

# Design Considerations and Selection of Head Block Type for Large Capacity Anchors using FEA

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Post-tensioned anchors have historically been installed to stabilise concrete dams, intake towers and spillway elements such as ogees, training walls and chute floors. Their advantages include precise loading over a small footprint, constructability benefits, and in many cases, competitive costs.

For cases where significant stabilising forces are required, post-tensioned anchors with up to 91-strands have been installed in several dams around the world, including five in Australia, while prototype 121-strand anchors are currently being developed. These large capacity anchors produce a very high force whereby the anchor load is transferred to the dam over the small area of the bearing plate and thence to the underlying concrete. The existing concrete in aging dams is generally not designed for the transfer of such high compressive stresses and concrete replacement and/or bursting reinforcement is required to prevent crushing or cracking of the existing structure.

To avoid damage to the existing concrete, the load from the anchor is typically distributed via a new reinforced concrete head block and spread over a larger footprint. In the past, this has been achieved by installing the anchor bearing plate(s) on a cast in-situ, reinforced concrete stress beam or block. More recently, cylindrical precast head blocks recessed into the existing concrete have also been used in several dams in Australia, a solution introduced in 2009 at Catagunya Dam by David Tanner, Richard Rodd and Hazell Bros.

This paper commences with a general discussion about some important considerations in the design of head blocks, such as constructability, operation, monitoring, testing and maintenance. Then the paper focuses on detailed Finite Element Analyses (FEA) to compare the behaviour of the stress beam and the cylindrical head block designs, assessing their ability to limit damage to the existing concrete from the large capacity anchor loads. FEA material nonlinearity in the way of a damage plasticity constitutive model was used to estimate the effects of the post-tensioning of 91-strand anchors at proof load on a typical concrete dam crest. A parametric study was undertaken to demonstrate the importance of the head block geometry, layout and existing concrete condition when selecting the appropriate head block type and dimensions.

Lastly, the paper provides design recommendations for the selection of the head block type and layout for 91-strand anchors to best mitigate potential damage to the existing concrete.

**Keywords:** Post-Tensioned Anchors, Anchor Head Block, Upgrade Design, Nonlinear FEA

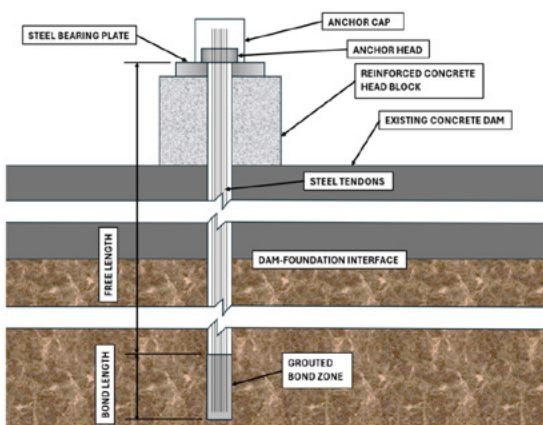
# 1.0 Introduction

Post-tensioned anchors have historically been installed to stabilise concrete dams, intake towers, and spillway elements such as ogees, training walls and chute floors. Their advantages include precise loading over a small footprint, constructability advantages, and in many cases, competitive costs in comparison to other methods of stabilisation.

Simplistically, post-tensioned anchors installed within a concrete dam provide additional restoring force and improve the stability of the dam. Installation firstly involves drilling through the dam concrete and into the foundation. Steel tendons consisting of multiple wires are inserted into the borehole and grouted at the base over a specific length (bond length). The tendon length between the bond length and the top of the anchor (free length) is unbonded to the surrounding rock/concrete but contains multiple corrosion protection measures. The tendons are stressed and locked-off at the top of the anchor such that the anchor head apparatus transfers the compressive load to the existing dam concrete.

For cases where large stabilising forces are required post-tensioned anchors with up to 91 strands have been installed in several Australian dams including Canning, Catagunya, Wellington and Keepit Dams and more recently North Pine Dam. These large capacity anchors produce a very high force whereby the anchor load is transferred to the dam over a relatively small area of the bearing plate and thence to the underlying concrete surface. The existing concrete in aging dams is generally not designed for the transfer of such high compressive and tensile stresses, and concrete replacement and/or bursting reinforcement is normally required to prevent crushing or cracking of the existing structure.

To avoid damage to the existing concrete, the load from the anchor is typically transferred via a new reinforced concrete head block to spread the demand over a larger footprint on the existing concrete. Figure 1 schematically shows a typical post-tensioned anchor assembly. The anchor force is transferred from the post-tensioned strands to the anchor head, then to the bearing plate and through the reinforced concrete head block, before the load is distributed to the existing concrete.



**Figure 1.** Details of typical anchor assembly

The objective of this paper is to provide design recommendations for the selection of an anchor head block type and layout for the largest commercially available anchors (91-strand anchors), to best mitigate potential damage to the existing concrete during stressing to proof load. To achieve this, the paper firstly describes and compares the two main types of anchor head blocks typically used in Australia (stress beams and cylindrical head block). The advantages

and disadvantages of each type of head block are then discussed with consideration to the different phases of the project (design, construction, operation and maintenance). Finally, the results of a parametric study using nonlinear Finite Element (FE) analyses are discussed to demonstrate the importance of the anchor layout and the existing dam concrete condition in the selection of the appropriate head block style.

## 2.0 Types of Anchor Head Blocks

Anchor head blocks for post-tensioned anchors have historically consisted of discrete reinforced concrete blocks for individual anchors or stress beams for multiple anchors. More recently, with the ability to core large diameter holes (up to 1.5 m diameter), precast cylindrical reinforced concrete head blocks have also been used.

Reinforced concrete stress beam head blocks are typically cast in-situ due to their size and weight. They can be located on top of existing concrete or built into a recess excavated into existing concrete. A diagram of a typical stress beam head block is shown in Figure 2.

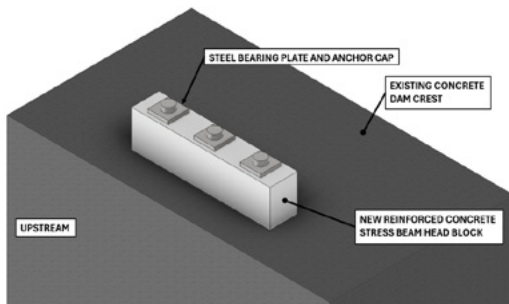


Figure 2. Typical stress beam head block

On the other hand, the cylindrical head blocks, a solution first introduced in 2009 at Catagunya Dam by David Tanner, Richard Rodd and Hazell Bros., are typically precast and delivered to site. Due to their smaller footprint, cylindrical head blocks are typically recessed into the existing concrete to reduce their impact on accessibility over the crest of the dam; or spillway sections to maintain the existing profile of ogees and chutes without disturbing the water flow. The existing concrete is recessed with a large diameter core barrel to allow placement of the cylindrical head block. The depth of the recess can be such that the anchor bearing plate is flush with the existing concrete surface (i.e., the anchor head and cap protrudes above the existing concrete surface); or it can be deeper so that the full anchor head assembly is fully contained below the existing concrete surface, typically within an access pit. A diagram showing a typical cylindrical head block installation with protruding anchor head is shown in Figure 3.

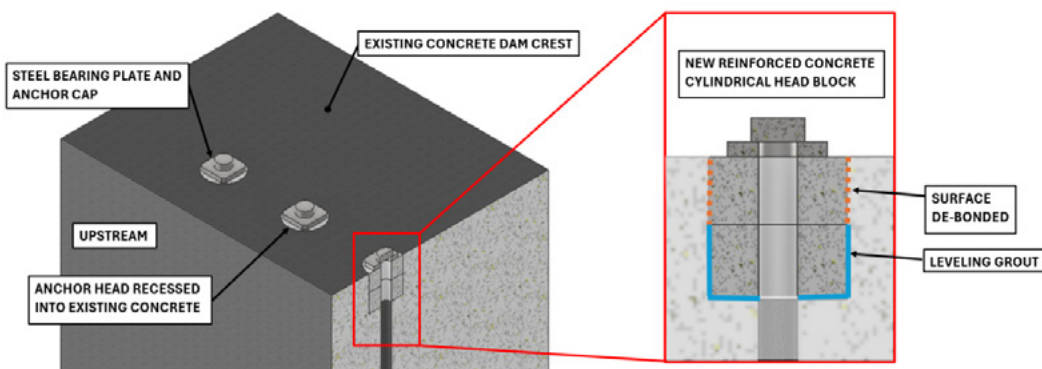


Figure 3. Typical cylindrical head block

## 3.0 Head Block Design Considerations

### 3.1 General

The selection of the type of head block for large capacity post-tensioned anchors needs to consider a variety of factors and constraints specific to each project. These include those directly related to the design of the anchor, such as the reinforcement requirements of the head block, the capacity, and the number of anchors required to stabilise the dam; and their optimal location (in terms of spacing and distance from the upstream face) to increase the stability of the dam while also avoiding internal drainage galleries. Likewise, construction, operational and maintenance/monitoring factors including access, costs and constructability should also be taken into consideration. The sections below provide a comparison between the stress beam and cylindrical head block types against several key considerations. For this comparison, it is assumed that the cylindrical head blocks are recessed such that the anchor heads are flush with the existing crest surface, and that the stress beam head blocks are located on top of the existing concrete surface.

### 3.2 Constructability

Both the stress beams and the cylindrical head block types offer distinct advantages and limitations during construction.

Cylindrical head blocks are typically simpler to recess into the existing concrete structure, which requires partial demolition commonly achieved using large-diameter coring equipment. The cylindrical head blocks are then carefully lowered into the recessed hole with small tolerance, and once in place they require high strength self-levelling grout and de-bonding of the top half as shown in Figure 3. In contrast, stress beam head blocks are simpler when constructed proud of the existing surface, requiring only surface preparation of the existing concrete prior to concrete placement. Despite the additional effort required to recess the anchor head, this is usually adopted for several operational benefits, as discussed in the next section.

Cylindrical head blocks are usually precast, allowing their fabrication early in the project timeline. Although not common practice, prefabrication of stressing beams for one or two anchors is possible before constraints for transportation and crange become problematic. This approach reduces potential delays associated with on-site forming, casting and curing of concrete, and accelerates the overall construction program. The anchor strands can be tensioned immediately after installation of the precast head block rather than waiting for a cast in-situ concrete to achieve a high enough strength before stressing. The precast head blocks are produced in controlled environments, ensuring consistent quality and geometrical accuracy. Cast in-situ head blocks, on the other hand, require formwork, reinforcement placement and concrete delivery or on-site batching (depending on proximity to concrete suppliers).

### 3.3 Operation, Monitoring, Testing and Maintenance

The requirements for monitoring, testing and maintenance of post-tensioned anchors are generally independent of the type of anchor head block. Continuous monitoring and maintenance throughout the life of the anchor is imperative to prevent corrosion of the anchor head and associated components. Corrosion can impact not only the strength of the anchor but hinder the ability to test and maintain it. Regular testing is required to ensure that the anchor load provided is maintained as intended (at or above the design load). Small reductions in anchor load over its life is not unexpected; however, significant load reductions over time can be an indicator of an issue with the anchor. Since anchor monitoring equipment (load-cell) must be placed directly over the anchor head, monitoring of anchors located on spillway sections

present bigger challenges, and specialised equipment is frequently developed for this purpose on a dam-by-dam basis.

While the fundamental requirements for monitoring, testing, and maintenance are similar for both types of head blocks, each type can significantly influence the ease with which these activities can be performed. Anchors are typically fully recessed below the dam crest to minimise day to day operational impacts of personnel and equipment traversing past them without causing damage. In situations where there is limited operational interaction, or where the anchoring is part of a longer-term dam augmentation, the anchor head would ideally be positioned at the dam crest to improve access to the anchor for periodic load monitoring.

Head blocks that are positioned above the existing concrete surface occupy more space and restrict access along the dam crest while requiring the use of pre-fabricated steel working platforms with access ladders or scaffolding to access the anchor head to undertake maintenance activities.

Post-tensioned anchors are preferably installed close to the upstream face to maximise their restoring capacity efficiency. This requirement affects the location of the anchor and may limit the size and movement of vehicles and equipment on the dam crest during and after construction. Existing operational equipment, such as gantry cranes, must also be considered when positioning the anchor head to avoid contact with anchor heads and eliminate potential pinch points that could pose safety risks to personnel. Fully recessed head blocks, such as cylindrical types, mitigate these risks by maximising the operational space on the dam crest. Figure 4 presents an example of operational clearance to vehicle access and gantry crane operation at a critical location of the dam, for recessed cylindrical head blocks with the anchor assembly protruding above the dam crest.

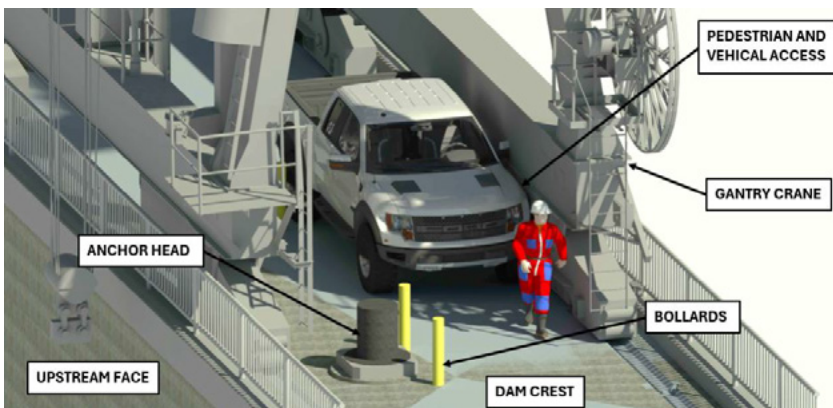


Figure 4. Dam crest operational clearance with cylindrical head block

### 3.4 Anchor Design

The size and number of anchors to achieve a required stabilising force is often the key factor in the anchoring design. The layout of the cross-section of the concrete dam, including the crest width, the size and position of any drainage galleries, the location and orientation of the grout curtain and any embedded equipment (e.g., piezometers), will also influence the optimal position and orientation of post-tension anchors. Coupled with the condition and strength of the existing concrete in the dam and monolith joint spacing, these factors have a significant influence on the optimal anchor spacing, distance to the upstream face and the selection of the head block type. To further explore the key design factors and provide meaningful design recommendations, the authors have conducted a parametric study to understand the impact of the number and layout of post-tension anchors and the adopted type and position of anchor head, as explained in the next section.

## 4.0 Parametric FE Study

To make recommendations for selecting an appropriate type of head block for large capacity anchors, a parametric study has been undertaken. The study involved running multiple 3D nonlinear FE models for 91-strand anchors, with the results summarised in charts that can be used for selection of suitable head block types during feasibility or concept stages. The variables examined in the parametric study were:

- **Tensile strength (Ft) of the existing dam concrete:** 0.2 MPa to 5.0 MPa.
- **Anchor spacing (Ds):** 2.0 m to 4.0 m.
- **Distance from the upstream face (Du):** 1.0 m to 3.0 m.

## 5.0 FE Model Details

### 5.1 Model Description

The study was undertaken with 3D nonlinear FE models with the commercial package Midas FEA NX® (Midas, 2022). A model of a generic concrete gravity dam monolith 14.0 m wide, with an 8.0 m long crest and 10.0 m high chimney section, was used for the analyses (refer to Figure 5). The head blocks were either a protruding stress beam or recessed cylindrical head blocks as these are the contemporary positions for each head block type. Both types were adopted to have a post-tension anchor arrangement of three (3) 91-strand anchors per monolith. The stress beam head block positioned above the dam crest was adopted as per dimensions observed in previously posttensioned dams, with a cross section 1.6 m high and 1.2 m wide. The length of the beam was variable with the end distances equal to half of the anchor spacing. The adopted cylindrical head blocks dimensions were 1.25 m in diameter and 1.28 m high (refer to Figure 6). The cylindrical head block was recessed with the bearing plate flush with the dam crest which is the minimum depth a recessed head block would be positioned. For both types of head block, a 0.9 m square, 0.14 m thick bearing plate was adopted to transfer the anchor load to the head block.

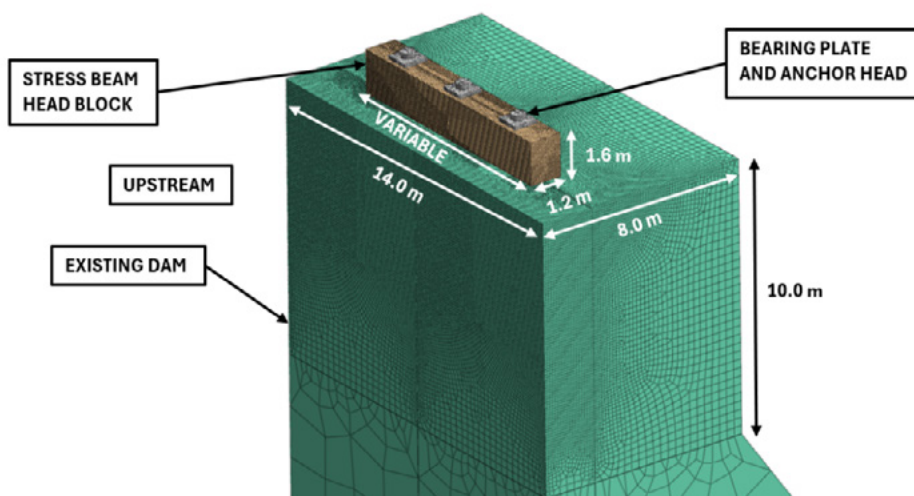


Figure 5. FE model geometry (stress beam head block model)

## 5.2 Material Parameters

Typical material properties were adopted for the study, which are summarised in Table 1 below. It was assumed that the new concrete head blocks contained sufficient reinforcement to prevent bursting, approximately 2% for the stress beam head block and 5% for the cylindrical head block.

Material	Property	Value
Existing Dam Concrete	Density ( $\gamma_c$ )	2,400 kg/m <sup>3</sup>
	Poisson's Ratio ( $\nu$ )	0.25
	Youngs Modulus ( $E_c$ )	30 GPa
	Compressive Strength ( $f_c$ )	25.0 MPa
	Tensile strength ( $f_t$ )	Variable
New Concrete	Density ( $\gamma_r$ )	2,400 kg/m <sup>3</sup>
	Poisson's Ratio ( $\nu$ )	0.2
	Youngs Modulus ( $E_r$ )	35 GPa
	Stress Beam Compressive Strength ( $f_c$ )	30.0 MPa
	Cylinder Compressive Strength ( $f_c$ )	50.0 MPa
Steel Bearing Plate	Density ( $\gamma_r$ )	7,850 kg/m <sup>3</sup>
	Poisson's Ratio ( $\nu$ )	0.3
	Youngs Modulus ( $E_r$ )	200 GPa

**Table 1.** FE model adopted material properties

## 5.3 Meshing

The dam and head blocks were modelled as 3D brick elements. For both the stress beam and cylindrical head block cases, the mesh density under and around the head block was increased to help capture the localised stress response. The mesh was graded to a reduced density away from the area of interest. A cross section through the mesh for the cylindrical head block model, including a close up of the area around the head block, is shown in Figure 6 below. The element sizes are shown in green ovals.

## 5.4 Applied Loads

The FE analyses considered the self-weight of the concrete elements and the post-tensioned anchor loading. A load of 19,000 kN was applied at each anchor, corresponding to a 91-strand anchor at anchor proof load of 75% of the Minimum Breaking Load (MBL). The anchor loading was applied as a distributed load over the anchor head on top of the bearing plate such that load is evenly distributed across the contact annulus surface with the bearing plate, as shown in Figure 6.

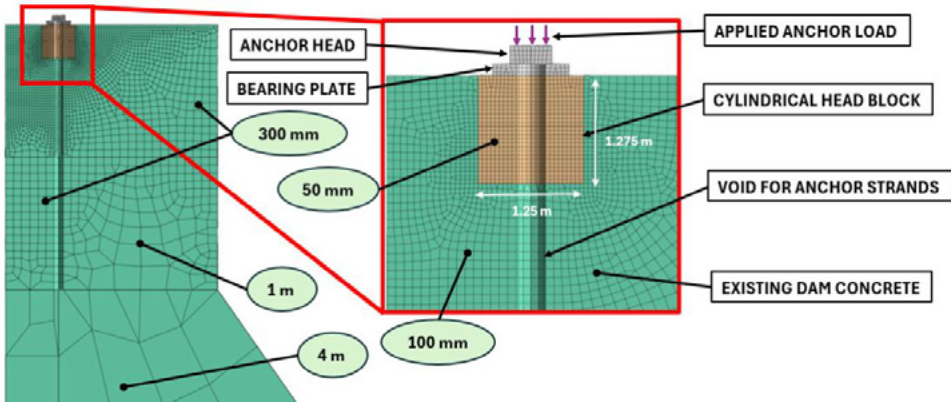


Figure 6: Cross section through mesh of cylindrical head block model

### 5.5 FE Nonlinear Features

The parametric modelling used nonlinear features to replicate the behaviour of the materials more realistically, including possible concrete cracking, and/or the potential sliding along and opening and closing of deboned surfaces. For the cylindrical head blocks, nonlinear surfaces were used to represent the interface between the head block and the vertical recessed face of the existing concrete; and for both head block types, a nonlinear constitutive model (i.e. smeared crack model) was used for the existing concrete.

Nonlinear Mohr–Coulomb interfaces were used around the vertical perimeter of the cylindrical head blocks to represent the de-bonding agent (bitumastic paint) as shown in Figure 7. While the interface can transmit compression due to Poisson’s effect, zero shear and tensile strengths were assumed to allow the cylindrical head block to move independently from the existing surrounding concrete, although in reality the gap between the recess and precast cylindrical head block will be infilled with high strength grout.

To estimate the potential for and the extent of cracking of the existing concrete, a smear crack constitutive model was adopted, with exponential tension–softening tensile behaviour and Thorenfeldt compressive behaviour (refer to the constitutive uniaxial concrete curves in Figure 7). Fracture energy was adopted to be 300 N/m, based on a maximum aggregate size of 75 mm (Comité Euro-International du Béton, 1993).

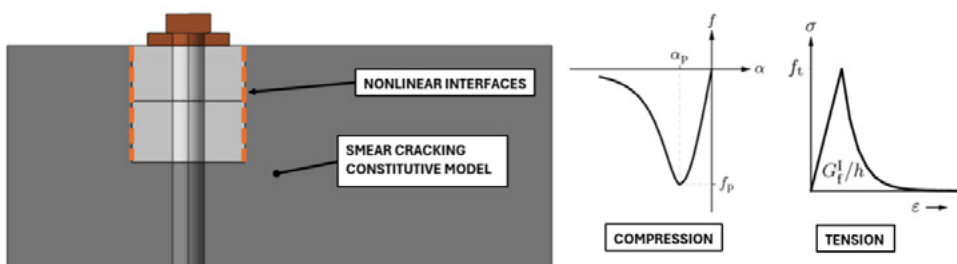


Figure 7. FE nonlinear features

## 6.0 FE Results and Observations

### 6.1 General

A total of 44 FE head block models (18 for the stress beam and 26 for the cylindrical head blocks) were run as part of this parametric study. Only a selection of the most meaningful results of the assessment for each type of head block are discussed in detail in the sections below; however, design charts developed with consideration of the results of all analysed models are presented in the Recommended Design Steps section later in this paper.

### 6.2 Stress Beam Head Block Results

A long section (cross-valley) contour plot of principal compressive stresses for a stress beam head block model with anchors at 3.0 m spacing is shown in Figure 8. As expected, the contour plot shows a bulb of high compression ( $> 25.0$  MPa) immediately under the anchor bearing plates that is distributed through the beam and reduces to about 5.0 MPa at its base, limiting the compressive stress transferred to the existing crest to around 2.5 MPa. Compressive stresses of this magnitude are not expected to cause crushing of concrete typically found in dams.

Figure 9 shows a similar situation for anchors at 2.0 m spacing. Here, the forces are concentrated over a smaller footprint and as such, there are higher compressive forces within the existing concrete. Ignoring the expected concentration of stresses in the corners of the beam, which can be remediated by increasing the beam length, the maximum compression transferred to the existing concrete is approximately 6.0 MPa, which is not expected to cause overstressing to concrete which is in at least fair condition.

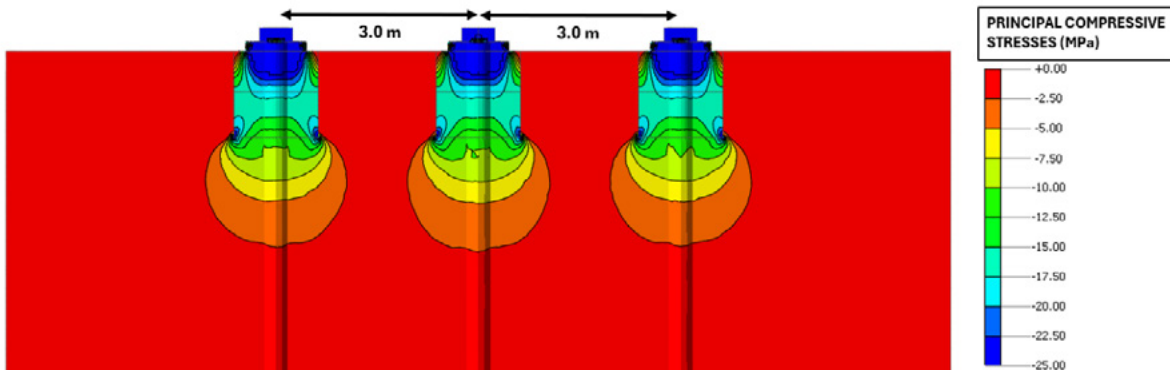


Figure 8. Principal compressive stresses long section – stress beam head block – 3.0 m spacing

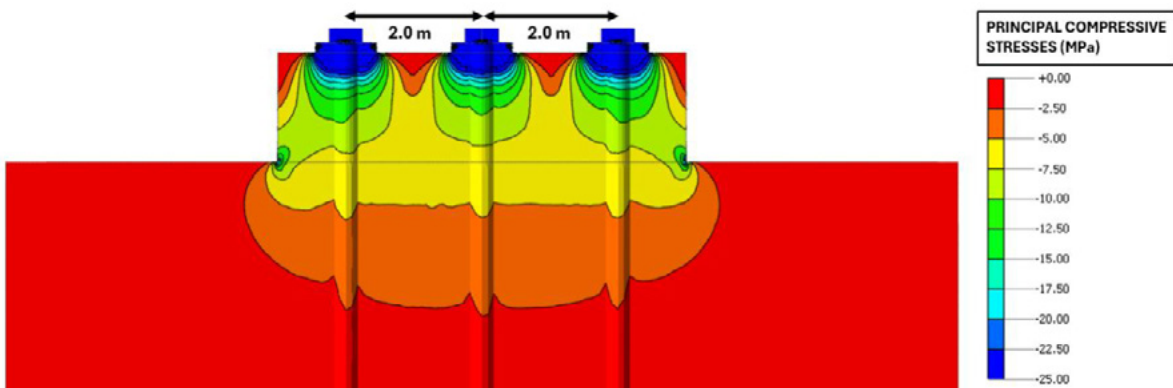


Figure 9. Principal compressive stresses long section – stress beam head block – 2.0 m spacing

A contour plot of principal tensile stresses for a stress beam head block model with 2.0 m spacing is shown in cross section (upstream/downstream) in Figure 10 below. The contour plot shows that the anchors subject the existing concrete to tension in several areas, including the upstream face and the surface immediately downstream of the head block. The maximum transferred tension to the existing concrete is approximately 0.7 MPa, which may cause overstressing and cracking to the existing dam concrete, depending on the condition and actual strength of the structure.

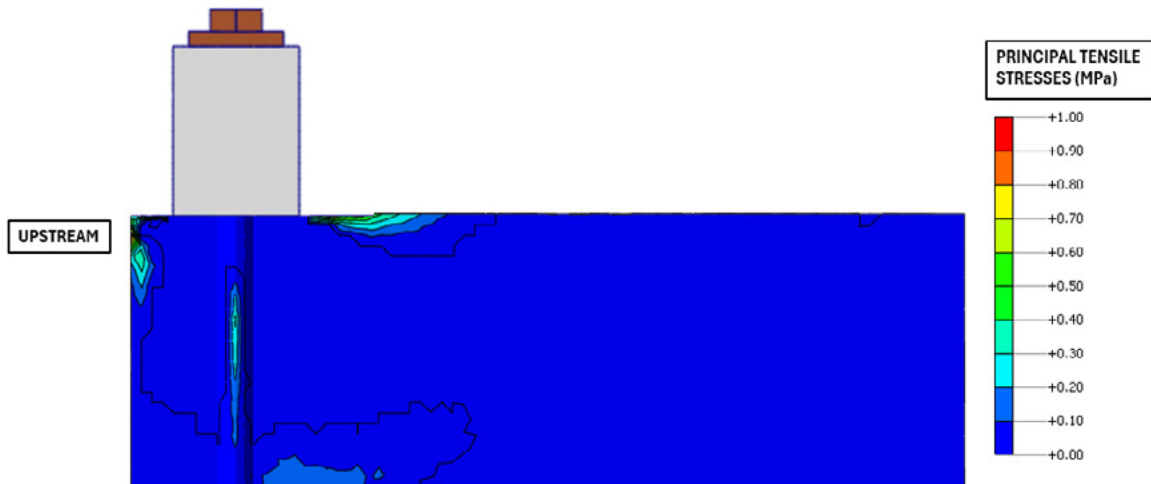


Figure 10. Principal tensile stresses cross section – stress beam head block – 2.0 m spacing

Figure 11 shows the cracking pattern from the smear cracking models, for concrete tensile strengths varying from 0.2 MPa to 3.0 MPa. In this figure the anchor spacing is 2.0 m and the distance between the upstream face and anchor centre line is 1.0 m. The smear cracking constitutive model was used to assess the expected extent of cracking for various tensile strengths of the existing concrete. As shown in the figure, there is a tendency for cracking to occur at the crest of the dam downstream of the head block. This cracking is a result of the large anchor force causing the crest of the dam to flex towards the upstream, hence leading to high tensile stresses in the upstream–downstream direction. As expected, the extent of cracking reduces as the tensile strength increases.

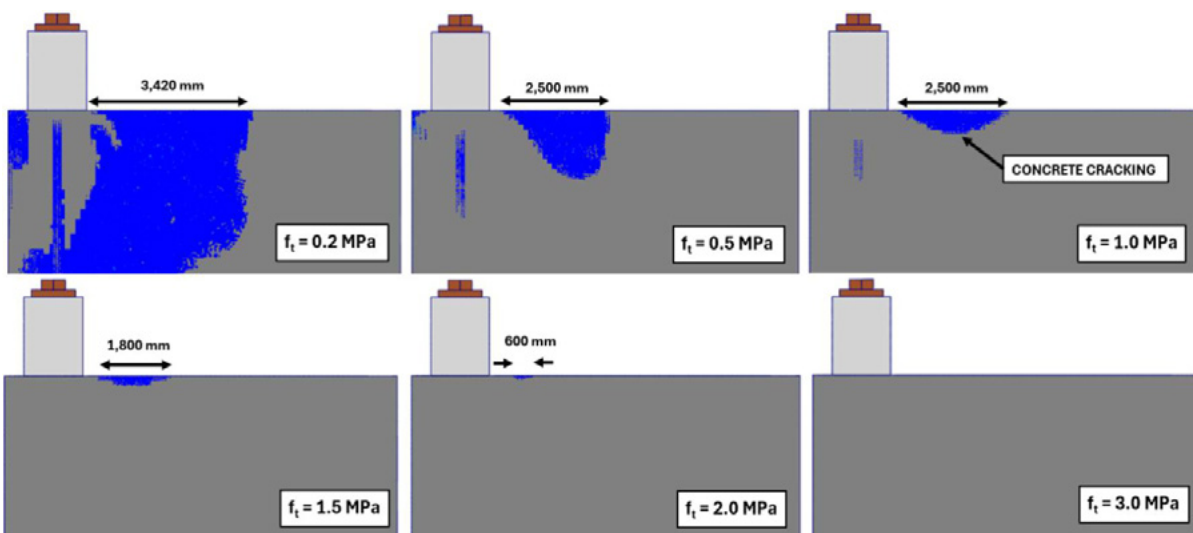


Figure 11. Extent of cracking cross sections – stress beam head block – 2.0 m spacing

Figure 12 shows the resulting relationship between tensile strength of the existing concrete, the extent of downstream cracking and the different anchor spacing. In all cases the distance from the upstream face to the anchor centre line is 1.0 m. The crack length is related to the anchor spacing and how the tensile stresses develop as cracking initiates. When the anchors were spaced at 4.0 m or more, no cracking was observed in the models.

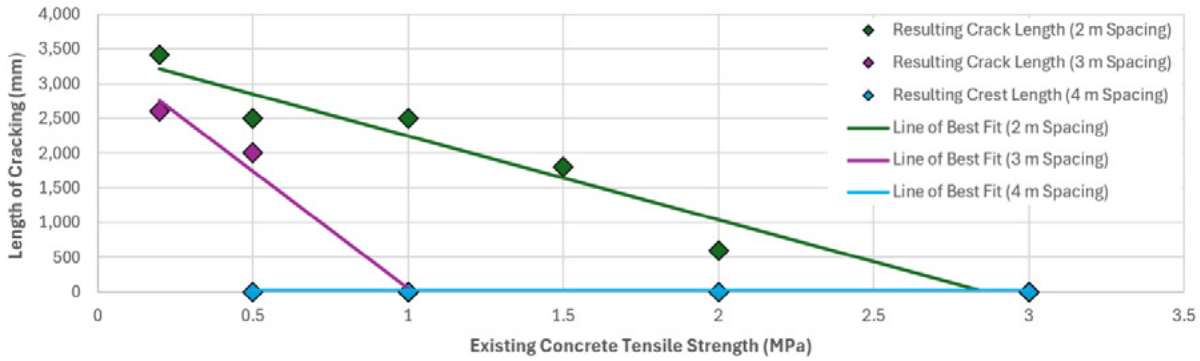


Figure 12. Crack length vs concrete tensile strength – stress beam head block 1.0 m from upstream face

To control cracking at the dam crest for a given tensile strength of the existing concrete, the stress beam head block can be placed at a further distance from the upstream face, or the anchors on the stress beam head block can be spaced further apart to better distribute the anchor load. Based on the observations from the various stress beam head block results and the adopted performance criteria (refer below), guidance on the selection of head block geometry and layout is provided in the Recommended Design Steps section.

An additional observation from several of the stress beam head block models was cracking of the concrete at the downstream end of the chimney, as shown in Figure 13. This cracking was observed in cases where the anchors were closer (e.g., 2 m spacing), concentrating the forces near the upstream face, causing upstream rotation of the chimney section and high tensile stresses to form at the downstream face. This condition is expected to exacerbate in existing concrete with low tensile strength and should be assessed for cases with low reservoir level, possibly requiring the installation of active or passive vertical reinforcement across the chimney base on its downstream end.

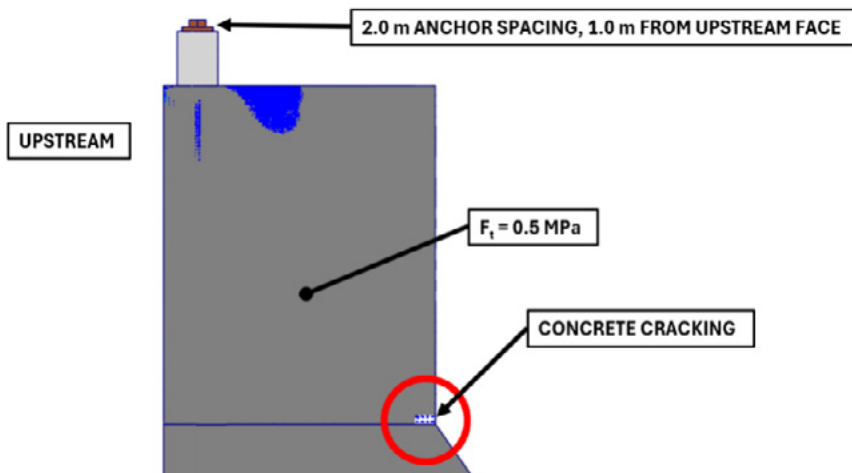
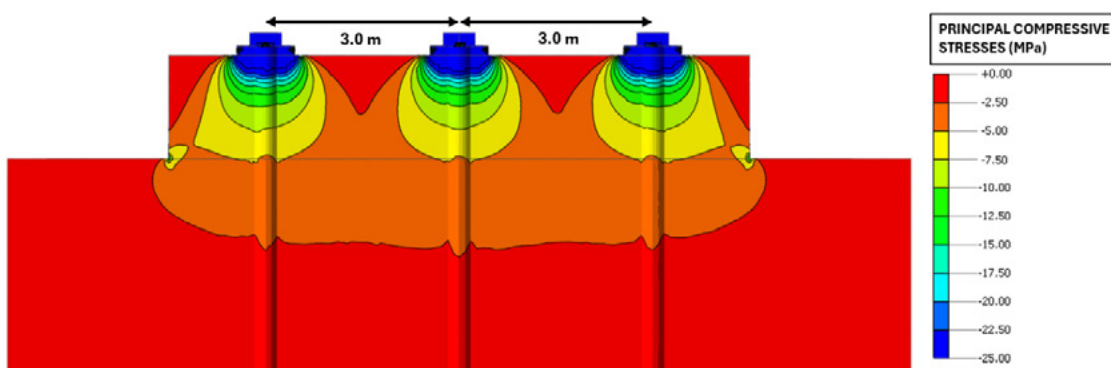


Figure 13. Downstream cracking of chimney – stress beam head block

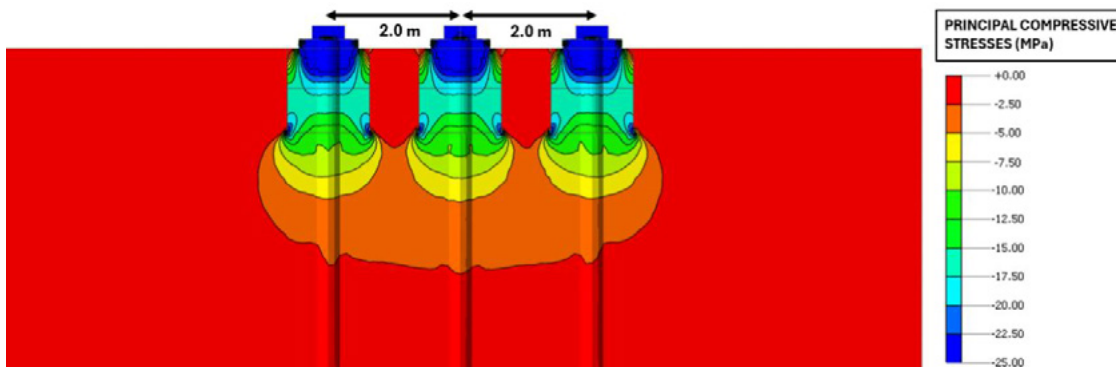
### 6.3 Cylindrical Head Block Results

A long section (cross-valley) contour plot of principal compressive stresses for a model with anchors at 3.0 m spacing is shown in Figure 14. As expected and similar to the stress beam head block, the contour plot shows a bulb of compressive stresses immediately under the anchor bearing plates that is transferred to the base of the cylindrical head blocks. The bulbs of stress at the base of the head blocks do not overlap with those from adjacent head blocks. The maximum compressive stress in the existing concrete is on average around 10 MPa, which is not expected to cause overstress in existing dams with concrete in fair condition.

Figure 15 shows a similar situation, with the anchor spacing reduced to 2.0 m. In this case the compressive stress bulbs do overlap, but the average maximum stress within the existing concrete remains around 10 MPa, which again is not expected to cause overstress in existing dams with concrete in fair condition.



**Figure 14.** Principal compressive stresses long section – cylindrical head block – 3.0 m spacing



**Figure 15.** Principal compressive stresses long section – cylindrical head block – 2.0 m spacing

A contour plot of principal tensile stresses for a cylindrical head block model is shown in cross section (upstream/downstream) in Figure 16. The contour plot shows a very localised concentration of tension within the existing concrete around the base of the cylindrical recess. The maximum tensile stress in the existing concrete is 5.9 MPa, which in most cases is expected to cause overstressing and cracking in concrete typically found in dams.

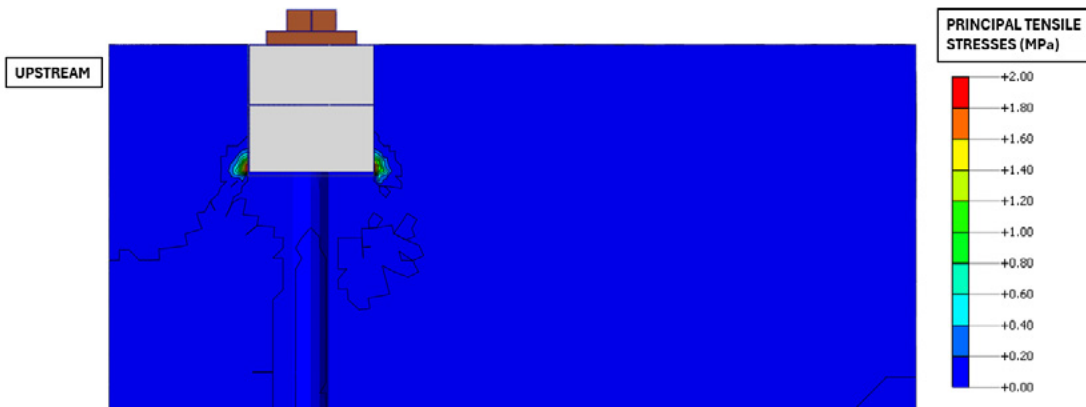


Figure 16. Principal tensile stresses cross section – cylindrical head block

As for the stress beam model, a smeared cracking constitutive model was used to assess the expected extent of cracking within the existing dam concrete at the base of the cylindrical recess, for varying tensile strengths of the existing concrete. Figure 17 shows the cracking pattern from the smeared cracking models for anchors at 2.0 m from the upstream face, for existing concrete tensile strengths varying from 0.2 MPa to 3.0 MPa. As expected, the extent of cracking increased as the tensile strength decreased.

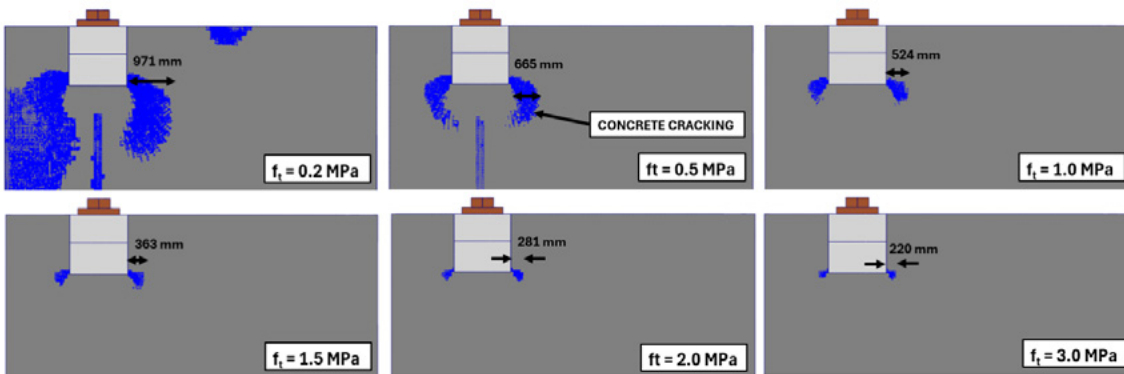


Figure 17. Extent of cracking cross sections – cylindrical head block

Figure 18 shows the resulting relationship between the tensile strength of the existing concrete and the length of cracking from the base of the cylindrical head block. The resulting crack length was found to be independent of the spacing between the anchors.

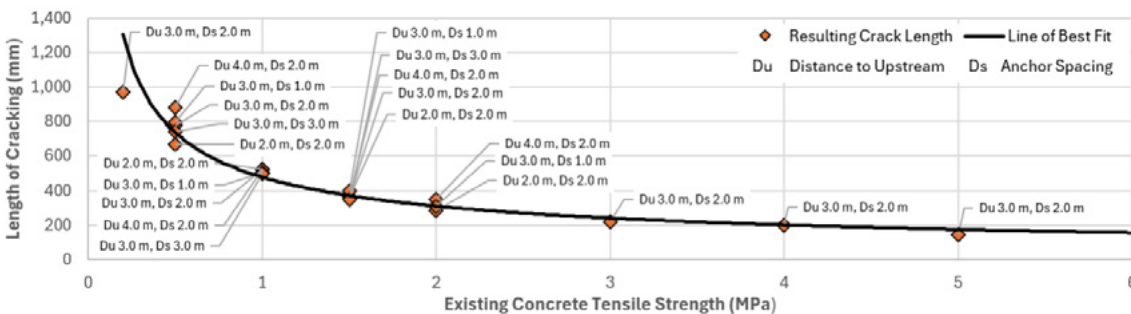


Figure 18. Crack length vs concrete tensile strength – cylindrical head block

The relationship between crack length and tensile strength for cylindrical head blocks confirms the need to consider the appropriate spacing of the anchors and the distance from the upstream face, based on the tensile strength of the existing concrete. If anchors are placed too close together the cracks from adjacent anchors could join, as shown in Figure 19 for the case of 1.0 MPa tensile strength and 2.0 m anchor spacing. If anchors are placed too close to the upstream face, cracking could daylight on the upstream face, creating a path for water ingress to the anchor strands, as shown in Figure 20 for the case of 1.5 MPa tensile strength and 1.0 m distance to the upstream face.

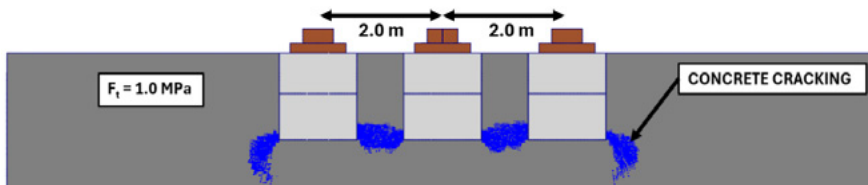


Figure 19. Extent of cracking long section – cylindrical head blocks

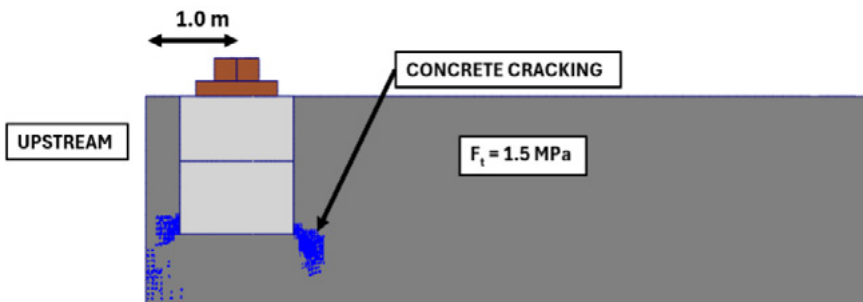


Figure 20. Extent of cracking cross section – cylindrical head block

## 7.0 Parametric Study Outcomes

Based on the results and observations from the various stress beam and cylindrical head block models, a proposed performance criteria and guidance on the selection of head block geometry and anchor layout is provided by the authors in the following sections.

### 7.1 Performance Criteria

Based on the results of the FE study, design charts have been developed to provide recommendations for the preliminary selection of the appropriate head block type, position and anchor layout, including anchor spacing and distance to the upstream face, as a function of the tensile strength of the existing dam concrete. These charts have been developed for the largest commercially available size of 91-strand anchors. In order to assess the outcomes of the parametric study and develop the design charts, performance criteria were established against which the model results could be categorised. The performance criteria were established considering the intended function of the post-tension anchors in stabilising the dam while minimising the detrimental effects of any damage caused to the existing structure.

#### **The following outcomes were considered acceptable:**

- No cracking of the existing concrete.
- Minor cracking in the existing concrete locally at the base of the head blocks, but cracking does not extend further than halfway to the upstream face or to adjacent head blocks. This is not considered to have a detrimental effect on the dam or longevity of the anchors.

#### **Models with the following behaviours were considered unacceptable:**

- Widespread cracking of the existing concrete in the area surrounding the head block.
- Cracking extended to the upstream face or crest of the dam which would allow water ingress to the structure or the anchor tendons.
- Cracking from adjacent head blocks joined to form a continuous crack.

### **Stress Beam Head Block Design Chart**

Figure 21 shows the proposed design chart for protruding stress beam head blocks, which provides recommended anchor spacing for different conditions of the tensile strength of the existing concrete and distance to the upstream face.

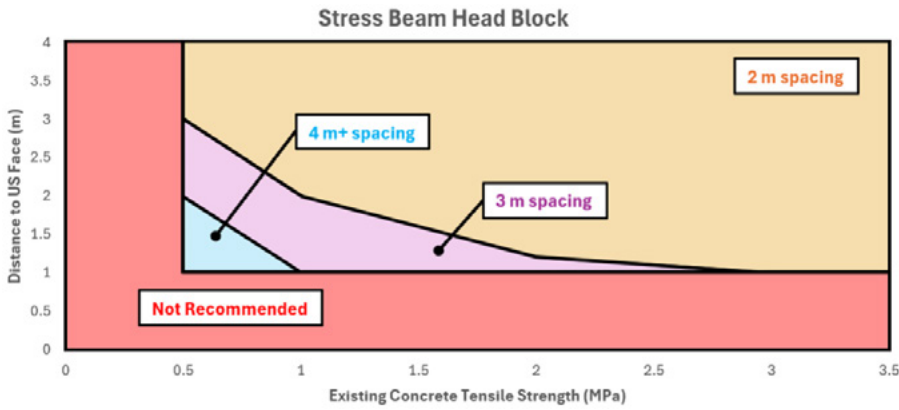


Figure 21. Preliminary design chart for stress beam head blocks (91-strand anchors)

### 7.2 Cylindrical Head Block Design Chart

Figure 22 shows the proposed tripartite design chart for recessed cylindrical head blocks, with acceptable and not recommended combinations of anchor spacing and distance to the upstream face, for different tensile strengths of the existing concrete. For the recessed cylindrical head blocks, the cracking pattern was observed to be equal in all directions (i.e., around the base of the recessed cylinder) and, consequently, the acceptable anchor spacing was found to be roughly twice the distance from the upstream face.

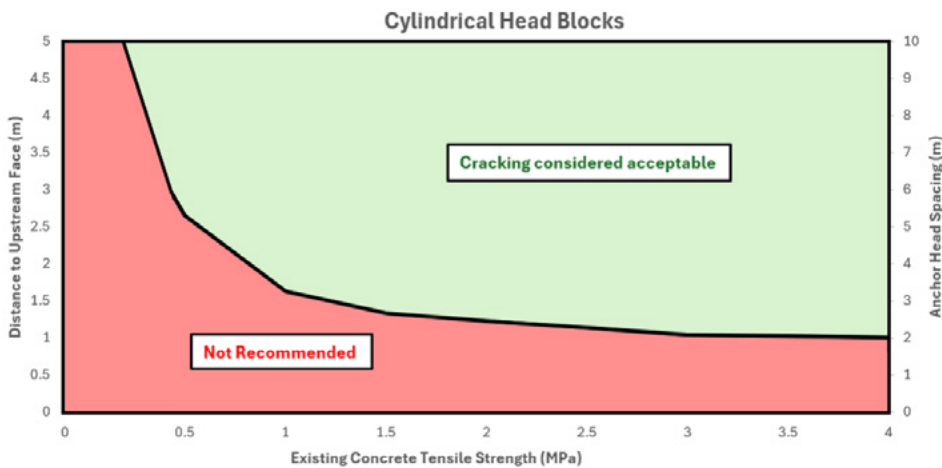


Figure 22. Preliminary design chart for cylindrical head blocks (91-strand anchors)

## 8.0 Recommended Design Steps

Based on the parametric FE study undertaken and the experience of the authors, preliminary design steps for implementation of large capacity post-tensioned anchors in concrete dam upgrades are recommended. The below recommendations are intended for projects in the feasibility or concept design phases. It is noted that when progressing to detailed design level, bespoke FE modelling should be undertaken to verify the stresses imposed by the anchors on the existing dam concrete, to determine the potential for any detrimental effects and to confirm the choice of anchor layout, head block position and type.

### The recommended steps are:

1. Consider factors such as constructability, operation, monitoring, testing and maintenance as discussed in this paper to make an initial selection of the anchor head block type.
2. Use the design chart to select a preliminary head block type (Figure 21 for stress beam or Figure 22 for cylindrical head blocks) to estimate an adequate combination of anchor spacing, position of the head block and distance to the upstream face, based on the adopted tensile strength of the existing concrete. If the tensile strength of existing concrete is unknown, correlations with the compressive strength from Rafael (1984) can be utilised, as recommended by USBR (2006).
3. Undertake structural analyses to determine the required anchor loads to stabilise the dam wall using as inputs the estimated required spacing and distance from the upstream face.

Should the findings of Steps 2 or 3 indicate that the chosen head block type in Step 1 is inappropriate with the existing conditions and constraints, the alternative head block type or other bespoke design should be considered.

### In addition to the recommended steps above, design of the post-tensioned anchors should also consider the following:

- Design of aspects other than the head block, such as corrosion protection, anchor head assembly, bearing plates, sheathing and bond zone should consider current industry practice, as further discussed in Wark et. al. (2017) and Sinclair and Rodd (2011).
- Consider that the anchor head may bulge under the large anchor forces, which would alter the thread diameters and thus the ability to thread a monitoring load cell onto the head. The anchor head requires a fixed contact area of steel (annulus) to transfer the load to the bearing plate. This sets the diameter of the hole in the bearing plate, such that the annulus bridges over the hole in the headblock, without significant cantilever bending-deflection.
- When determining the anchor spacing, consideration must be given to not only the influence at the dam crest, but also the requirements in the foundation. When anchors are spaced closely, staggering in depth may be required in order to engage larger volumes of rock to prevent a rock pull-out failure (Australian practice since 1981).

- The installation of anchors near the upstream face of the dam will likely increase the tensile forces at the downstream edge of the chimney section. In load cases where the dam is expected to move towards the upstream (such as an empty reservoir load case or seismic cases), there is a potential for cracking from the downstream end of the base of the chimney. In this case, consideration could be given to strengthening of this area by installation of passive reinforcement or post-tensioned stress bars, prior to stressing of the post-tensioned anchors.
- During seismic load cases, a dam is expected to deflect and deform, which can elongate the anchor strands. Generally, the change in strand free-length is minor compared to the length of the anchors, meaning that the strain and therefore additional force during the seismic event is unlikely to result in the anchor exceeding the proof load unless the anchor is short and the earthquake results in significant displacements. The additional load from the anchor on the head block under seismic loading should be assessed on a case-by-case basis as part of the anchor design.
- Consideration should be given to the condition and location of the lift joints when designing the posttensioned anchor system. The preliminary focus of the FE analyses conducted for this paper is on the tensile strength of the existing parent concrete. It should be recognised that concrete lift joints are often the weakest part of the structure, especially if they are unbonded. As a results, FE analyses may require the explicit modelling of the said lift joints.

## 9.0 Conclusion

In this paper the authors have discussed typical considerations for the design of large capacity post-tensioned anchors in concrete dam upgrades, from the perspective of their practical experience. Using nonlinear finite element analysis, the comparative behaviour of cylindrical and stress beam head blocks was assessed for a range of cases with varying concrete tensile strengths, anchor spacing, and distance to the upstream face. The results indicate that both head block types can be effective, but their suitability depends on the specific constraints of each dam and project.

The FE parametric study has been used to develop a framework for selecting head block types, head block position and anchor configurations based on expected stress distributions and potential cracking of the existing concrete. By considering both quantitative performance criteria and qualitative factors such as constructability, operation, monitoring, testing and maintenance, the recommended steps outlined in this paper provide a basis for head block selection for large capacity post-tensioned anchors in concrete dams.

Further study is recommended in this field focusing on the use of smaller capacity anchors (65-strands or less) or higher capacity anchors (121-strand anchors), noting that 121-strand anchors are not yet available.

## 10.0 References

Comité Euro-International du Béton (1993). CEB-FIP model code 1990: Design code. Thomas Telford Publishing.

Harman T., Herweynen., R and Ghosh M. (2013). Analysis and Design Challenges Associated with the Catagunya Dam Restoration Project

Ladiges S., Wark R. and Rodd R. (2016). Maintenance and Testing of Post-Tensioned Anchors for Dams and Appurtenant Structures. ANCOLD Conference Proceedings 2016. Adelaide.

MIDAS Information Technology (2022). Midas FEA NX Advanced Nonlinear and Detailed Analysis System.

Raphael, J.M. (1984). Tensile Strength of Concrete. Journal Proceedings, 81(2), 158–165

Sinclair M. and Rodd R. (2011). The Recent Developments and Application of Large Ground Anchors for Dams. ANCOLD Conference Proceedings 2011. Melbourne.

USBR (2006). State-of Practice for the Nonlinear Analysis of Concrete Dams at the Bureau of Reclamation.

Wark R., Sinclair M., Rodd R., and Ladiges S. (2017). Developments in the Design, Construction and Operation of Large Capacity Multi Strand Anchors in Australia. ICOLD Conference Proceedings 2017. Prague.



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