley is not significantly changed”.

The other sector where wind funnelling has been researched is in forestry where the design of plantations requires an assessment of the risk of windthrow (loss of trees by wind damage) which is influenced by topographic effects. The most relevant reference found was by Ruel (1998) where a physically model test of mountainous terrain was used to evaluate wind speed increases in valleys and on hilltops. The model by its nature is site specific, but appears not dissimilar to Highland conditions. Results of the model test suggested wind speed increases of 25 – 40 % for wind directions parallel to valley axes and increases of 80 – 120 % over hilltops.

Wind funnelling will be specific to a particular site. The literature shows that topography can cause variations in local wind speeds but does not provide conclusive evidence that wind funnelling over a long fetch will occur causing increased wave heights.

Waves in Shallow Water

Incoming wave are transformed as they pass from deep water to shallower near-shore waters. The transformation is by refraction, shoaling, diffraction and breaking. Refraction is the change in wave velocity as waves propagate in varying depths. As a result waves change direction so that they tend towards the direction normal to the local bed contours. Shoaling is the change in wave height as waves propagate through varying water depths. This may have an effect, particularly where the bathymetry in front of the dam is high and the wave heights are large. Diffraction is the transformation

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of waves by obstacles such as headlands or breakwaters. For all but simple obstacle shapes diffraction is complex to analyse requiring numerical modelling. Diffraction can both attenuate and increase wave heights. Wave breaking before waves reach the dams could result in significant wave energy dissipation, thus reducing the hydraulic loading on the structures. Wave breaking is dependent on depth and steepness. The CIRIA/CUR manual: Manual on the use of rock in coastal and shoreline engineering. (1991) provides details of analysis of the above wave transformation conditions.

Outline methodology for analyses

Based on the above the methodology shown in the figure below was adopted to consistently assess each dam.

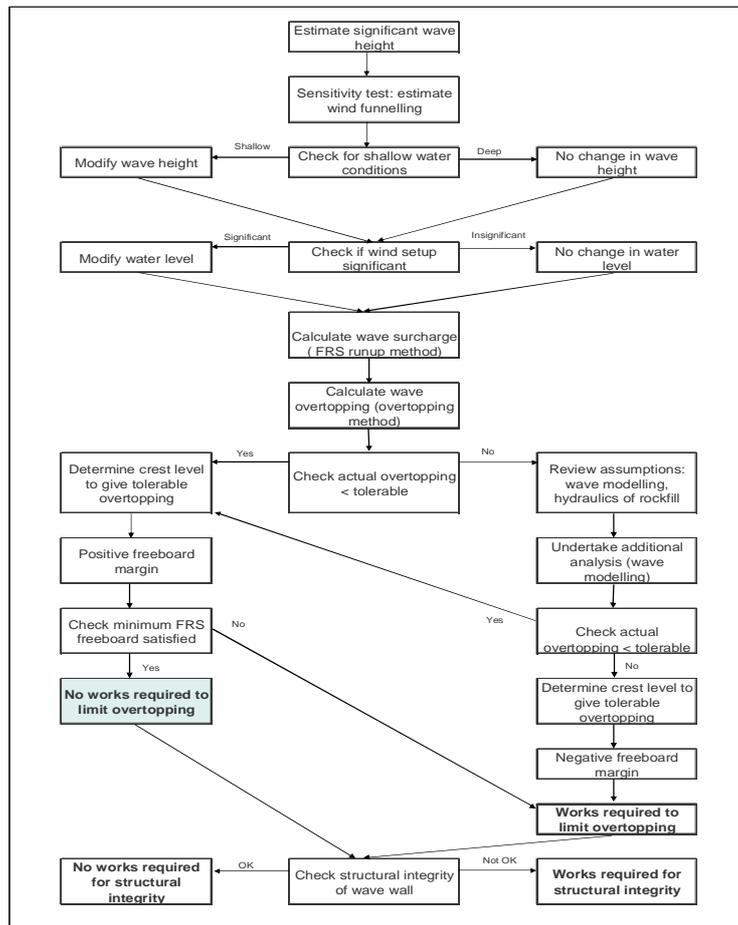


Figure 3. Wave surcharge assessment methodology

WAVE MODELLING

To review the applicability of using the total reservoir length as the fetch length at Loch Shin and Loch Fannich wave modelling was carried out using MIKE21 using the “NSW” module. MIKE 21 NSW is a spectral wind-wave model, which describes the propagation, growth and decay of short-period waves in nearshore areas and are therefore reasonably applicable to reservoir conditions. The model includes the effects of refraction and shoaling due to varying depth, wave generation due to wind and energy dissipation due to bottom friction and wave breaking. The module has some limitations in that it does not include diffraction, reflection or wave-wave interaction. Other modules are available that include these factors, but are more normally used for modelling wave effects in harbours or around breakwaters.

A problem with developing wave models for relatively small scale studies is the cost of collecting bathymetric data, which can easily be significantly more costly than the study itself. We were fortunate in being able to overcome this problem using data from an unlikely source. Between 1897 and 1909 bathymetric surveys were carried out of all the freshwater lochs of Scotland (Murray, 1897-1909). This gives bathymetric data as contours at 50 foot intervals and spot depths along survey lines at about 250 m spacings. Copies of these surveys were held by SSE as well as the National Library of Scotland. Though the survey is old it gives very good detailed coverage of the lochs which would be costly to obtain by re-surveying the reservoir.

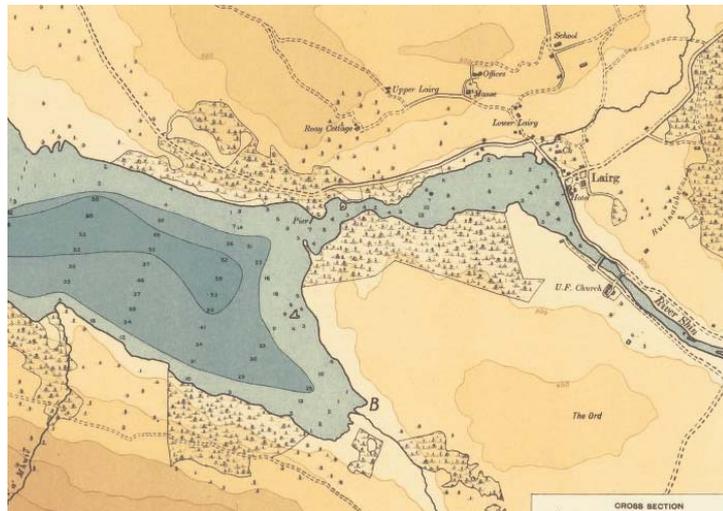


Figure 4. Bathymetric survey from 1897-1909

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The survey pre-dates dam construction and some sedimentation may have occurred in the reservoir since construction. However due to the nature of the catchment this was judged to be minor.

Another problem faced with the data was correlating the survey datum, referred to in the survey just as “sea level”, with Ordnance Datum (Newlyn). The offset between datums was not known so an attempt was made to correlate known features between the bathymetric survey and Ordnance Survey mapping to estimate a datum offset. Correlation of these features showed that the two datums matched within a few metres, though more accurate estimation of the datum offset was not possible. Instead the sensitivity of wave height to changes in the datum was tested by raising or lowering the bed level relative to water level.

The bathymetric survey was scanned and then digitised on-screen using the Arcview GIS package to develop a digital terrain model (DTM). The reservoir water edge as shown on OS mapping was digitised and overlain into the DTM both as additional water edge data and to confirm the correlation between the two maps. The DTM was developed by interpolating a 20 m x 20 m grid of bed levels from the bathymetric data. The DTM was then used as input to MIKE21.

Wind speeds and directions were developed along the reservoir for different wind and water level conditions. The wind directions adopted assumed that the topography would funnel the wind along the axis of the reservoir towards the dam. A number of different wind directions were analysed to find the worst case. Wind speeds were developed taking account of the increase in the speed of wind as it travels over-water.

The results showed the general features of wave generation that one would expect:

- Narrow reservoir widths limit wave generation
- Headlands and an uneven reservoir shore limit wave generation and can provide a considerable sheltering effect
- Wave heights generated are slightly greater than those calculated assuming a straight line fetch length confirming the anecdotal evidence that waves to a certain extent can be steered around the “banana shaped” reservoir
- Wave heights generated are significantly lower than those calculated assuming the total length of the reservoirs for wave generation

confirming that judgement is required in applying the bent fetch length principle.

For large scale modelling it would be normal practice to calibrate the MIKE21 model with observed wind/wave data. In this case no calibration data was available. The cost of collecting the data would be high, of the order of £ 20,000. It was not considered necessary for this study to undertake data collection and calibration. Instead sensitivity tests were carried out and the model output was used with the understanding that there is a degree of uncertainty in the wave heights calculated and safety factors should be applied.

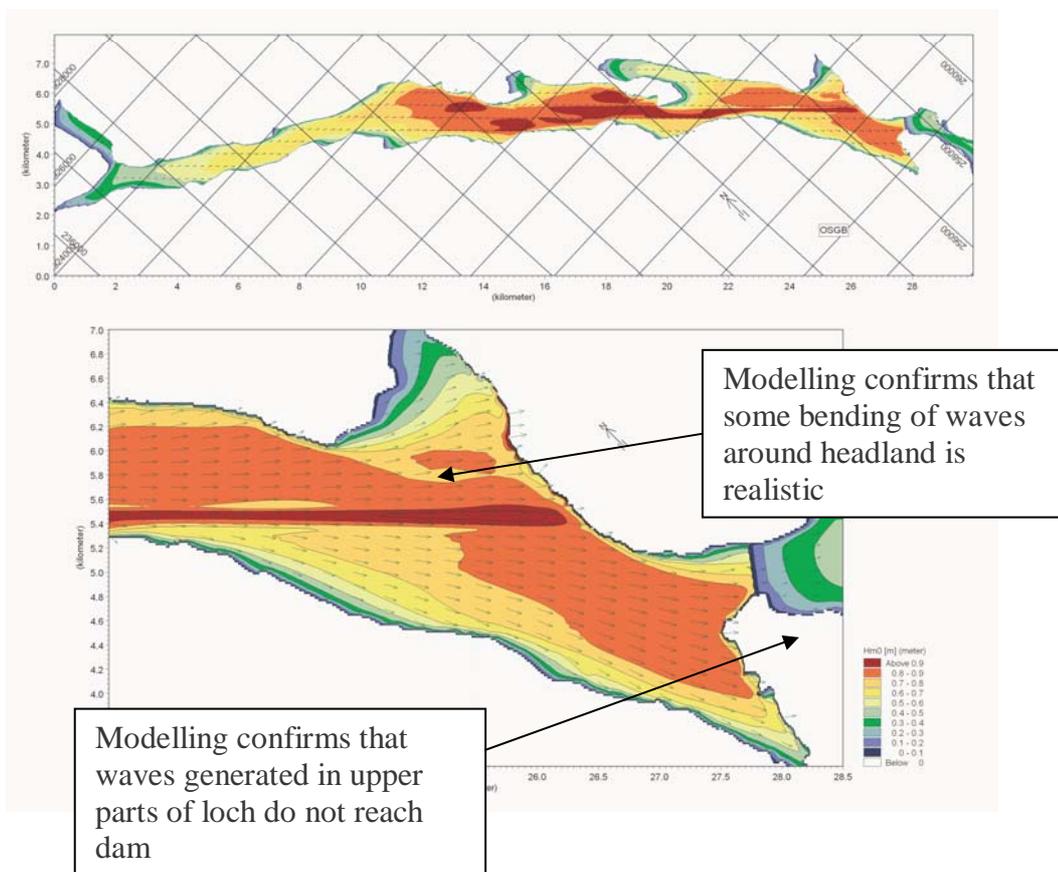


Figure 5. Wave modelling – Loch Shin

There would be opportunities to give additional confidence in the model outputs by using the wind and wave data collected by HR Wallingford for Glascarnoch and Megget as calibration of a model of Glascarnoch or Megget reservoirs but this has not been carried forward in this study.

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CONCLUSIONS

The wave modelling reduced the freeboard deficit to a more realistic level. A range of remedial works to wave walls at these dams are now planned into SSE's works programme covering wave wall raising and strengthening.

The study confirmed the need to apply common sense and judgement when assessing wave surcharge for existing dams. For long narrow reservoirs, with fetch length to width ratios of about 10 or more, use of a standard straight line fetch along the full reservoir axis may be inappropriate for estimating wave surcharge. Numerical modelling techniques provide an alternative method of analysis, and are particularly cost effective where existing bathymetric data is available.

Improved methods for assessing overtopping have been developed since publication of the latest edition of Floods and Reservoir Safety, such as the Environment Agency's wave overtopping manual. Further research in this area is ongoing in the coastal sector such as the development of a European Overtopping Manual. Such knowledge can be transferred and applied to the dams and reservoirs sector when detailed wave surcharge assessments are required.

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