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Attention: Greg Mason

Enlarged Cotter Dam – Stability Review of Dam Post Cracking

Please find attached a copy of the report '*Enlarged Cotter Dam – Additional Finite element Analysis of Cracked Section*', Report No GHD-ECD-DAM-GN-RPT-0005, November 2012. This document is also being separately transmitted to you electronically.

Following the identification of the cross valley cracking in the dam along the surface of the placed roller compacted concrete (RCC) at RL 511.3 m AHD in April 2012, the Bulk Water Alliance (BWA) undertook a number of analyses to assess the potential of the propagation for the crack and the stability of the dam should there be any significant propagation and movement along the crack.

This work was undertaken in a number of stages. The intent of the initial stage (undertaken in May 2012) was to provide sufficient confidence that defensive measures employed to limit the propagation of the crack were adequate and therefore ongoing placement of the RCC was possible. (See report '*Enlarged Cotter Dam Cross Valley Cracking*', Report No GHD-ECD-GEN-GN-RPT-6103, July 2012 – a copy of which has previously been provided.)

The later analysis as discussed in the attached report ('*Enlarged Cotter Dam – Additional Finite element Analysis of Cracked Section*', Report No GHD-ECD-DAM-GN-RPT-0005, November 2012) provides a more rigorous analysis confirming assumptions made in the initial stages, and assessing the cracked dam for more long term load cases based on thermal and seismic loading of the dam.

Conclusions from the May 2012 Analysis

The initial analysis, undertaken in May 2012, assumed that the crack would propagate the downwards from the RL 511.3 m AHD level to the foundation. This assumption was based on previous thermal analysis which showed tensions in the lower part of the dam. And although these tensions were within acceptable limits, it was considered prudent to conservatively assume that cracking would occur, given the known crack at RL 511.3 m AHD. This analysis showed that upward propagation of the crack was unlikely even without the defensive measures employed.

Conclusions from November 2012 Analysis

The main conclusions that can be drawn from the additional analyses reported in the attached document are as follows:

- *Crack Propagation*

Subject to the thermal stresses it is unlikely that sufficient tension will be developed to allow the crack to propagate upwards from the RL 511.3 m AHD level.

It was further shown that the crack is unlikely to propagate downwards more than a few metres below the RL 511.3 m AHD level. However as previous analyses have shown the probable development of reasonably high tensile stresses (<2 MPa) as the dam cools it has been conservatively assumed that the dam will crack from RL511.3 m AHD to the foundation for the purpose of the seismic analysis.

- *Seismic Stability Assessment*

Analysis for the *Operating Basis Earthquake* (OBE) events (Annual Exceedance Probability (AEP) = 1:500) demonstrated that the Cotter Dam was both stable and structurally sound. Any possible cracking would likely be relatively minor in nature and be localised to the upstream face at approximately mid height of the dam.

Analysis for the *Maximum Design Earthquake* (MDE) events (AEP = 1:10,000), indicate potential for full crack development at the base and potential cracking along the lift joints. As with the previous uncracked analysis of Cotter Dam, the dam is deemed safe to withstand the MDE events but large remediation works would be necessary to reinstate its structural integrity and operational capacity after the earthquake. The inclusion of the assumed vertical crack within the dam does not appear to negatively impact on the dam structural integrity with respect to earthquake loading.

- *Post Seismic Stability Assessment*

Post seismic analysis undertaken showed that the dam structure would still be stable in its post seismic conditions even with the addition of the intersecting horizontal and vertical cracks through the maximum height section of the dam.

In summary, from the analyses undertaken the extent of propagation of cross valley cracking in the dam appears likely to be limited and localized. Further the stability analysis of the dam the shows the dam to remain stable under all assessed loading conditions.

Should you require any further information with respect to this report please contact me on the numbers above.

Yours sincerel[redacted]

[redacted]

[redacted] 30/11/12

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ater Security Projects

ttachments:

Report No GHD-ECD-DAM-GN-RPT-0005 - *'Enlarged Cotter Dam – Additional Finite element Analysis of Cracked Section'*, November 2012

Bulk Water
Alliance

Enlarged Cotter Dam
Additional Finite Element Analysis of Cracked Section

November 2012

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Certificate of approval for issue of documents

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EXECUTIVE SUMMARY

Background

Following the identification of the cross valley cracking along the surface of the placed RCC at RL 511.3 mAHD in April 2012, the BWA undertook a number of analyses to assess the potential of the propagation for the crack and the stability of the dam should there be any significant propagation and movement along the crack. This work was undertaken in a number of stages. The intent of the initial stages was to provide sufficient confidence that defensive measures employed to limit the propagation of the crack were adequate and therefore ongoing placement of the RCC was possible.

The later analysis as discussed in this report provides a more rigorous analysis confirming assumptions made in the initial stages, and assessing the cracked dam the more long term load cases.

Previous Analysis

The initial analysis, undertaken in May 2012, assumed that the crack would propagate the downwards from the RL 511.3 m AHD level to the foundation. This assumption was based on previous thermal analysis which showed tensions in the lower part of the dam. And although these tensions were within acceptable limits, it was considered prudent to conservatively assume that cracking would occur, given the known crack at RL 51.3 m AHD. This analysis showed that upward propagation of the crack was unlikely even without the defensive measures employed.

Current Analysis – Sensitivity Analysis of Crack Behaviour subject to Thermal Loading

The current series of analyses considered the likely behaviour of the crack and the resulting behaviour of the dam under for a number of different scenarios. The previous analysis only considered the crack in one location (the most upstream position), however it occurs at different upstream – downstream locations within different monoliths. This sensitivity of its position has been considered in the current work. It was shown that irrespective of the crack position it is unlikely to propagate upwards, and therefore it will not daylight on the downstream face.

The previous analysis assumed that the crack would propagate to the foundation from the RL511.3 m AHD, and therefore it was modelled to be present from the start of the analysis. This assumption was tested by assuming that the crack was only 2.4 m long below the RL 511.3 m AHD level. The analysis showed that that the crack is not likely to propagate any significant distance downwards. However as previous analyses have shown the probable development of reasonably high tensile stresses (<2MPa) as the dam cools it has been conservatively assumed that the dam will crack from RL511.3 m AHD to the foundation for the seismic analysis.

Current Analysis – Seismic Analysis

This current analysis assessed the stability of the dam subject to the :-

- OBE (Annual exceedence probability (AEP) = 1 in 500, Modified Mercalli Intensity (MMI) = 7.0 and peak ground acceleration (pga) = 0.1 g) and
- MDE (AEP = 1 in 10,000, MMI = 9.5, pga = 0.35g)

Only the maximum section, with the crack propagated to the foundation was considered for the OBE loading. The results indicated that dam may suffer some minor cracking of the upstream face at about mid height, however neither the stability or structural integrity of the dam would be compromised.

For the MDE loadings the following sections were considered:-

- Maximum section – crack in its most upstream position
- Maximum section – crack in its most downstream position
- Abutment sections.

The analysis indicated that the dam at the maximum section would suffer extensive damage during a MDE seismic event. There would be significant cracking on both the upstream and downstream faces. This cracking was represented as a single crack extending from the upstream to the downstream, as the limitations of the software did not make it practical to assess a multiple crack model.

Both the block above the horizontal crack and the lower part of the dam are shown to move downstream during the MDE seismic event. The dam did not become unstable during the events however it is likely that it will be badly damaged and as such emergency action would be required as well as extensive remedial works to bring the dam back into service.

The abutment sections suffered similar damage but to a lesser extent.

Current Analysis – Post Seismic Assessment

The post seismic stability of the dam was considered for a number of different scenarios of crack opening and pore pressure distributions within the crack. In all cases the dam was found to remain stable in its damaged condition.

Conclusions

The main conclusion that can be drawn from the additional time history analysis is as follows:

- Crack Propagation

Subject to the thermal stresses it is unlikely that sufficient tension will be developed to allow the crack to propagate upwards from the RL 511.3 m AHD level.

It was further shown that the crack is unlikely to propagate downwards more than a few metres below the RL 511.3 m AHD level. However as previous analyses have shown the probable development of reasonably high tensile stresses (<2MPa) as the dam cools it has been conservatively assumed that the dam will crack from RL511.3 m AHD to the foundation for the purpose of the seismic analysis.

- Linear Analysis

Analysis for the OBE events demonstrated that the Cotter Dam was both stable and structurally sound. Any possible cracking would likely be relatively minor in nature and be localised to the upstream face at approximately mid height of the dam.

For the MDE events, the stresses were too great in magnitude and area to be adequately assessed through linear analysis. If propagation of the assumed crack were to occur it would possibly connect with cracking along the lift joints between the upstream and downstream faces. As such further non-linear analysis was undertaken to include a possible vertical crack for the MDE events.

- Non-linear Analysis

Results of the nonlinear time-history analysis for the MDE events indicate potential for full crack development at the base and potential cracking along the lift joints. The inclusion of a horizontal crack between the upstream and downstream faces of the dam intercepting the assumed vertical crack at RL 510.8 m AHD produces modest residual downstream displacements of the dam. As with the previous uncracked analysis of Cotter Dam, the dam is deemed safe to withstand the MDE events but large remediation works would be necessary to reinstate its structural integrity and operational capacity after the earthquake. The inclusion of the assumed vertical crack within the dam does not appear to negatively impact on the dam structural integrity with respect to earthquake loading.

- Post Seismic Analysis

Post seismic analysis undertaken showed that the dam structure would still be stable in its post seismic conditions even with the addition of the intersecting horizontal and vertical cracks through the maximum height section of the dam.

Contents

1 Introduction

1.1 Introduction

RCC placement was put on hold at ECD on 27th February following the overtopping of the partially completed dam due to flooding, estimated to be in the order of 1 in 100 AEP. The flood waters overtopped the partially constructed dam (which was at RL511.3m at the time) by approximately 2m at the peak of the flood. The dam continued to be overtopped for eleven days. Following the recession of the flood clean up works and preparation for the recommencement of placement was undertaken. Placement of RCC was recommenced on 5 May 2012, resulting in a total delay of 68 days.

Prior to Easter (6th to 9th of April) an upstream- downstream crack adjacent to the left abutment was identified and was being monitored. Over the Easter long weekend a cross valley crack developed in the then left abutment monolith (Monolith D) extending from the induced monolith joint to the cross valley crack (this crack was observed by the TRP during the meeting of 23 April). The BWA consider the cause of this crack to be thermal shock as the ambient temperature fell to near or possibly below 0°C on the morning of 10 April 2012.

As the surface clean up continued for the recommencement of placing RCC, additional cracks were identified across adjacent monoliths. The last of these was identified on 3 May where it appears to have terminated about midway through the monolith containing the intake tower. The timing of when these cracks occurred is not known but is suspected that they formed over the Easter weekend or some time thereafter as it got further into the cold season. The cracks are located at approximately 15 to 20 m from the downstream face. The locations of the crack are shown in Appendix A.

It is conceivable that the monoliths to the right of this last observed cracked monolith may also contain cracks, however one layer of RCC was placed in this area on 20 April to bring a low area up to the general level of 511.3 m AHD. This may have covered cracks prior to them being identified, although the area was thoroughly inspected before the RCC was placed and none were found. The more likely situation is that the heat generated by hydration of the small amount of RCC was sufficient to protect the surface. Furthermore the right abutment sees the most sun of any part of the dam, which would have limited the extent to which this part of the dam cooled. The crack adjacent to the left abutment was investigated by drilling to about a depth of 450 mm. Cores over the crack were found to get stuck in the barrel of the simplistic single tube coring rig used, so a more extensive coring campaign to ascertain the depth of the cracks was not undertaken. The crack was visible in the base of this hole. All cracks remained relatively tight with the maximum measured surface width being 0.9mm wide.

2 Assessment for Crack to Propagate

2.1 Downward Propagation

The extent to which the cracks have propagated below the RL 511.3 m surface is unknown as there was no opportunity to undertake any investigative drilling prior to the recommencement of the placing of the RCC above RL 511.3 m. This was due to the lack of a suitable drilling rig and the urgency to recommence RCC placement (both as a means of applying thermal protection to the surface and to limit the commercial impacts of the delay). However it has been assumed that the crack will eventually propagate to the foundation subject to thermal loading. This assumption is supported by the original thermal stress analysis which indicated that areas of tension in the upstream / downstream direction will develop at the base of the dam as the RCC cools. It is hypothesised that given the dam is cracked, the estimated tensions will be sufficient to promote the propagation of the crack to the foundation. Therefore the majority of the analyses discussed in this memo, have assumed this crack to be present at the commencement of any loading event. However to confirm the validity of the assumption an analysis has been undertaken assuming that the crack had propagated only a short length below RL 511.3 m and the thermal stresses allowed to develop to determine if they exceed the assumed tensile strength of the RCC and therefore the crack would propagate to the foundation.

2.2 Upward Propagation

Crack treatment has been put in place to prevent the propagation of the crack upwards. This is discussed in principal in the BWA memo "ECD - Cross Valley Crack in Monolith D" dated 30 April and subsequently modified by Site Instruction issued 5 May 2012. However to assess that the defensive measures put in place are adequate to prevent the propagation of cracks thermal analyses were undertaken for the cracked section. These are discussed GHD-ECD-DAM-GN-TMM-004-0-0 (ref 4).

2.3 Sensitivity of Crack Location

The location of the top of the crack as observed at RL 511.3 m varied from about 15 m from the upstream face to about 23 m from the upstream face for the three monoliths at the maximum height of the dam. The majority of the analyses were undertaken considering the most upstream crack. However to confirm that the propensity for the crack to propagate and that the stability of the dam is not sensitive to the location of the crack (under either thermal or seismic loading), the section was analysed with the crack in the most downstream location.

3 Thermal Analysis Undertaken During Current Review

3.1 Description of the Models

Two additional thermal models have been analysed for the current review. These were:-

- Cross valley crack from foundation to RL 511.3 m AHD (nom) located in the most downstream position recorded.
- Cross valley crack extending from to RL 511.3 m AHD (nom) to 2.4 m below this surface, before the recommencement of the RCC placing (2.4 m was adopted as this is 2 elements deep within the FE model)

The first of these models is identical to the model used in the previous thermal analysis undertaken (ref 4), with the exception the cross valley crack is located 23 m from the upstream face (previously 15 m). The crack has been modelled to extend from the foundation to 510.8 m AHD (the model assumes 1200 mm lifts to simplify the analysis and this is the nearest left surface to the actual 511.3 m AHD. This discrepancy is not considered to be a significant). The crack has been modelled with elements that can transfer shear and compressions across the crack. This assumes that the crack does not open up to the point that shear can no longer be transferred.

For the second model an identical model to that used in the previous analysis with the exception that the crack is assumed to have no tensile capacity from the tip of the crack at RL 510.8 to RL 508.4. Below RL 508.4 to the base of the dam the assumed crack path has been modelled with cut off bar element that have a tensile capacity of 2.0 MPa. This was done to assess the possibility of the crack propagating vertically towards the base of the structure in addition to upwards through the structure.

For both models

- the assumed internal pore pressure distribution is reservoir head on the upstream face linearly reducing to atmospheric pressure at the downstream face or at the location of the assumed vertical crack
- The material parameters adopted are unchanged from the analysis discussed in reference 1.
- The rate of convection is the adjusted rate (ref 3) determined by calibrating the FE model with the recorded temperatures within the partially constructed dam.
- The construction program has been modified to reflect the actual construction rate up to RL 511.3 mAHD and the programed rate above this level.

No attempt has been made to model the actual ambient conditions. The long term average temperatures have been used. This was not considered critical, in that although the cold nights are considered to be the cause of the cracking, the model assumes the dam has cracked and therefore no initiating event is required.

3.2 Modelling Results

The following sections provide contour plots of the and upstream downstream stress from the model at various ages.

Figure 3.1 to Figure 3.10 shows maximum principal and upstream downstream stress for the model with the most downstream crack location.

Figure 3.11 to Figure 3.19 provides maximum principal and upstream downstream stress for the model with the assumed existing crack depth limited to 2.4m below RL 510.8 m AHD.

Figure 3.20 and Figure 3.21 show the displacement one side of the crack relative to the other at various heights for the downstream crack model and limited crack depth model respectively.

3.2.1 Stress Plots for Most Downstream Location of Vertical Crack

Figure 3.1 Maximum Principal Stress - Winter 2012 – Most downstream crack location

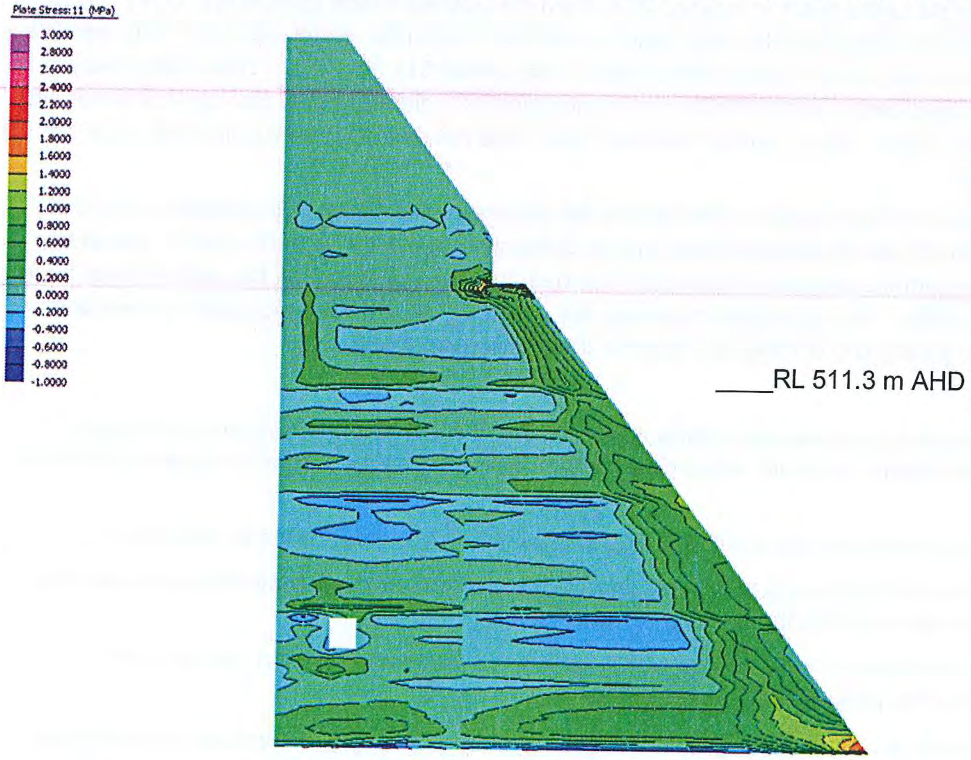


Figure 3.2 Maximum Principal Stress – Summer 2013/14 (Filling of Reservoir) – Most downstream crack location

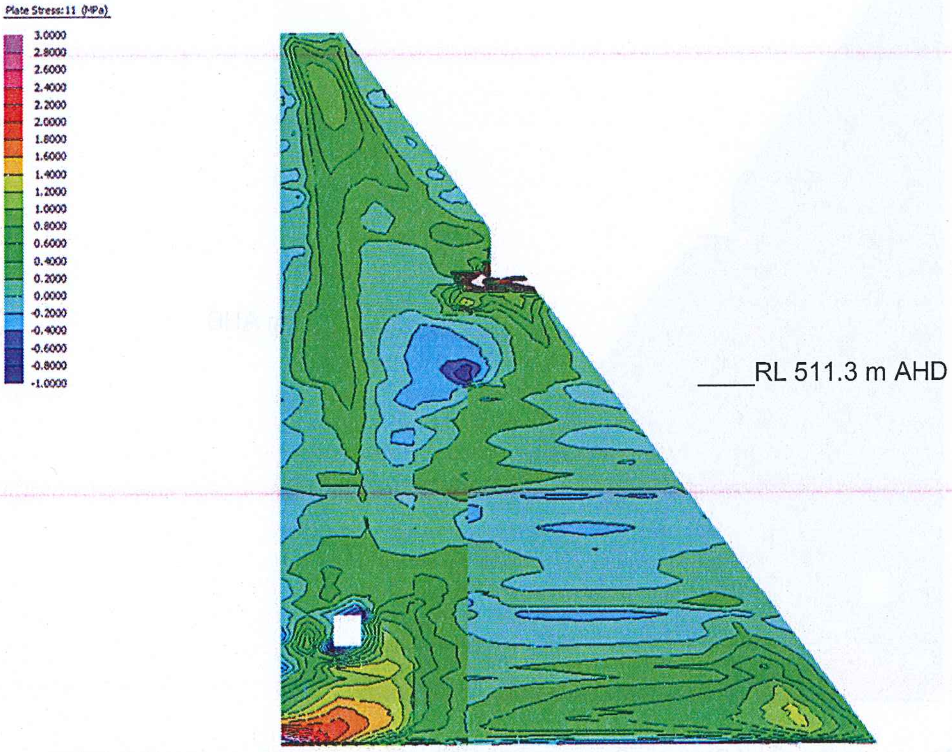


Figure 3.3 Maximum Principal Stress – Winter 2014 – Most downstream crack location

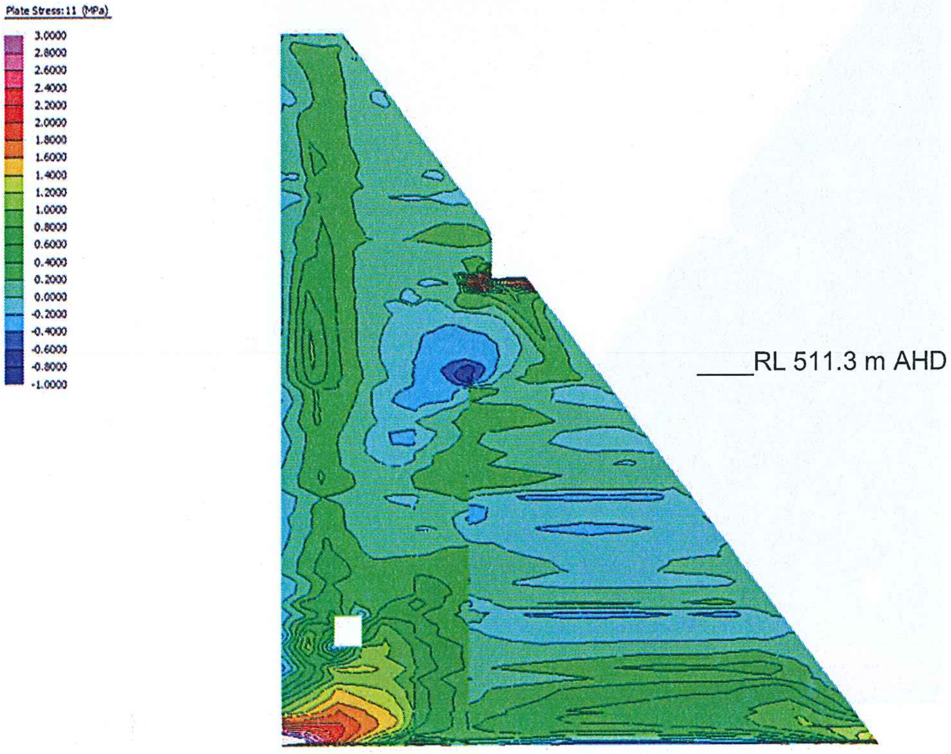


Figure 3.4 Maximum Principal Stress – Winter 2031 – Most downstream crack location

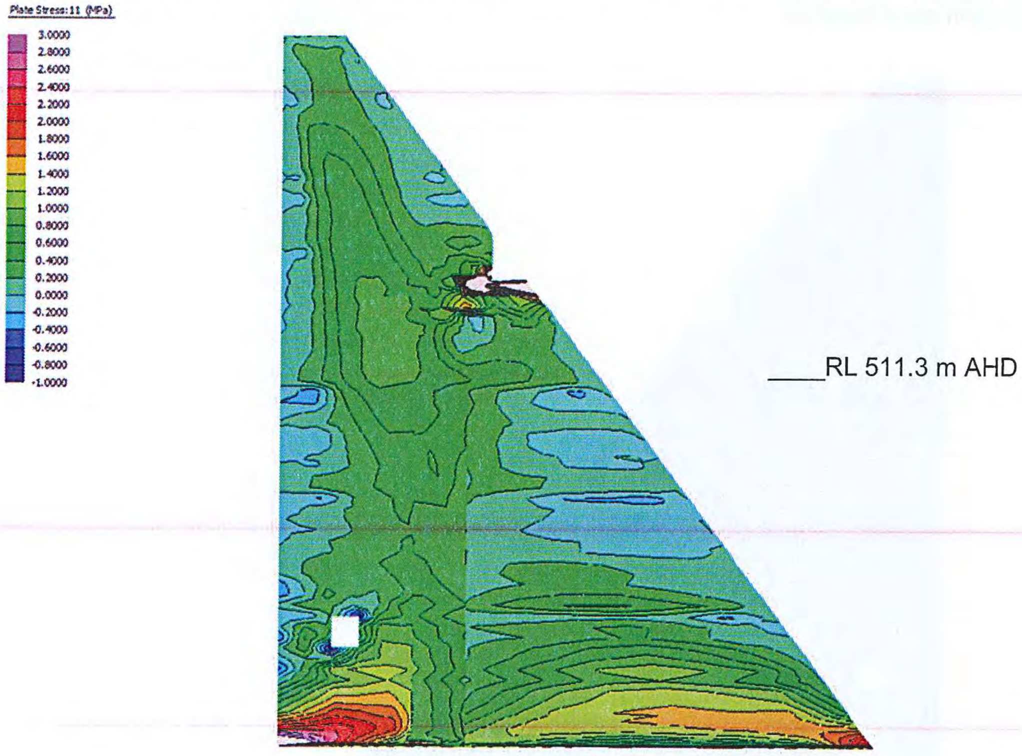


Figure 3.5 Maximum Principal Stress – Summer 2031/32 – Most downstream crack location

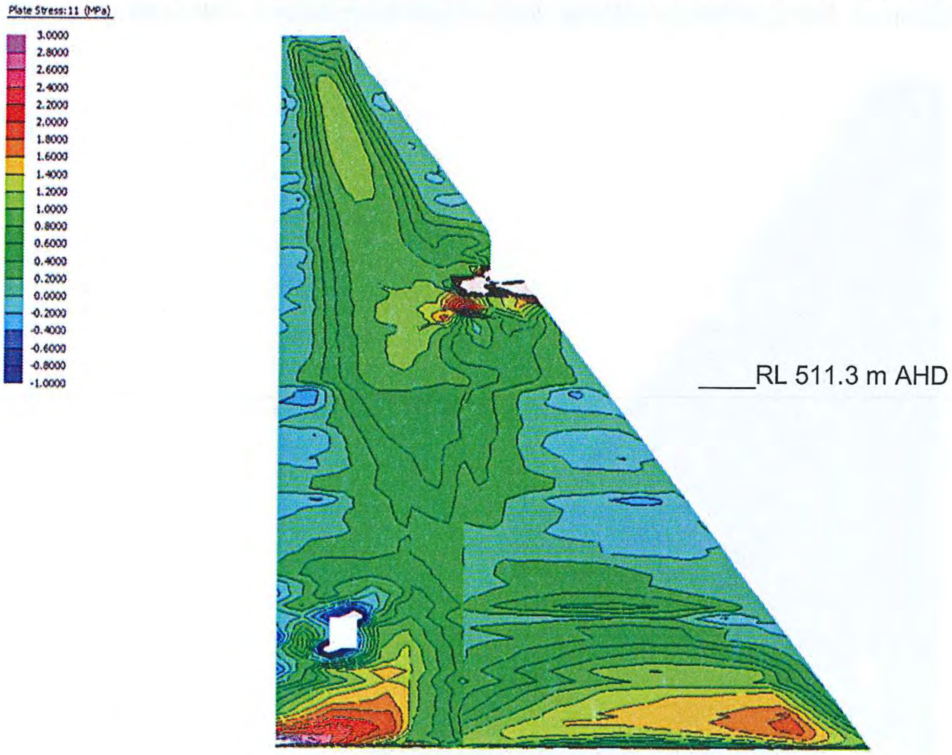


Figure 3.6 Upstream Downstream Stress - Winter 2012 – Most downstream crack location

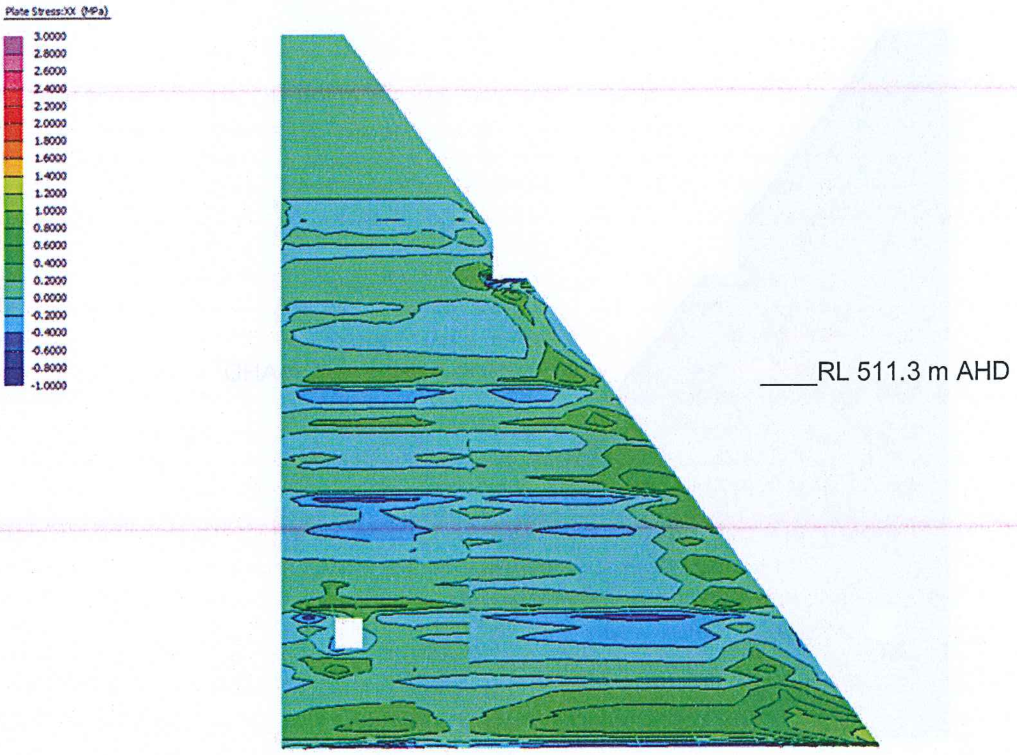


Figure 3.7 Upstream Downstream Stress – Summer 2013/14 (Filling of Reservoir) – Most downstream crack location

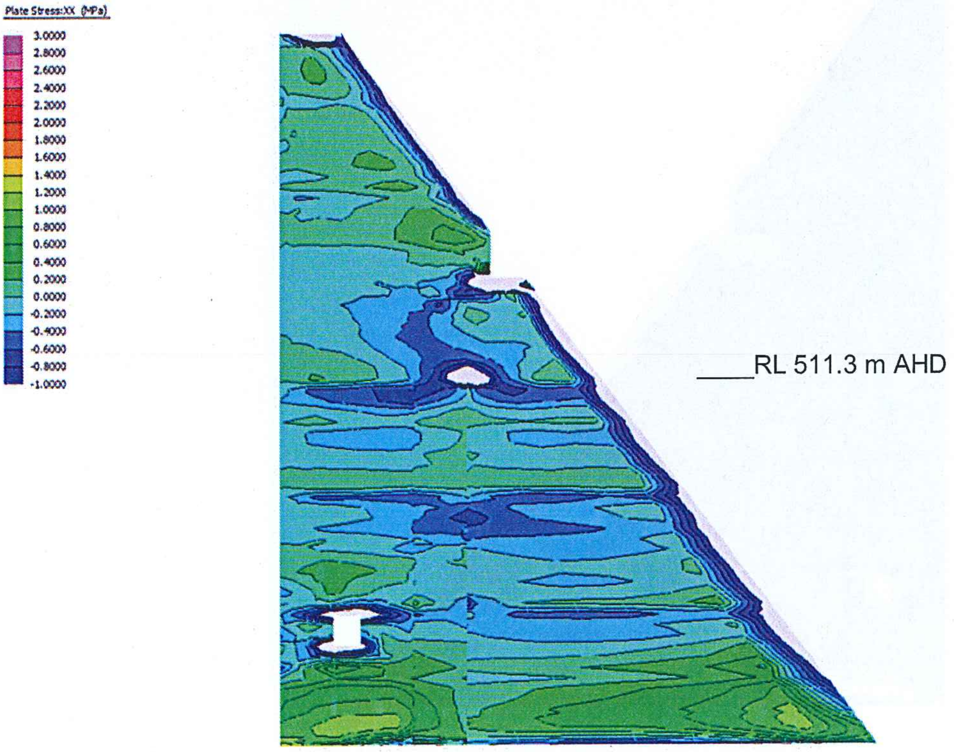


Figure 3.8 Upstream Downstream Stress – Winter 2014 – Most downstream crack location

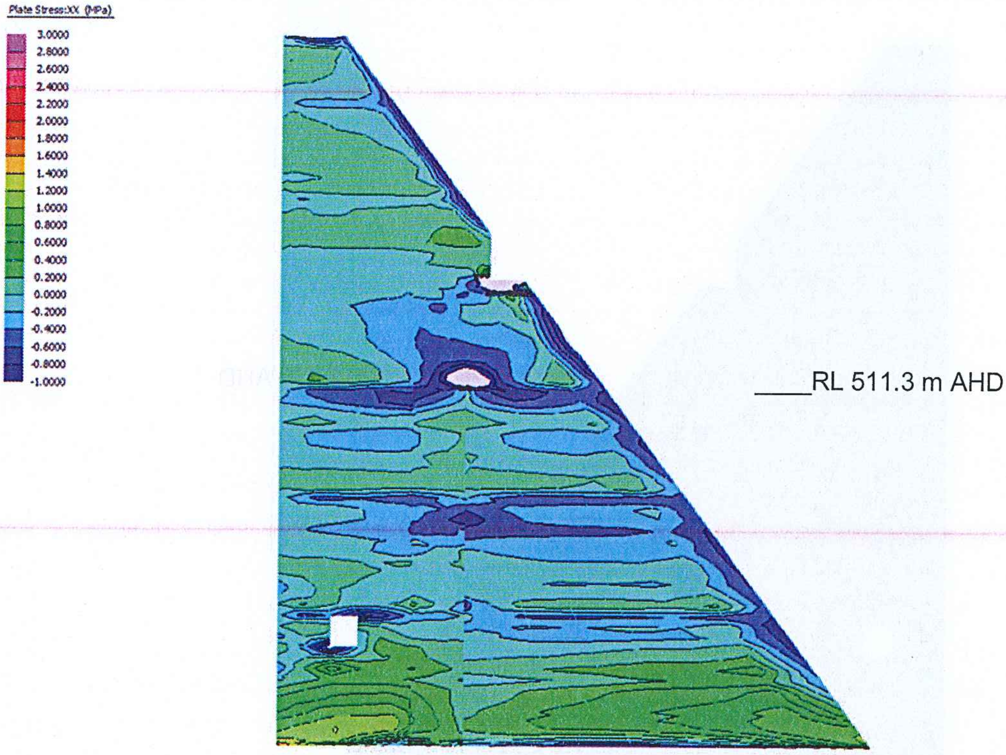


Figure 3.9 Upstream Downstream Stress – Winter 2031 – Most downstream crack location

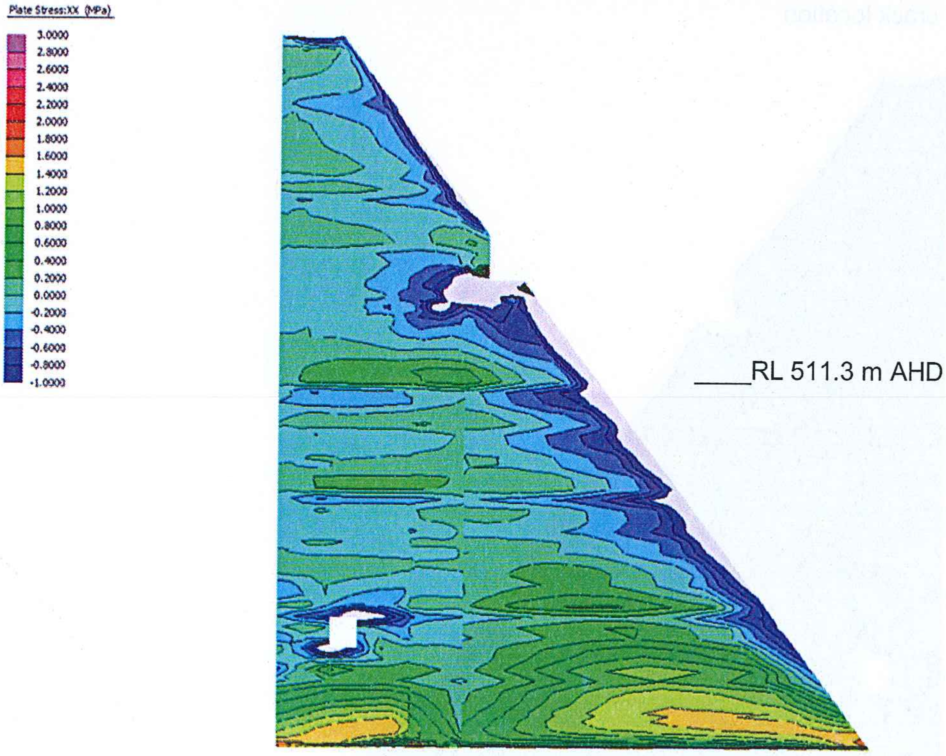
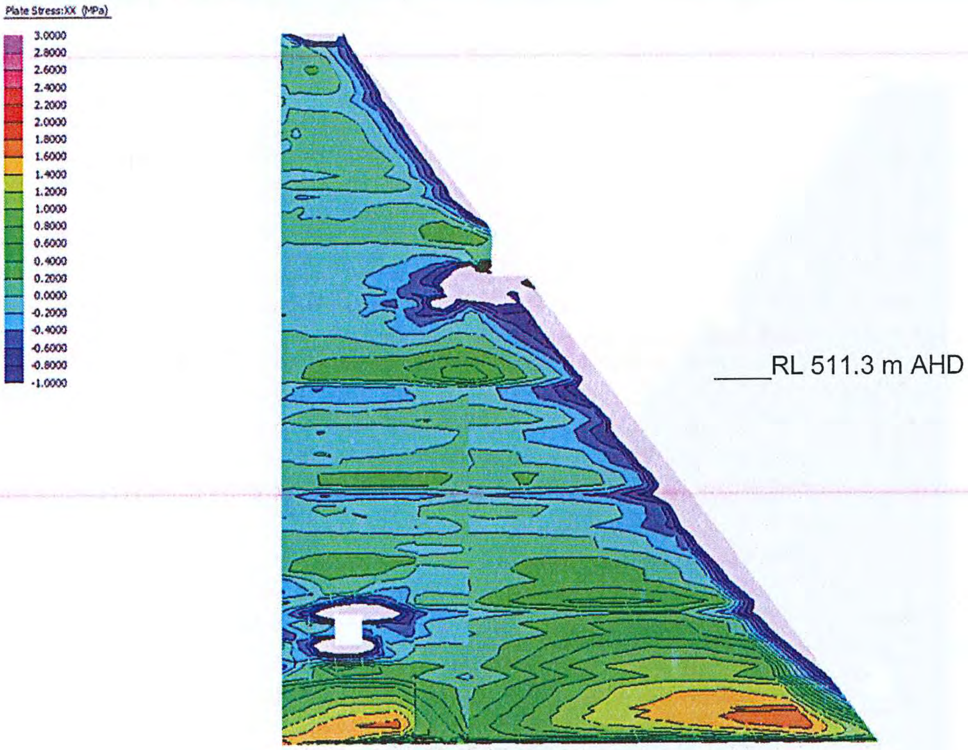


Figure 3.10 Upstream Downstream Stress – Summer 2031/32 – Most downstream crack location



3.2.2 Stress Plots for Limited Depth Crack

Figure 3.11 Maximum Principal Stress – Summer 2013/14 (Filling of Reservoir) – Limited Depth Crack

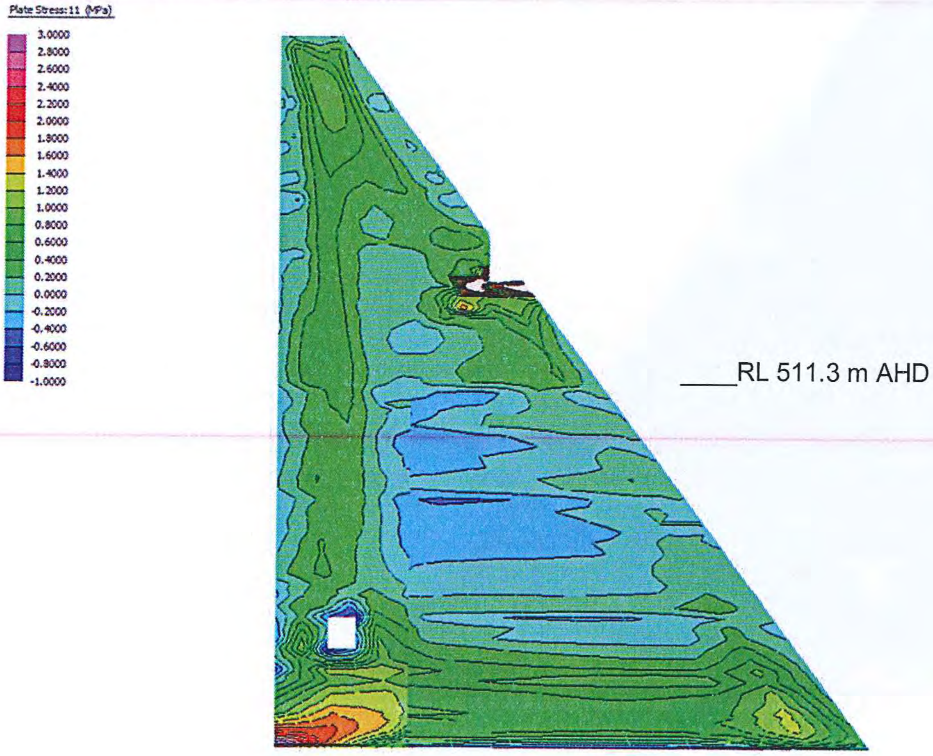


Figure 3.12 Maximum Principal Stress – Winter 2014 – Limited Depth Crack

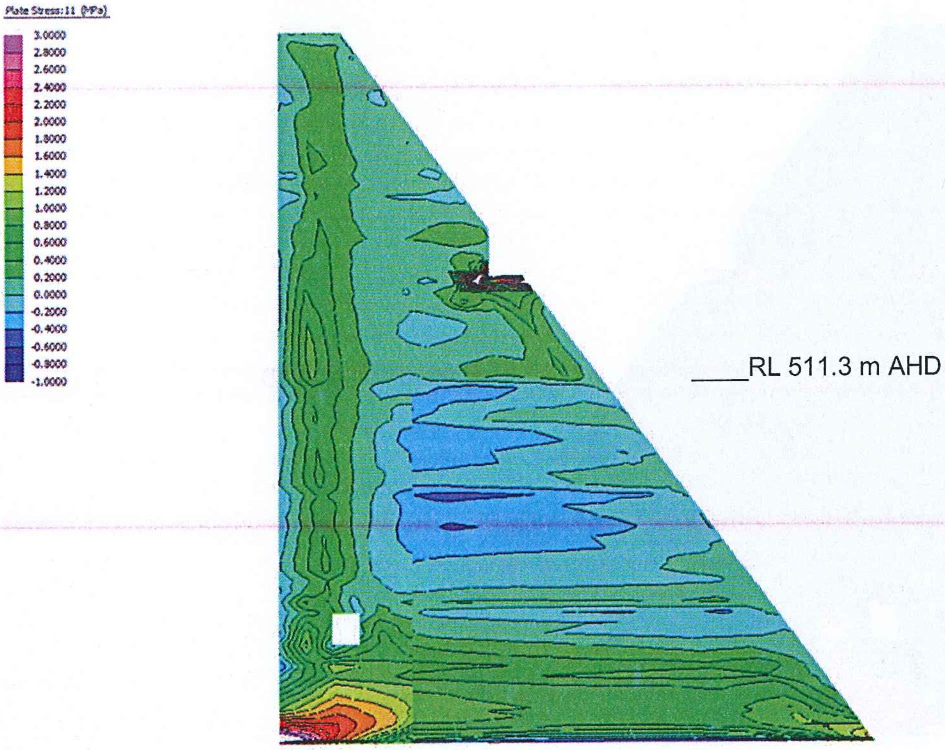


Figure 3.13 Maximum Principal Stress – Winter 2031 – Limited Depth Crack

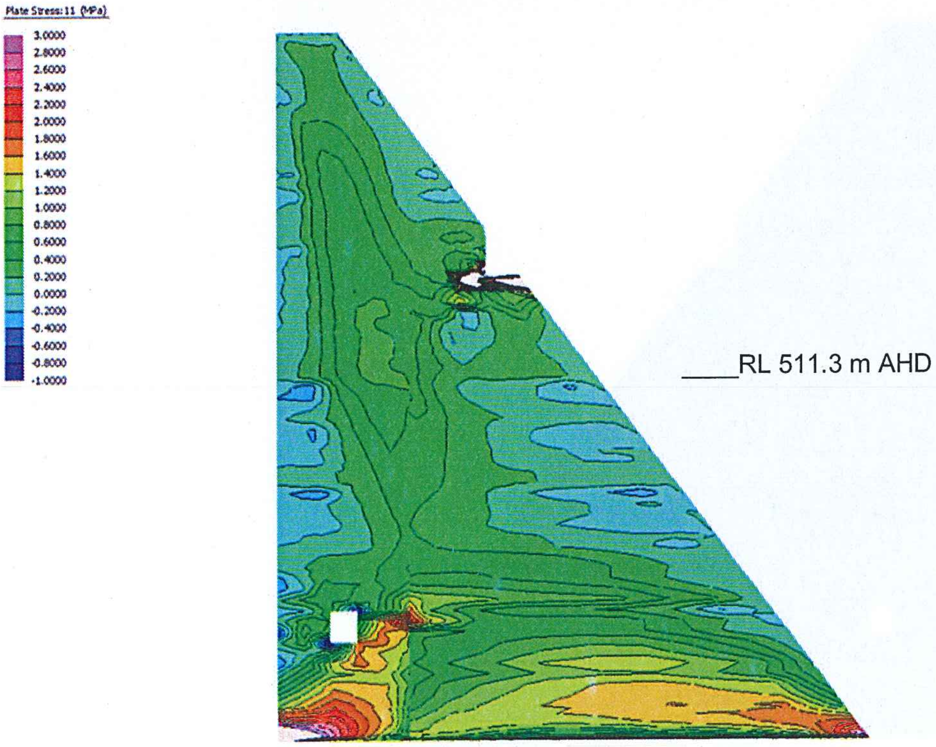


Figure 3.14 Maximum Principal Stress – Summer 2031/32 – Limited Depth Crack

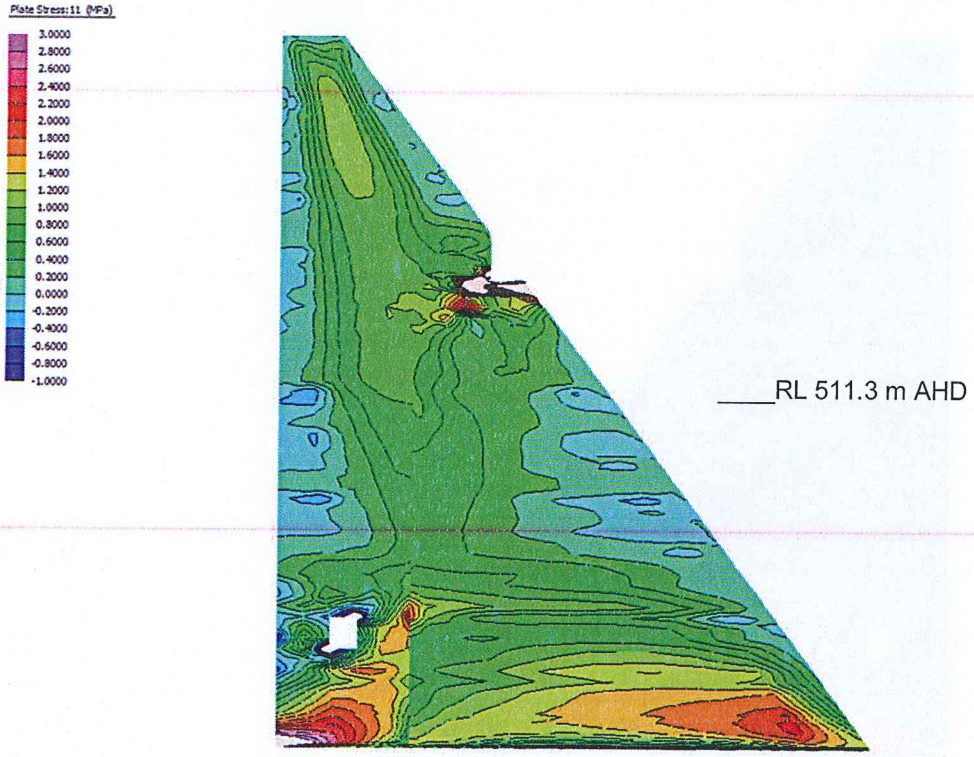


Figure 3.15 Upstream Downstream Stress - Winter 2012 – Limited Depth Crack

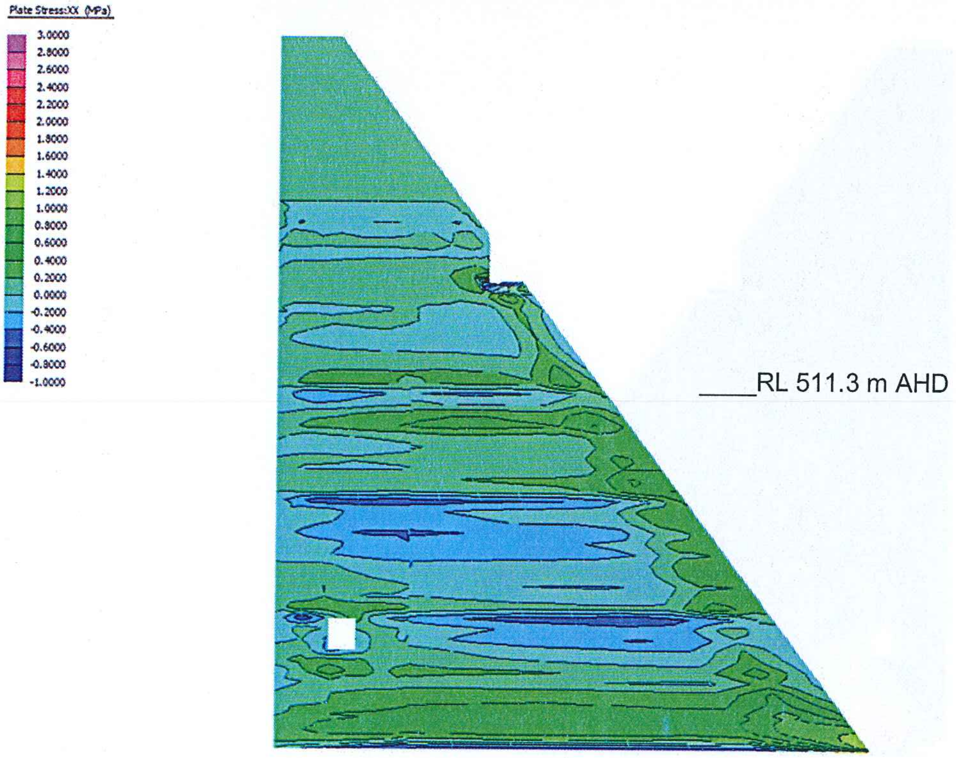
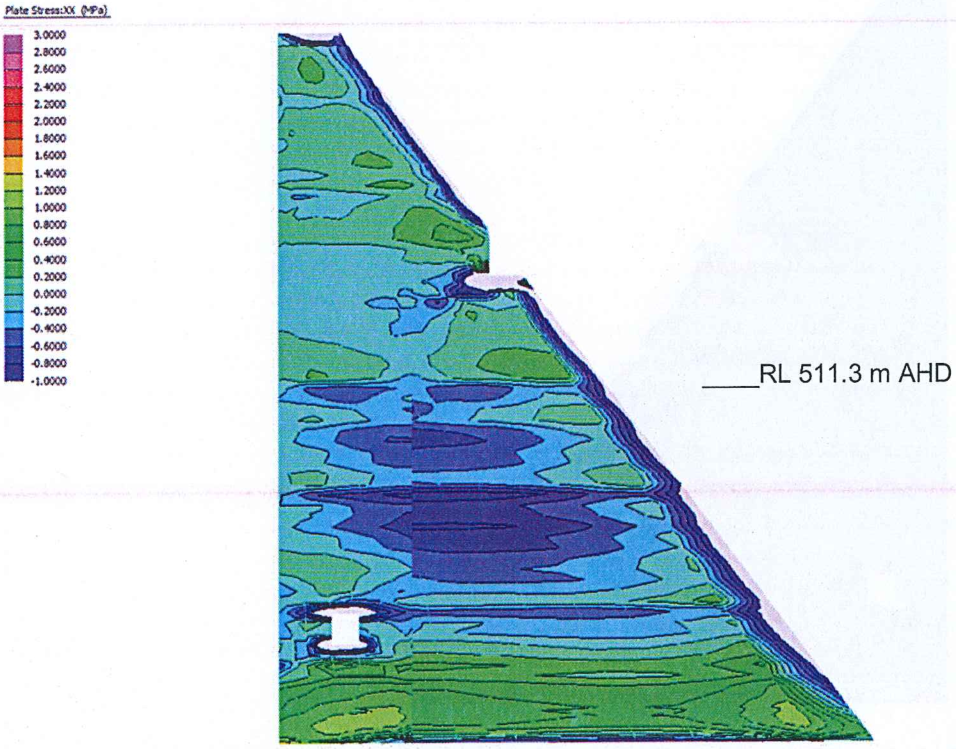
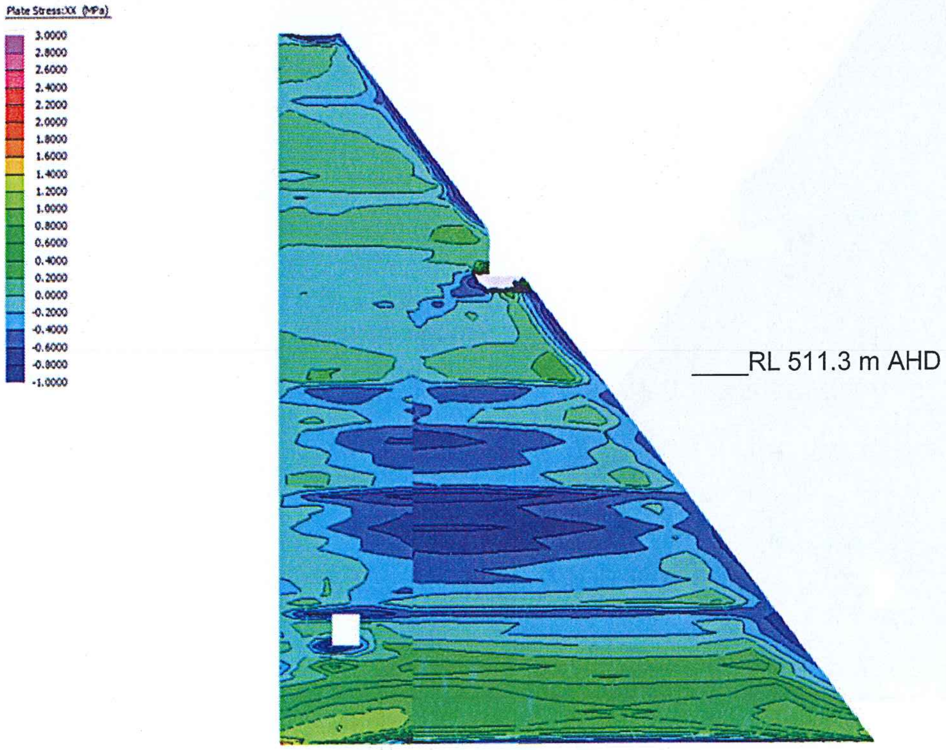


Figure 3.16 Upstream Downstream Stress – Summer 2013/14 (Filling of Reservoir) – Limited Depth Crack location



RL 511.3 m AHD

Figure 3.17 Upstream Downstream Stress – Winter 2014 – Limited Depth Crack



RL 511.3 m AHD

Figure 3.18 Upstream Downstream Stress – Winter 2031 – Limited Depth Crack

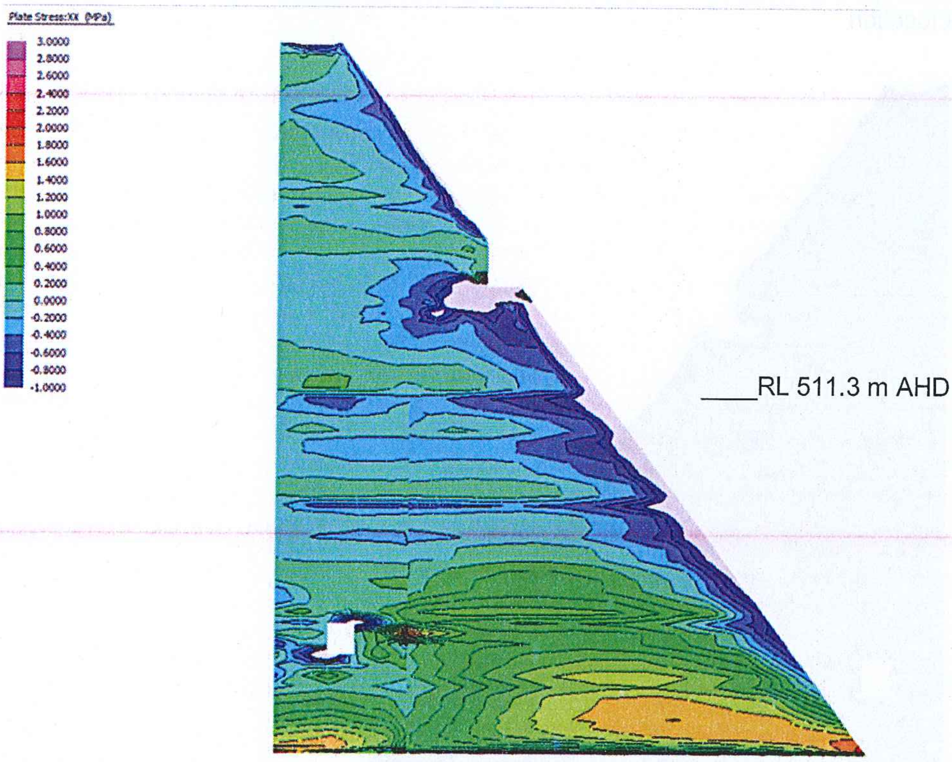
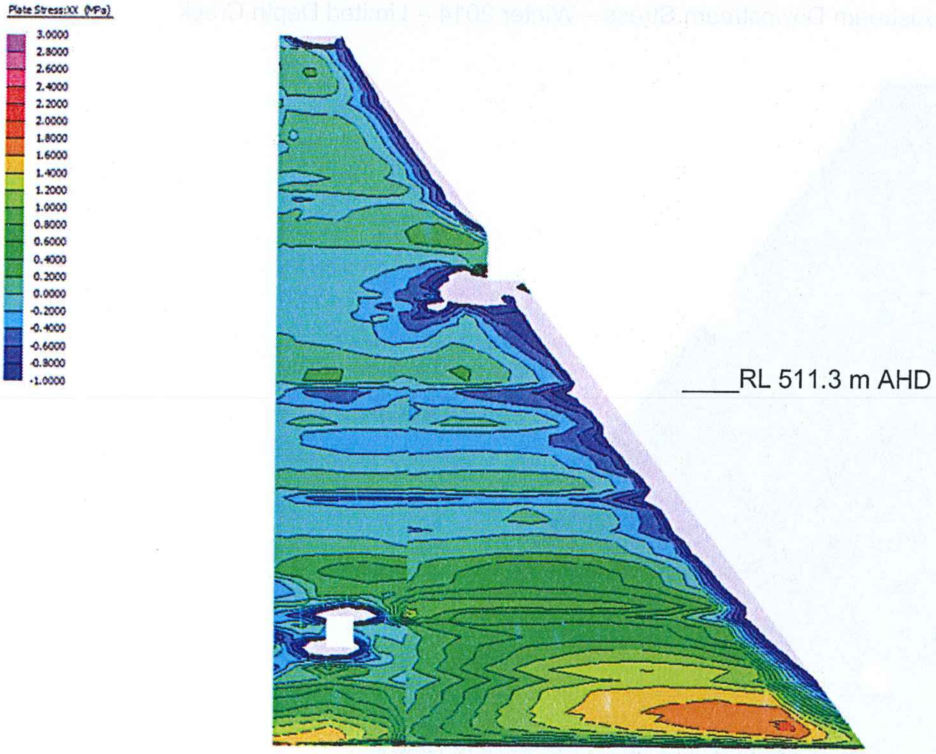


Figure 3.19 Upstream Downstream Stress – Summer 2031/32 – Limited Depth Crack



3.2.3 Relative Displacements across the Vertical Crack for the Most Downstream Crack Location

Figure 3.20 Relative Horizontal Displacement in Crack at Various Elevations – Most downstream crack location

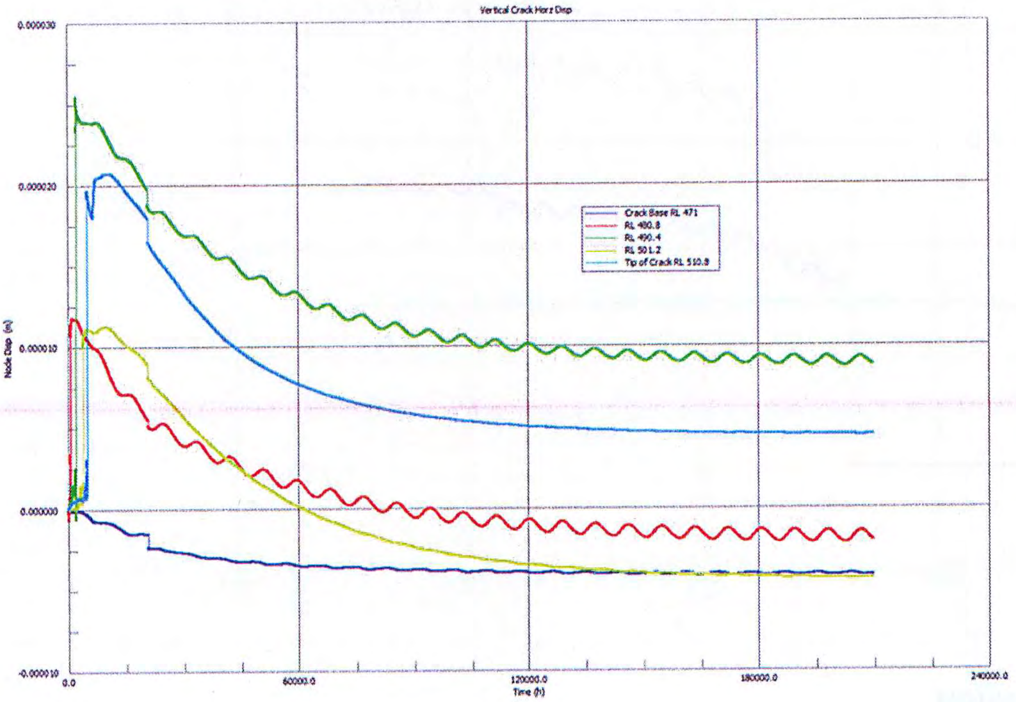
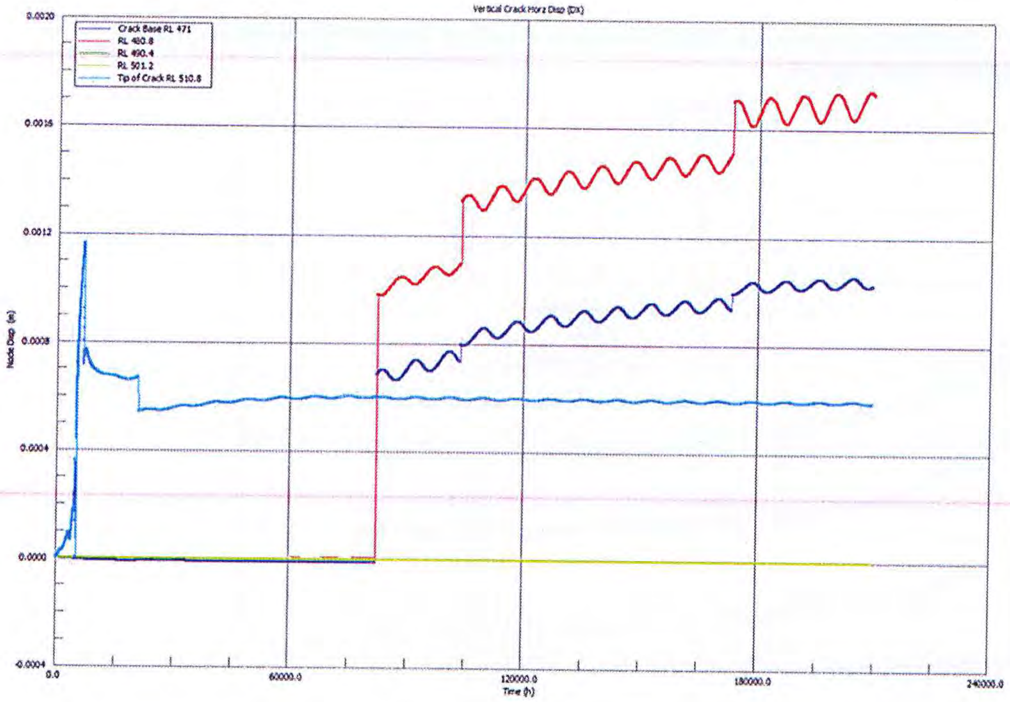


Figure 3.21 Relative Horizontal Displacement in Crack at Various Elevations – Limited Depth Crack



3.3 Discussion

For the model of the most downstream crack location it can be seen in Figure 3.1**Error! Reference source not found.** to Figure 3.10 that much of the length of the assumed crack is within a zone of compression or of relatively low tension. There does not appear to be a high concentration of tension developing at the tip of the crack with time. This is further observed in Figure 3.20 which shows a negligible opening (less than 0.03 mm) at very early ages and a negligible closing tending towards zero displacement at later ages. Because of these results there does not appear to be a significant indication of further crack propagation of the assumed crack at this location.

These results are similar to those previously published for the initial analysis of the cracked section with the crack in the most upstream observed location (ref 4), indicating that the behaviour of the cracked monolith is not dependent on the position of the crack with the range of observed locations. .

A further concern of the most downstream location of the crack was the possibility that the crack may propagate to the aerator notch. The analysis indicates that such propagation of the crack is unlikely. As can be seen in Figure 3.5 tensions are present in the region between the top of the crack at 511.3 and the aerator however these tensions are typically less than 1 MPa and therefore cracking is unlikely.

Similarly the results from the limited depth crack model appear to show little indication of crack propagation either upwards or downwards from the assumed 2.4 m deep crack. Figure 3.11 to Figure 3.19 does not show any development of regions of high tensile stress around the top or bottom of the crack 2.4m deep crack. Little relative displacement is observed for the assumed crack except at early ages in Figure 3.21. Additionally a majority of the modelled crack path from the bottom of the assumed crack (RL 508.4) to the foundation does not show any relative displacement or opening of the crack. This is reflected in the stress plots that show a significant amount of the assumed crack path is in a region of compression (in the upstream downstream direction) or tension which does not exceed the 2 MPa tensile capacity of the modelled crack elements. Furthermore in the vicinity of the crack, where a lower tensile stresses would be required to allow propagation of the crack, the maximum tensions seen are in the order of 100 to 200 kPa, likely to be insufficient to generate further cracking. However some cracking was observed to develop in the model from the base to RL 485.6 which is also shown as opening displacement show for elements close to the foundation in Figure 3.21. This did not appear to connect with the existing crack modelled at RL 510.8.

This analysis indicates that the assumption that the crack will extend to the foundation is conservative, and in all likelihood cracking will not progress more than a few metres below RL 511.3 m AHD, the level at which the cracks were observed. If this is the case the dam will behave almost identically to the uncracked section with short cracks within the body of the dam not having any significant on how the dam will perform.

However the fully cracked monolith (from RL 511.3 to the foundation) section has been analysed to demonstrate that should the crack propagate to the foundation (considered to be a “worst case”) then dam will remain stable under all the design loadings.

(Note:- given the coarseness of the model mesh and the scale of the model, the magnitude of the relative displacements observed in the modelled crack should be used only as an indicator of trends within the model. In both models the assumed cracks have shown relative displacement at very early ages which is a result of the model including the development of elastic modulus with time which includes a relatively low modulus at very early ages. This results in larger displacements due to temperature changes particularly when the concrete is generating heat from hydration of the cement. As such the early age displacement in the assumed existing crack (which has no tensile capacity) may not be indicative of actual behaviour.)

4 Seismic Analysis Undertaken During Current Review

Additional seismic analysis has been undertaken to show that the cross valley crack (assumed to extend from the point it was detected to the foundation) does not compromise the overall safety of the dam for all load cases. The analysis considered both the maximum section and an abutment section subject to the seismic load cases for which the original dam section was designed for (refer Table 1).

4.1 Proposed Analysis

4.1.1 Model Development

The FE model previously developed for the thermal model has been utilised for this analysis. The Finite Element model is similar to those used in the recent 2D plane strain analysis (ref 2), however the mesh was redefined to provide suitably fine and well-proportioned elements in the areas of interest and to allow for simple and quick modification to the model should it be necessary to extend the crack. Internal pressures have also been recalculated from the previous modelling. It is assumed that the crack will act as a drain, therefore downstream of the drain the concrete will not experience any internal pressure.

4.1.2 Assessment of the Crack Behaviour

The behaviour of the cracked section will be dependent on the extent to which the crack opens under loading. Should the crack remain closed or only open a small amount, there should be sufficient irregularity in the cracked surface that shear will be transferred across the crack. If this is the case the dam should act monolithically. As the extent of crack opening at which shear transfer is lost will be a subjective assessment it is proposed to undertake the analysis assuming both full shear transfer and no shear transfer for each post seismic load case. The overall stability will be assessed on the results of each analysis.

The model was developed to allow for crack propagation and five possible directions of propagation have been allowed for; horizontal upstream, horizontal downstream, vertical, 45° to the upstream and to the aerator slot (approximately 45° downstream).

4.1.3 Seismic Analysis

Analysis was undertaken using the methodology proposed in United States Army Corps of Engineers (USACE) manual on the Earthquake Design and Evaluation of Concrete Hydraulic Structures (EM 1110-2-5063 2007). This method involves undertaking a two dimensional linear elastic analysis initially and comparing the results against various performance requirements. If the performance requirements are met then the dam behaviour is acceptable during the earthquake event in question and no further analysis is required. If the results indicate the dam does not meet the performance requirements then further non-linear cracked analyses need to be undertaken to assess cracking of the dam structure with post seismic stability assessed against the outcomes of the cracked analysis. As the previous analysis (ref 2) of the uncracked dam section indicated that the non-linear analysis was required, it has been assumed that this will also be required for the cracked model. Therefore, although the linear analysis was undertaken, the performance criteria were not evaluated, assuming that a non-linear analysis would be required. Additionally the linear analysis that was undertaken was not strictly a linear analysis as the model includes non-linear point contact elements along the dam foundation interface and along the length of the assumed crack.

The results of the linear analysis were used to assess if the assumed vertical crack adequately represented the cracking or if additional cracking would be required.

A suite of time histories will be used in the analysis is given in Table 2 below. These are a subset of the time histories previously used (ref 2).

ID	Earthquake Name	Year
Operating Basis Earthquake		
ACLV	Friuli, Italy-01	1976
CPE	Baja California	1987
CHY017	Chi-Chi, Taiwan-02	1999
CHY116	Chi-Chi, Taiwan	1999
TCU118	Chi-Chi, Taiwan	1999
Maximum Design Earthquake		
NORTH529	Northridge-06	1994
NORTH-WON	Northridge-01	1994
SMADRE-4734	Sierra Madre	1991

Table 1 – Selected Time Histories for the Seismic Analysis

Magnitude	Annual Exceedance Probability (AEP)	Modified Mercali Intensity (MMI)	Peak Ground Acceleration (pga)
Operating Basis Earthquake (OBE)	1 in 500	7.0	0.1g
Maximum Design Earthquake (MDE)	1 in 10,000	9.5	0.35g

Table 2 – Characteristics of Selected Events

4.2 Operating Basis Earthquake – Linear elastic Analysis

4.2.1 Stress Envelopes

Figure 4.1 to Figure 4.18 shows the maximum principal stress and the maximum vertical stress envelopes for the Operating Basis Earthquake load cases undertaken with the updated model including the assumed vertical crack from RL 510.8 to the foundation.

Note – plots of maximum principal stress envelopes are a summary plot of the maximum principal stress recorded at each node. As such the maximum stress at any node may occur at any time step during the analysis period, and does may not necessarily occur at the same time step for all nodes.

ACLV Operating Basis Earthquake

Figure 4.1 ACLV – East & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

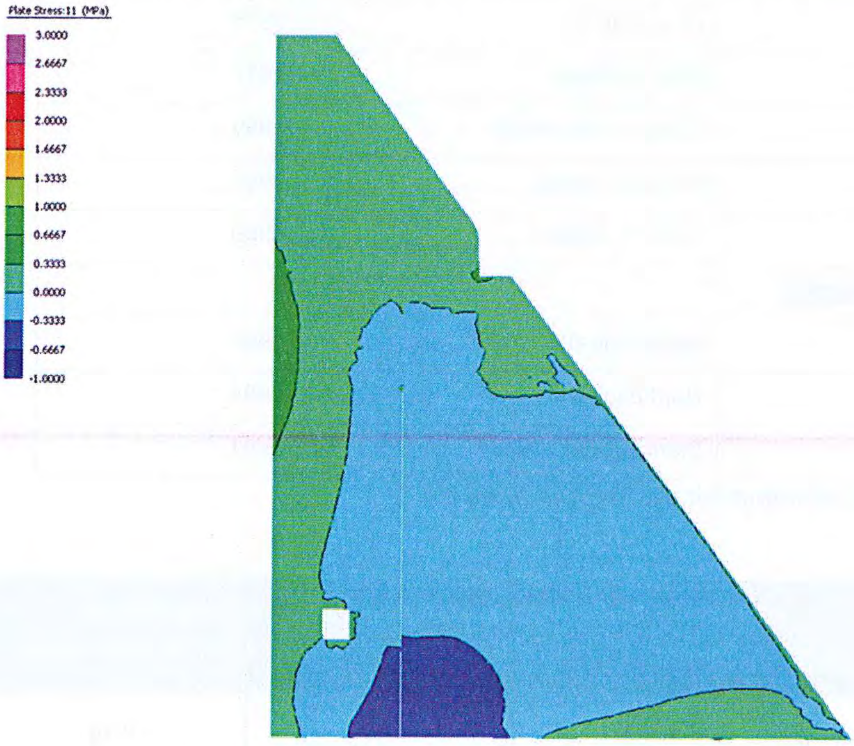


Figure 4.2 ACLV – East & Vertical Components – Maximum Stress Envelope – Vertical Stress

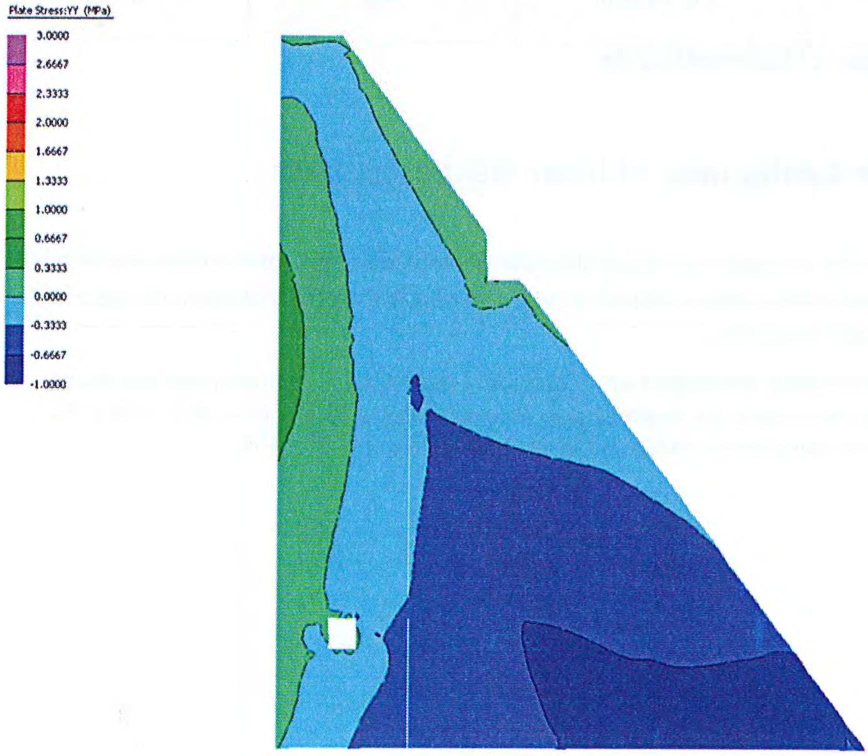


Figure 4.3 ACLV – North & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

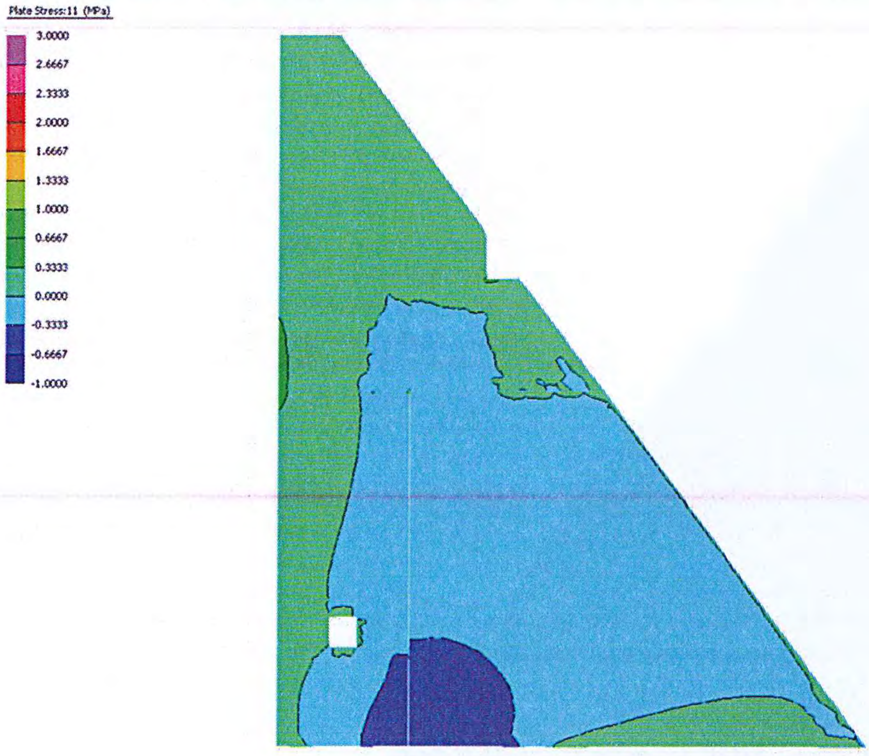
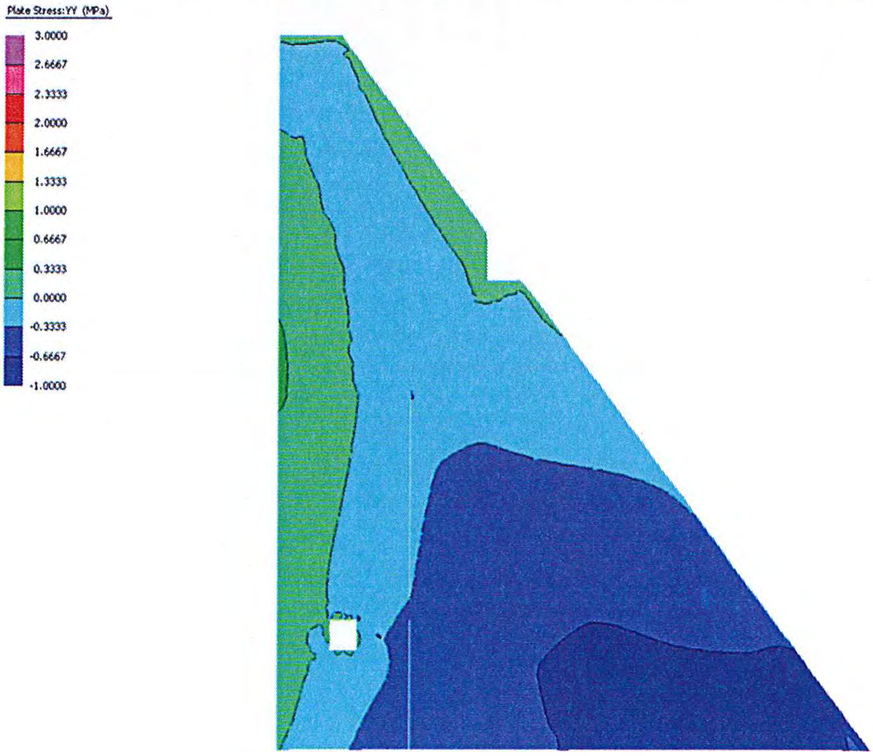


Figure 4.4 ACLV – North & Vertical Components – Maximum Stress Envelope – Vertical Stress



CPE Operating Basis Earthquake

Figure 4.5 CPE – North & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

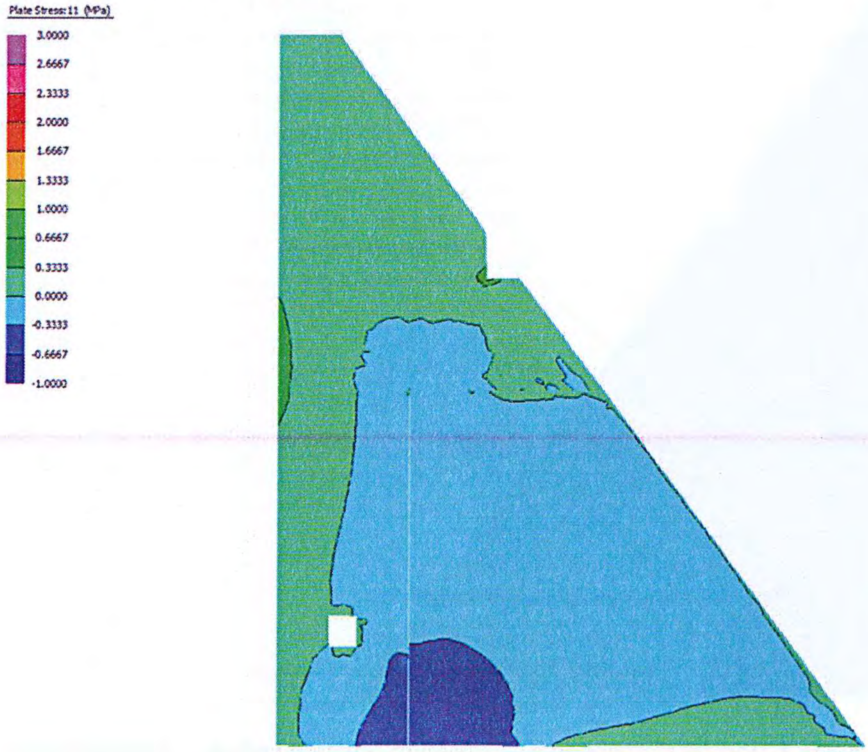


Figure 4.6 CPE – North & Vertical Components – Maximum Stress Envelope – Vertical Stress

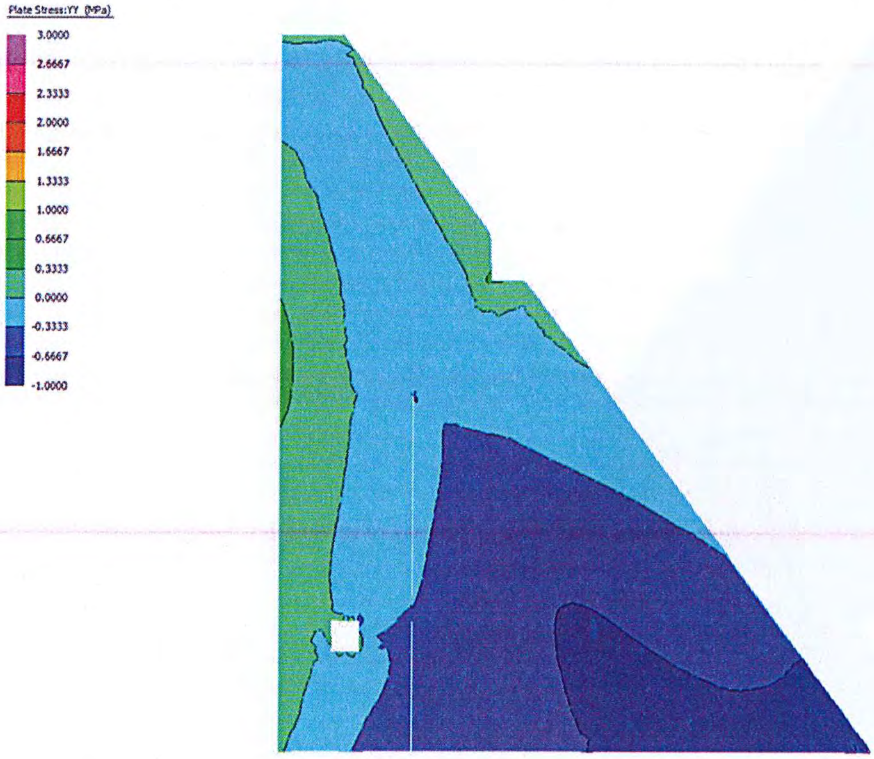


Figure 4.7 CPE – West & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

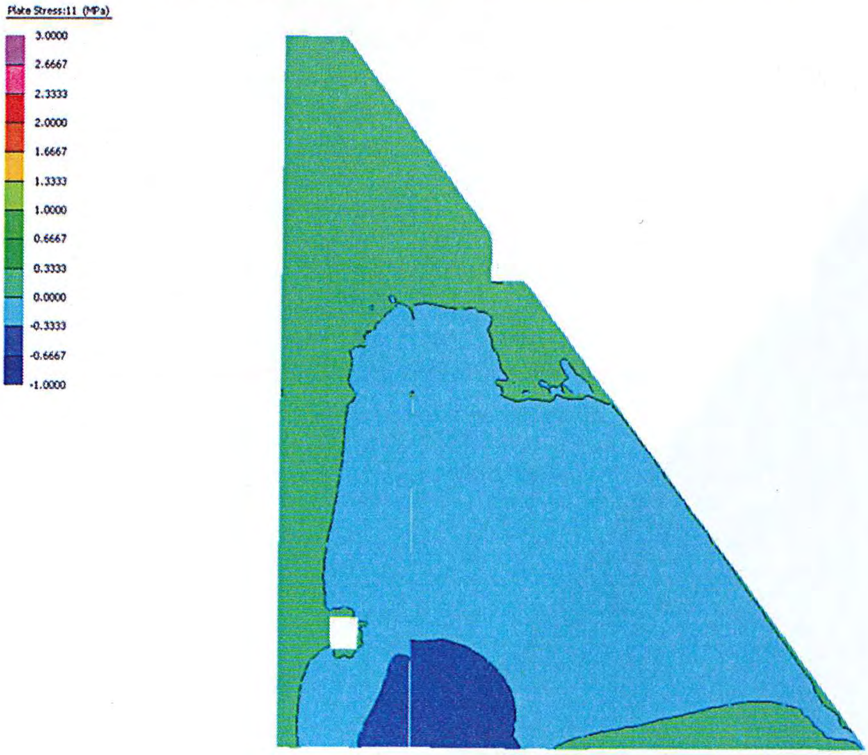
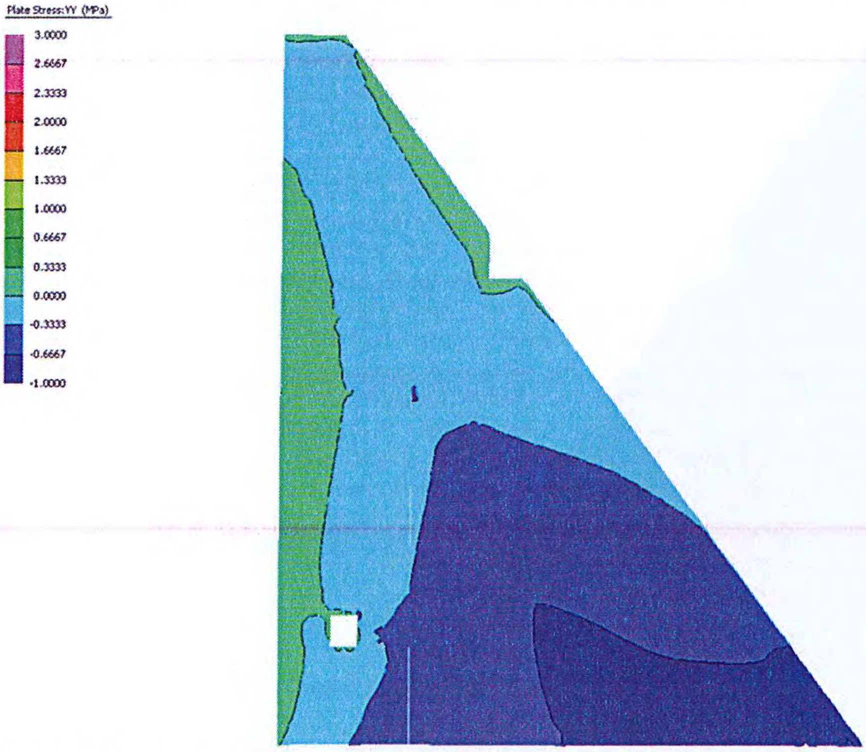


Figure 4.8 CPE – West & Vertical Components – Maximum Stress Envelope – Vertical Stress



CHY017 Operating Basis Earthquake

Figure 4.9 CHY017 – North & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

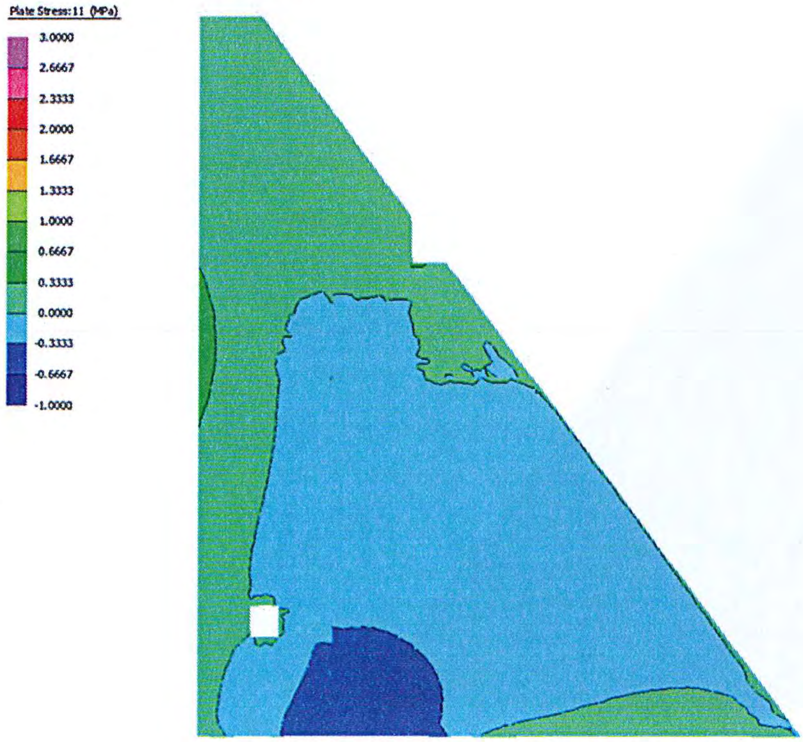


Figure 4.10 CHY017 – North & Vertical Components – Maximum Stress Envelope – Vertical Stress

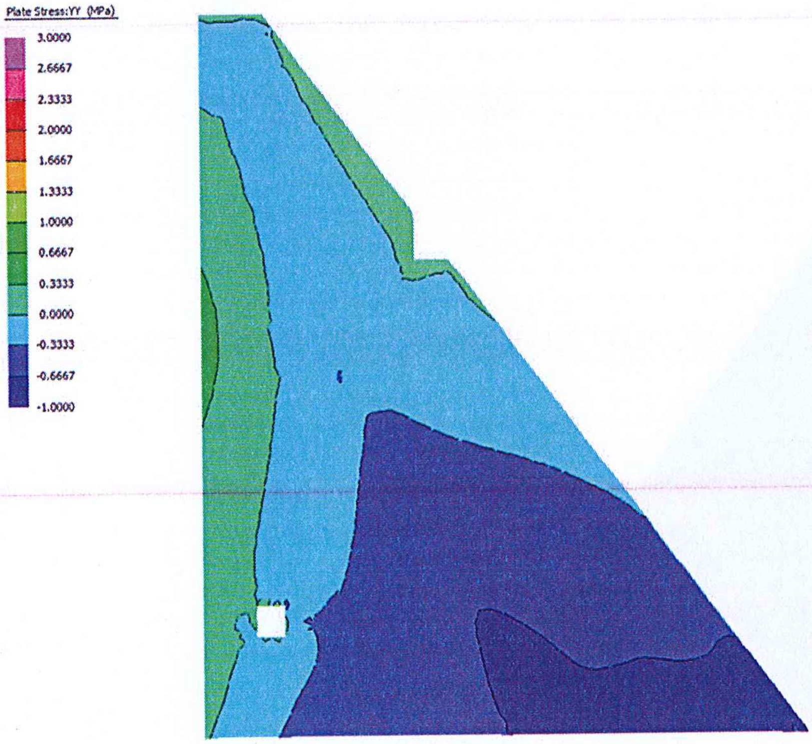


Figure 4.11 CHY017 – West & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

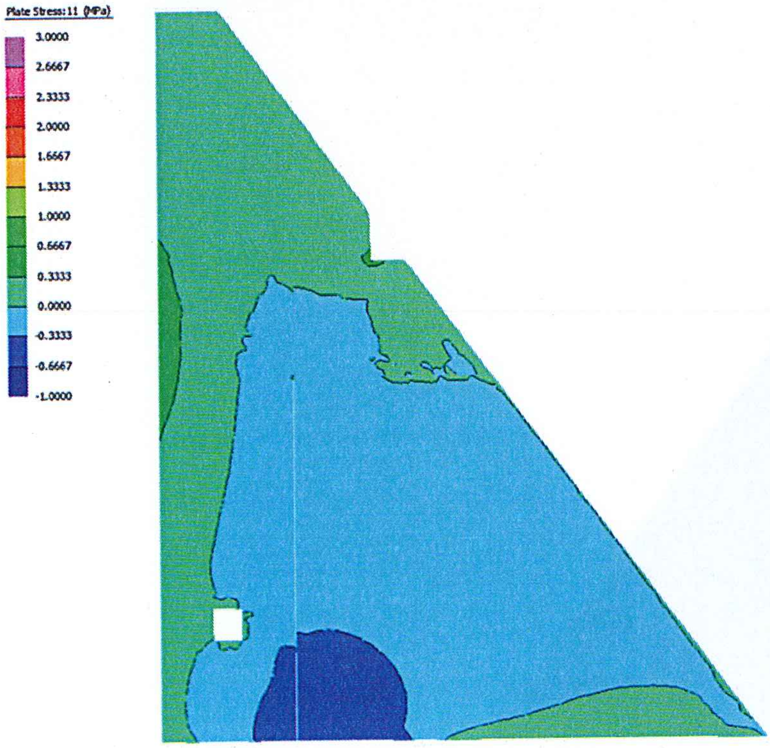


Figure 4.12 CHY017 – West & Vertical Components – Maximum Stress Envelope – Vertical Stress

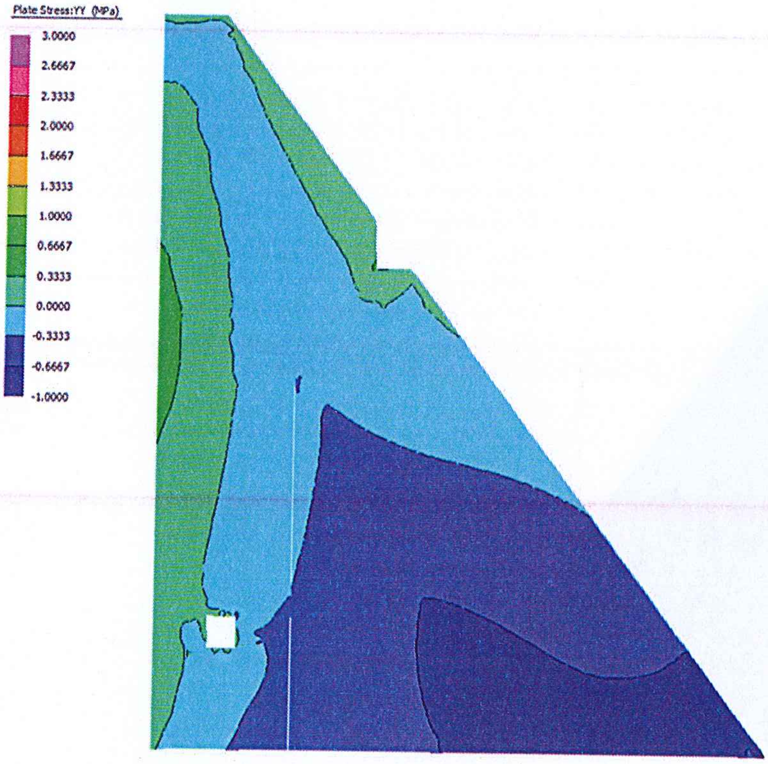
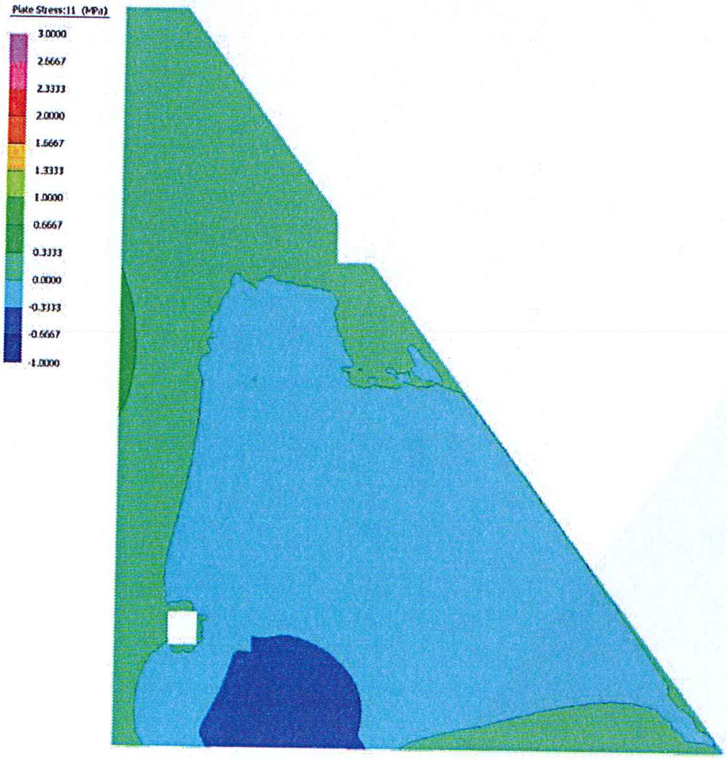


Figure 4.13 CHY116 – North & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress



CHY116 Operating Basis Earthquake

Figure 4.14 CHY116 – North & Vertical Components – Maximum Stress Envelope – Vertical Stress

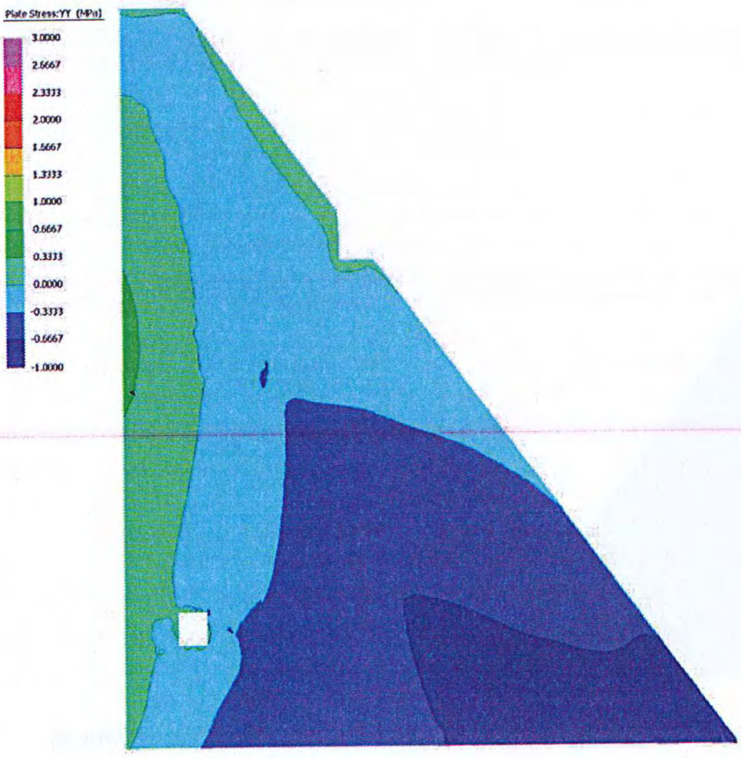


Figure 4.15 CHY116 – West & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

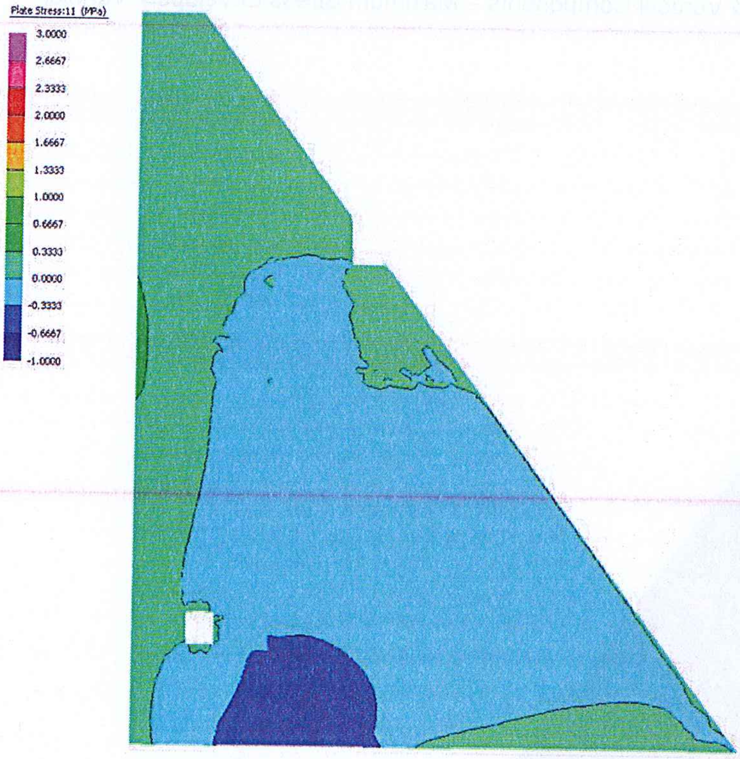
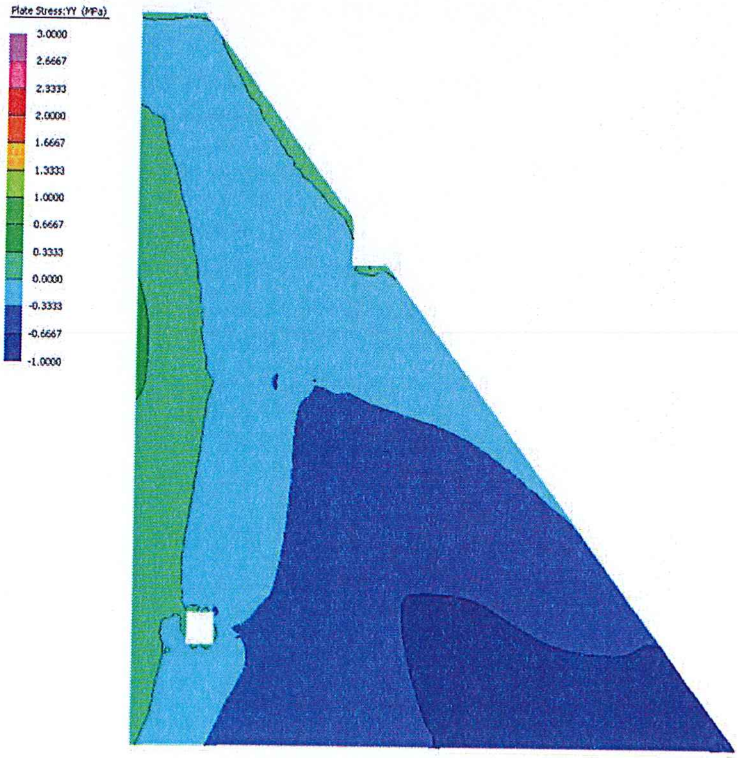


Figure 4.16 CHY116 – West & Vertical Components – Maximum Stress Envelope – Vertical Stress



TCU118 Operating Basis Earthquake

Figure 4.17 TCU118 – North & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

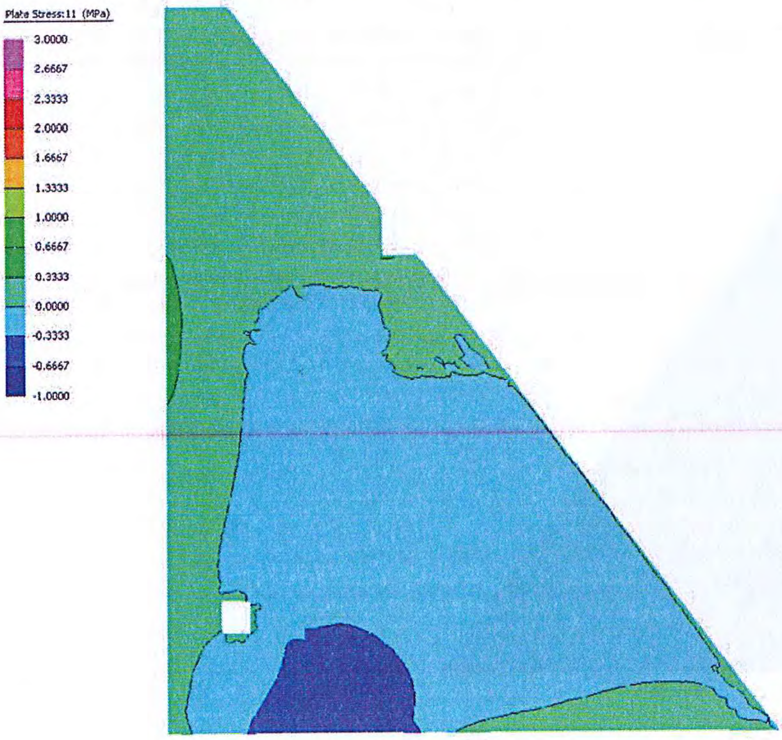
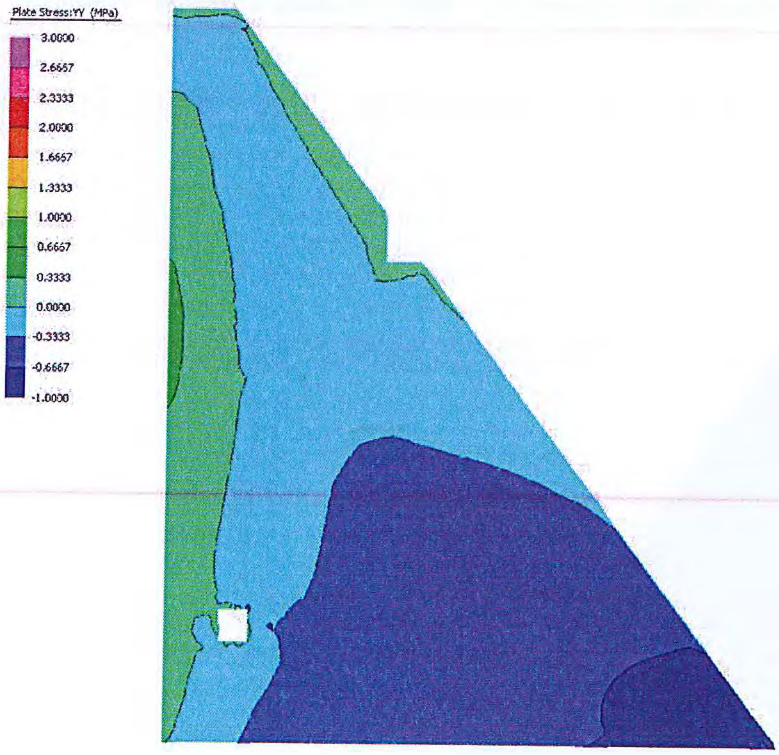


Figure 4.18 TCU118 – North & Vertical Components – Maximum Stress Envelope – Vertical Stress



4.2.2 Discussion – OBE Events

The results from the OBE load cases (as shown in Figure 4.1 to Figure 4.18) demonstrates very small areas on the upstream face where the dynamic tensile capacity of the lift joints (600 kPa) may be exceeded. When compared the to the original linear analysis undertaken on the uncracked dam profile the stresses are of a lesser magnitude in this analysis due to the inclusion of the non-linear point contact elements along the dam foundation interface. For all of the OBE load cases negligible displacement was observed in the non-linear elements along the foundation interface. Any recorded residual displacement was less than 3 mm in magnitude which could be considered negligible given the coarseness and scale of the model. The cumulative inelastic duration and the special extent of overstress regions has not be assessed for the OBE load cases as these criteria were met in the previously undertaken analysis and there is no indication that these have been exceed with the inclusion of the crack within the dam given the reduction of stresses observed in the results. It could therefore be inferred that the inclusion of the crack within the structure has little to no negative impact on the durability of the structure in an OBE event.

4.3 Maximum Design Earthquake – Linear Elastic Analysis

4.3.1 Stress Plots

For each of the earthquakes considerer Figure 4.19 to Figure 4.42 show the maximum principal stress, maximum principal stress direction, maximum horizontal stress and the maximum vertical stress envelopes (Note – plots of maximum principal stress envelopes are a summary plot of the maximum principal stress recorded at each node. As such the maximum stress at any node may occur at any time step during the analysis period, and does may not necessarily occur at the same time step for all nodes) for the updated model including the assumed vertical crack from RL 510.8 to the foundation.

Figure 4.43 to Figure 4.48 provides graphs of the relative displacement of the non-linear elements along the dam foundation interface for each of the MDE events.

North529 Maximum Design Earthquake

Figure 4.19 NORTH529 – East & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

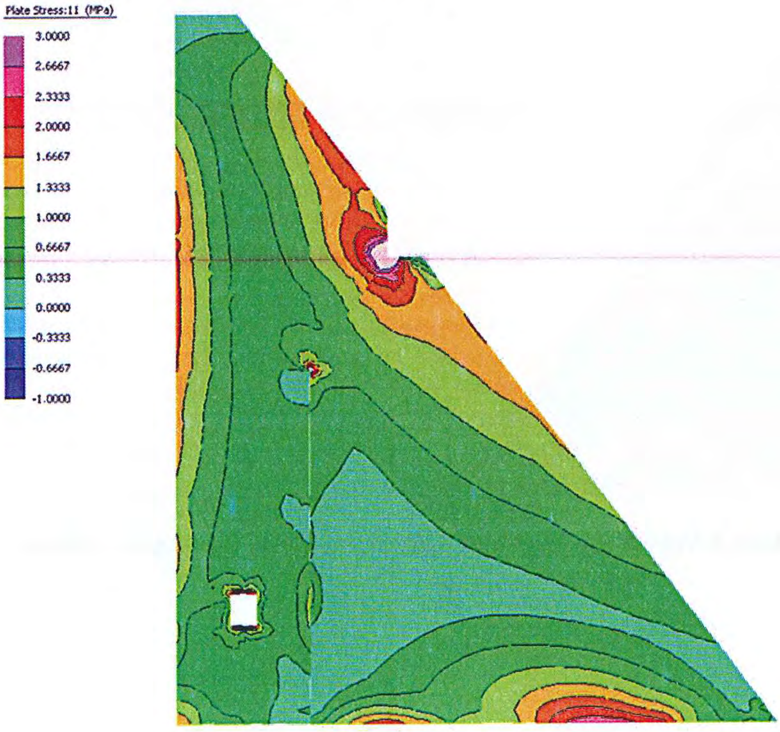


Figure 4.20 NORTH529 – East & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress Direction

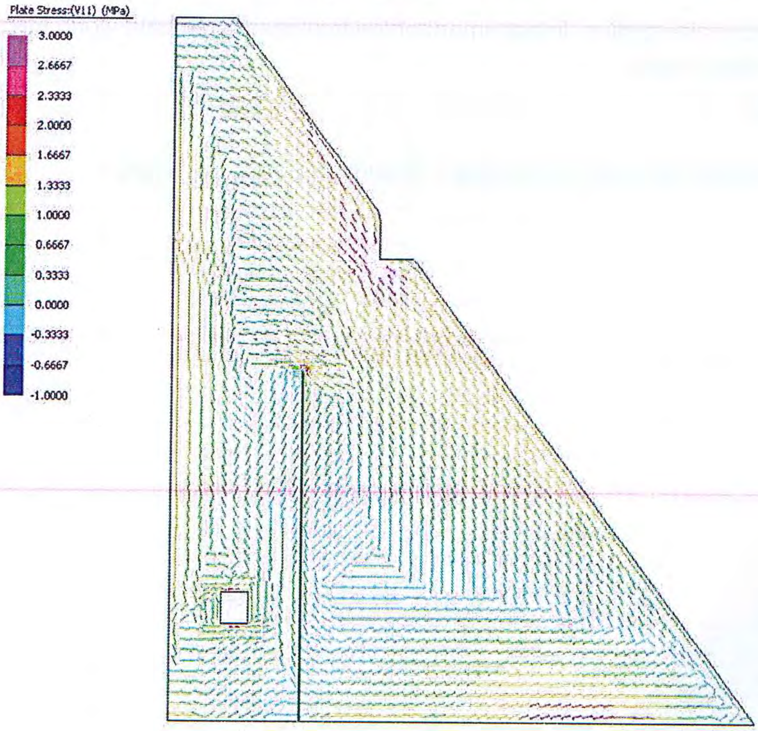


Figure 4.21 NORTH529 – East & Vertical Components – Maximum Stress Envelope – Vertical Stress

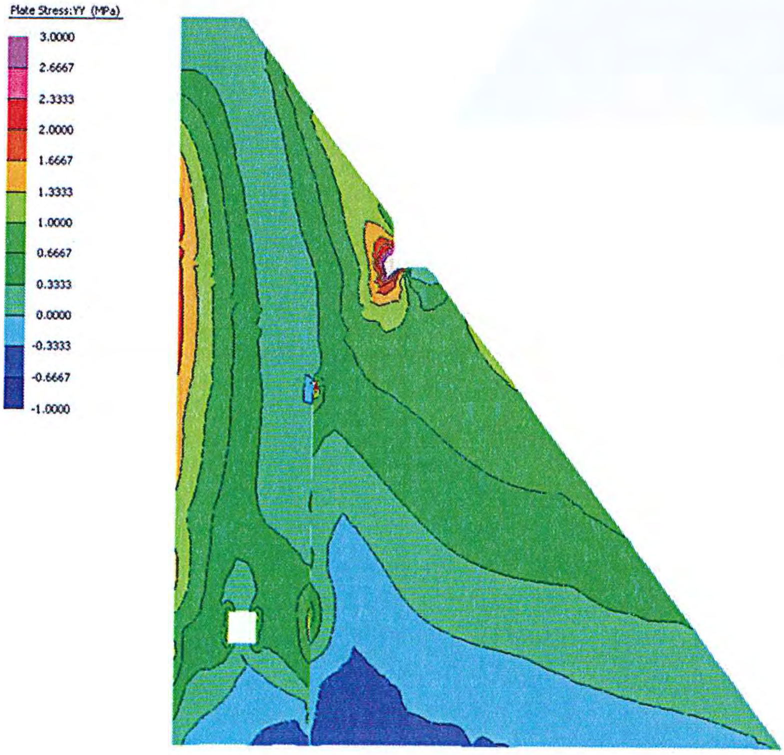


Figure 4.22 NORTH529 – East & Vertical Components – Maximum Stress Envelope – Upstream Downstream Stress

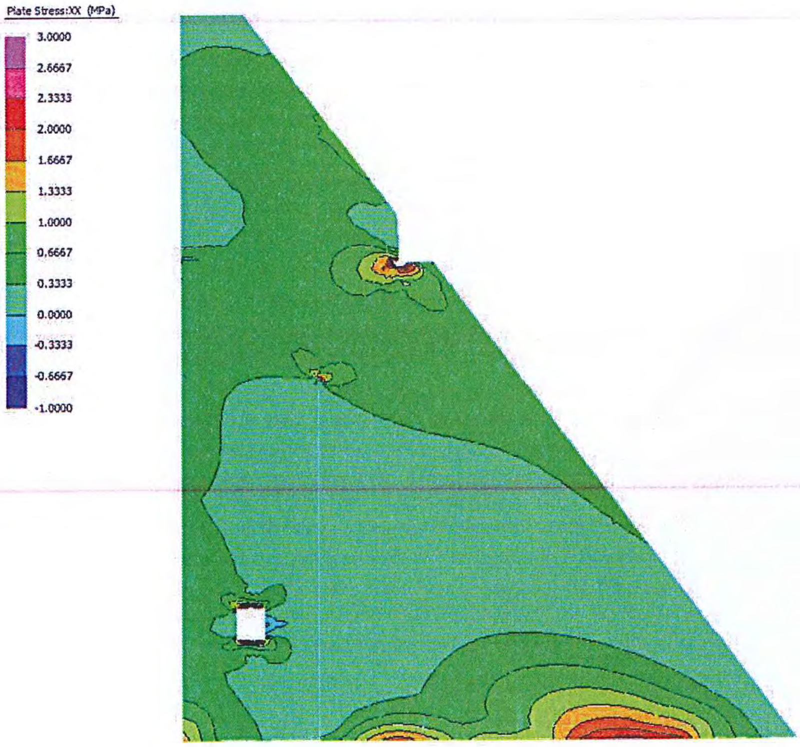


Figure 4.23 NORTH529 – North & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress

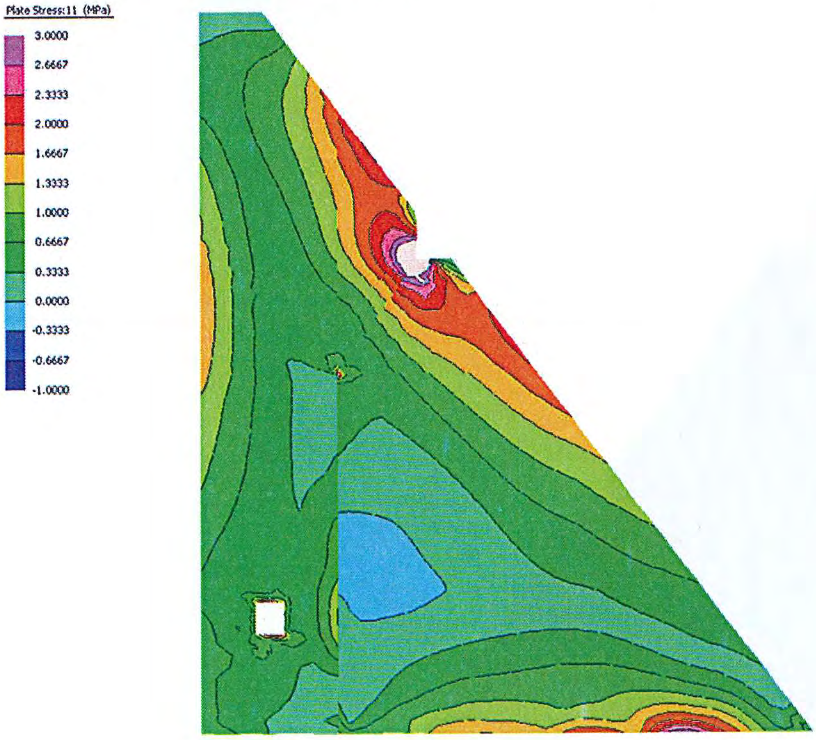


Figure 4.24 NORTH529 – North & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress Direction

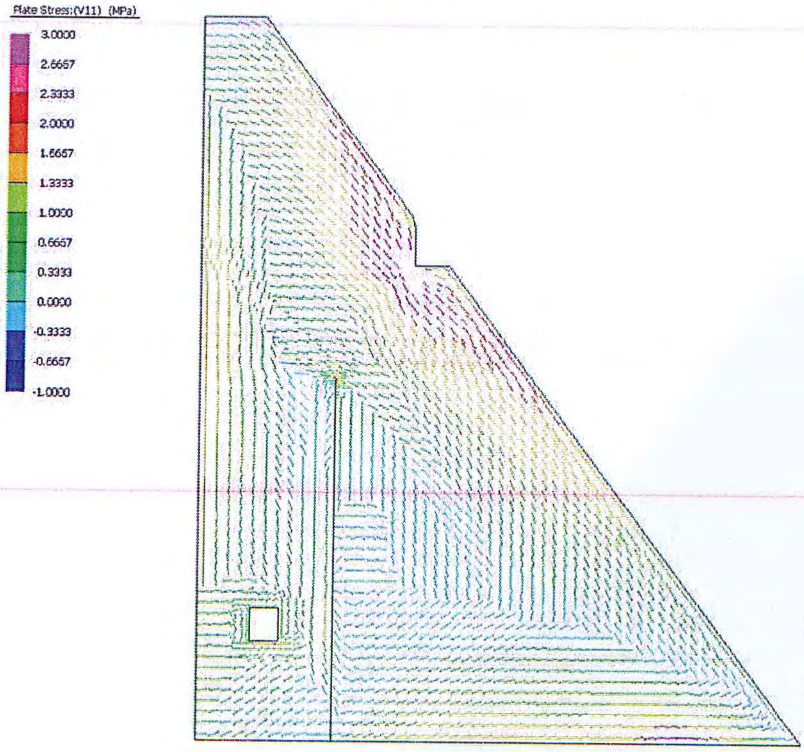


Figure 4.25 NORTH529 – North & Vertical Components – Maximum Stress Envelope – Vertical Stress

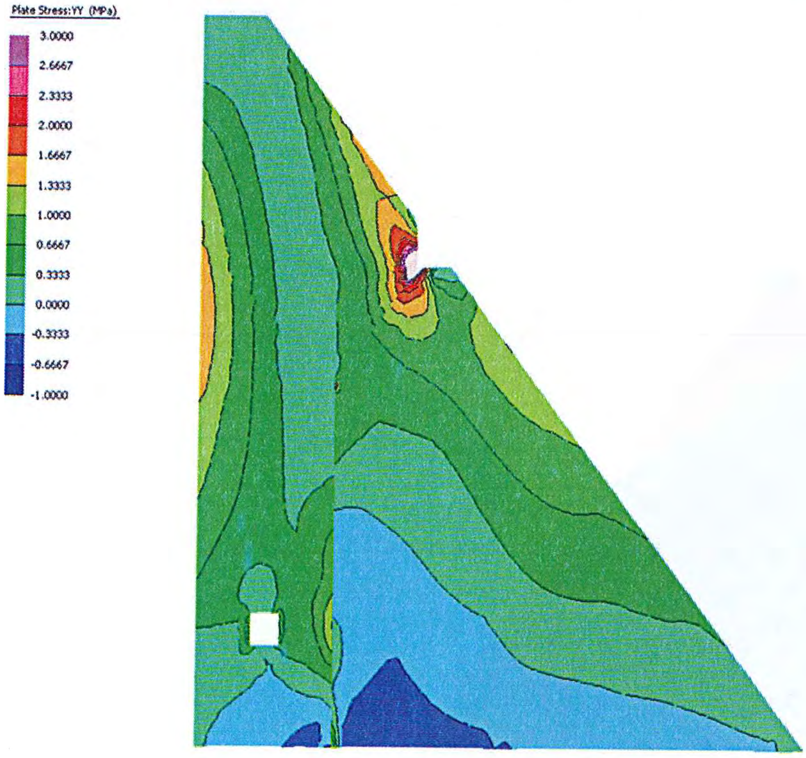
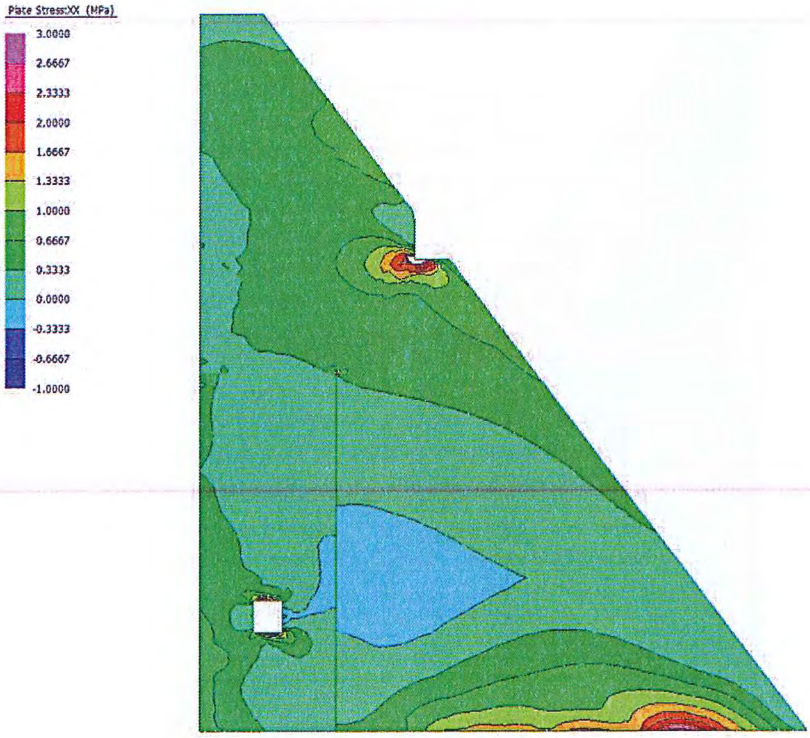


Figure 4.26 NORTH529 – North & Vertical Components – Maximum Stress Envelope – Upstream Downstream Stress



North-Won Maximum Design Earthquake

Figure 4.27 NORTH-WON – South & Vertical Components – Maximum Stress Envelope – Maximum Principal Stress