The British Dam Society

Different approaches to assessing and improving stability of dam structures

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SYNOPSIS Mott MacDonald Bentley (MMB) was commissioned by Dŵr Cymru Welsh Water (DCWW) to undertake dam stability works which have flexed through various approaches and different analytical tools to reduce risks and to extend the lives of existing assets. This paper covers the following projects.

Llandegfedd: a stability analysis of a combined overflow and draw-off tower, access bridge and piers under seismic conditions. The tower is a 35m tall concentric twin cylindrical reinforced concrete shell. The bridge is a 90m long reinforced concrete structure with 4No. unreinforced concrete piers with history of alkali-silica reaction.

Rosebush is a concrete arch-gravity dam. MMB undertook stability analysis, employing a 3D Finite Element model under static, thermo-mechanical and seismic loading. The seismic response was computed using fully dynamic analysis with UK-specific accelerograms generated by a tool developed in-house.

Upper Carno: refurbishment and strengthening of this double-leaf masonry structure needed to ensure both static and seismic stability. An innovative technique was employed adding fibre-reinforced concrete to the inner leaf of the masonry wall, coupled with dowels ensuring composite behaviour.

Llyn Egnant: stability analysis of a concrete gravity dam considering the effects of ice and seismic loading concluding that the above ground dam section did not meet modern design standards with further works being required to stabilise the dam.

Pond-y-Gwaith: a peat dam faced by dry stone walls upstream and downstream. Ground investigation was undertaken despite difficult access and sensitive environmental constraints. Analysis using Slope/W; rigid block analysis for overturning and sliding; and finite element structural analysis.

LLANDEGFEDD

MMB was commissioned to undertake analysis of the dam and draw-off tower at Llandegfedd to address a measure in the interest of safety (MITIOS) following an inspection under Section 10 of the Reservoirs Act 1975. Situated near Pontypool, South Wales, Llandegfedd reservoir has a draw off tower which is a concentric twin cylindrical reinforced concrete shell with an outer diameter of circa 9.75m, height of 27.5m to top water level (TWL) and a total height of 35.0m (**Figure 1**).

The seismic assessment was undertaken based on UK guidance for dams and reservoirs: the BRE publication *An engineering guide to seismic risk to dams in the United Kingdom* (Charles et al 1991) and *An Application Note to an engineering guide to seismic risk to dams in the United Kingdom* (ICE, 1998). Following the Swansea earthquake of 17 February 2018, the Qualified Civil Engineer (QCE) for the scheme requested that peak ground accelerations encountered were modelled as part of an ongoing study for information.

Figure 1. Llandegfedd water draw-off tower and access footbridge

The seismic response of the structure was undertaken adopting an innovative approach consisting of using accelerograms compatible with the response spectrum proposed by the BRE guide for the safety evaluation earthquake (SEE), with peak ground acceleration (PGA) of 0.19g, generated using a tool developed in-house by Mott MacDonald. This allowed for a more accurate determination of the seismic response when compared with the use of the envelope-based approach of response spectra analysis.

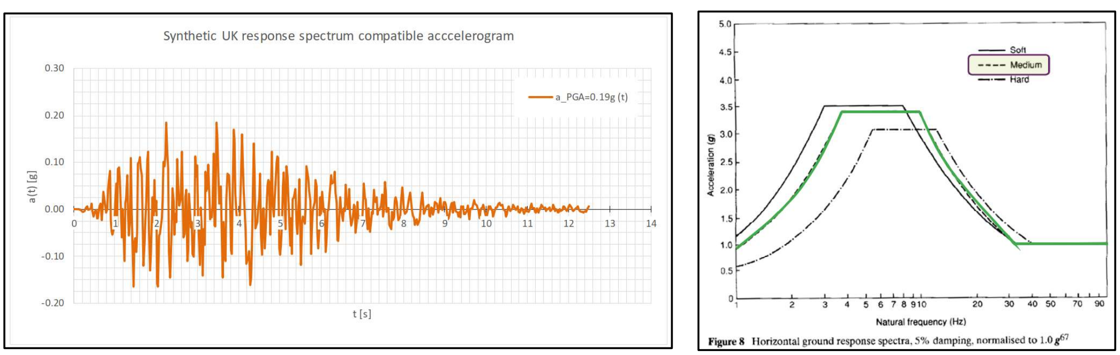
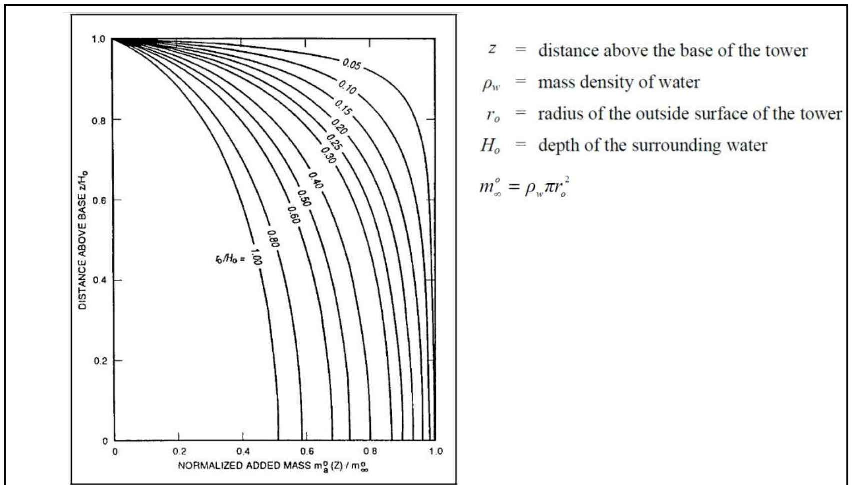


Figure 2. Synthetic accelerogram and BRE Response spectrum

The hydrodynamic effects induced by the mass of water surrounding both the draw-off tower and access footbridge piers in the case of a seismic event were modelled by adding extra mass along the height of the tower. These were derived in accordance with the expressions developed by Goyal and Chopra (1989).



Source: "Structural Design and Evaluation of Outlet Works (EM 1110-2-2400) 2003" [6]

Figure 3. Added masses to model hydrodynamic effects (Goyal et al, 1989)

The seismic response of the draw off tower was computed employing a 3D finite element (FE) model based on a fully implicit dynamic formulation, loaded with the accelerograms previously derived. Both Midas Civil (Midas, 2018) and Project Vifem (Teixeira, 2018) software were used to allow for cross-platform validation of results.

Typical outputs from the analysis can be seen in **Figure 4** below.

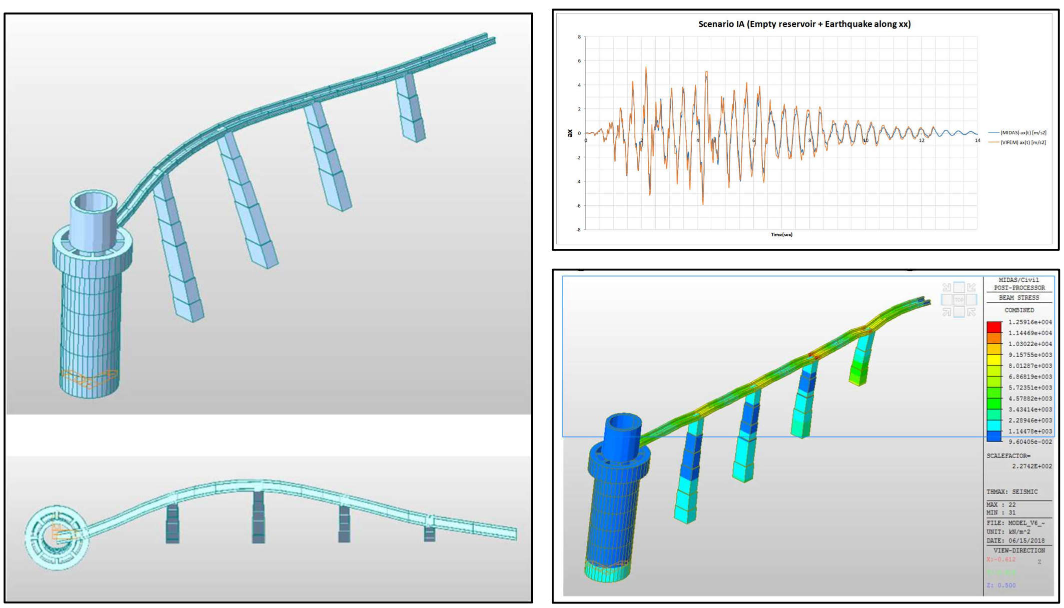


Figure 4. Seismic analysis outputs (MMB)

Historic concern associated with the asset had led to the installation of a steel bulkhead in the tunnel, in the event the valve tower was sufficiently damaged during a seismic event. The output of the assessment, along with the associated study, helped to prove that the valve tower structural performance was adequate, and no capital works were required, thus resulting in the MITIOS sign-off for the associated recommendation being received prior to the statutory date.

ROSEBUSH DAM

MMB was commissioned to undertake a stability analysis of Rosebush reservoir to address a MITIOS following an inspection under Section 10 of the Reservoirs Act 1975.

Located in Pembrokeshire, Rosebush dam was first constructed in 1931 and was subsequently raised in 1941. No calculations were known to exist to prove the suitable stability of the dam, and there were concerns that the dam did not act as a gravity structure alone but also relied on arch action for its stability.

To understand the behaviour of the structure and the significance of the spillway bridge deck to resist failure, 3D modelling of the dam by Finite Element (FE) analysis was undertaken using an efficient combination of Euler Bernoulli beam elements and shell elements (in lieu of a more cumbersome 3D solid finite elements approach), implemented in Midas Civil and Project Vifem.

Figure 5. Rosebush Dam (MMB)

Both the static and seismic response of the dam were analysed. The seismic action was modelled by generating synthetic accelerograms compatible with the horizontal ground response spectra for the UK as defined in the BRE document and ICE guide. The accelerograms were scaled to the appropriate PGA corresponding to both the SEE and the operating basis earthquake (OBE).

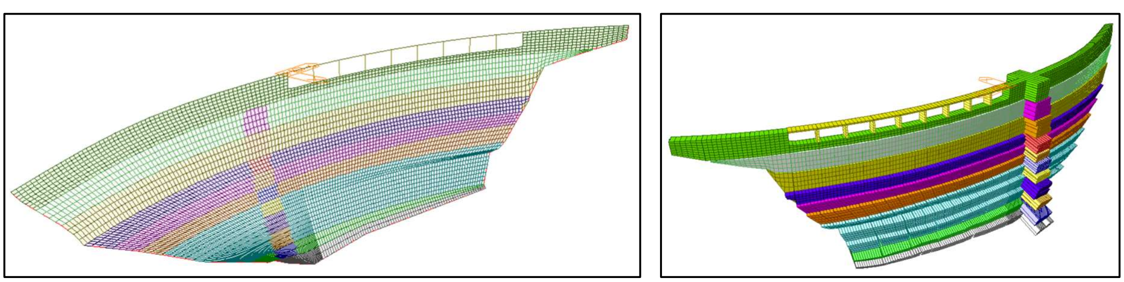


Figure 6. Rosebush Dam 3D FE model: wireframe (left) and rendered (right) (MMB)

The typical outputs of the results of the seismic analysis can be seen below in **Figure 7**

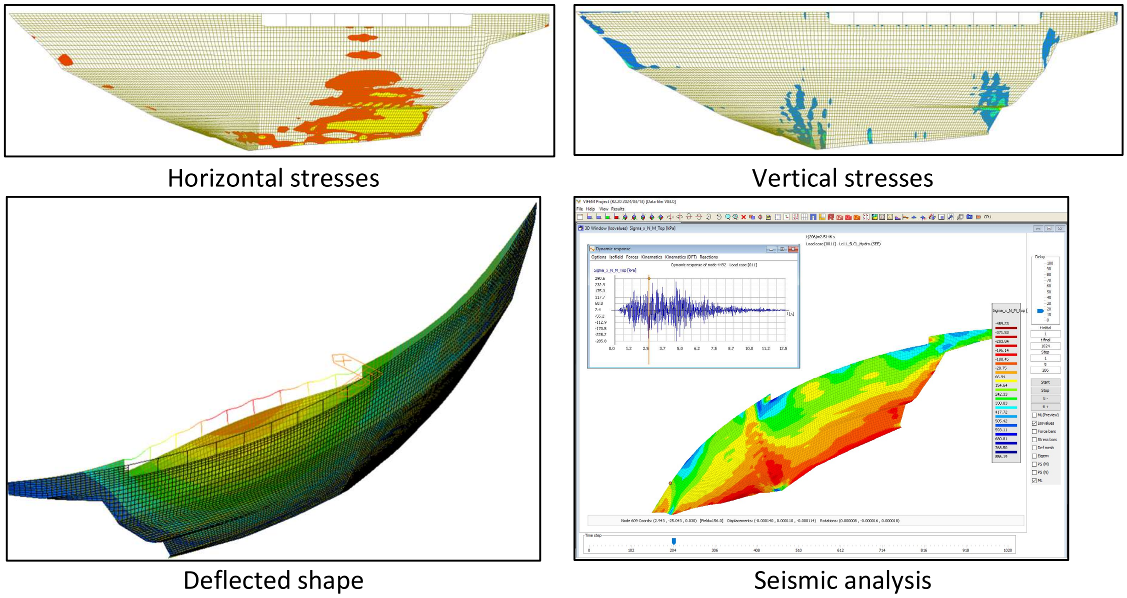


Figure 7. Rosebush dam 3D. Typical outputs of the FE model (MMB)

The adoption of a global 3D FE model based on finite elements was essential to accurately evaluate both the level of safety of the asset under normal operation, extreme flood, extreme seismic conditions and the thermomechanical impact of seasonal variations of temperature, which proved to be a governing factor. The 3D FE model was key in determining that the bridge over the spillway was not essential in contributing to the arch effect or the structural response of the dam.

The output of the assessment, along with the associated study, helped to prove that the dam was suitably stable and the structural performance adequate to prove no capital works were required. The study resulted in the MITIOS sign-off for the associated recommendation received prior to the statutory date.

UPPER CARNO DAM SHAFT

MMB was commissioned as part of a wider remediation scheme at Upper Carno reservoir, amongst which was the conversion of a semi-wet well valve shaft to a fully dry tower. The structural lining of the tower shaft was required to withstand both static loading and recommended seismic loading corresponding to an SEE with a maximum PGA of 0.22g. For wider scheme details see parallel paper by Swetman et al (2024).

The adopted solution, following an optioneering stage, consisted of an in-situ concrete lining, doweled to the existing masonry wall to achieve a composite behaviour between the new lining and the double leaf existing brickwork. The local stiffening (and strengthening) of the shaft to avoid distortion to its cross section was assured by steelwork frames placed at different levels installed top-down to act as both permanent and temporary works (Figure 8).

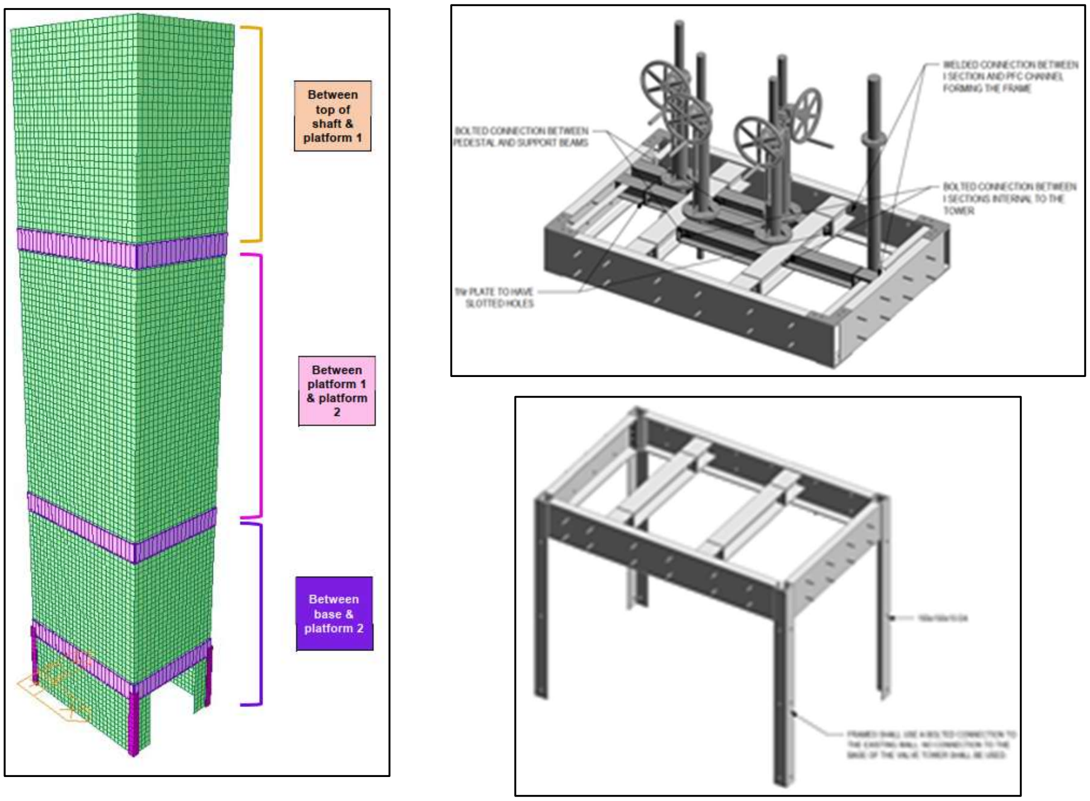


Figure 8. Strengthening zones (concrete - green , steelwork frames - purple) and details (MMB)

To accurately model the behaviour of the structure, a 3D model of the shaft, based on the FE method, was prepared using an efficient combination of Euler Bernoulli beam elements to model metallic members and shell elements to model brickwork and concrete, implemented in Midas Civil and Project Vifem.

To correctly capture the interaction effects between the shaft and the surrounding earth fill dam when conducting the seismic modelling, an ancillary FE model was prepared, which explicitly included the geometry of the dam embankment and its mechanical properties (Figure 9).

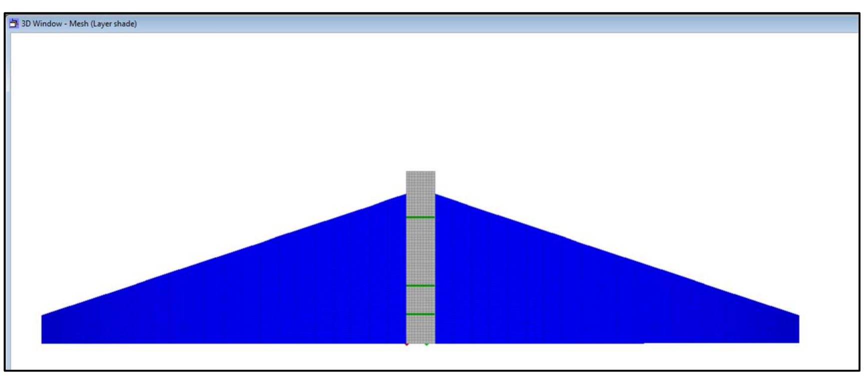


Figure 9. Ancillary FE model for dynamic analysis calibration (MMB)

The distributed spring stiffness and added mass to the shaft walls of the main 3D FE model ensured a good match with the response of the ancillary model in both magnitude, frequency and damping characteristics.

The typical stress outputs from the 3D FE model can be seen in (**Figure 10**) below.

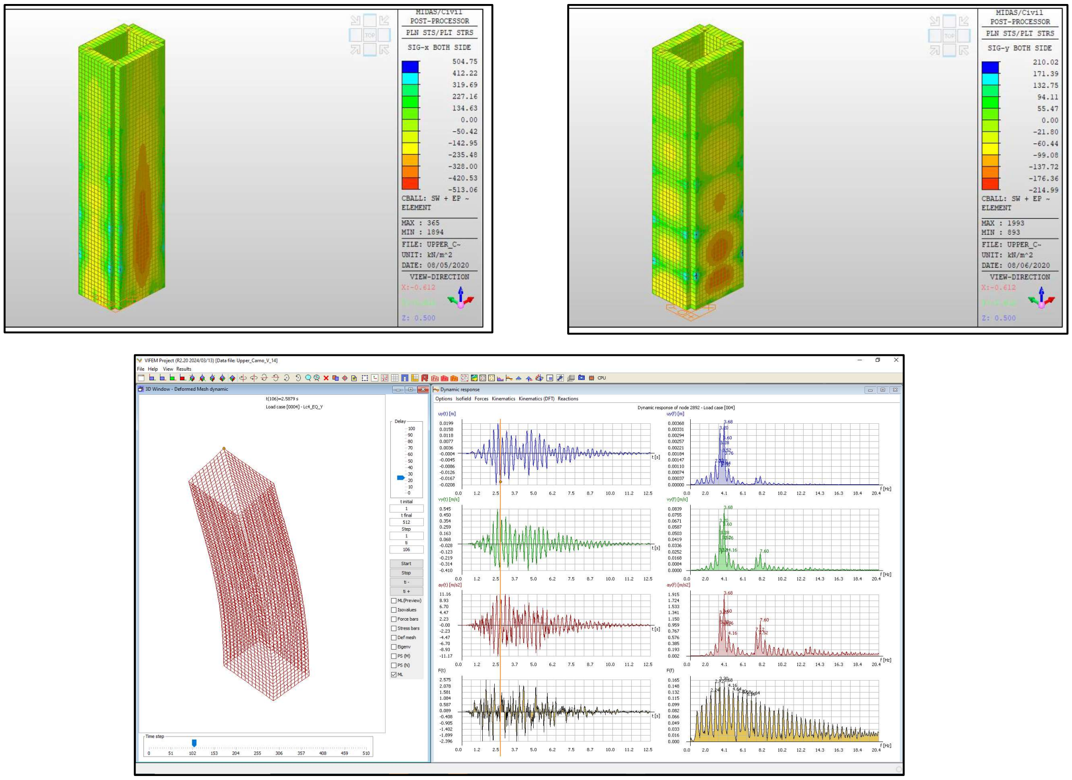


Figure 10. Shaft static and seismic analysis outputs (MMB)

The proposed solution achieved the required capacity to withstand both static and seismic actions, and acted as both temporary and permanent works, without compromising the buildability. This approach allowed the assessment of structural performance to minimise capital works and maximise buildability. The work contributed to a MITIOS sign-off for the associated recommendation received prior to the statutory date.

LLYN EGNANT

MMB was commissioned to undertake works to improve the stability of the dam at Llyn Egnant to address a MITIOS following an inspection under Section 10 of the Reservoirs Act 1975. Situated near Aberystwyth, the reservoir was constructed in 1965 by raising a natural lake. The dam is a concrete gravity dam approximately 75m in length and 12m in total height, of which only 5.6m is above natural ground. The reservoir lies at an elevation of approximately 400mAOD and supplies a treatment works downstream.

The dam itself can be considered in three parts: the central part comprises the overflow weir and spillway, flanked by two non-overflowing walls which tie into the valley sides. The dam is divided into bays approximately 7.6m in width, as shown in Figure 11.

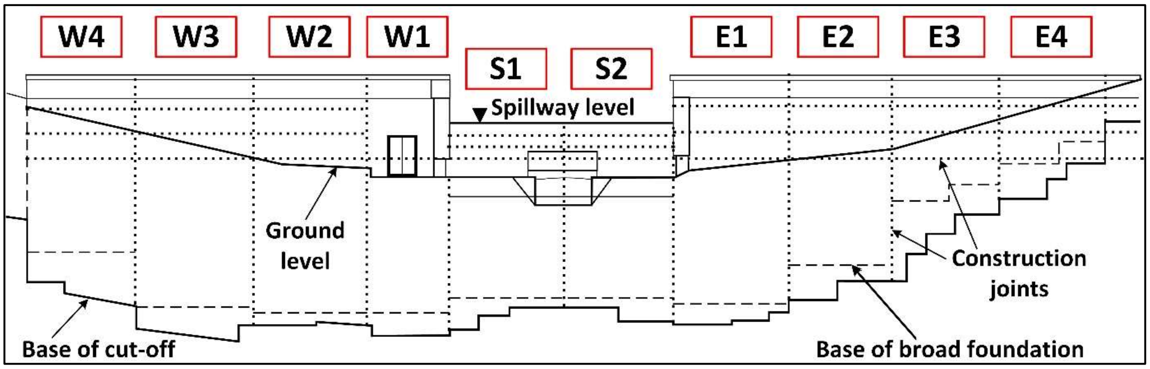


Figure 11. Downstream elevation of the dam (MMB)

For the stability assessment, two key cross sections through the overflow weir (bays S1 and S2) and the left abutment wall (bay E1) were analysed. The worst observed condition of the joints was in bay E1 which also has the greatest exposed dam height above the downstream ground level. The sections were analysed at three locations, all of which were above ground horizontal construction joints (

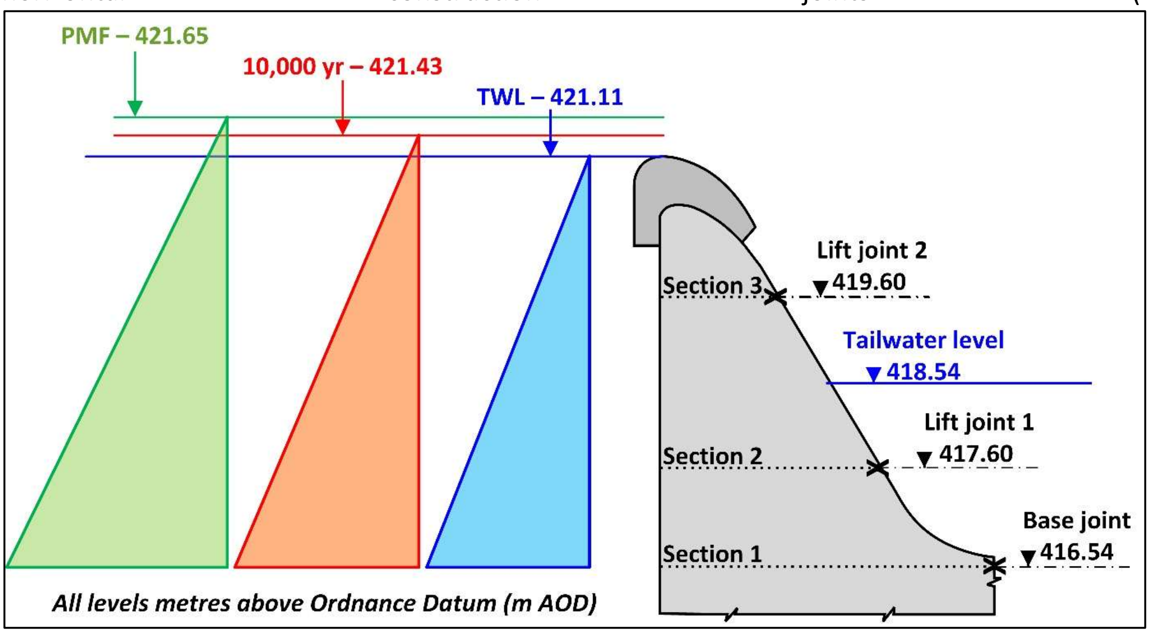


Figure 12).

When assessed against UK and international guidance, the analysis showed that the overflow weir did not achieve the adequate factors of safety (FoS) for sliding under the usual and the unusual scenarios. The FoS for the abutment walls was sufficient in all scenarios other than those including unusual and extreme ice loading.

There was an increased risk of instability both in the spillway weir and the abutment in more unusual and extreme events, where the reservoir is at risk of freezing. Results indicated that the FoS approached unity.

Whilst the risk of failure of the dam due to instability in the short term was low, mitigating measures were required to address the stability concerns under unusual and extreme ice loading.

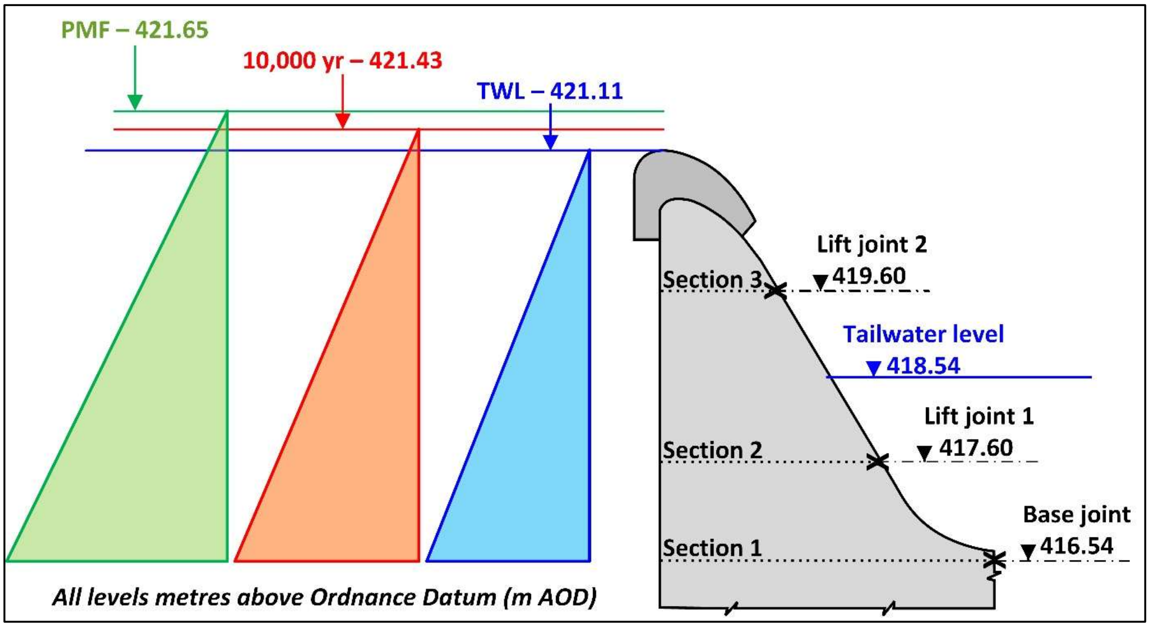


Figure 12. Hydrostatic loading on the spillway weir used in the stability analysis (MMB)

Following the stability analysis and an optioneering exercise, it was recommended to bring the stability of the dam in line with required guidance. This was achieved by installing post-tensioned anchors through the dam into the underlying bedrock.

Figure 13. Anchors being installed on the abutment walls (MMB)

Figure 14. Anchors being installed on the abutment walls (MMB)

POND Y GWAITH

MMB was commissioned to undertake an investigation and analysis of the dam at Pond y Gwaith, in Ceredigion. Constructed around 1900, the dam is 4m in height with a 38m long crest and a centrally placed spillway slab set into the dam with any overflow then passing over gabion boxes onto a concrete slab and then into the downstream channel. Although little was known about the construction of the dam prior to investigation, the results showed a peat dam faced by dry stone retaining walls upstream and downstream at slopes of 2:1 (vertical : horizontal).

Figure 15. Temporary access

Figure 16. Ground investigation showing access arrangement, ramps, plant and water level management pumping system

The geotechnical global stability assessment was undertaken in GeoStudio Slope/W 2021.3 software (GeoStudio, 2024). The Morgenstern-Price analysis type was used and slip circles shallower than 0.1m were excluded. Parameters were applied to all materials based on the results of investigations, treating the masonry walls as rock fill.

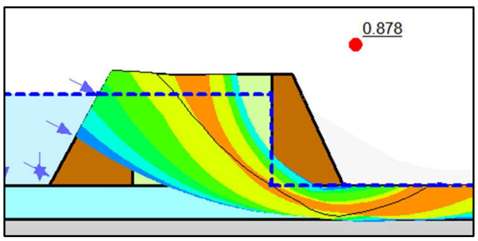


Figure 17. Left of the spillway (ignoring the passive resistance using top water level)

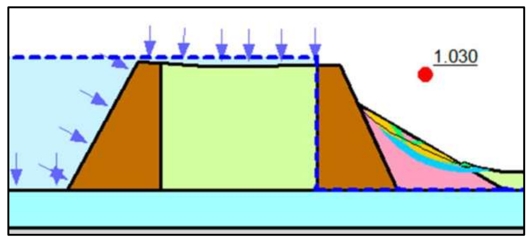


Figure 18. Left of the spillway (including the passive resistance with extreme water level)

Separately, local instability due to tensile stress was checked in the masonry retaining walls to demonstrate that the wall is sufficiently thick to carry the load. The lack of mortar in the dry-stone walls would suggest zero tensile capacity. However, due to the interlocking of the stones, limited tensile strength can be generated in the wall. The basis of this analysis is 'thrust line theory' typically used in the assessment of masonry arches. The assessment showed that the wall is sufficiently thick to accommodate the line of thrust of the load and thus transmit the load into the ground.

Two additional conceptual structural models were created for the analysis of Pond y Gwaith dam: a rigid block conceptual model and a 2D finite-element-based model. Stability sections were assessed for the left-hand side of the dam and the spillway as these represent the most critical sections.

Rigid blocks were used to model the downstream retaining wall of the embankment, similar to the design assessment of a mass gravity retaining wall. The assessment of the downstream wall accounts for the largest destabilising forces with assumed static loading consisting of that from the peat core, the hydrostatic load from the reservoir and a 5kN/m² surcharge to represent possible live loading.

The structural 2D finite element model was created using MIDAS Civil 2022 (Midas, 2022). For dynamic seismic modelling a synthetic accelerogram corresponding to a PGA of 0.125g (1.23 m/s²) was adopted. The response spectrum provided by the BRE guide was used to develop this synthetic accelerogram. An example is presented in Figure 19.

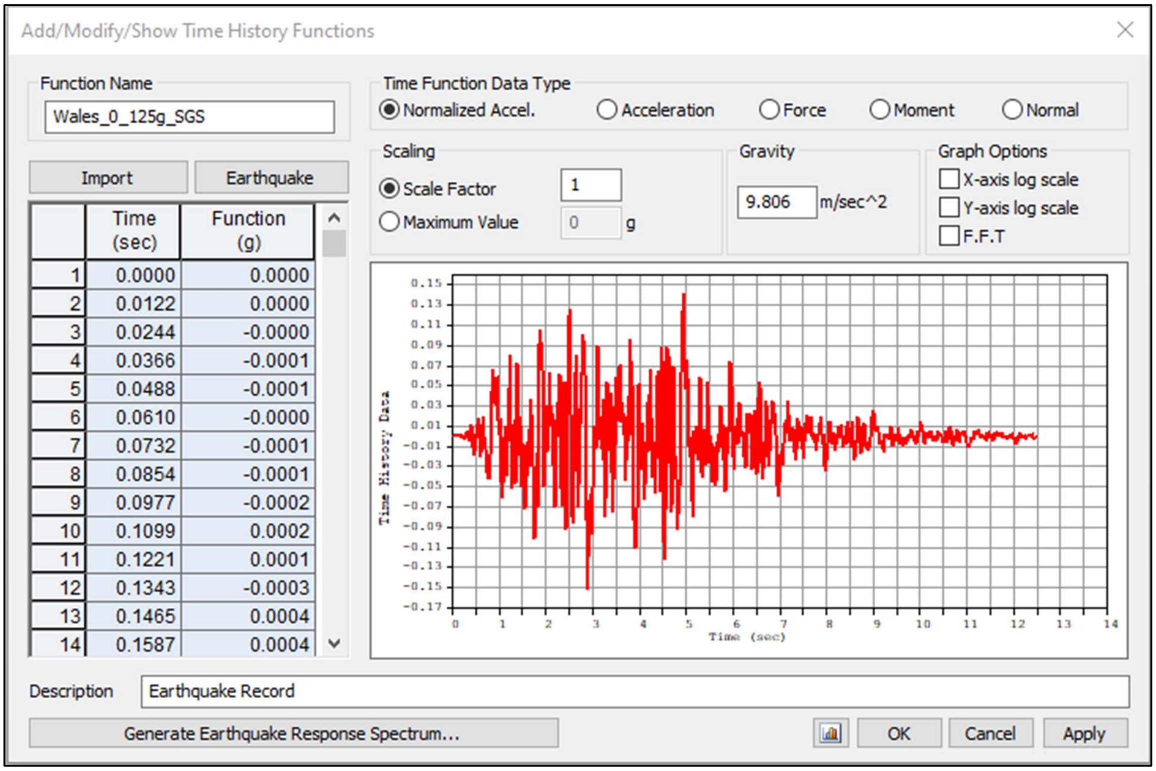


Figure 19. Seismic time history function (MMB)

It is noted that the peat is highly deformable and thus it dissipates the energy released by the earthquake and as such the dam was found to be sufficiently resilient to dynamic seismic loading.

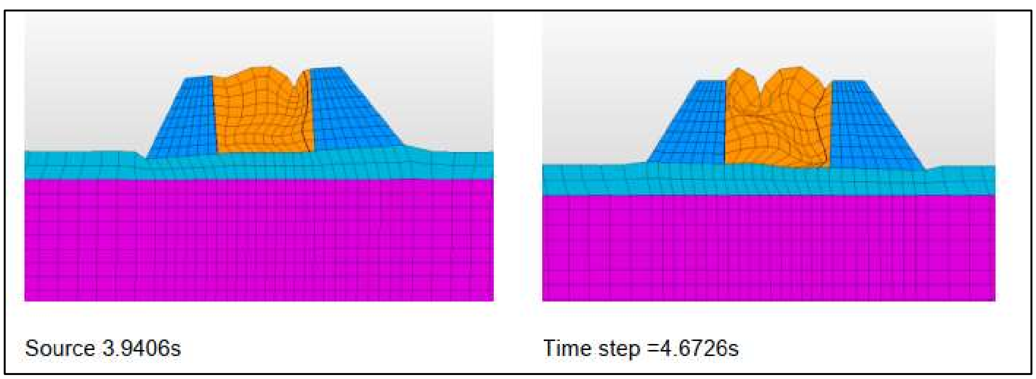


Figure 20. Dam displacement under seismic dynamic loading – displacement is exaggerated (MMB)

The FoS against overturning of rigid blocks were all in excess of 1.5 for static analysis and in excess of 1.1 for seismic analysis. The geotechnical analysis for slip circles and the rigid block structural analysis for sliding returned similar FoS close to unity for critical scenarios when ignoring the passive supporting fill on the downstream face but these were satisfactory when the supporting fill is included.

CONCLUSION

The project team as well as society more broadly have benefitted from a wide range of stability analysis techniques and skills. Making the most of advances in digital technology the project team has connected geographically hybrid teams working on remote dam sites across Wales.

Managing Risks for Dams and Reservoirs

The team has developed in-house tools used in tandem with industry standard software to cross-check results and increase understanding and certainty. In doing so the team has reduced and more accurately assessed the risk of aging dam structures while ensuring a proportionate response leading to significant cost and carbon savings.

ACKNOWLEDGEMENTS

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