Undermining of an Unlined Tunnel in Rock - *FLAC*^{3D} Modelling

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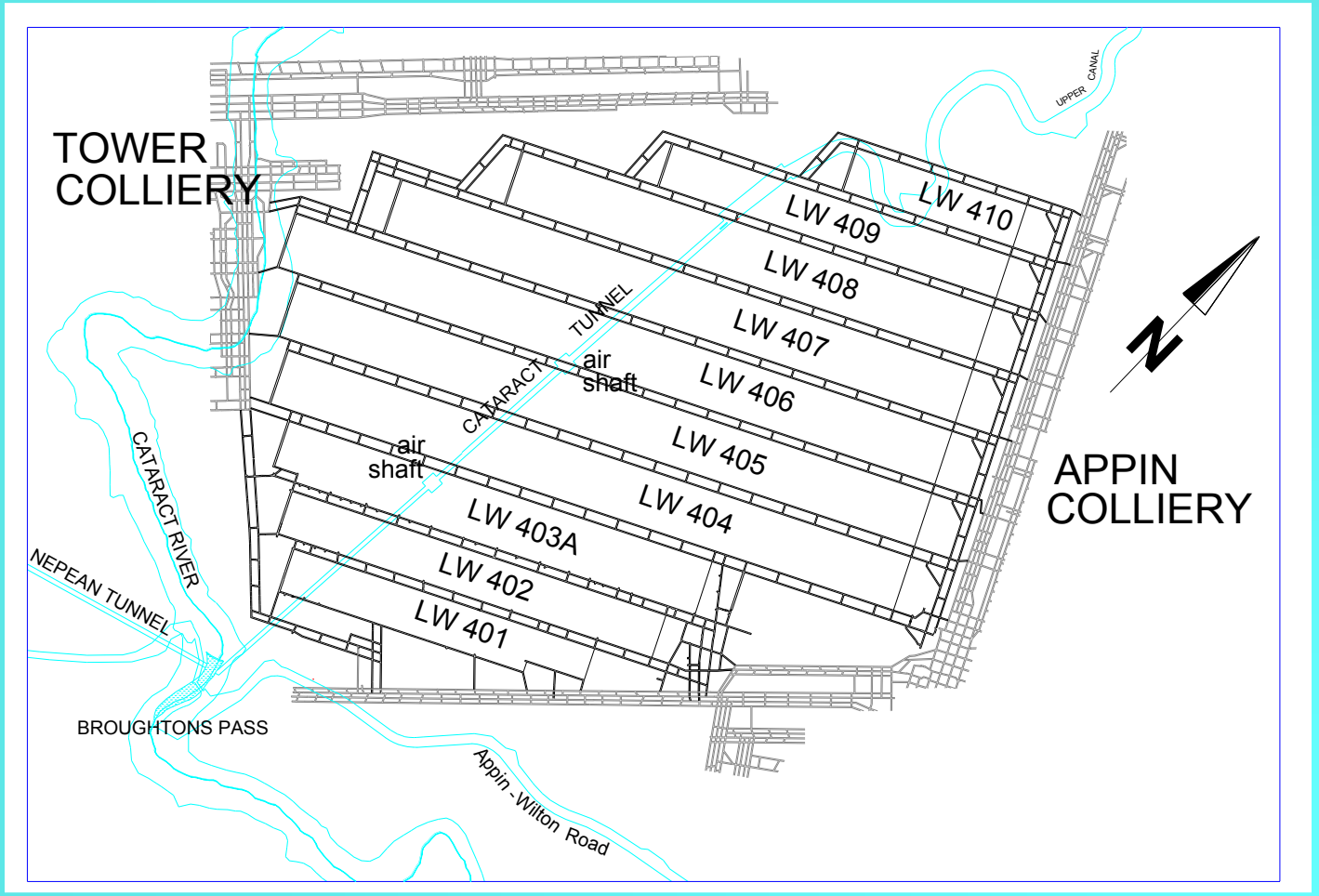
Introduction - 1

- Cataract Tunnel, near Wollongong, Australia, carries 25% of Sydney's water supply
- Unlined, 3 m diameter, 40 m average depth
- Longwall coal mining proposed, at 400 m depth, under almost full length of tunnel
- Rock support to be designed to preserve integrity of tunnel and access shafts

Introduction - 2

- **Project coordinated by Australian Water Technologies, Sydney**
- **Empirical predictions of subsidence by Waddington Kay & Associates, Sydney**
- ***FLAC*^{3D} modelling by M.A. Coulthard & Assoc.**
- **Rock support design by Strata Control Technology, Wollongong**

Cataract tunnel, shafts and planned mining

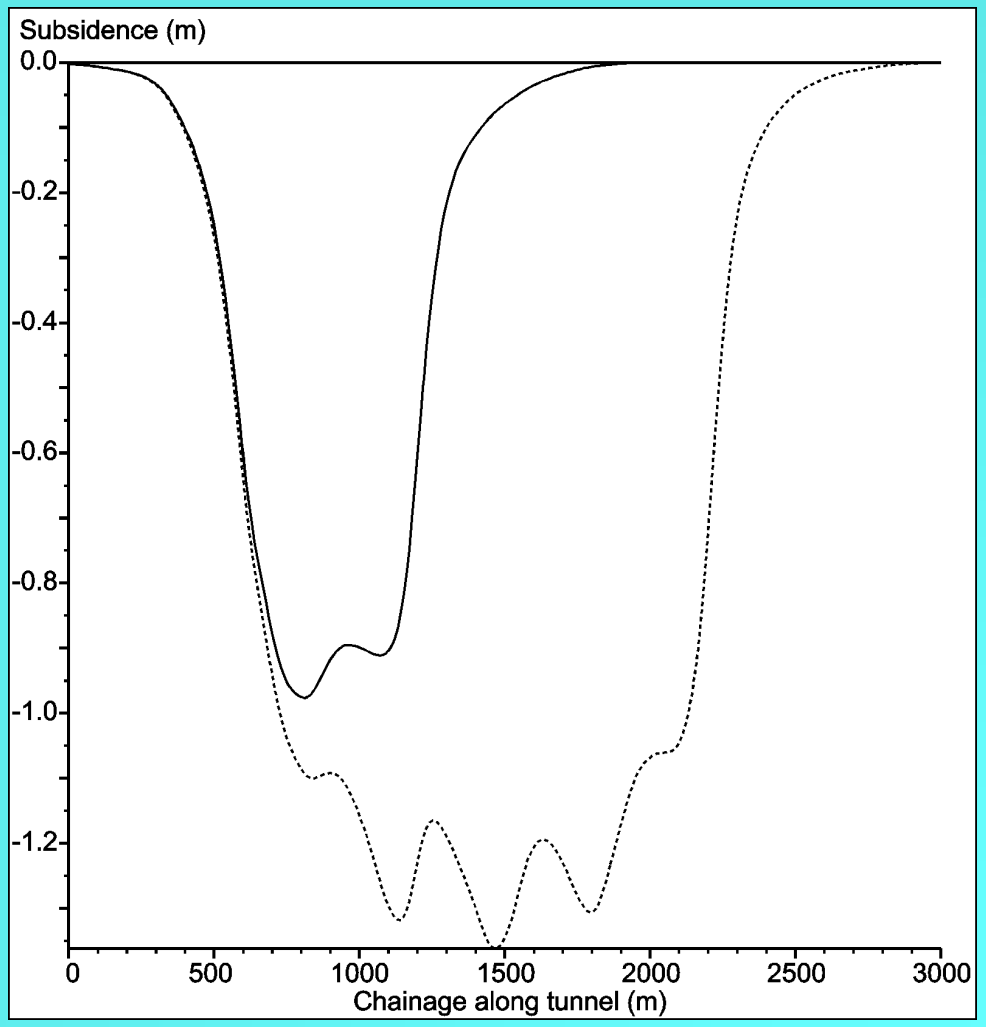


Geotechnical and other data

- Surface topography on scanlines parallel to tunnel
- Rock mass: sandstone + dipping interbedded unit, specified by AWT to be treated as elastic with limited tensile strength
- Horizontal in situ stresses oblique to tunnel
- Surface subsidence after mining each panel adjusted, via empirical formulae, to account for 4-stage extraction of each longwall

Waddington Kay subsidence predictions

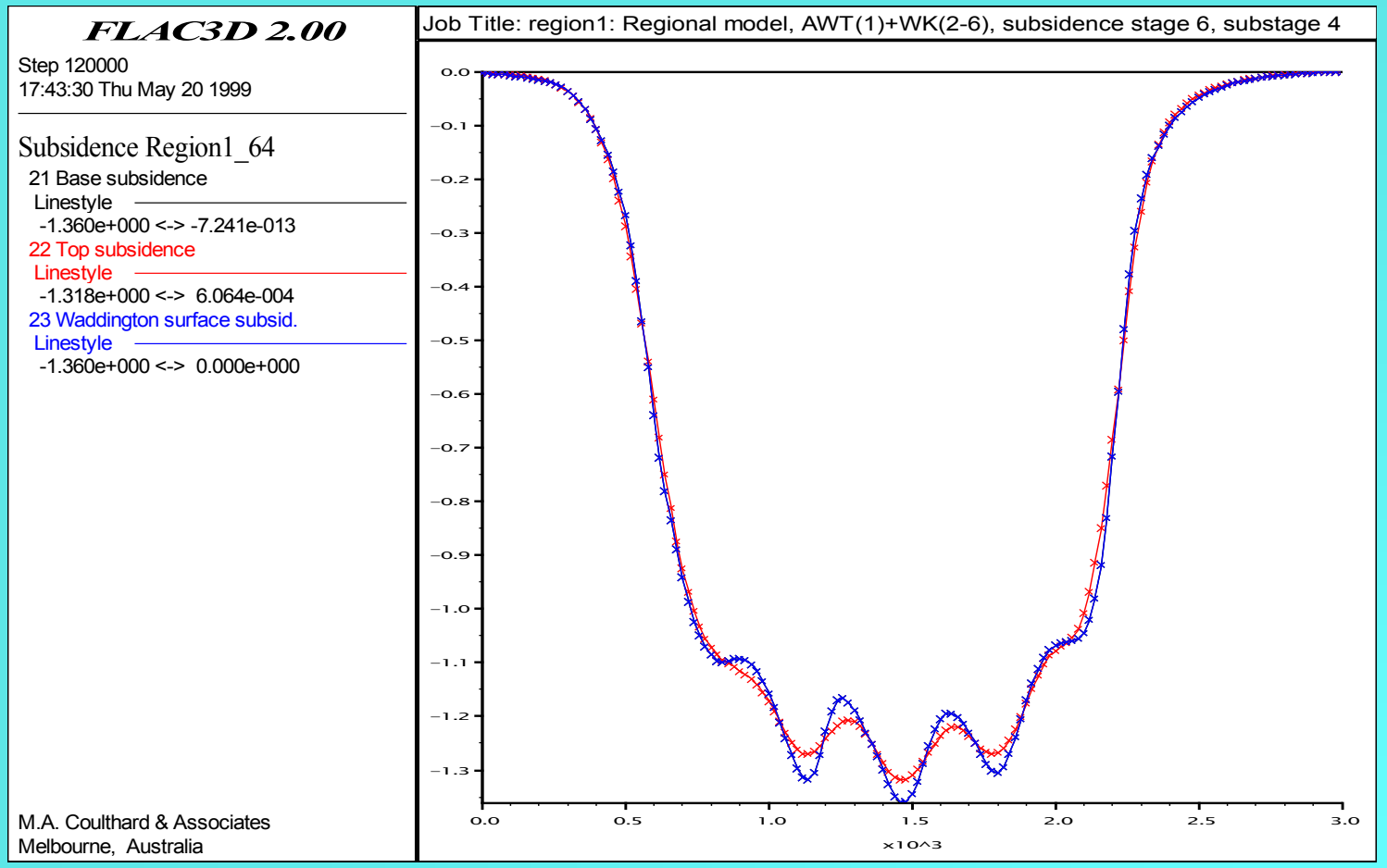
Surface subsidence along line of tunnel after mining:
LW403 _____
LW406 ……



Modelling Strategy - Subsidence

- **Predicted *surface* subsidence applied as boundary conditions on *base* of 100 m - deep global model**
- **Previous *FLAC* and *UDEC* modelling: procedure satisfactory if subsidence "applied" very slowly**
- ***FISH* coding used to calculate incremental subsidence at each sub-stage of mining**
- **Results confirm that there is little "filtering" of subsidence curve between base and surface**

Undermining of Cataract Tunnel



Total subsidence applied at base (blue) and computed at surface (red) in regional model. Tilt and curvature also match reasonably.

Modelling strategy - other issues

- Interbedded unit represented approximately (see next Figure)
- Mohr-Coulomb model in *FLAC*^{3D} implies ductile tensile yield
- Initial stresses: *FISH* computation of vertical stress to reflect surface topography, horizontal stresses as specified, then equilibrate
- Grid boundaries: tests, discussed in paper, showed that results were reliable in central part of model

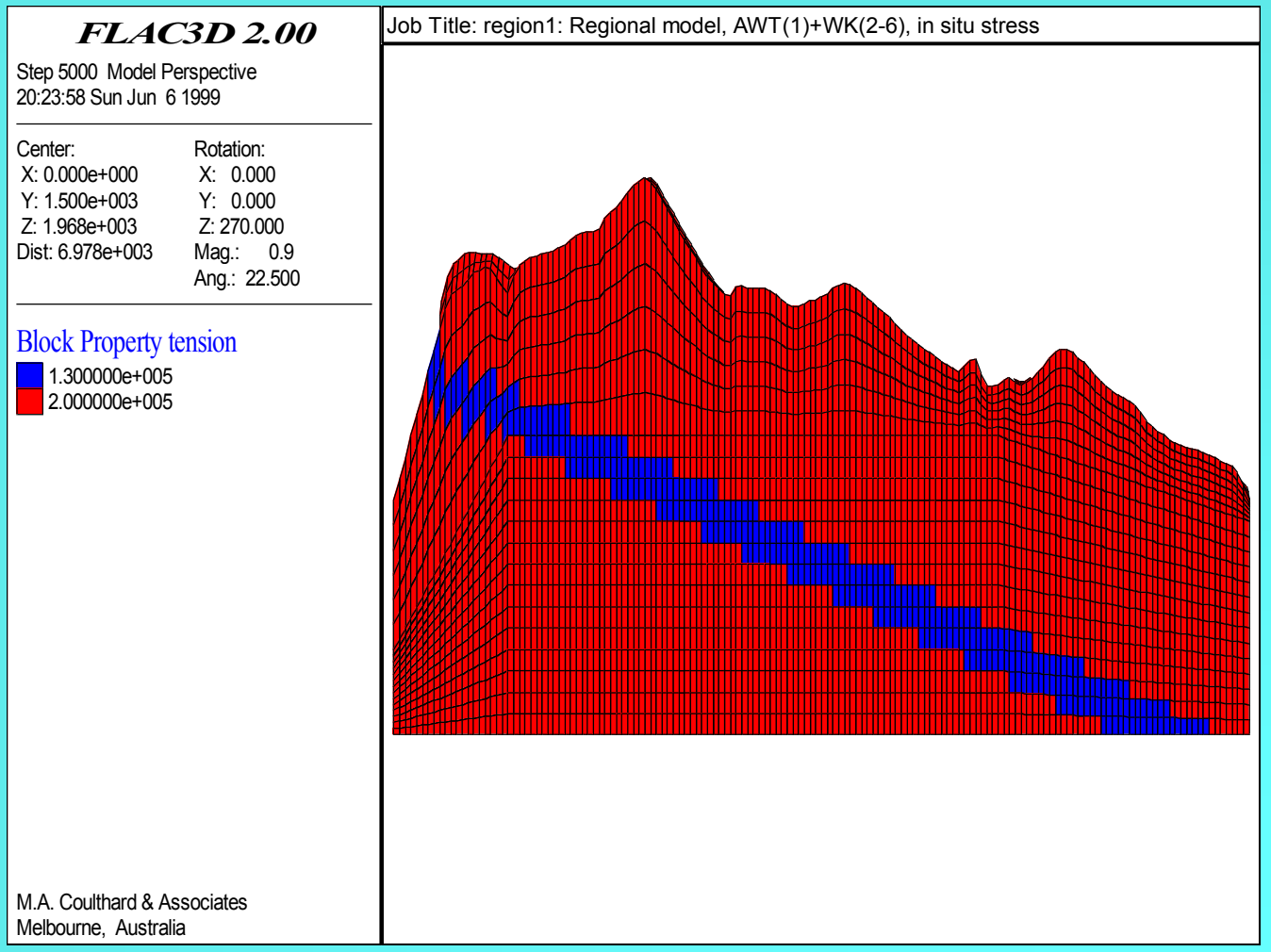
Representation of rock units in model

Sandstone (red)

Interbedded unit (blue)

Vertical scale exaggerated

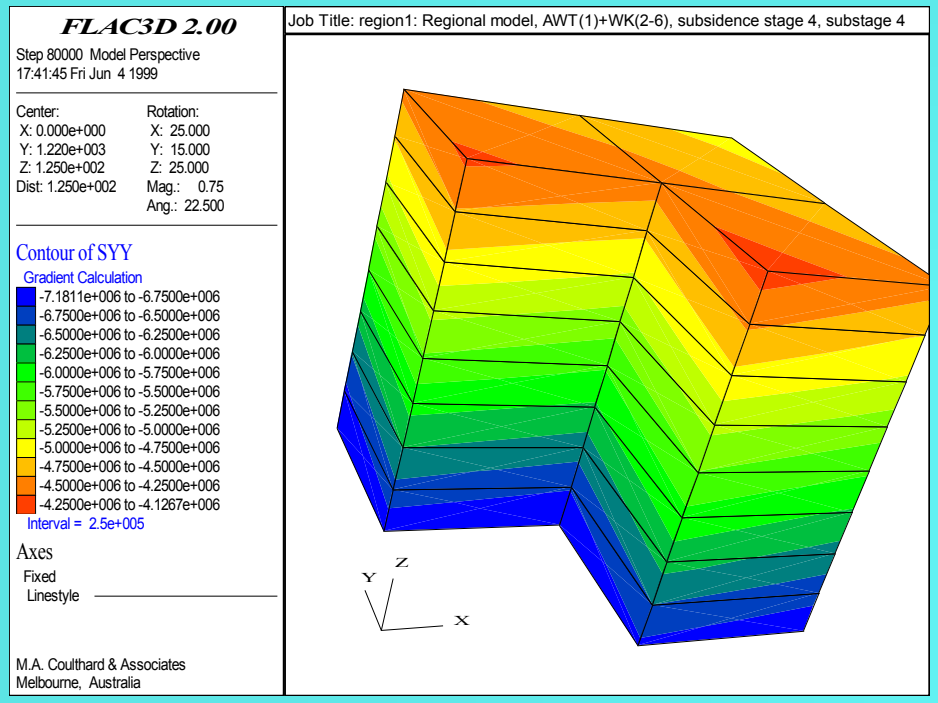
Section along tunnel

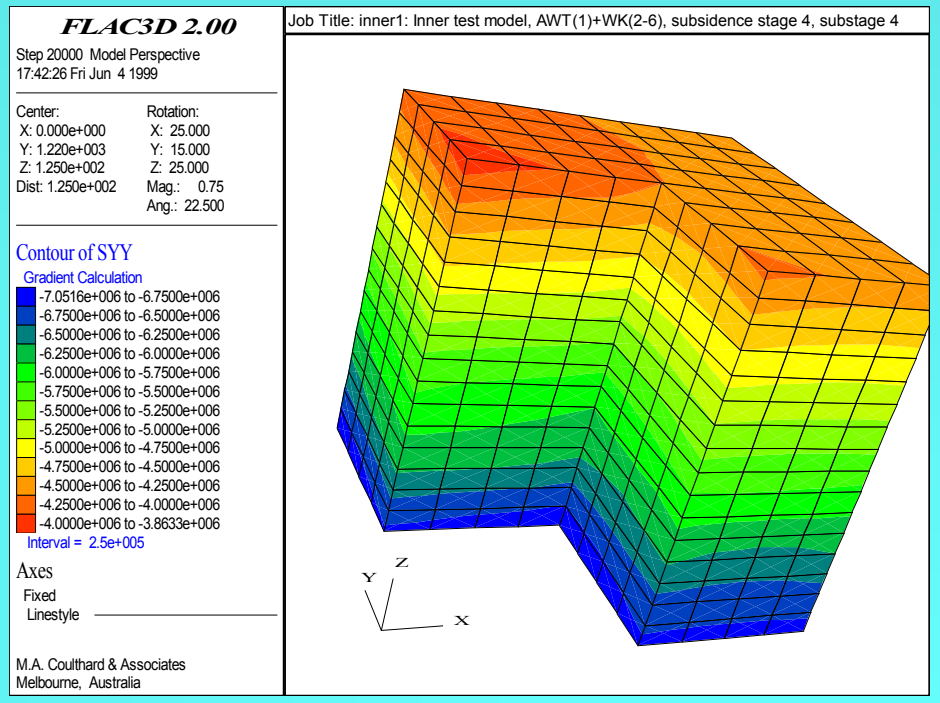


Modelling strategy - regional & detailed models

- ***FISH*** **code to extract computed** displacements **on planes in regional model, and apply as boundary conditions in detailed models**
- **Verification analysis confirmed reliability of approach and *FISH* implementation**
- **Used for our model of shaft-tunnel intersection and for detailed tunnel sections + support by SCT**

Verification of regional-detailed coupling



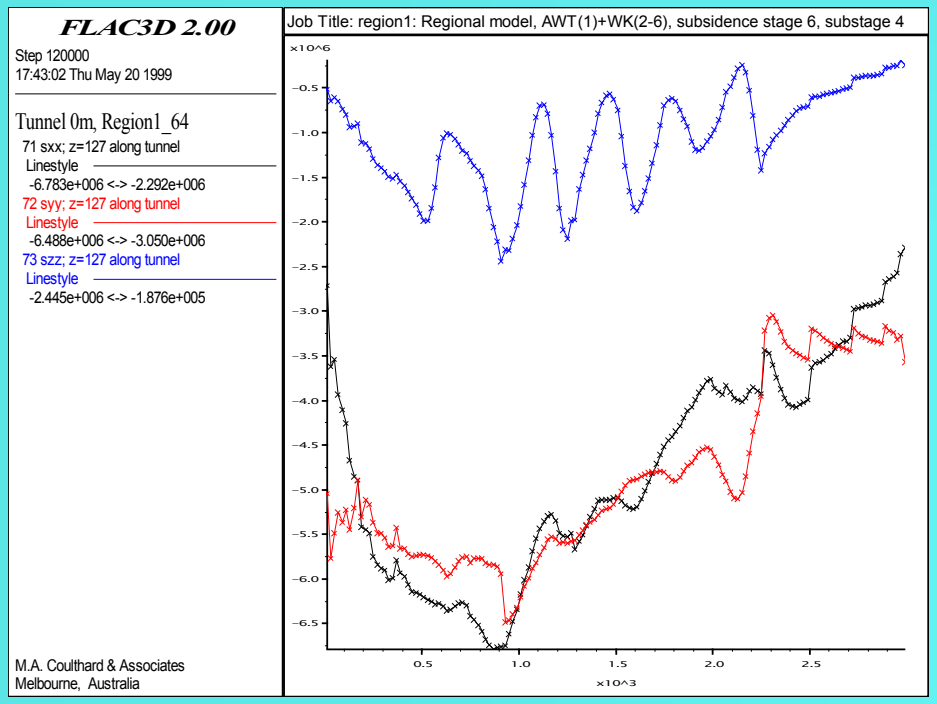


Stress σ_{yy} within regional model (left) and corresponding part of detailed model (right), after mining to end of longwall 404

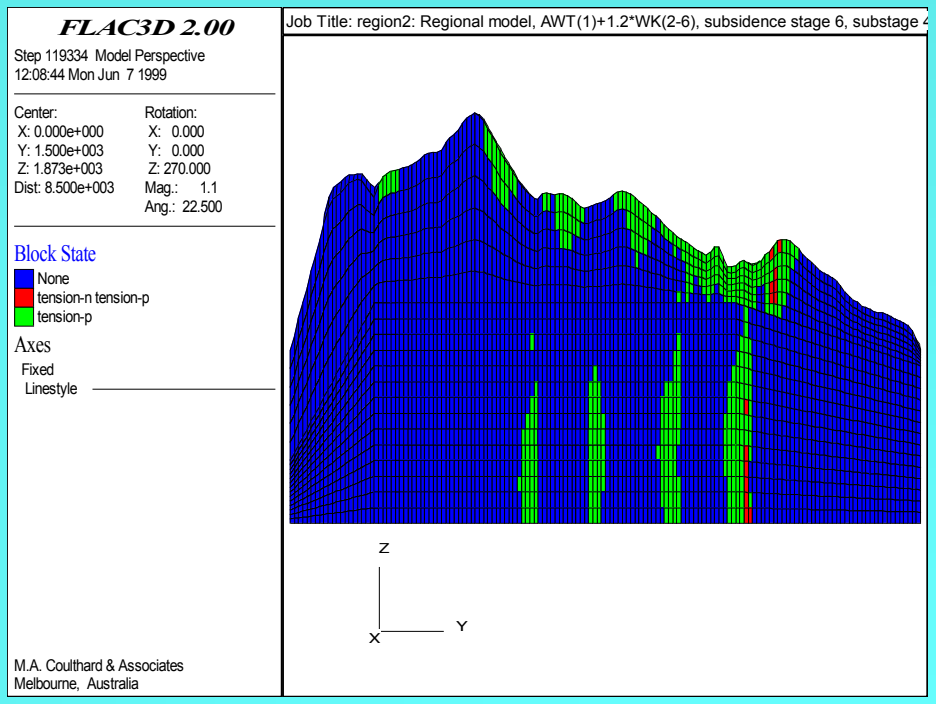
Regional models

- (a) 100% and (b) 120% of predicted subsidence
- Some tensile yield along line of tunnel in (b) (i.e. even without any stress concentrations due to tunnel and shafts)
- Stress variations reflect both subsidence boundary conditions and surface topography
- Each model took 6 days to run on a P2-450 in mid-1999, including 24 stages of mining

Results from regional models



Stresses along line of tunnel at end of mining

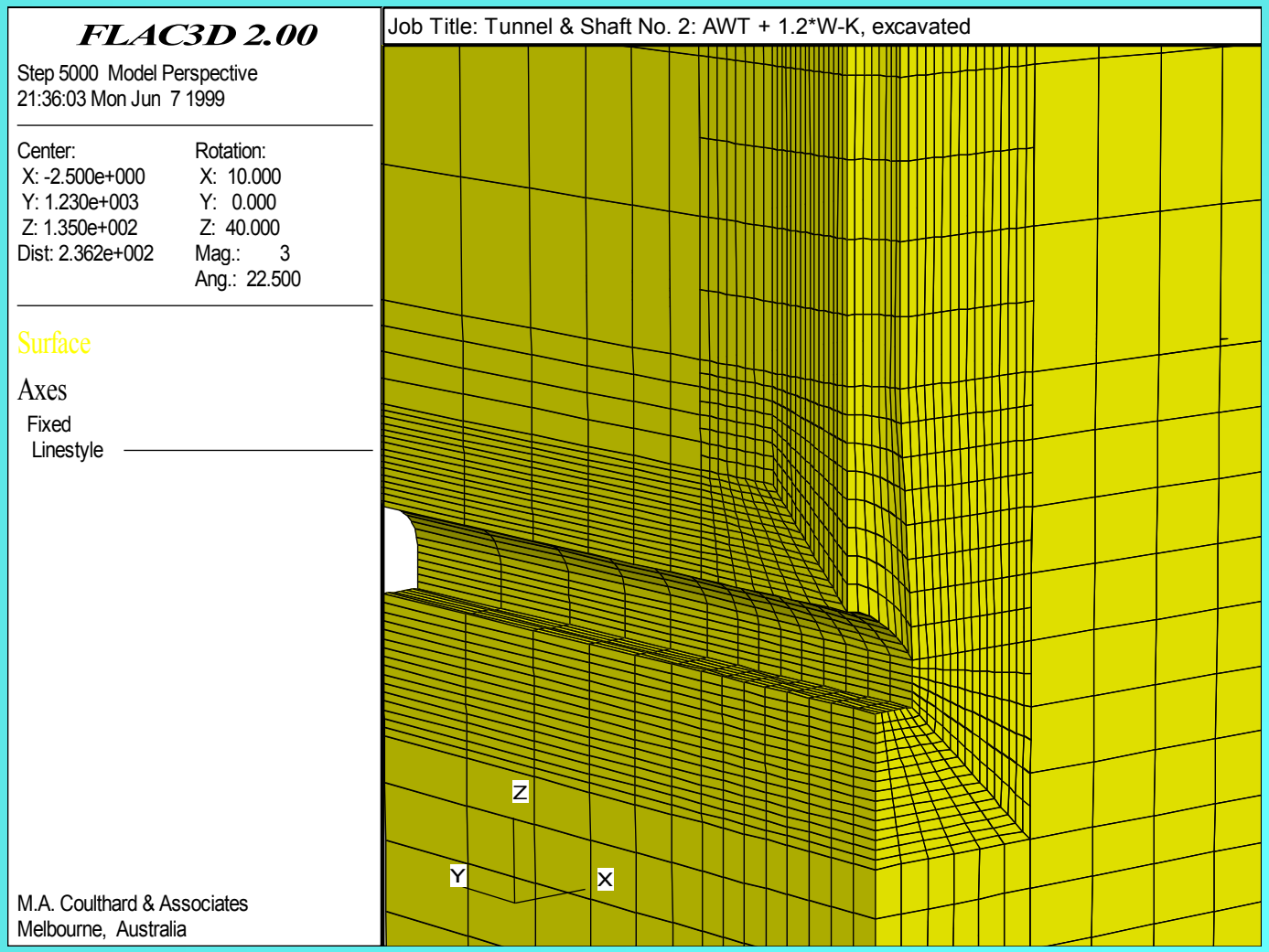


Tensile yield in rock after 120% subsidence

Tunnel-shaft intersection models

- **Models for each of Shaft 2 and Shaft 3**
- **Half-widths 20 m normal to tunnel axis, 30 m parallel to axis; from 30 m below tunnel to surface**
- **First excavate tunnel and shaft in *in situ* stresses**
- **Boundary conditions from regional model for all 24 stages of mining**
- **Mismatch where tunnel meets sides of model, but response around intersection is reliable**

Inner section of tunnel-shaft model

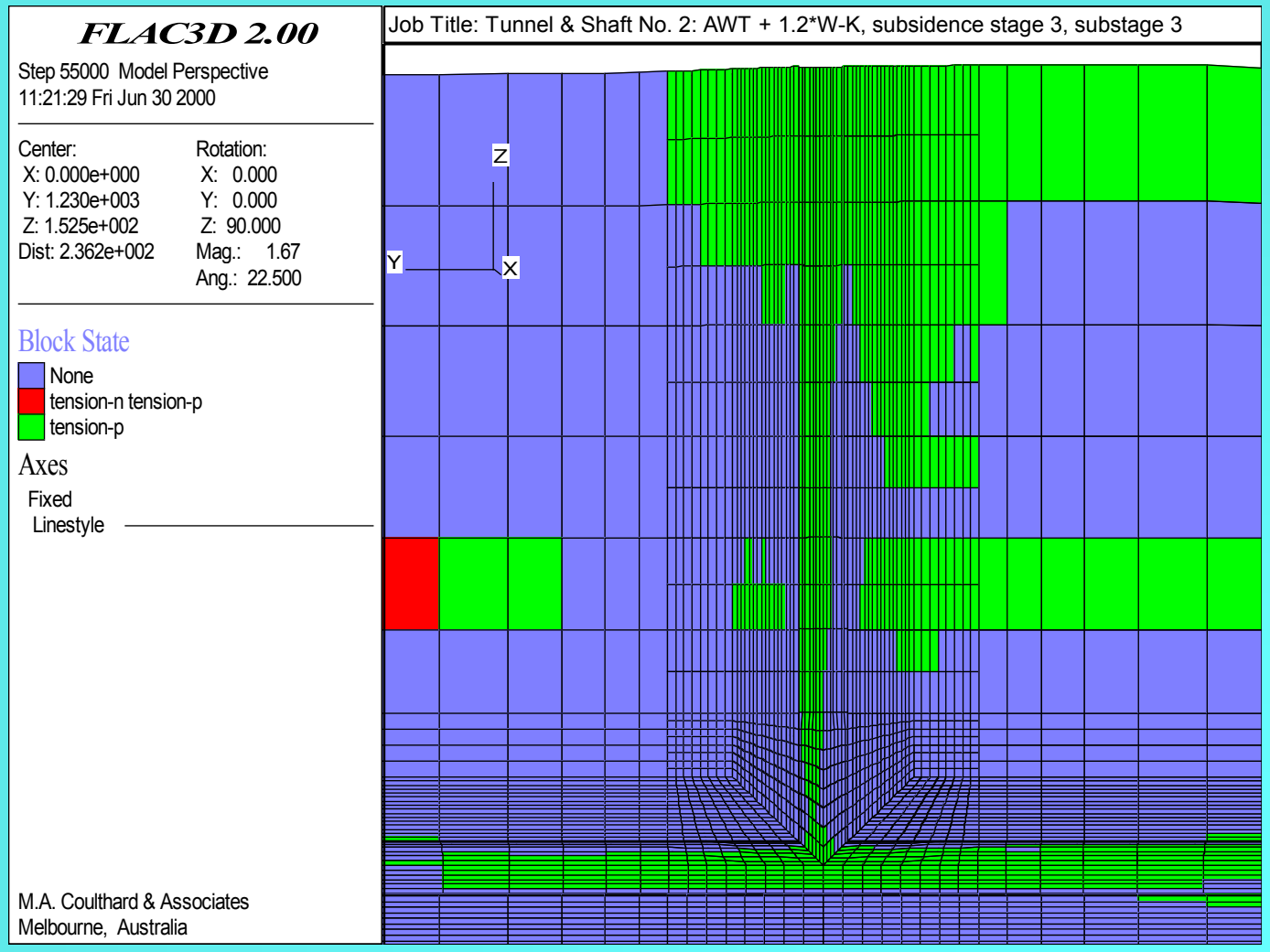


Results from tunnel-shaft models

- Tensile yield around upper walls of shaft 2, and around Tunnel, by stage 1 of mining LW403
- By stage 3 of LW403 (after mining face has passed shaft), extensive yield in tunnel walls and surrounding rock
- Little change at shaft 2 from subsequent mining
- Similar effects at shaft 3 from LW405/406

Tunnel-shaft intersection, LW403 stage 3

Predicted yield - on and behind centre plane of detailed model



Conclusions

- **Wide range of scales: 200 m wide longwall panels, depth 400 m; 3 m diameter tunnel and shafts; 1.4 m maximum predicted subsidence**
- **Coupling between regional and detailed models required to make problem tractable numerically**
- ***FISH* programming an essential component**
- **Rock support designed and installed; mining to LW404 has occurred safely**