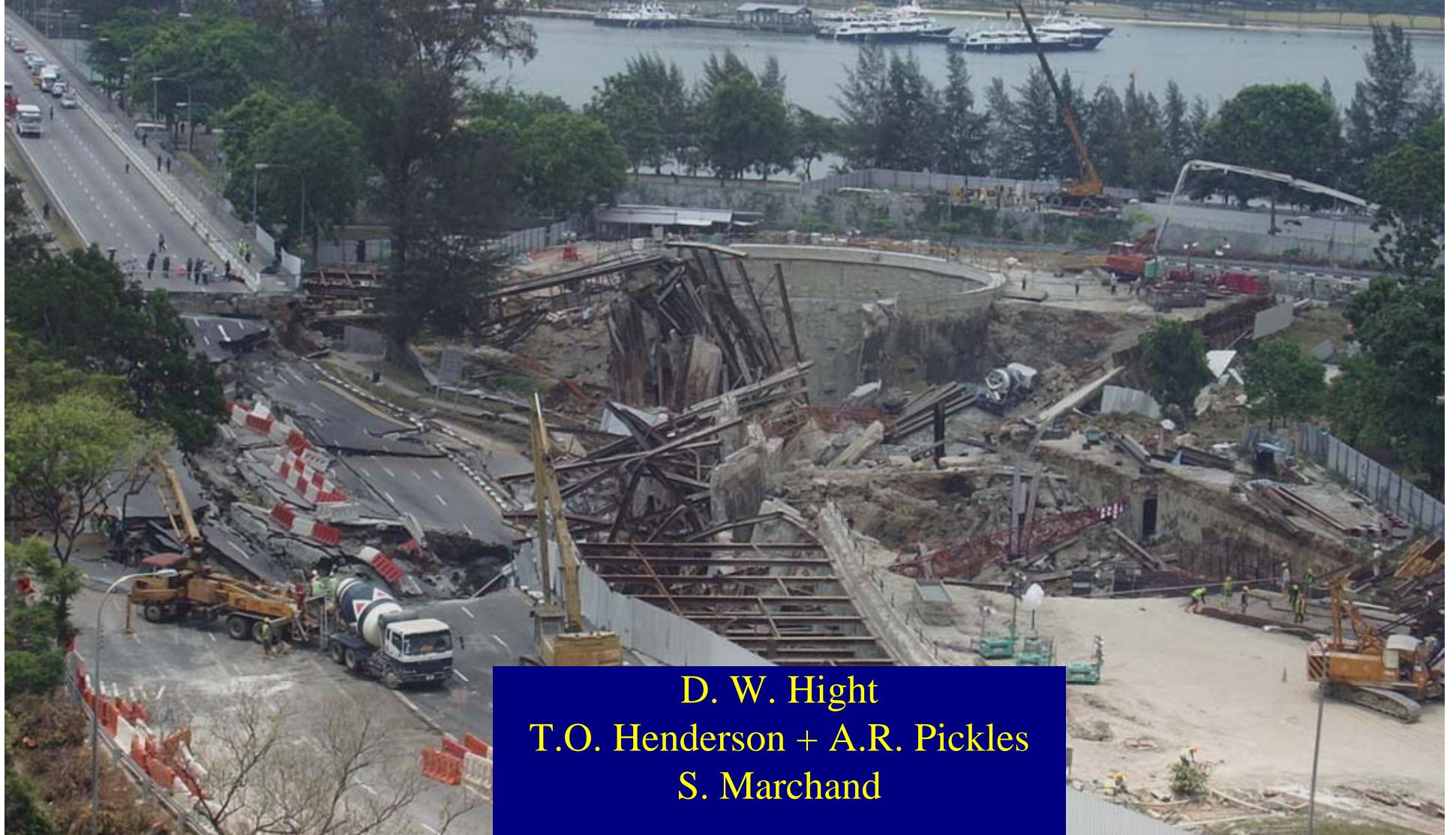


# The Nicoll Highway Collapse

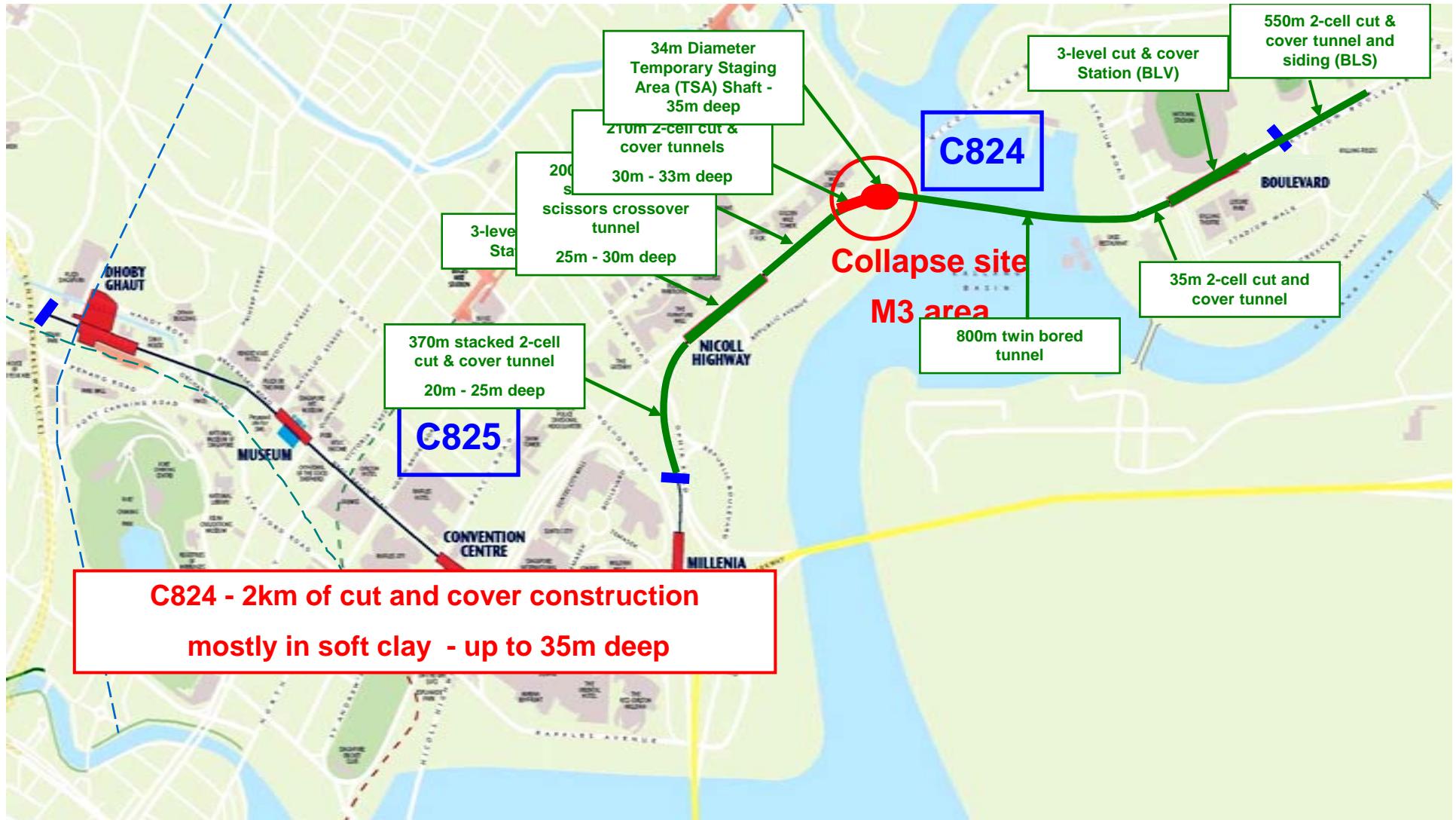


D. W. Hight  
T.O. Henderson + A.R. Pickles  
S. Marchand



## *Content*

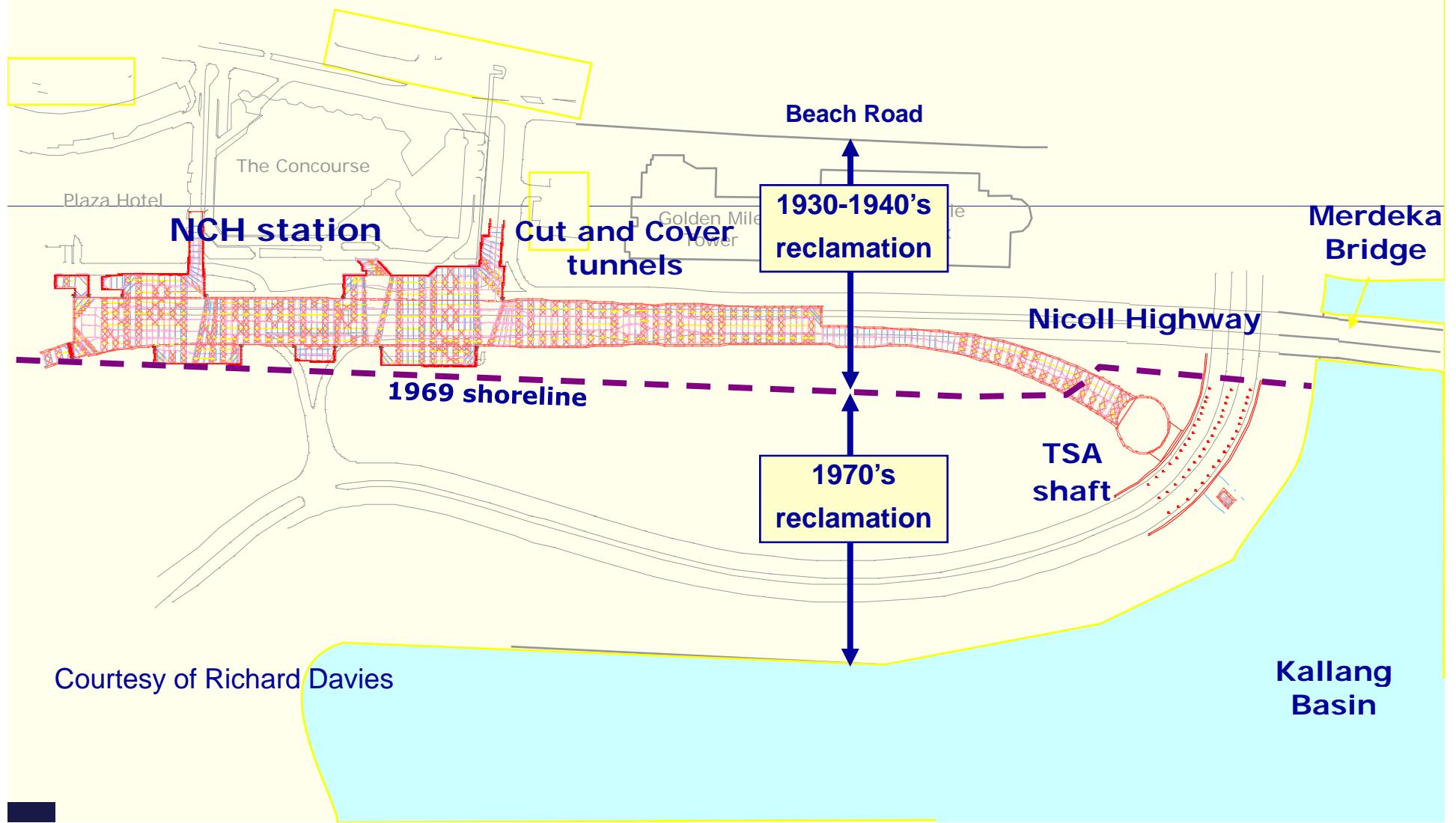
- Background and construction sequence
- Observations up to the point of collapse, including monitoring
- The collapse
- Post-collapse investigations
- Design errors
- Jet grout layers
- Ground conditions and the buried valley
- The need for a trigger
- Back analyses of the collapse
- Relative vertical displacement and forced sway
- The bored piles
- Collapse mechanism and its trigger
- Lessons to be learnt

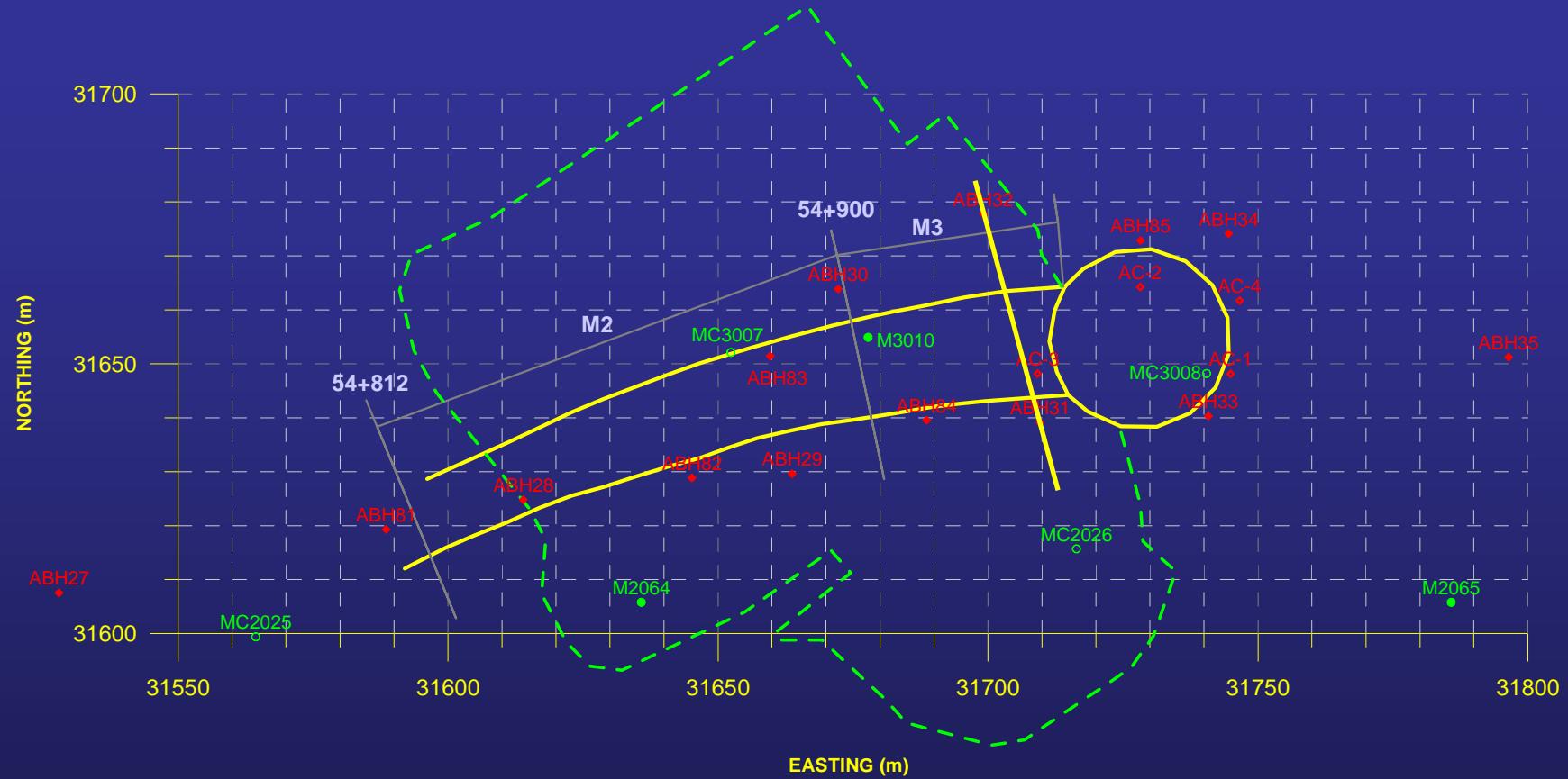


*Circle Line Stage 1*



# Reclamation dates





*Pre- and post-tender site investigation*



SOUTH

ABH 31

100

Fill

Upper estuarine

Upper  
Marine  
Clay

Upper F2

Lower  
Marine  
Clay

Base marine clay

Old  
Alluvium

M309

M304

ABH 32

NORTH

100

Upper estuarine

Upper  
Marine  
Clay

Upper F2

Lower  
Marine  
Clay

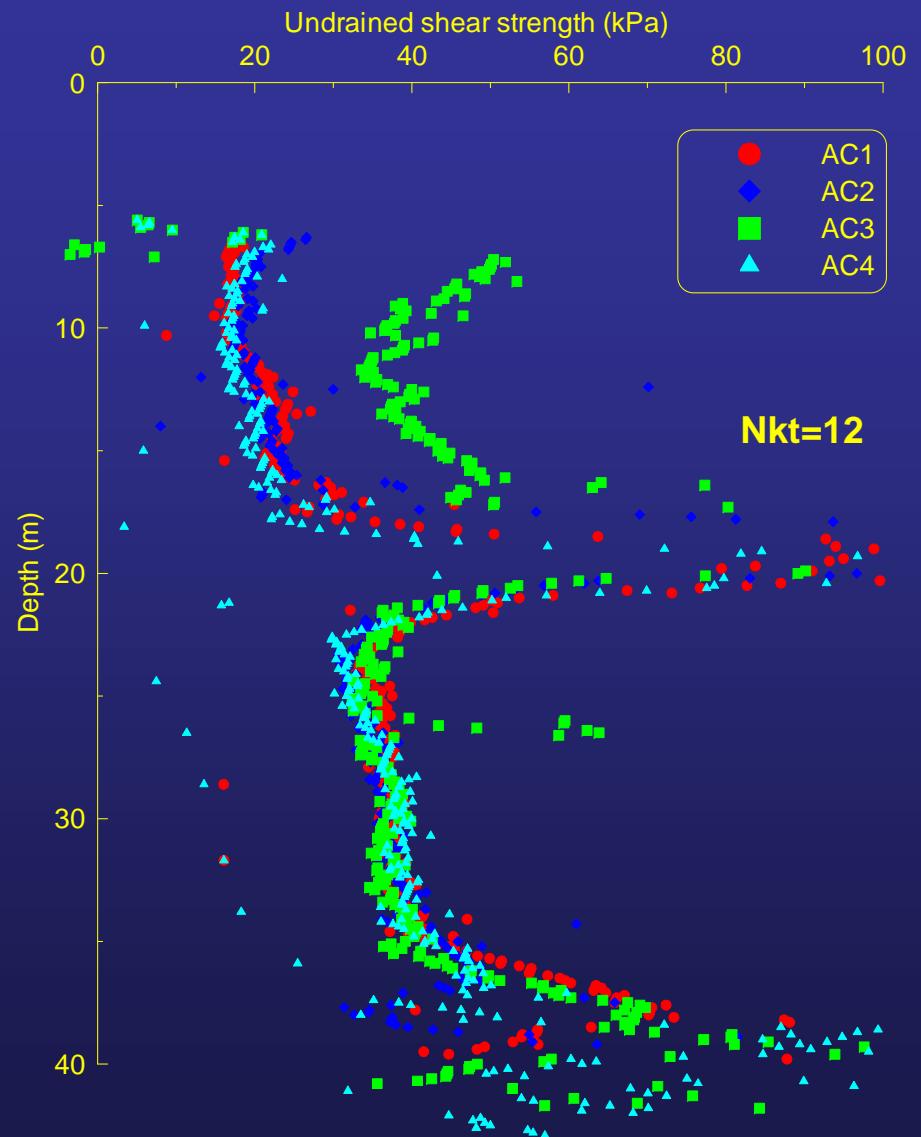
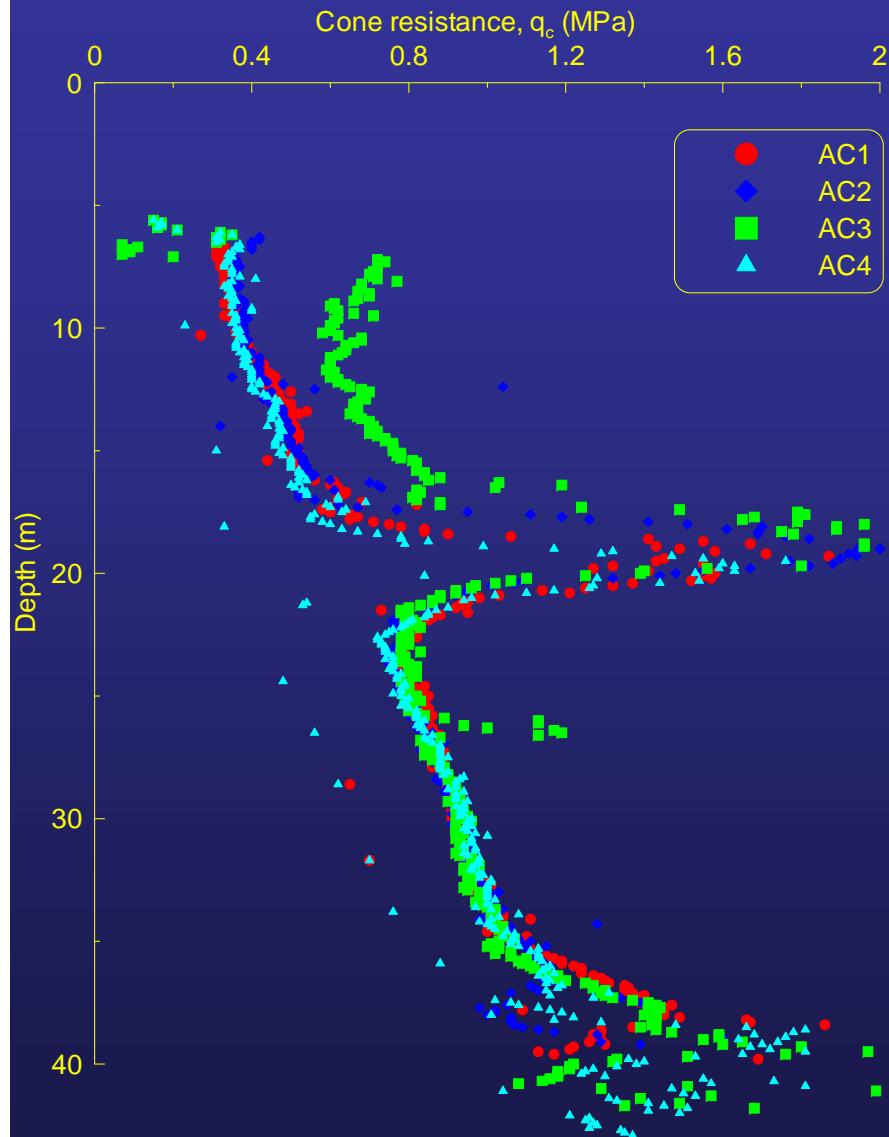
Top of OA

Lower  
estuarine

Lower F2

Old  
Alluvium

*Typical section in M3*



*Piezocene data for M3 area*



*Construction details and sequence*



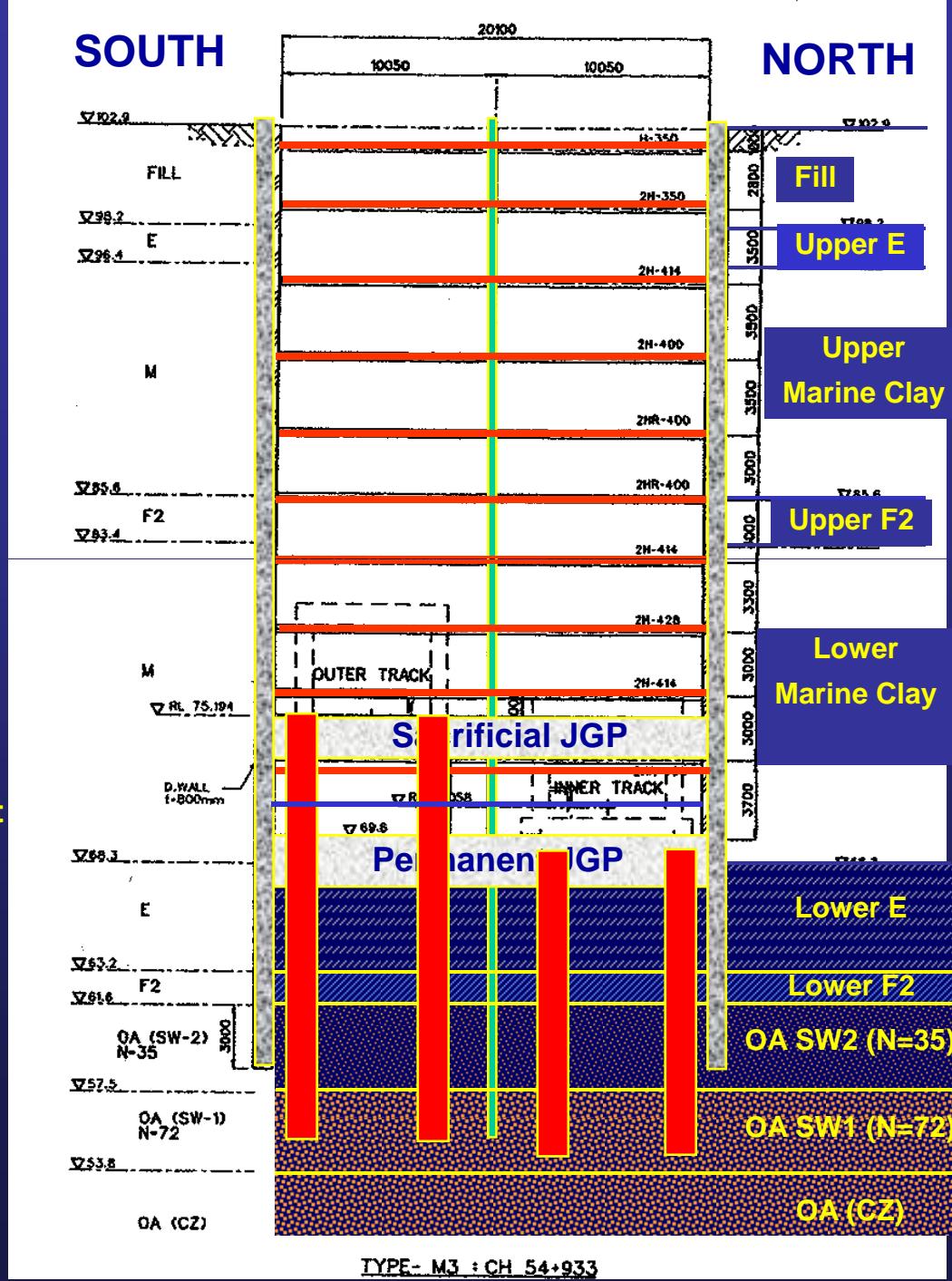
Formation level  
approx 33m bgl

Temporary diaphragm  
walls, 0.8m

Driven kingpost

Permanent bored piles  
supporting  
rail boxes

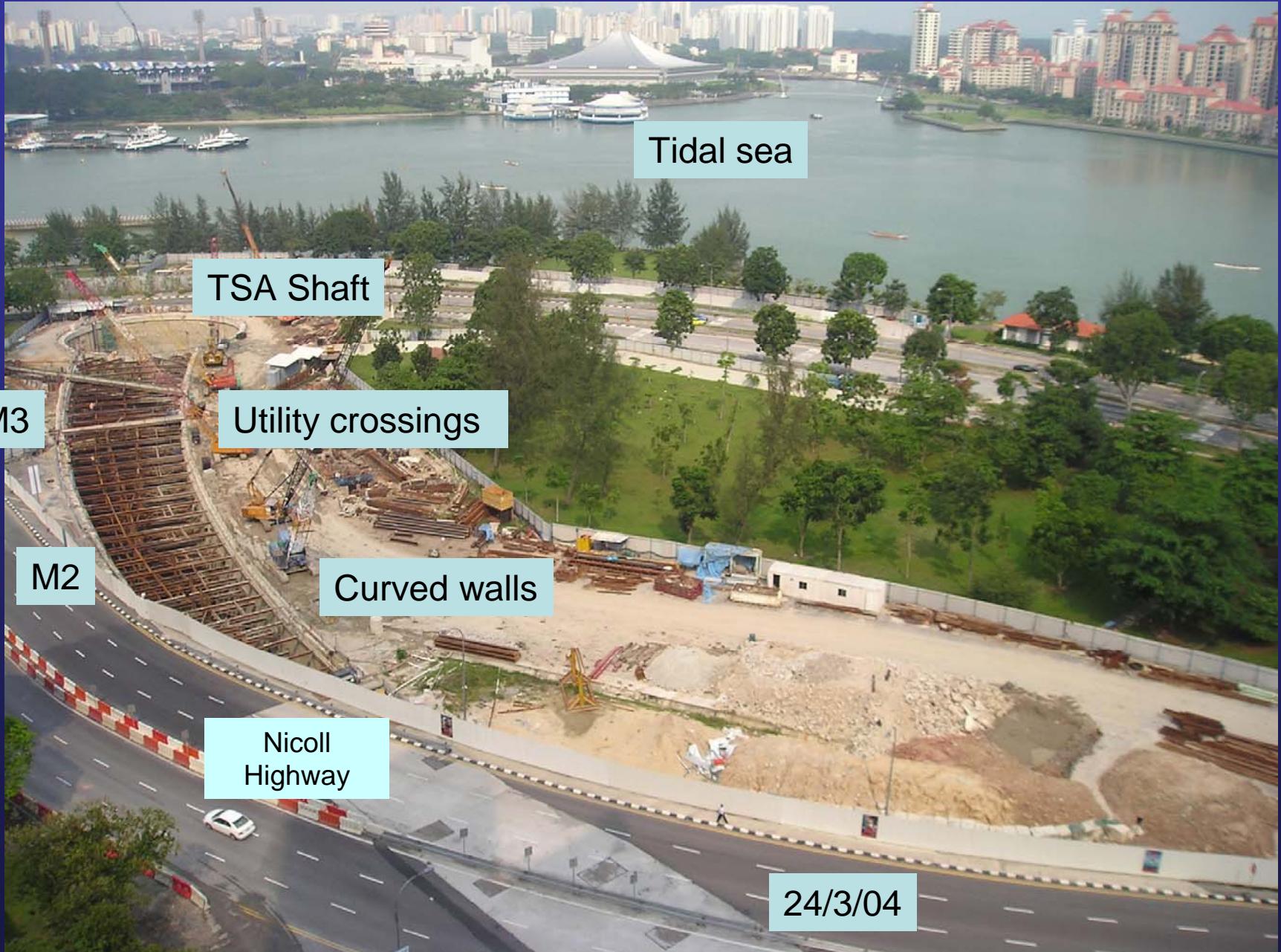
10 levels of steel struts at  
3m +3.5m vertical  
centres



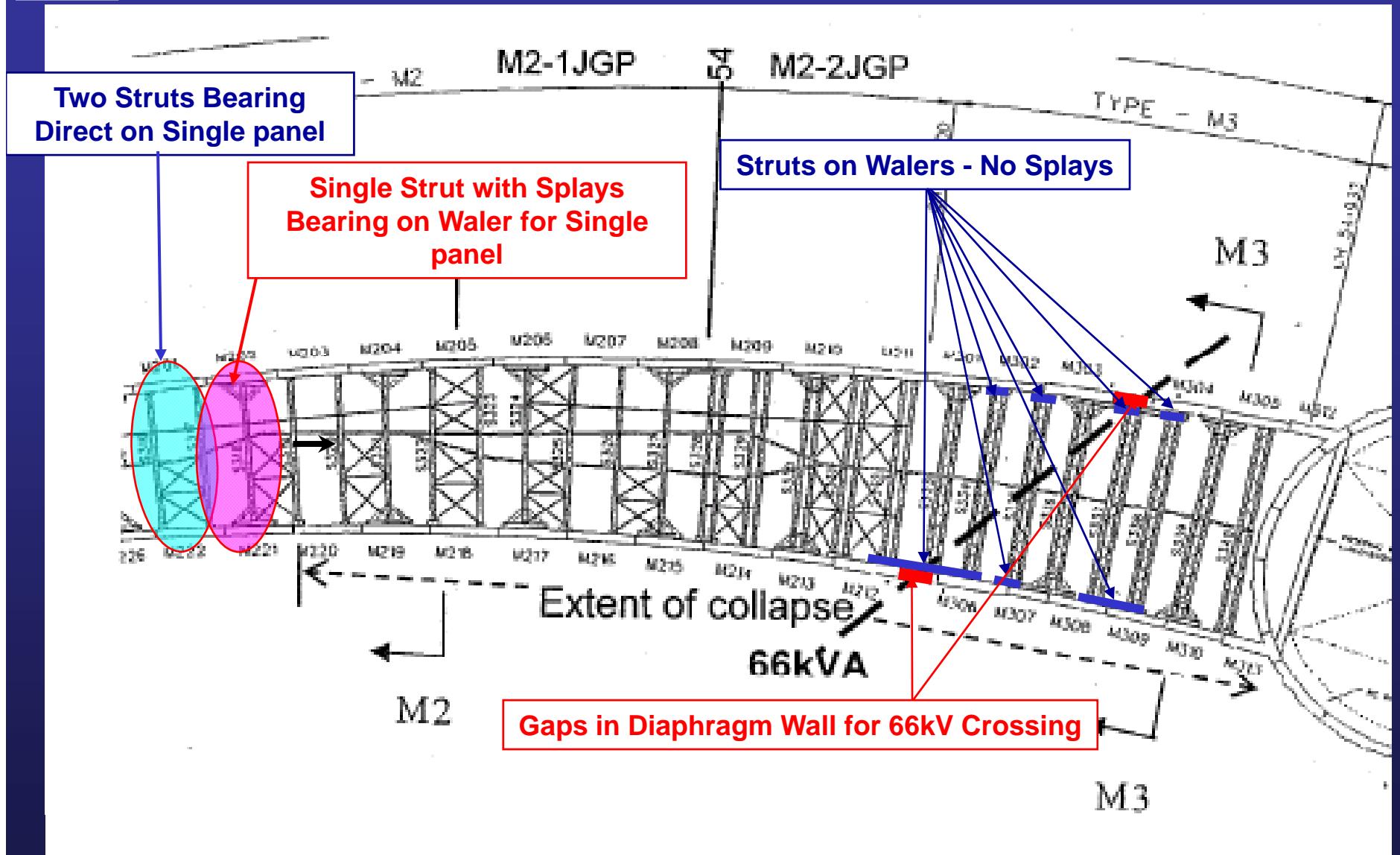


## General Excavation sequence for M3 – up to level for removal of sacrificial JGP and installation of 10<sup>th</sup> level strut











*South side 13 March 04*



*Events and observations prior to collapse*



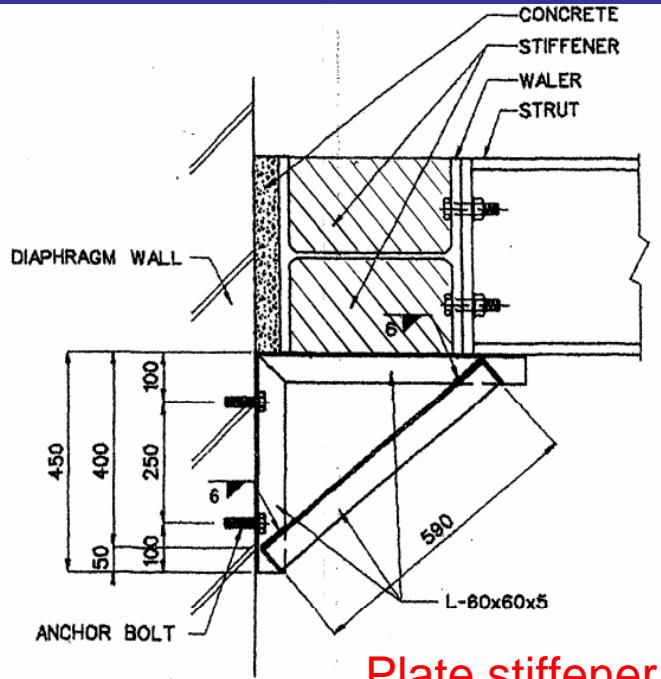
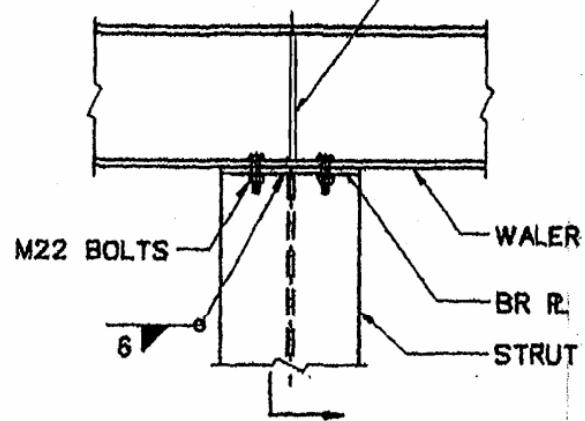
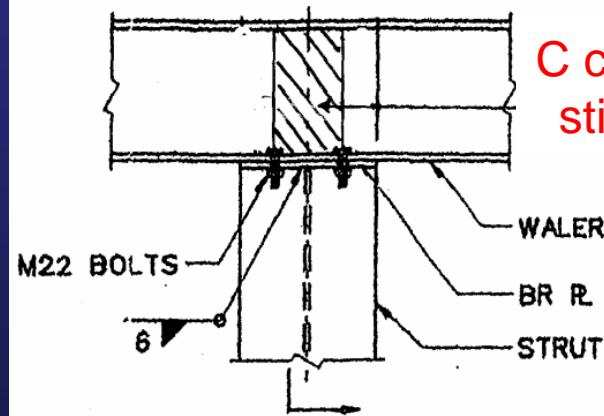
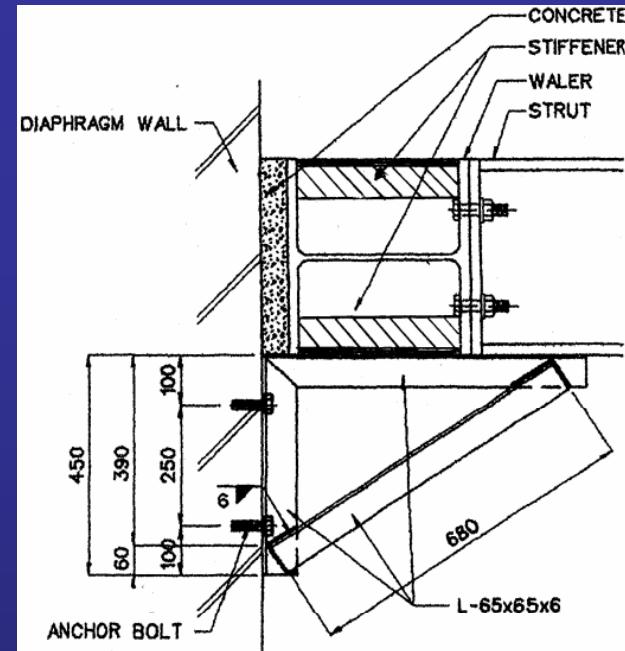


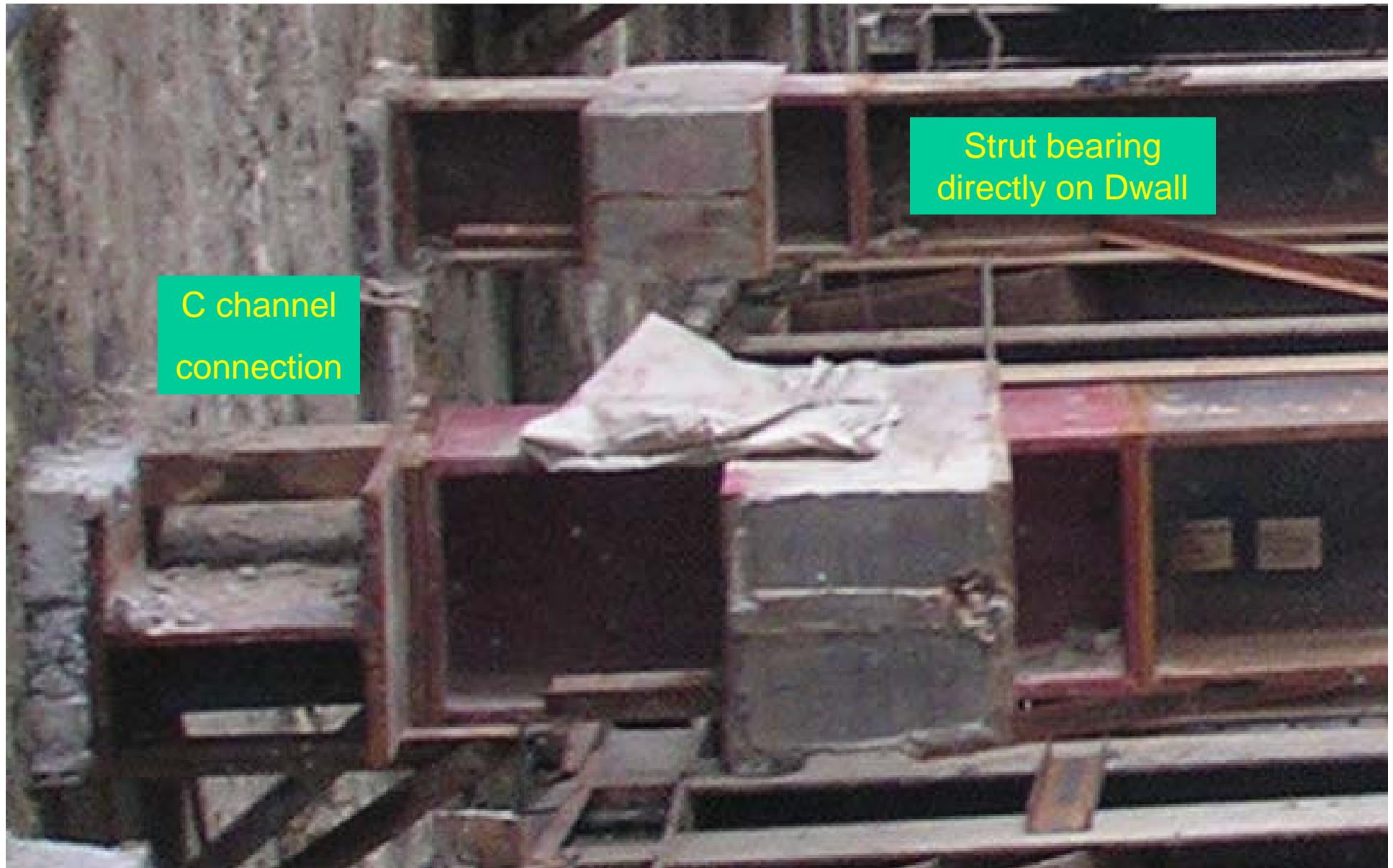
Plate stiffener



C channel  
stiffener

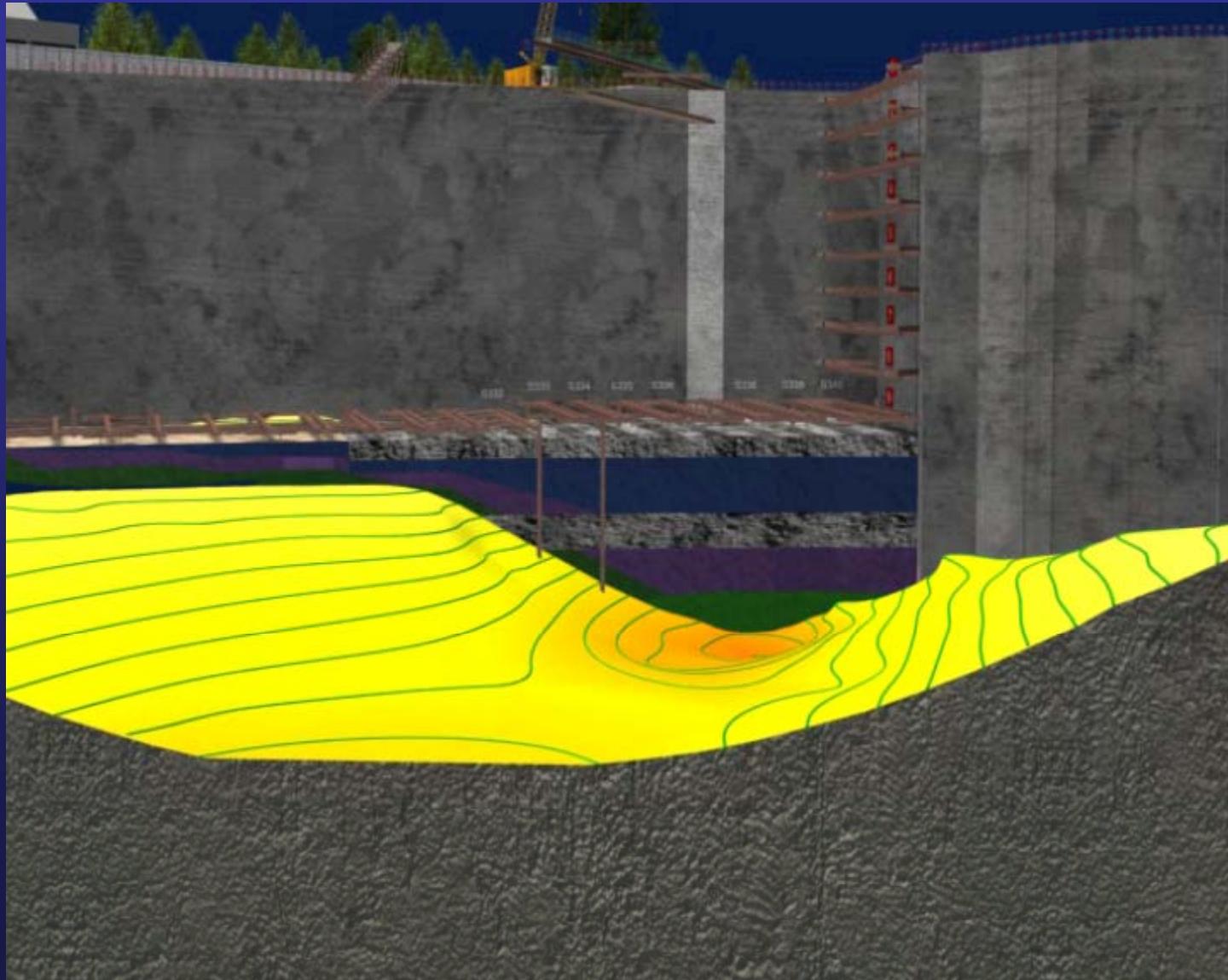


*Replacement of plate stiffeners at strut-waler connection*



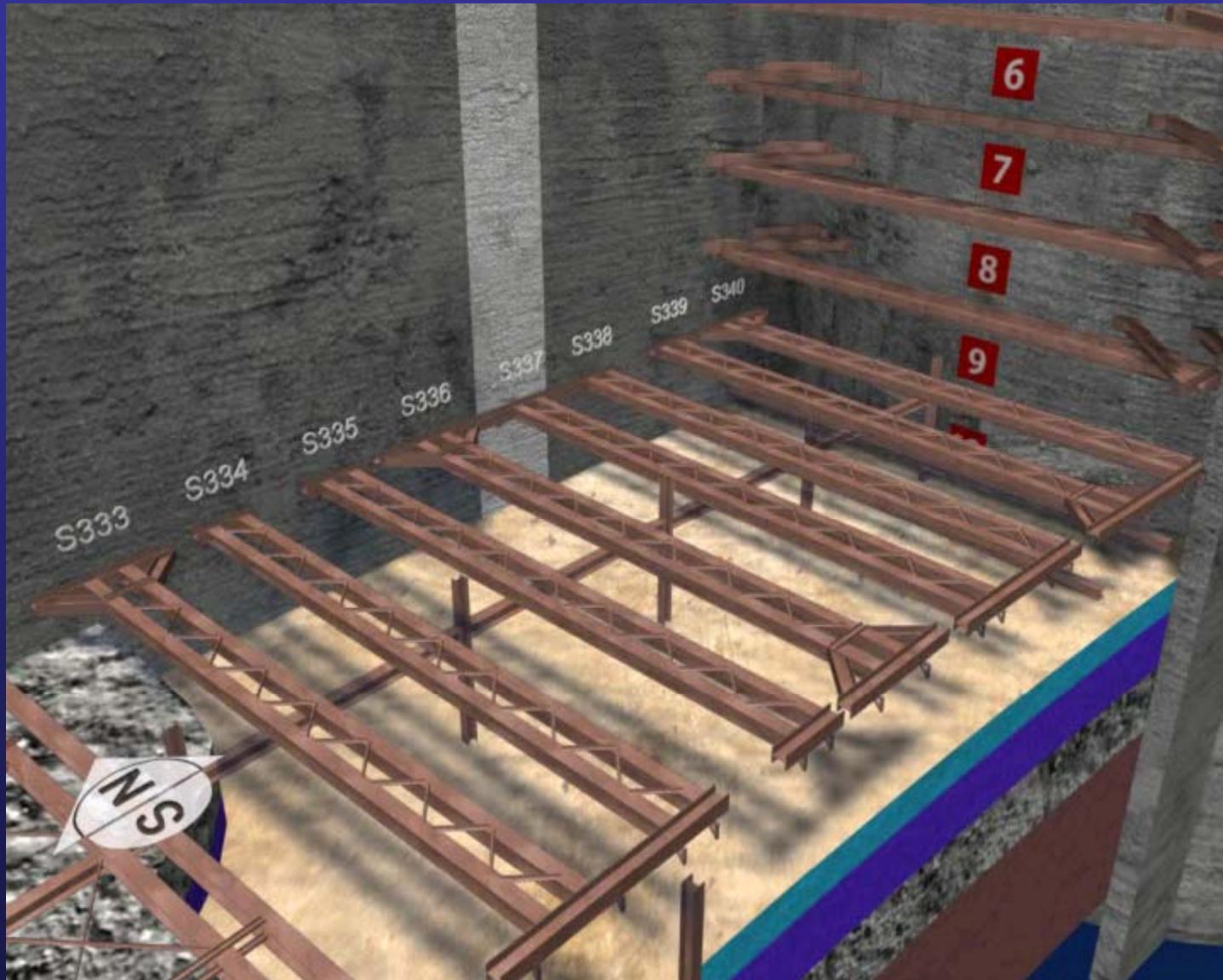


Excavation for the 10<sup>th</sup> level of struts, including removal of the sacrificial JGP



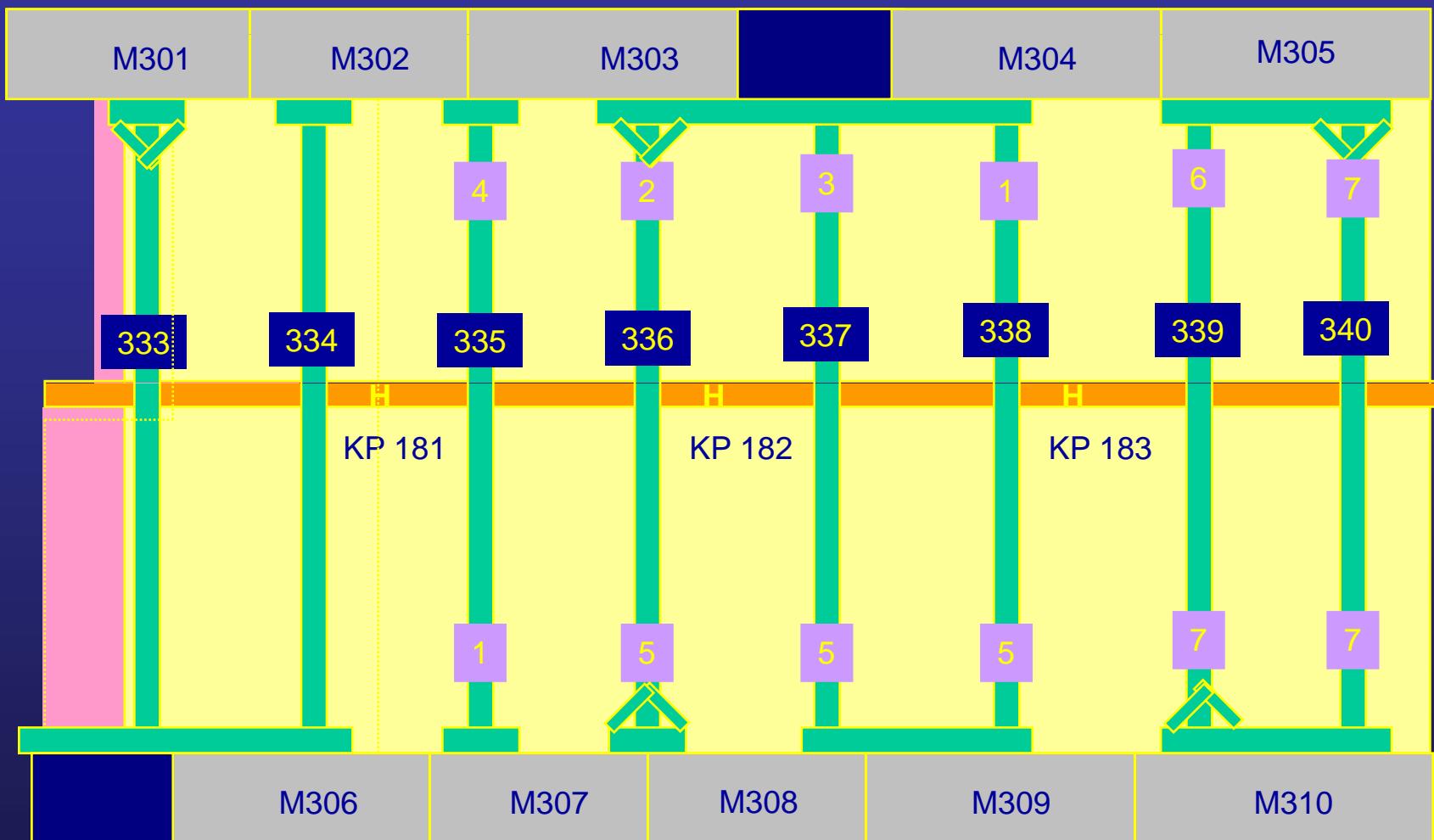


## Observations on the morning of the collapse





## North wall



Order in which distortion to waler noted



Excavation in progress



Excavation to 10<sup>th</sup> complete

Location of walers, splays and Dwall gaps

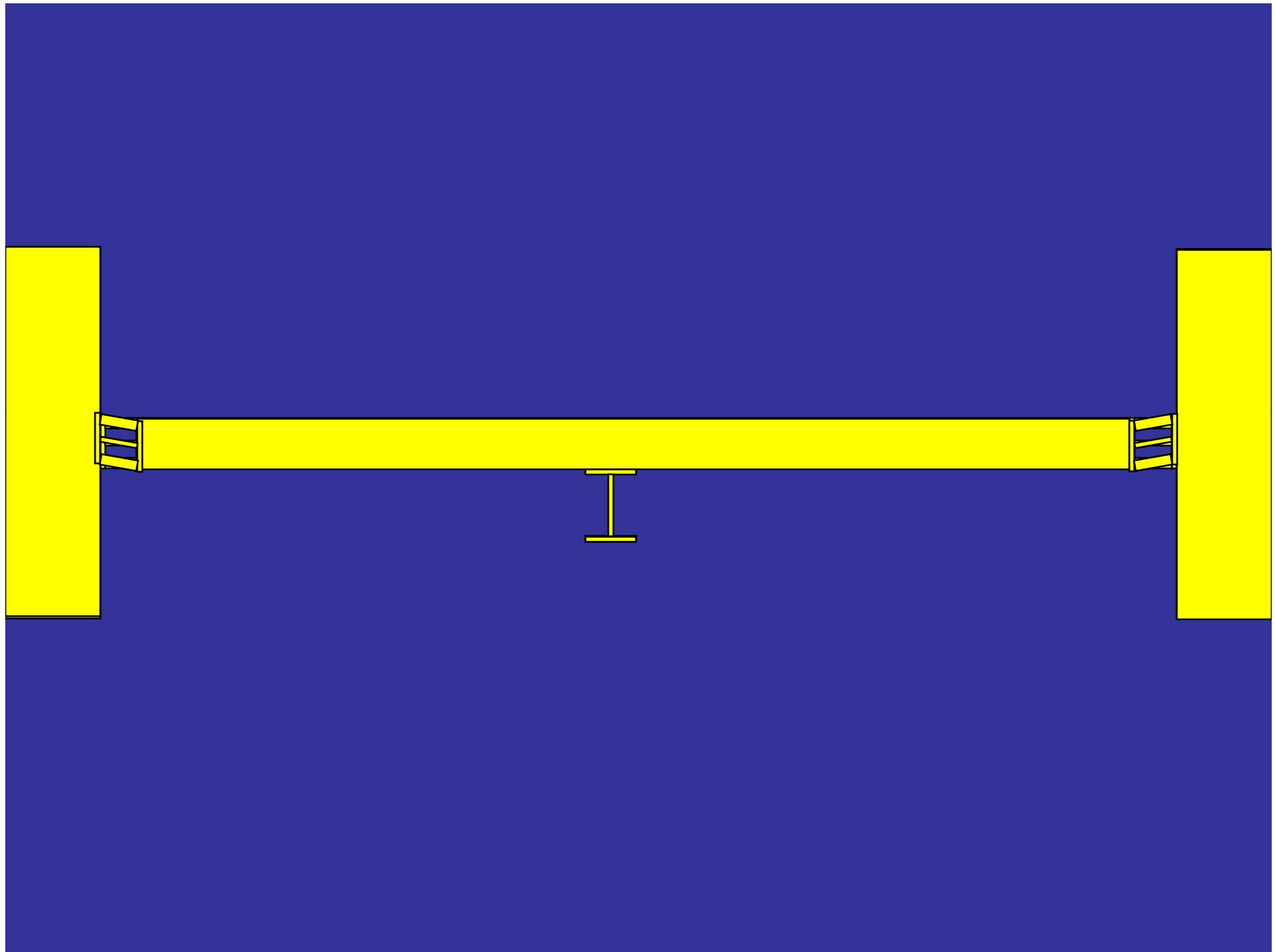


*Strut 335-9 south wall*



S338-9

*Strut 338-9 north wall*

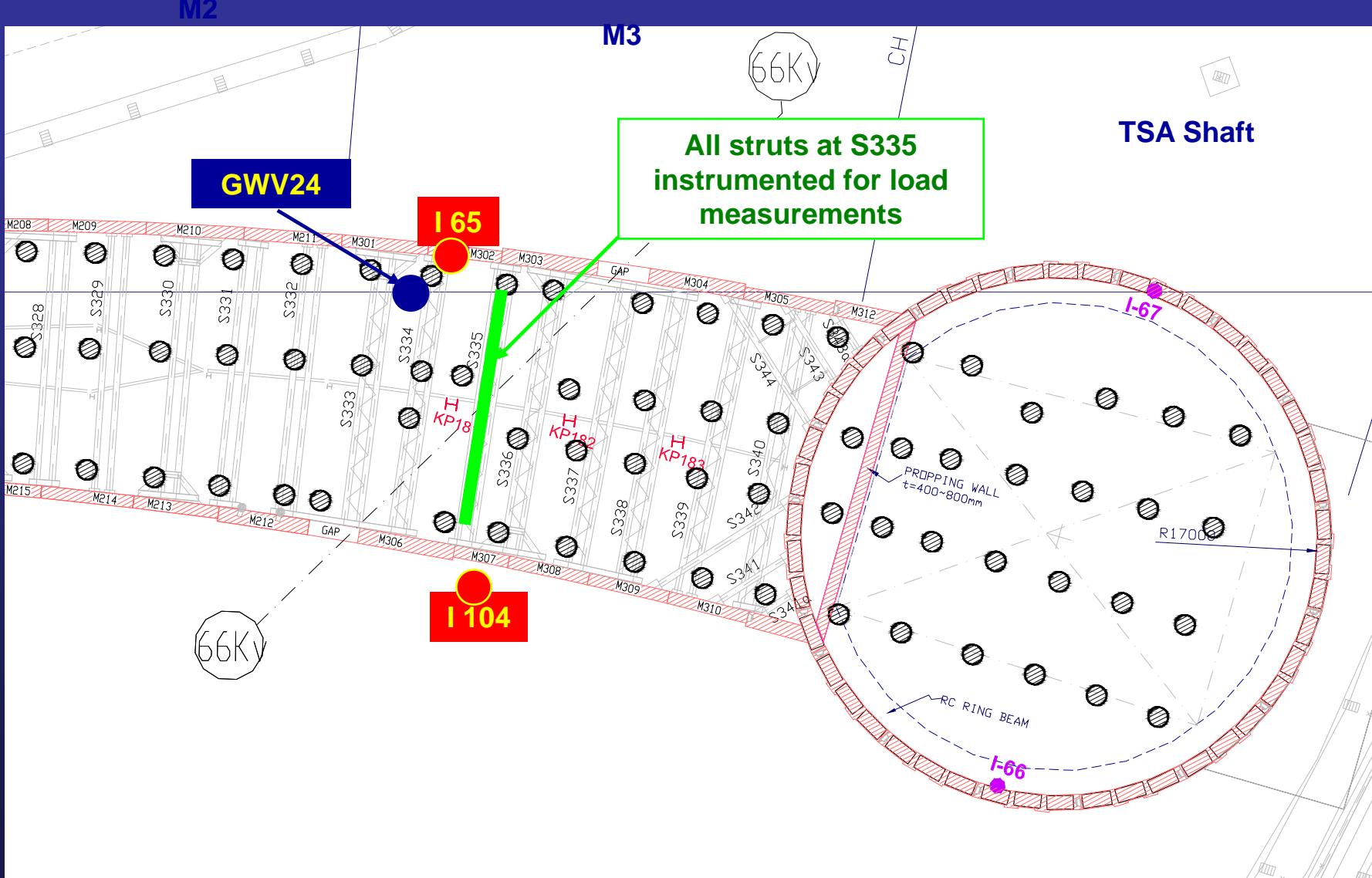


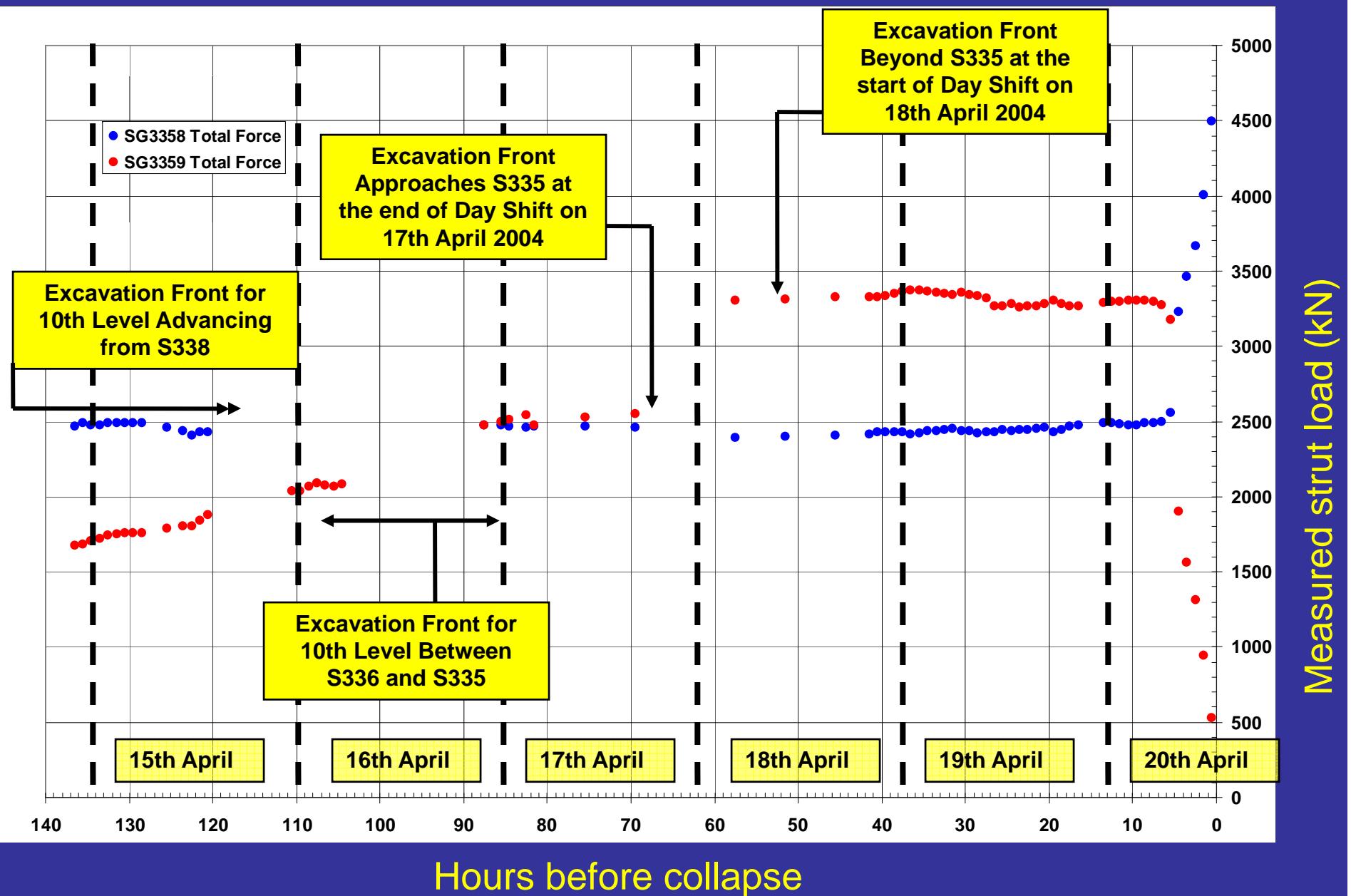


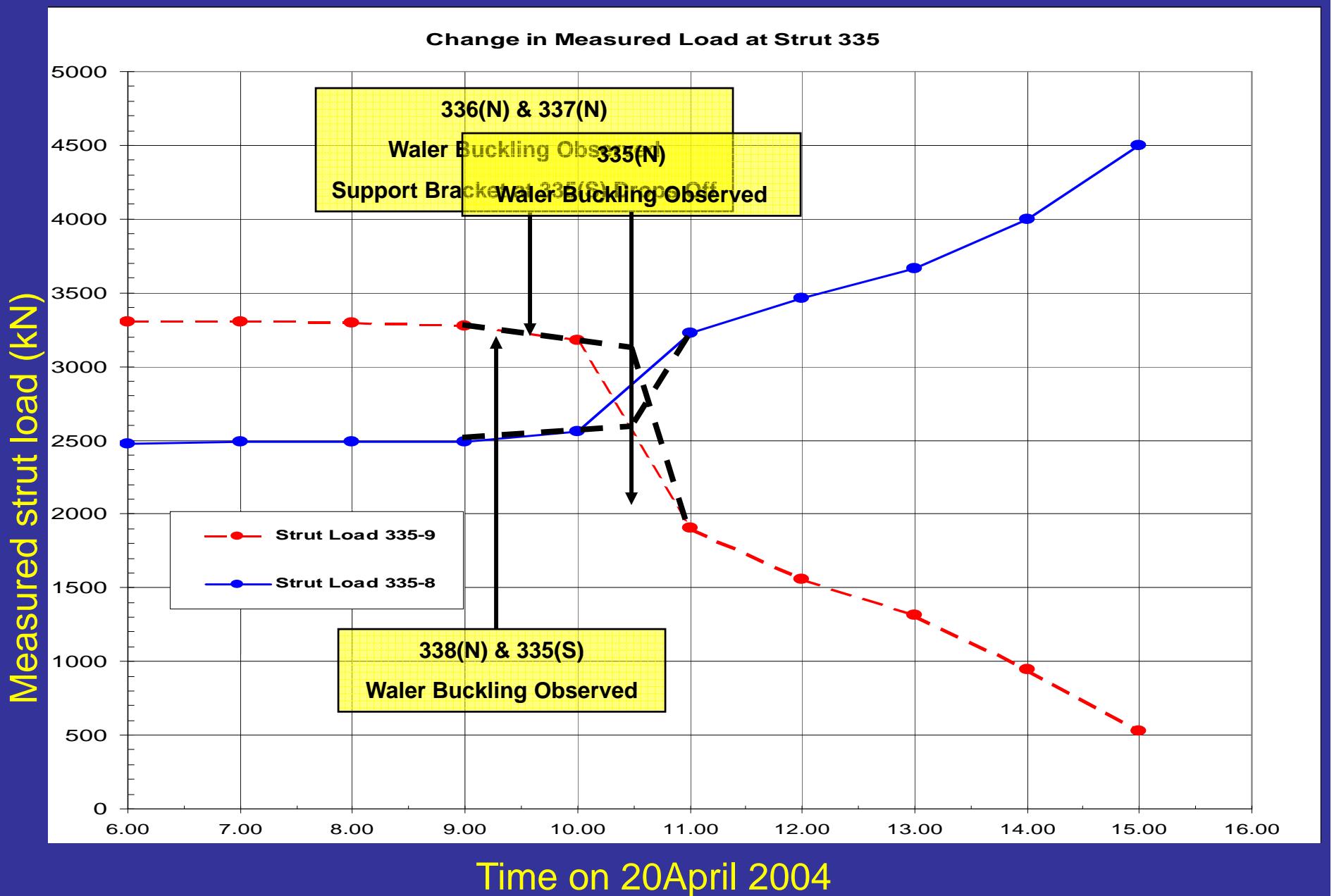
## *Instrumentation and results of monitoring*



# M2/M3 plan at 9<sup>th</sup> level

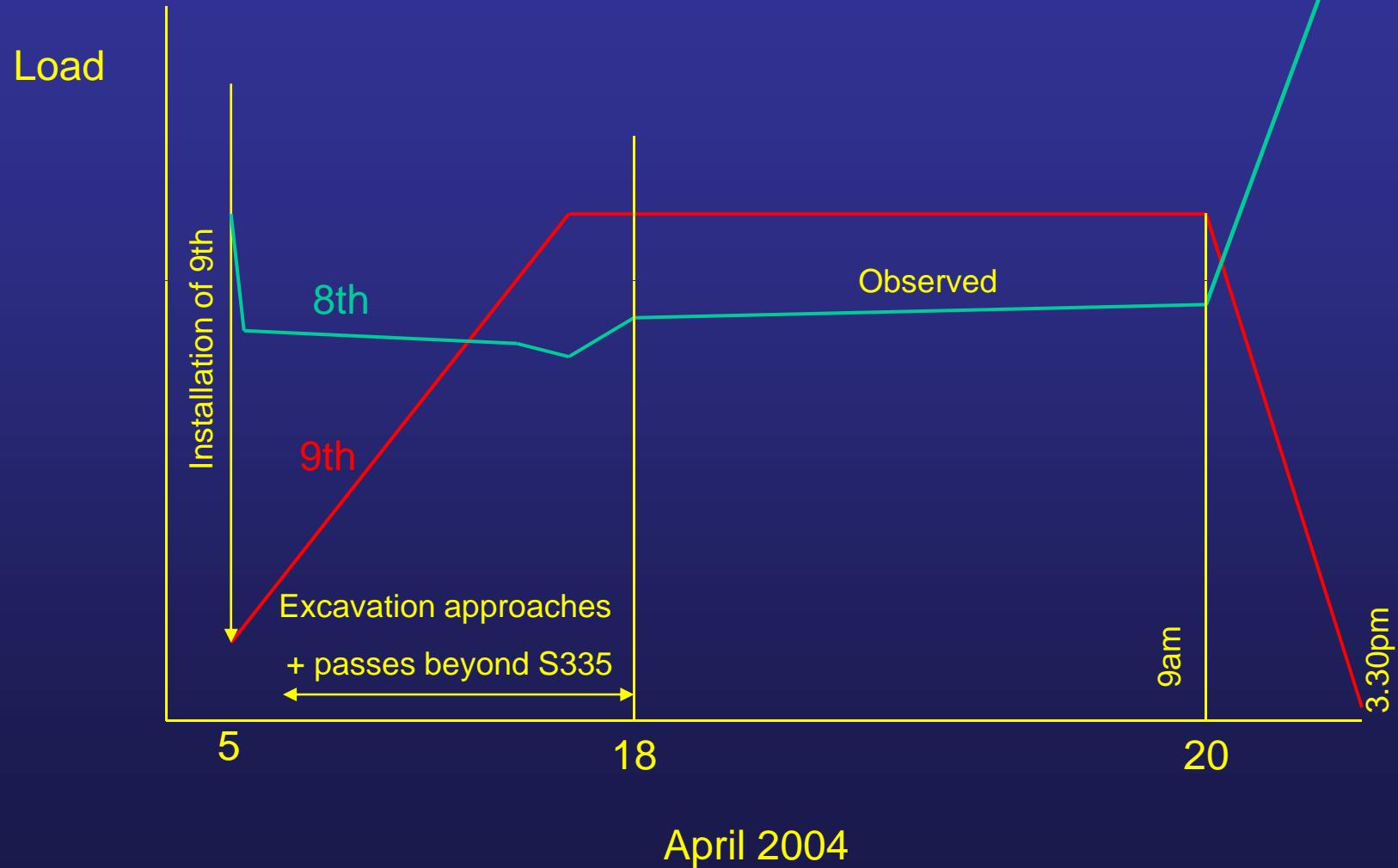








## Observed trends in 8<sup>th</sup> and 9<sup>th</sup> strut loads





The trends were consistent with there being yielding of the 9<sup>th</sup> level strut-waler connection when the excavation passed beneath but with no further significant changes in load in either the 9<sup>th</sup> or 8<sup>th</sup> level struts until the collapse was initiated



Horizontal displacement (mm)

200

400

0

Horizontal displacement (mm)

400

200

0

0

10

20

Depth (m)

30

40

50

0

10

20

Depth (m)

40

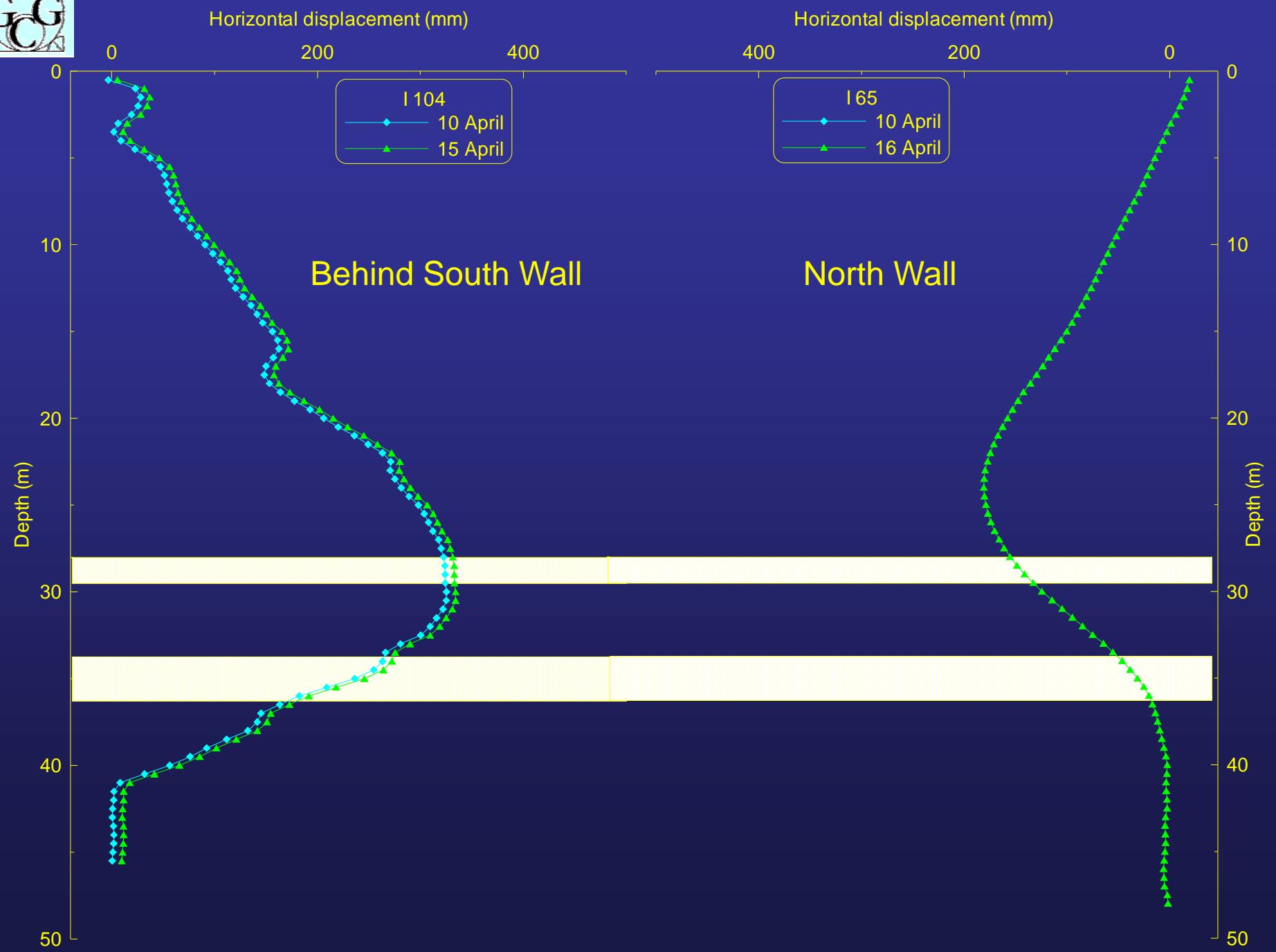
50

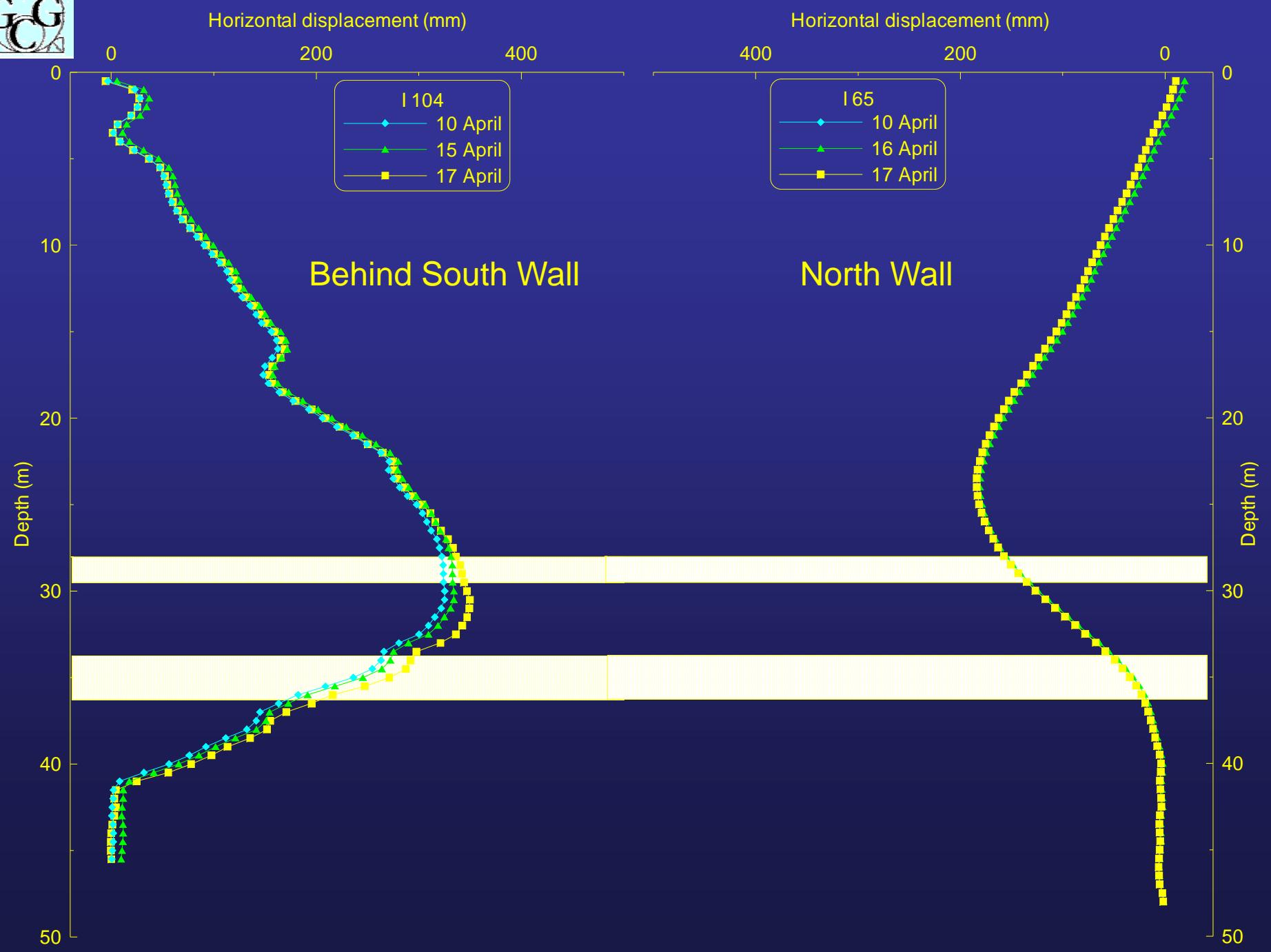
Behind South Wall

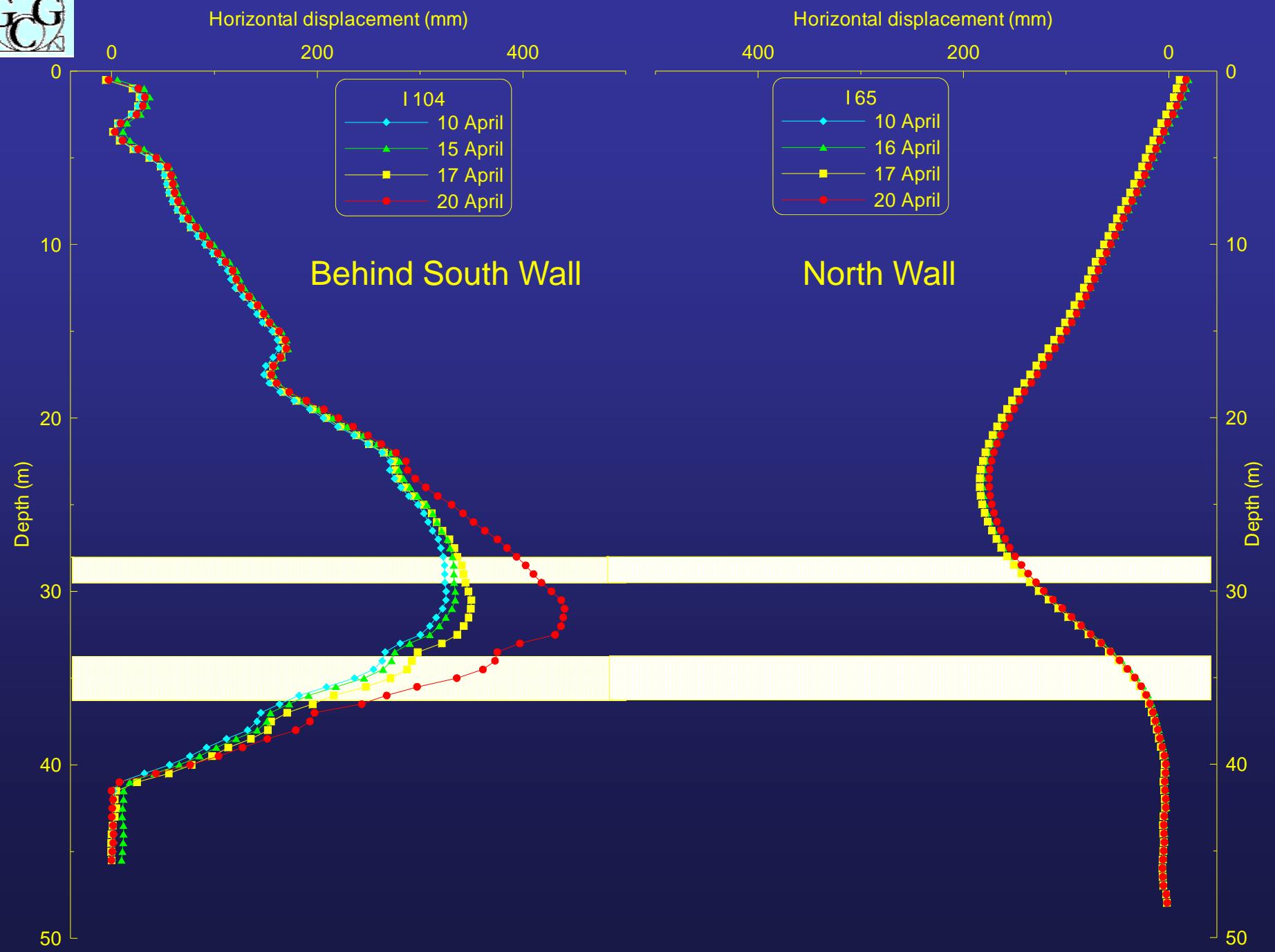
North Wall

I104  
10 April

I165  
10 April









Maximum horizontal displacement, mm

500

0

I104 max  
I65 max

5-Jul 9-Aug 13-Sep 18-Oct 22-Nov 27-Dec 31-Jan 6-Mar 10-Apr

2003

South wall

North wall

*Comparison of inclinometer readings I65 and I104*



- S338-9 stood for 8 days under load and was 20m from excavation front
- S335-9 stood for 2.5 days under load and was over 8m from excavation front
- Both S335-9S & S338-9N buckled within 10 minutes
- Load in S335-8 and S335-9 was almost constant between 18 April and initiation of collapse
- All C-channel connections failed downwards at both ends
- The south wall was pushing the north wall back

*Key observations*



*The collapse*



3.33pm



3.33pm



3.34pm



3.34pm



3.34pm



3.41pm



3.46pm



*Post-collapse investigations*

Design errors



## Errors

- Misinterpretation of BS5950 with regard to stiff bearing length
- Omission of splays

## Effects

- Design capacity of strut-waler connection was 50% of required design capacity where splays were omitted

*Errors in structural design of strut-waler connection*



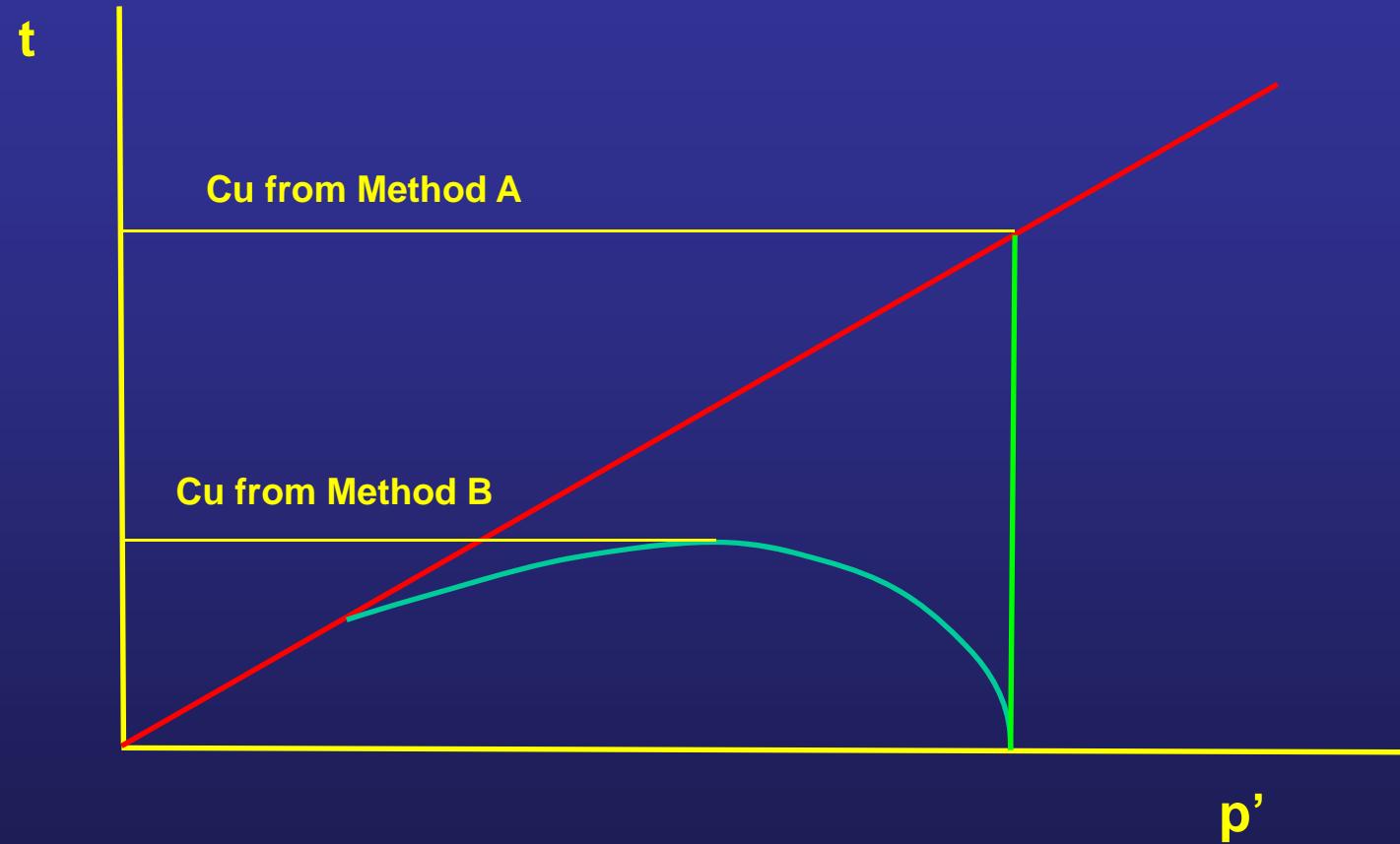
- Capacity based on BS5950:1990 = 2550 kN
- Average ultimate capacity based on physical load tests = 4100 kN
- Based on mill tests, 95% of connections had capacity of 3800 kN- 4400kN
- Predicted 9<sup>th</sup> level strut load in 2D analyses which ignored bored piles was close to ultimate capacity **therefore collapse was considered by the COI to be inevitable**

*Inevitability of collapse*



- Method A and Method B refer to two alternative ways of modelling undrained soil behaviour in Plaxis (Pickles, 2002)
- Method A is an effective stress analysis of an undrained problem
- Assumes isotropic elastic behaviour and a Mohr-Coulomb failure criterion
- As a result mean effective stress  $p'$  is constant until yield
- Method A was being applied to marine clays which were of low over-consolidation or even under-consolidated because of recent reclamation
- Method B is a total stress analysis

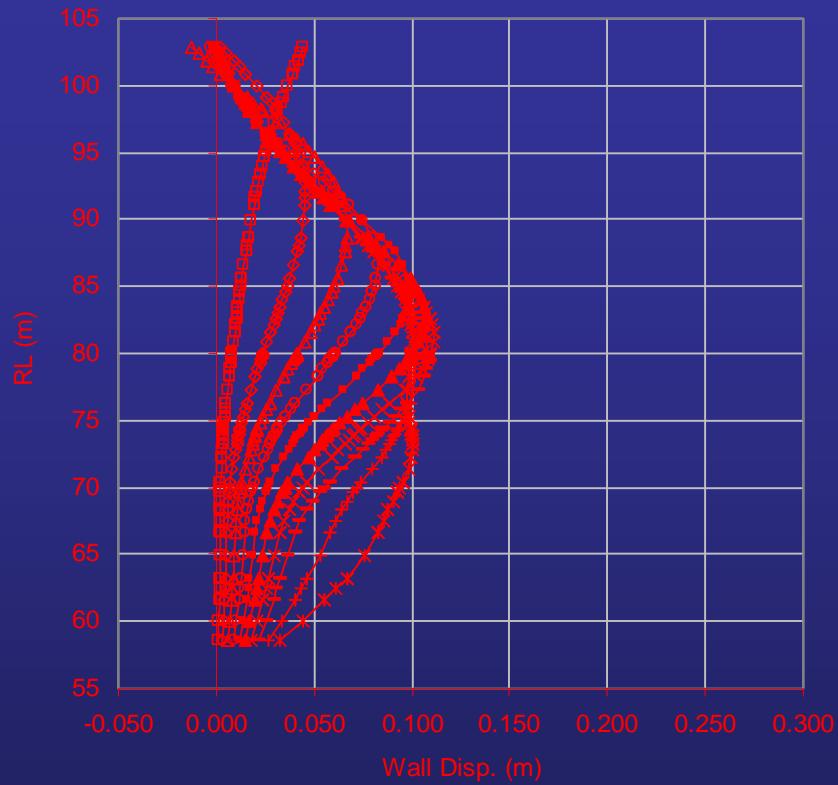
*Methods A and B*



*The shortcomings of Method A*



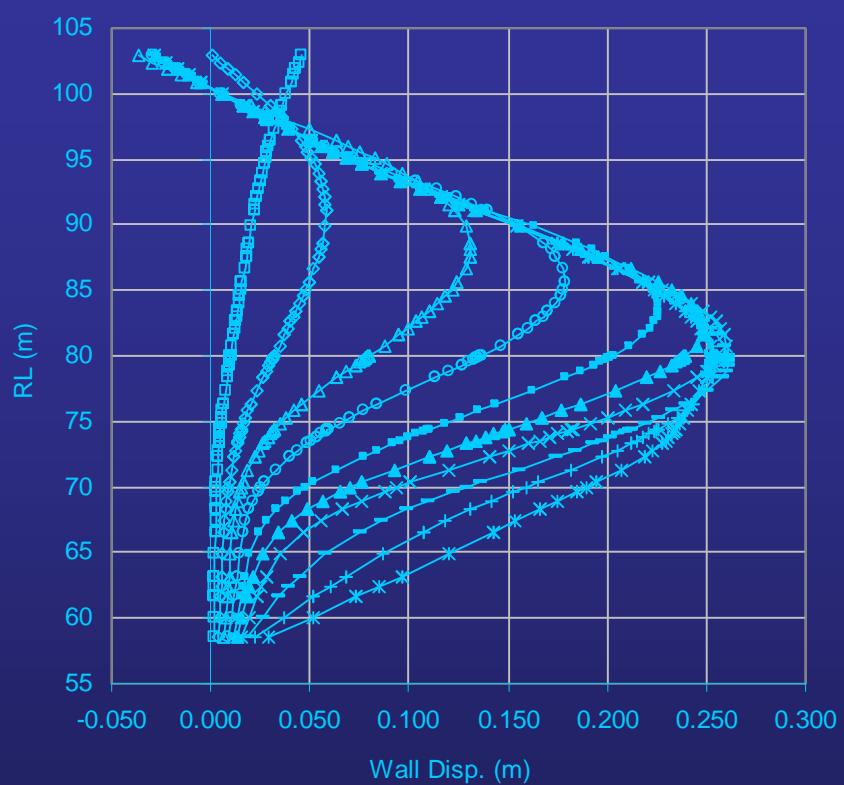
Method A



Legend for Method A:

- Exc to RL 100.9 for S1
- Exc to RL 98.1 for S2
- Exc to RL 94.6 for S3
- Exc to RL 91.1 for S4
- Exc to RL 87.6 for S5
- Exc to RL 84.6 for S6
- Exc to RL 81.6 for S7
- Exc to RL 78.3 for S8
- Exc to RL 75.3 for S9
- Exc to RL 72.3 for S10

Method B



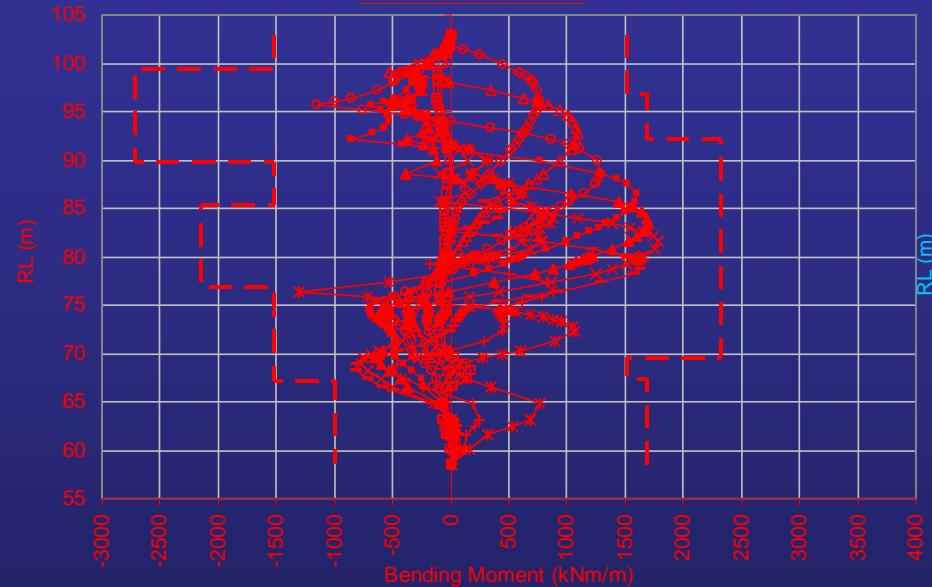
Legend for Method B:

- Exc to RL 100.9 for S1
- Exc to RL 98.1 for S2
- Exc to RL 94.6 for S3
- Exc to RL 91.1 for S4
- Exc to RL 87.6 for S5
- Exc to RL 84.6 for S6
- Exc to RL 81.6 for S7
- Exc to RL 78.3 for S8
- Exc to RL 75.3 for S9
- Exc to RL 72.3 for S10

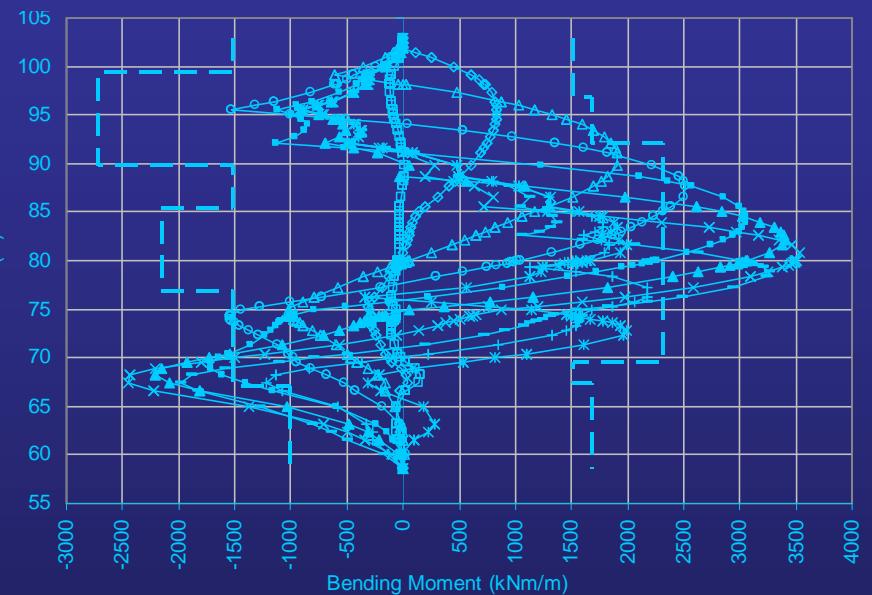
*M3 - South Wall Displacement  
Method A versus Method B*



**Method A**



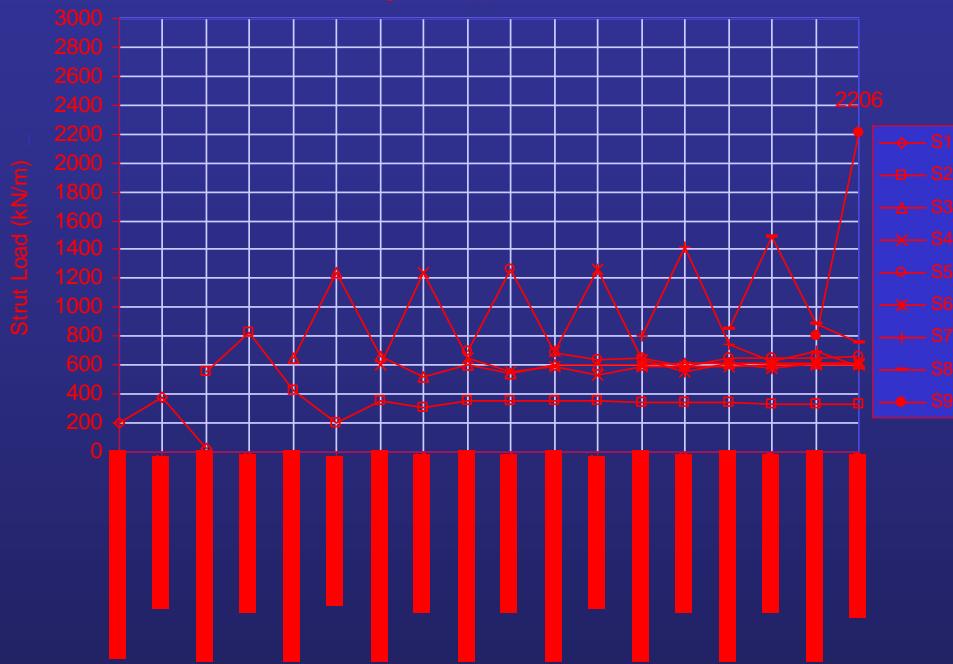
**Method B**



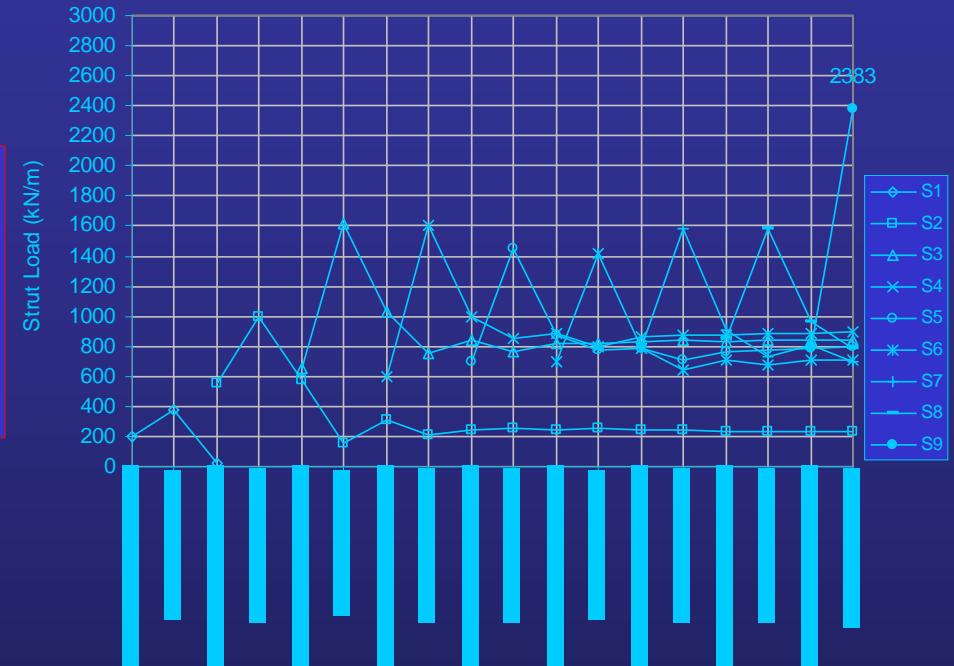
*M3 - South Wall bending moments  
Method A versus Method B*



Method A



Method B



*M3 – strut forces*  
*Method A versus Method B*



- Method A over-estimates the undrained shear strength of normally and lightly overconsolidated clays
- Its use led to a 50% under-estimate of wall displacements and of bending moments and an under-estimate of the 9<sup>th</sup> level strut force of 10%
- The larger than predicted displacements mobilised the capacity of the JGP layers at an earlier stage than predicted

*Method A*



- Structural design errors
- Removal of splays at some strut locations
- Introduction of C-channel waler connection detail
- Use of Method A in soil-structure interaction analysis
- Collapse was an inevitable consequence of the design errors which led to the applied loads on the struts increasing with time and equalling the capacity of the strut-waler connection

*COI view on the principal causes of  
the collapse*



- Structural design errors
- Removal of splays at some strut locations
- Introduction of C-channel waler connection detail
- Use of Method A in soil-structure interaction analysis
- Collapse was an inevitable consequence of the design errors which led to the applied loads on the struts increasing with time and equalling the capacity of the strut-waler connection

*COI view on the principal causes of  
the collapse*

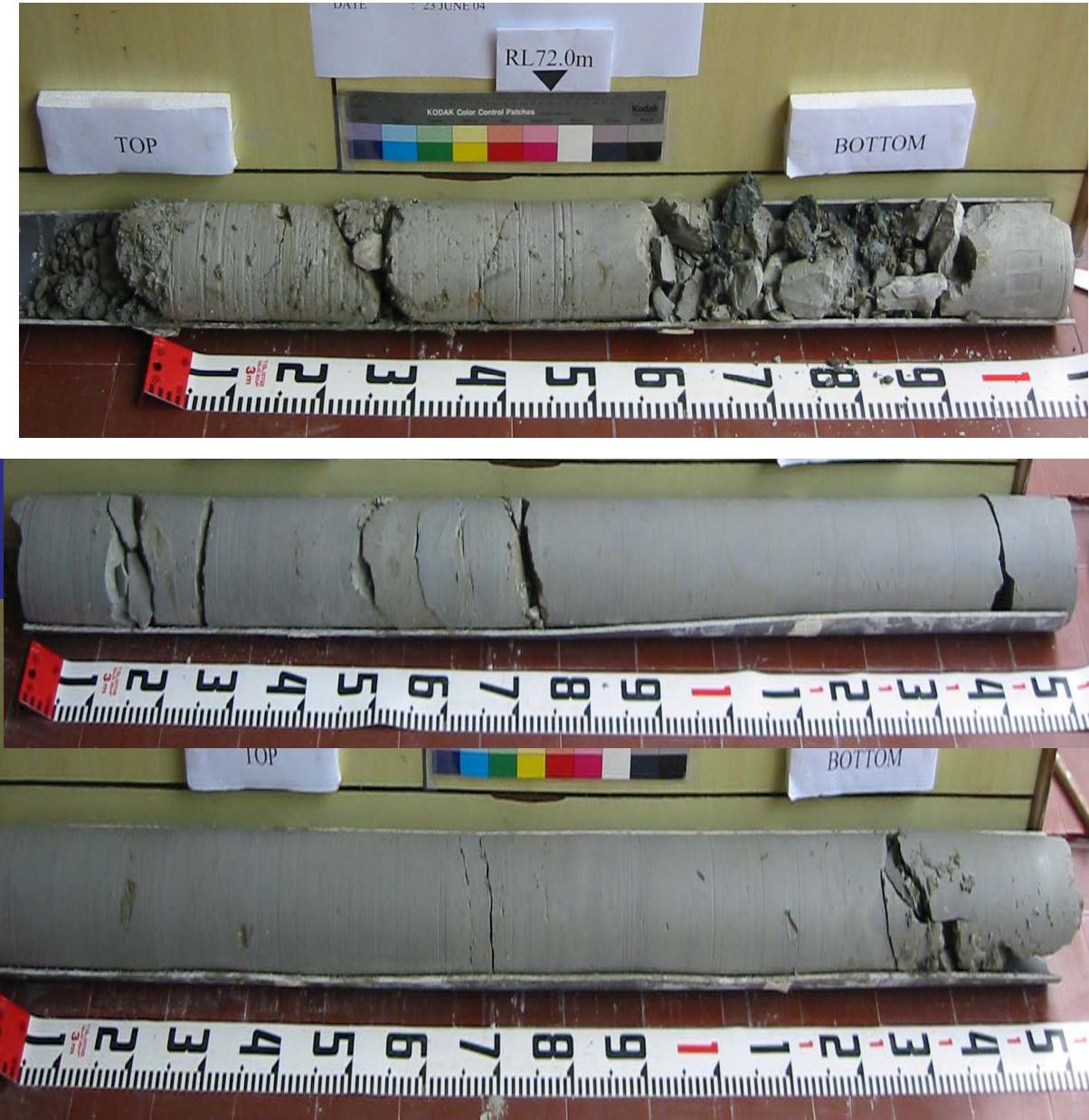


*Post-collapse investigations*

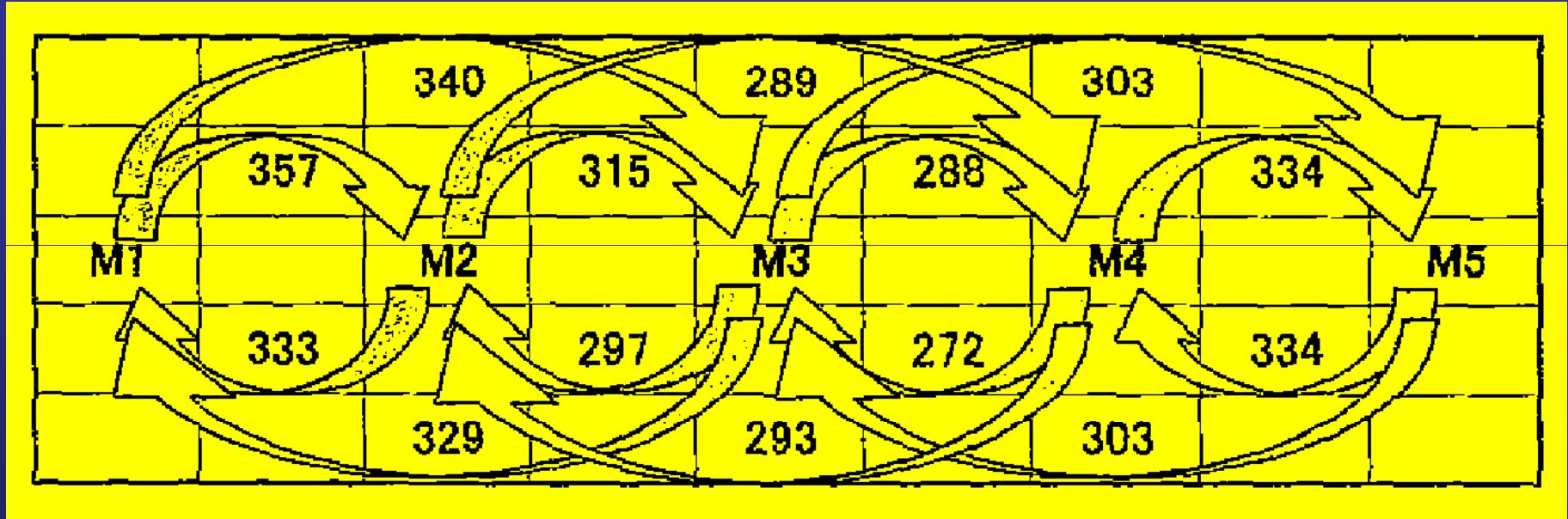
Jet grout



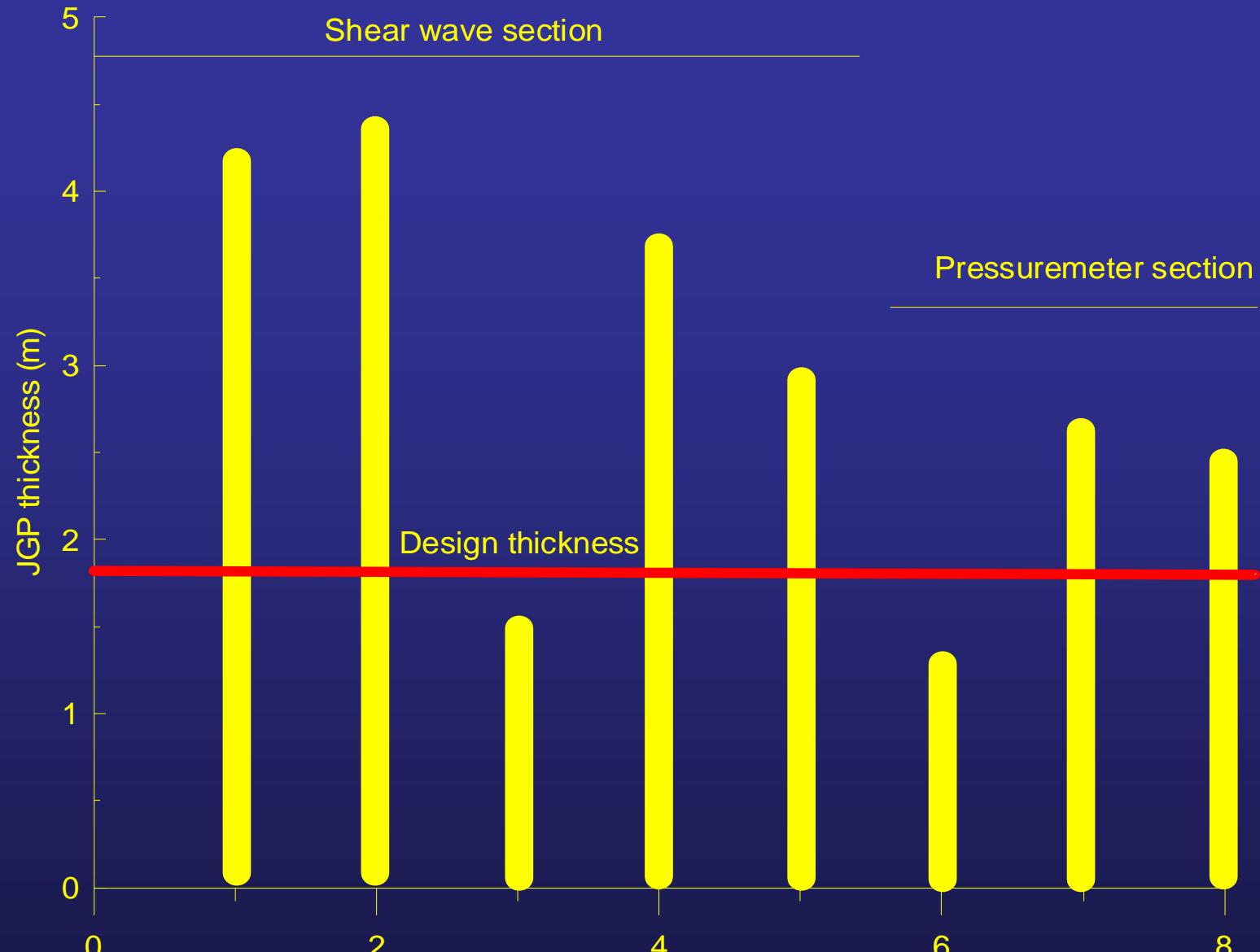
*Excavation of sacrificial JGP in Type H*



*JGP quality in 100mm cores from borehole M1 in Type K*



*Shear wave velocity measurements in JGP at Type K*



*Thicknesses of JGP in Type K*

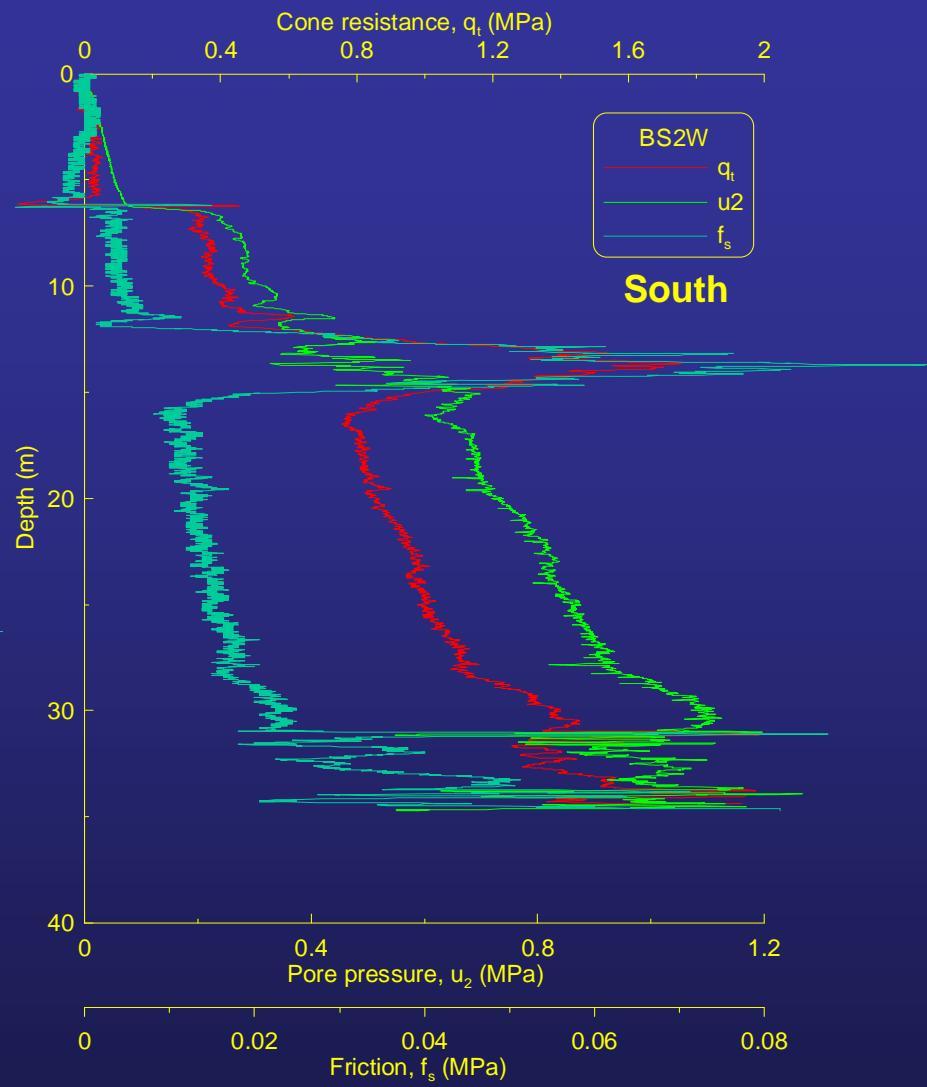
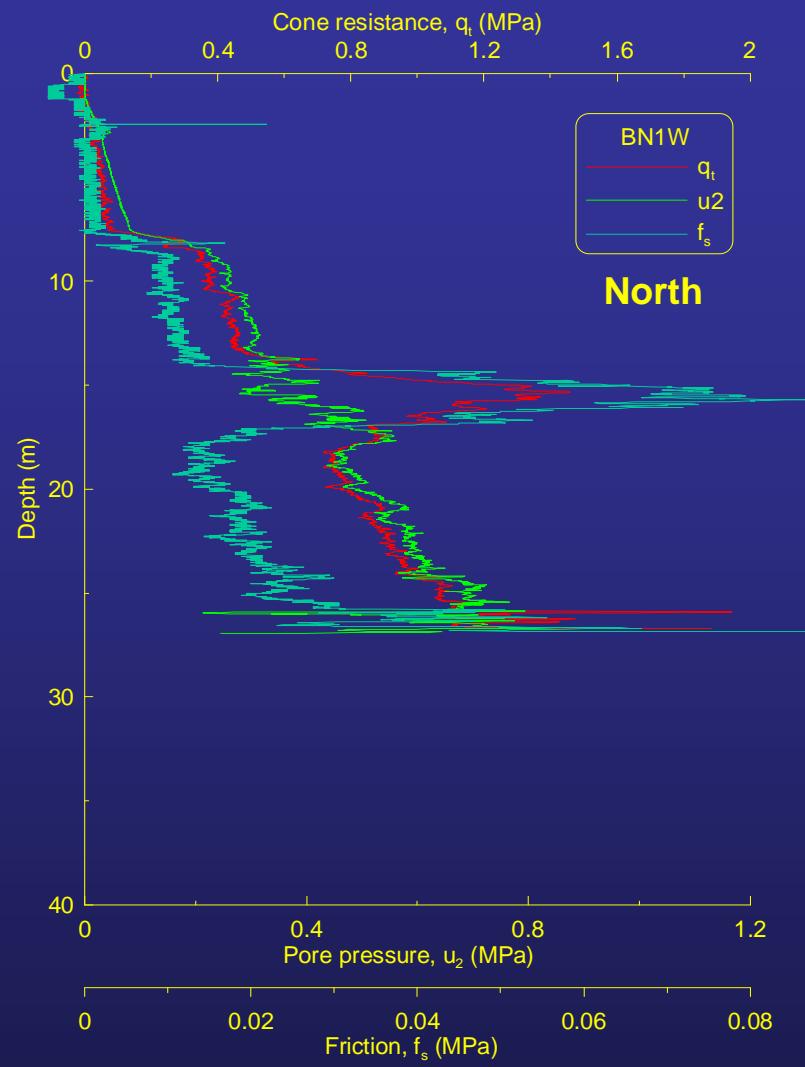


*Post-collapse investigations*

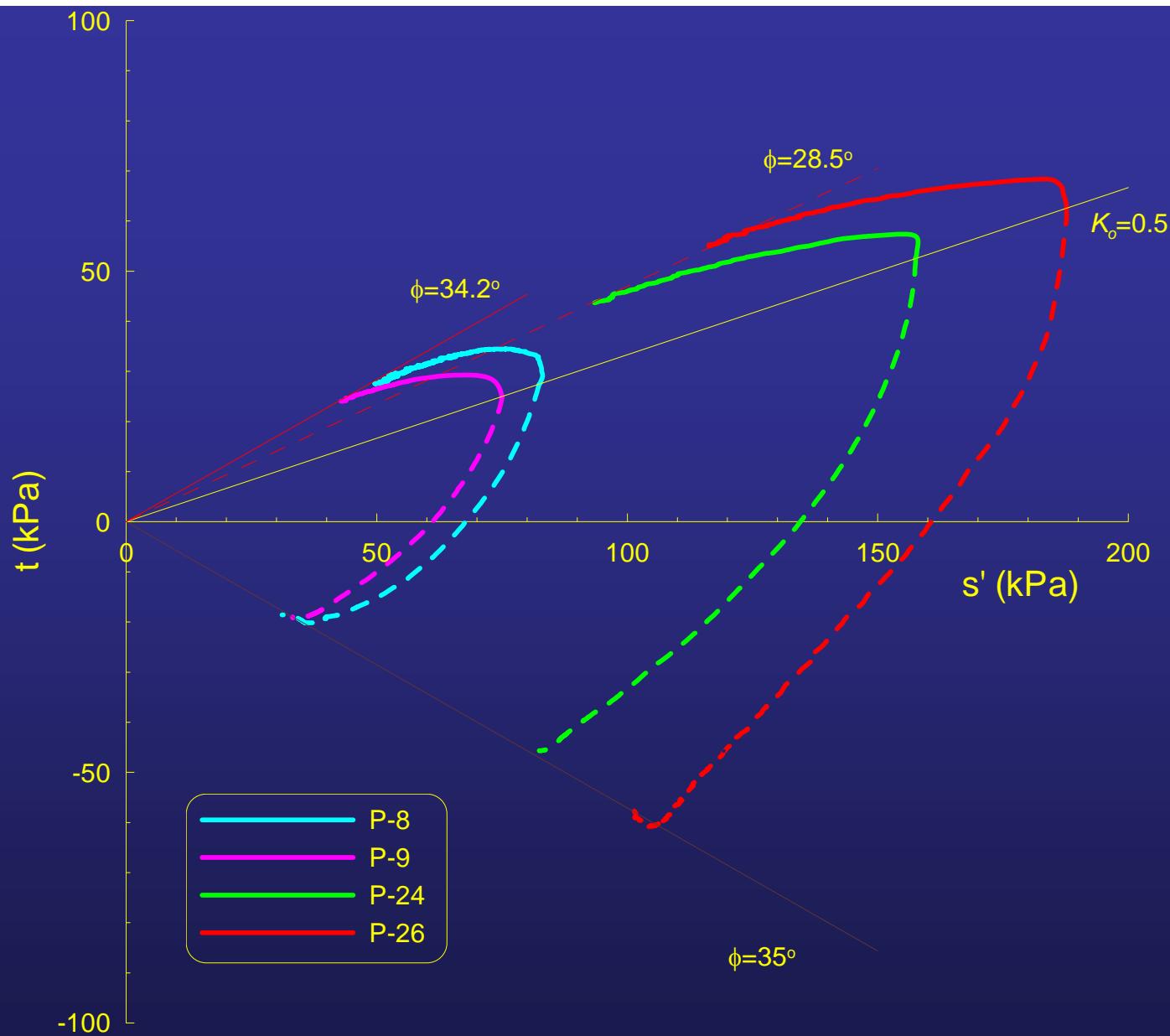
Ground conditions and  
soil properties



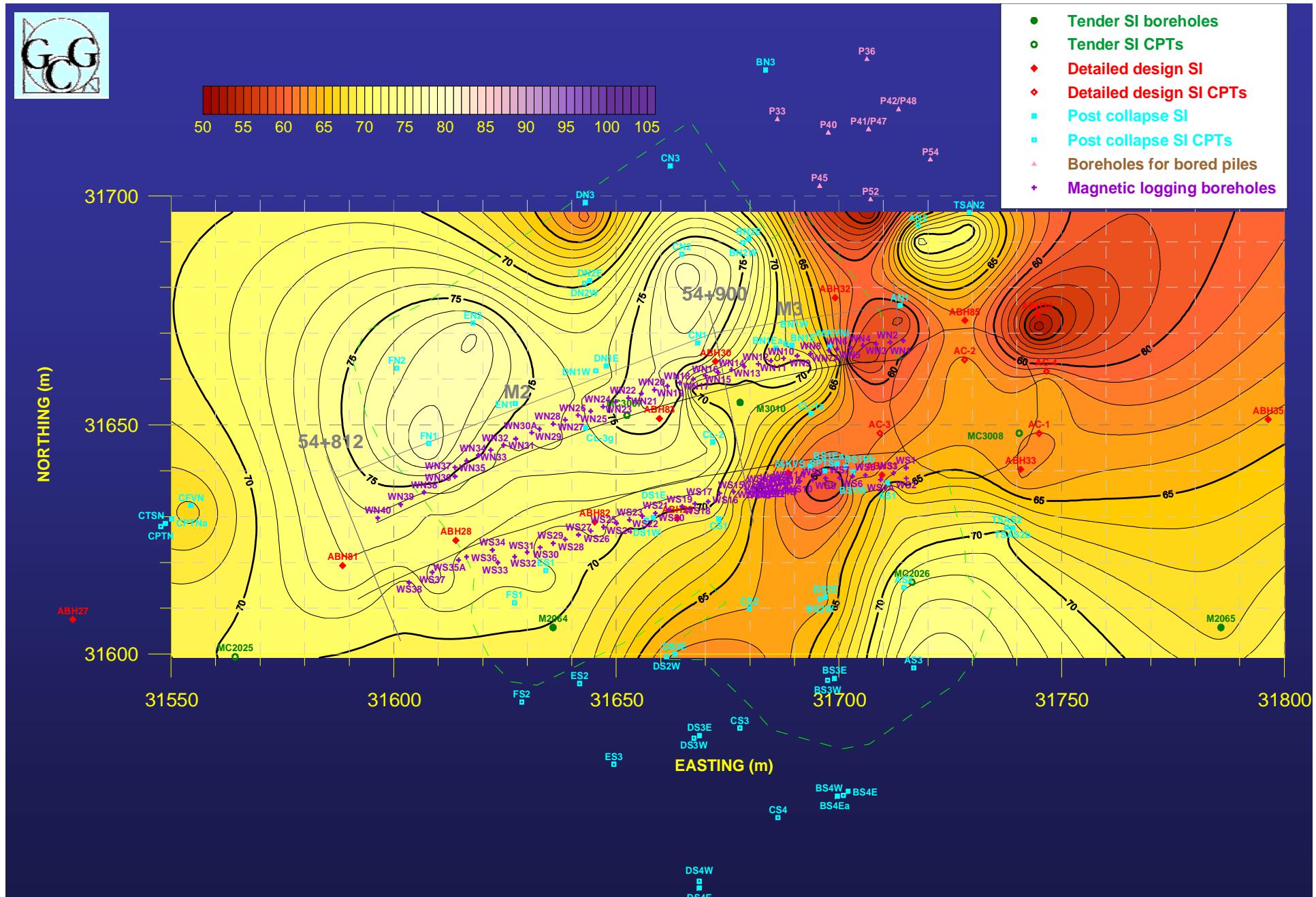
# *Post-collapse ground investigation*



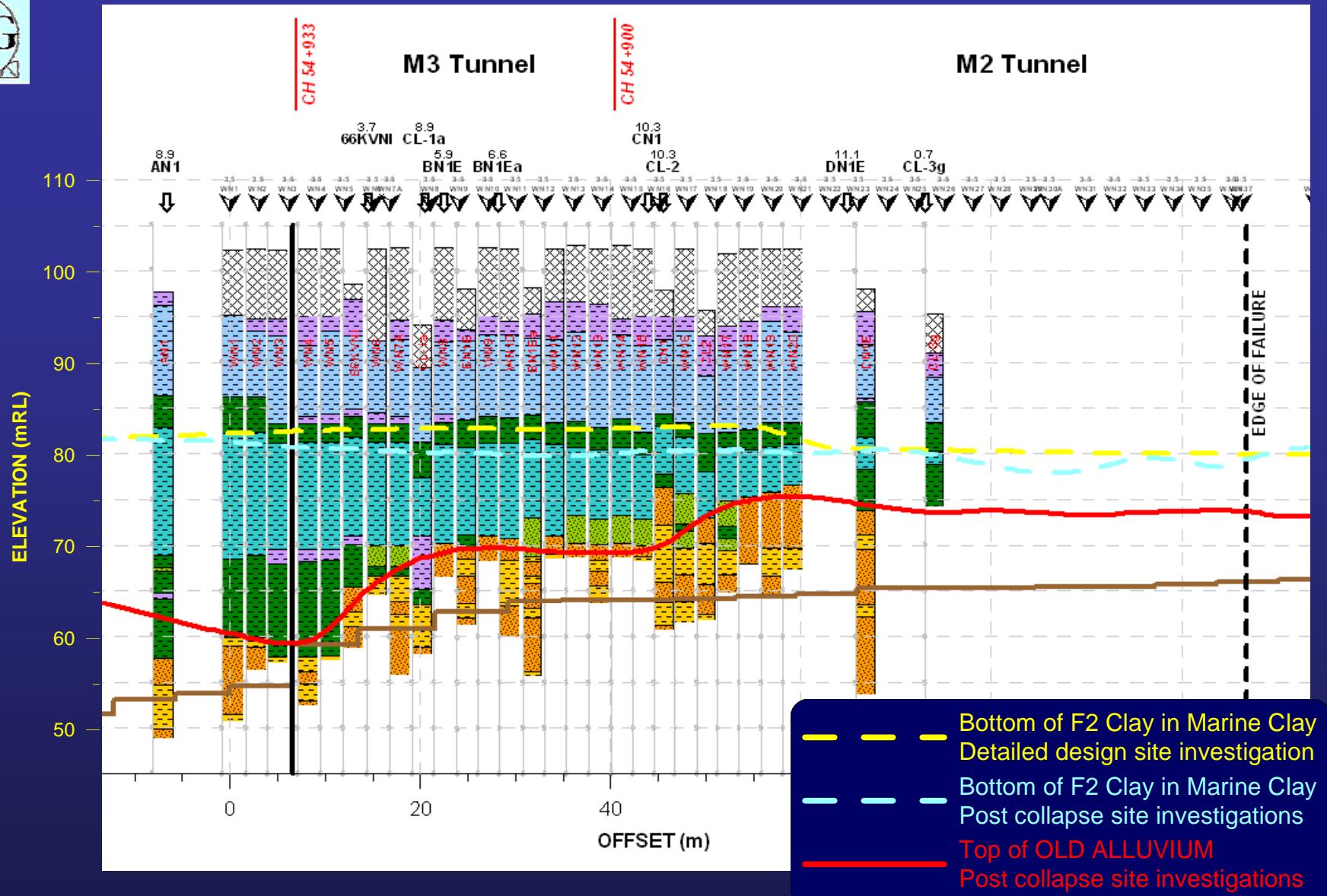
*CPT profiles north and south of collapse area*



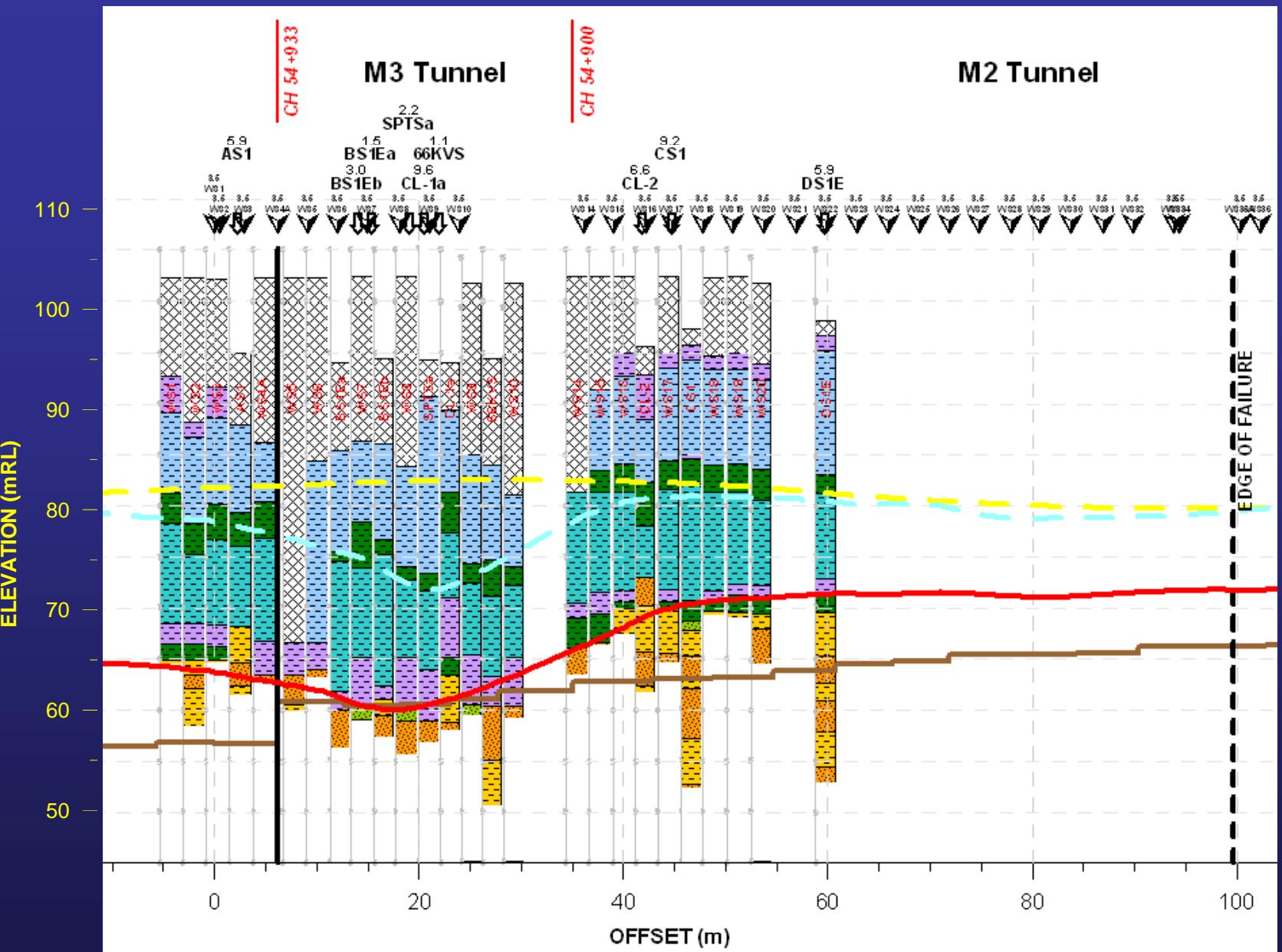
*Kisojiban's CAU tests on  
Upper and Lower Marine Clay*



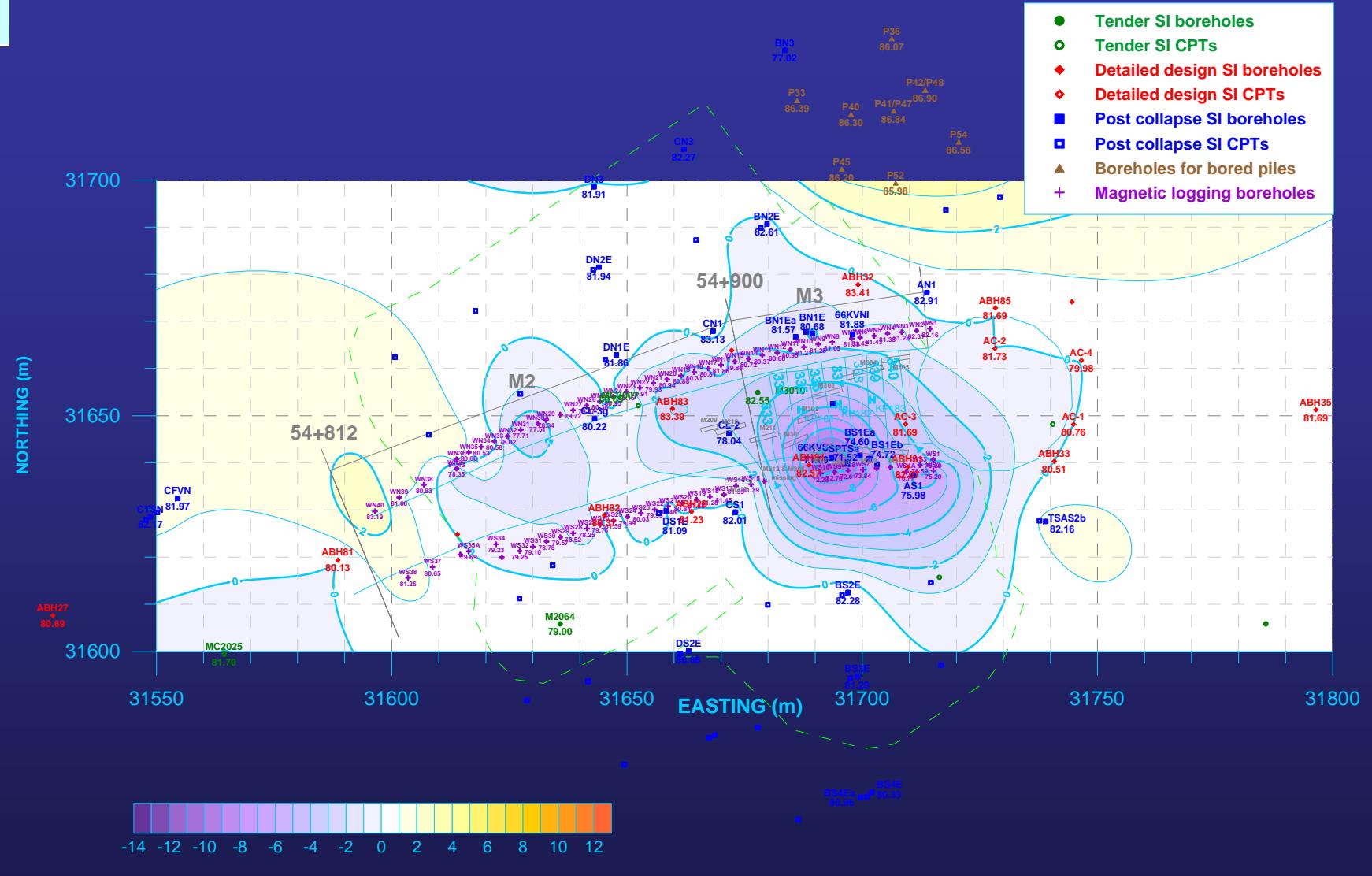
# *Evidence for a buried valley in the Old Alluvium*

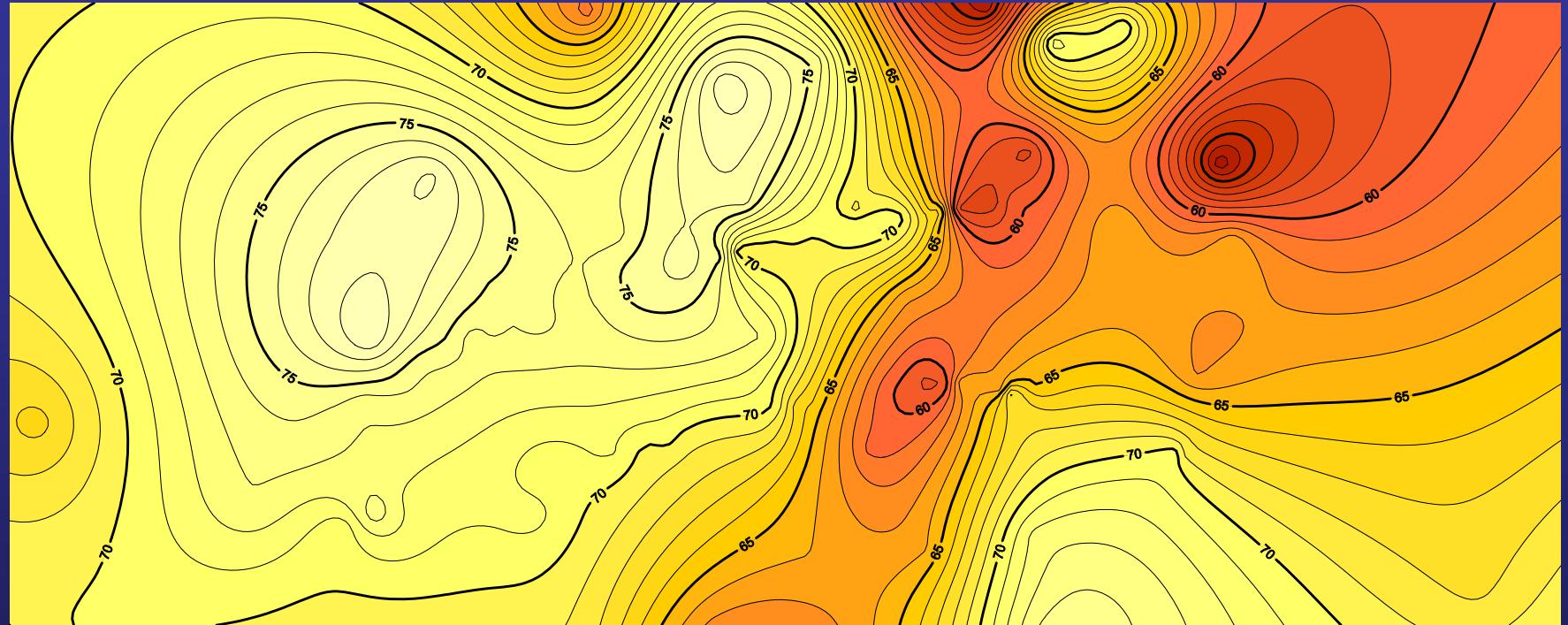


*Section along north wall*

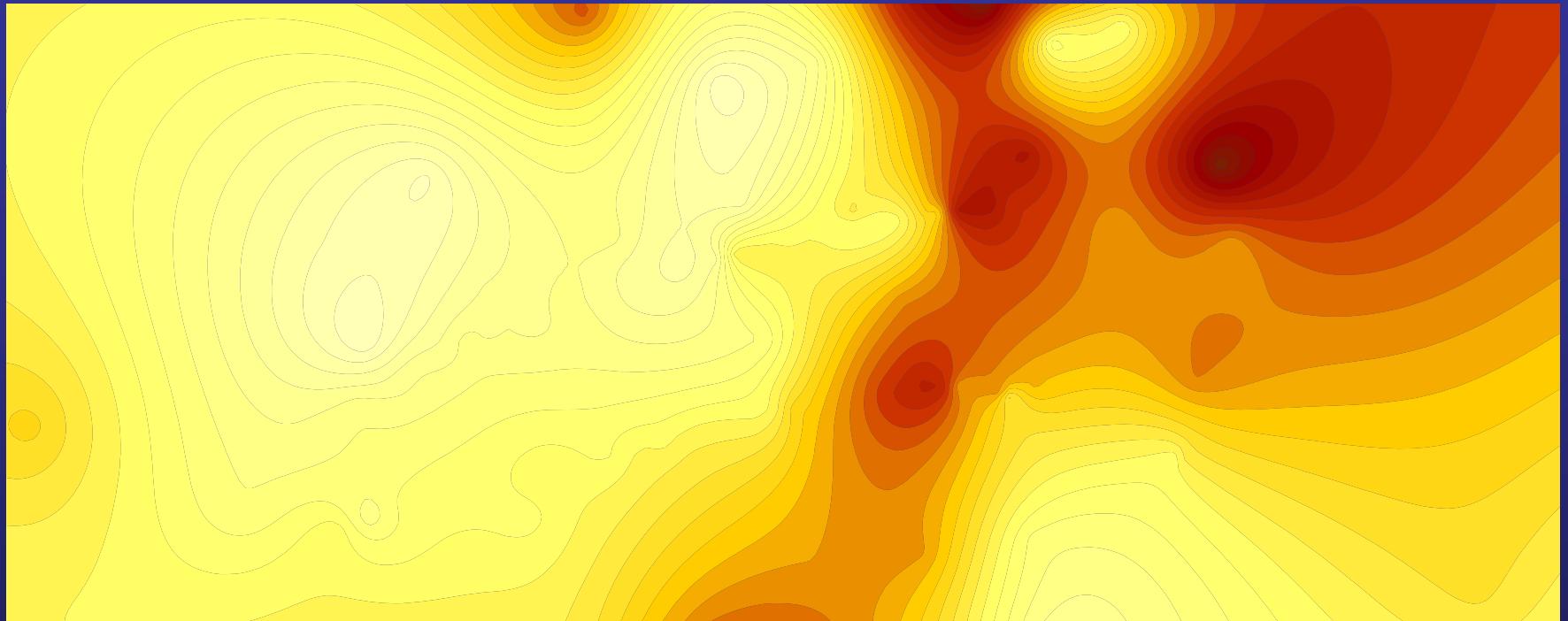


## *Section along south wall*

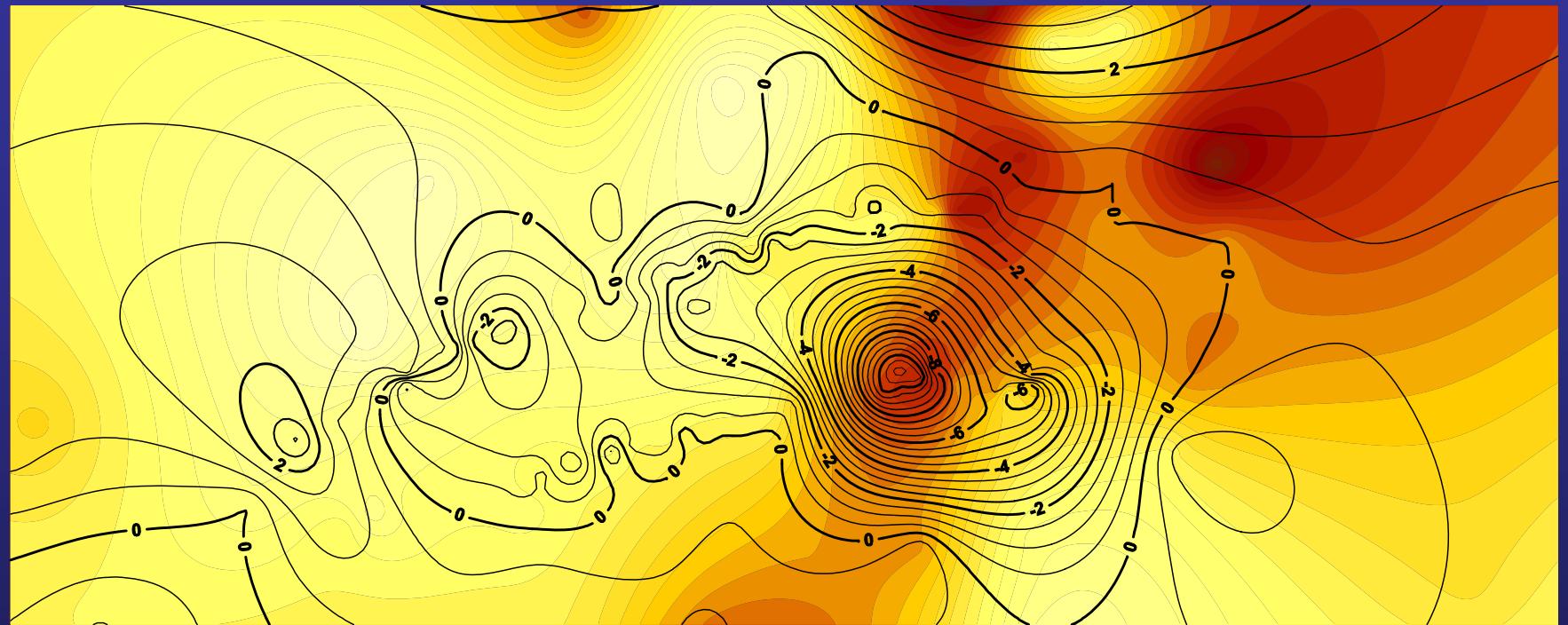




*Buried valley in the Old Alluvium*



*Buried valley in the Old Alluvium*

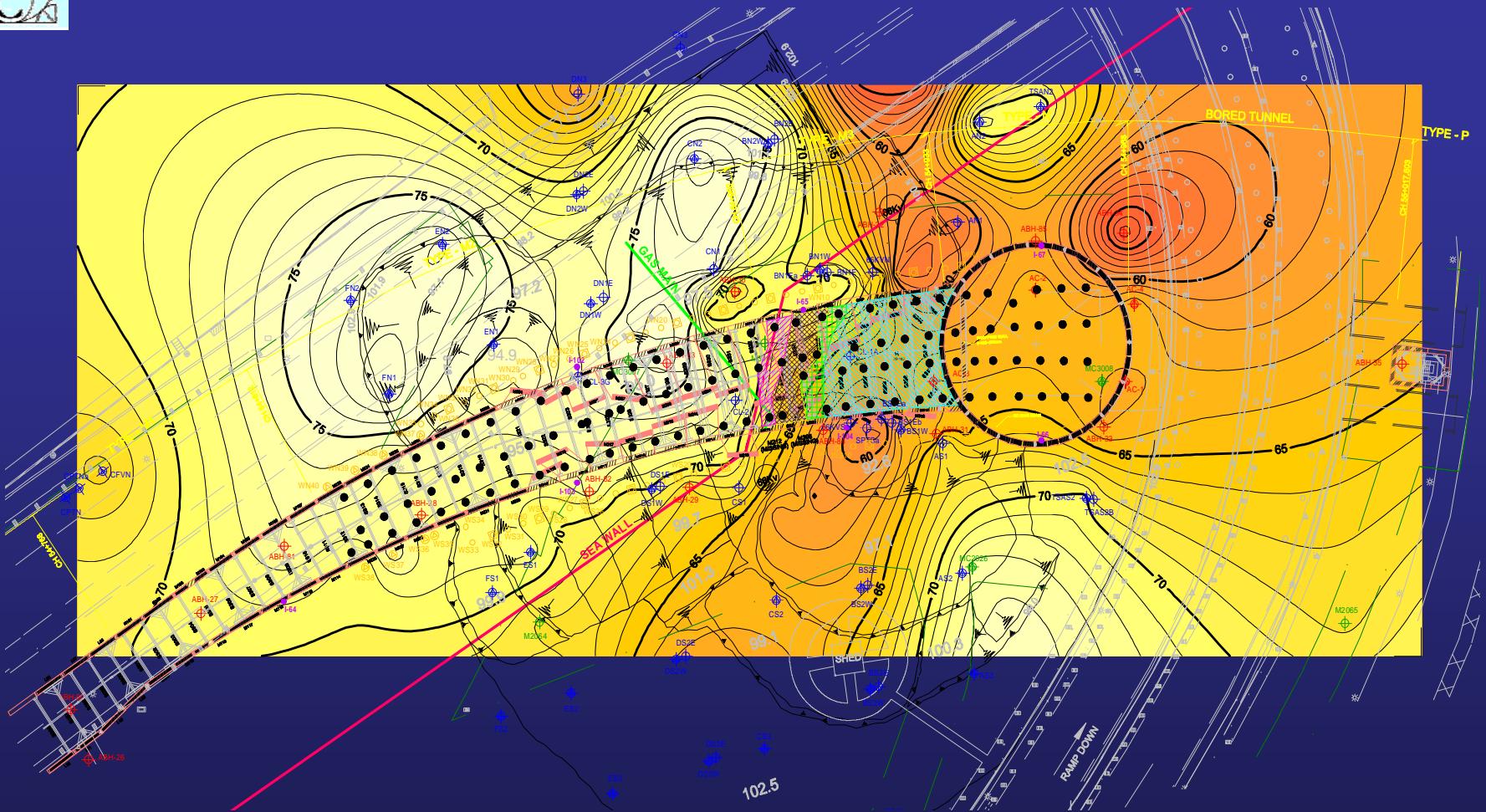


*Coincidence between buried valley and  
distortion to upper F2 layer*

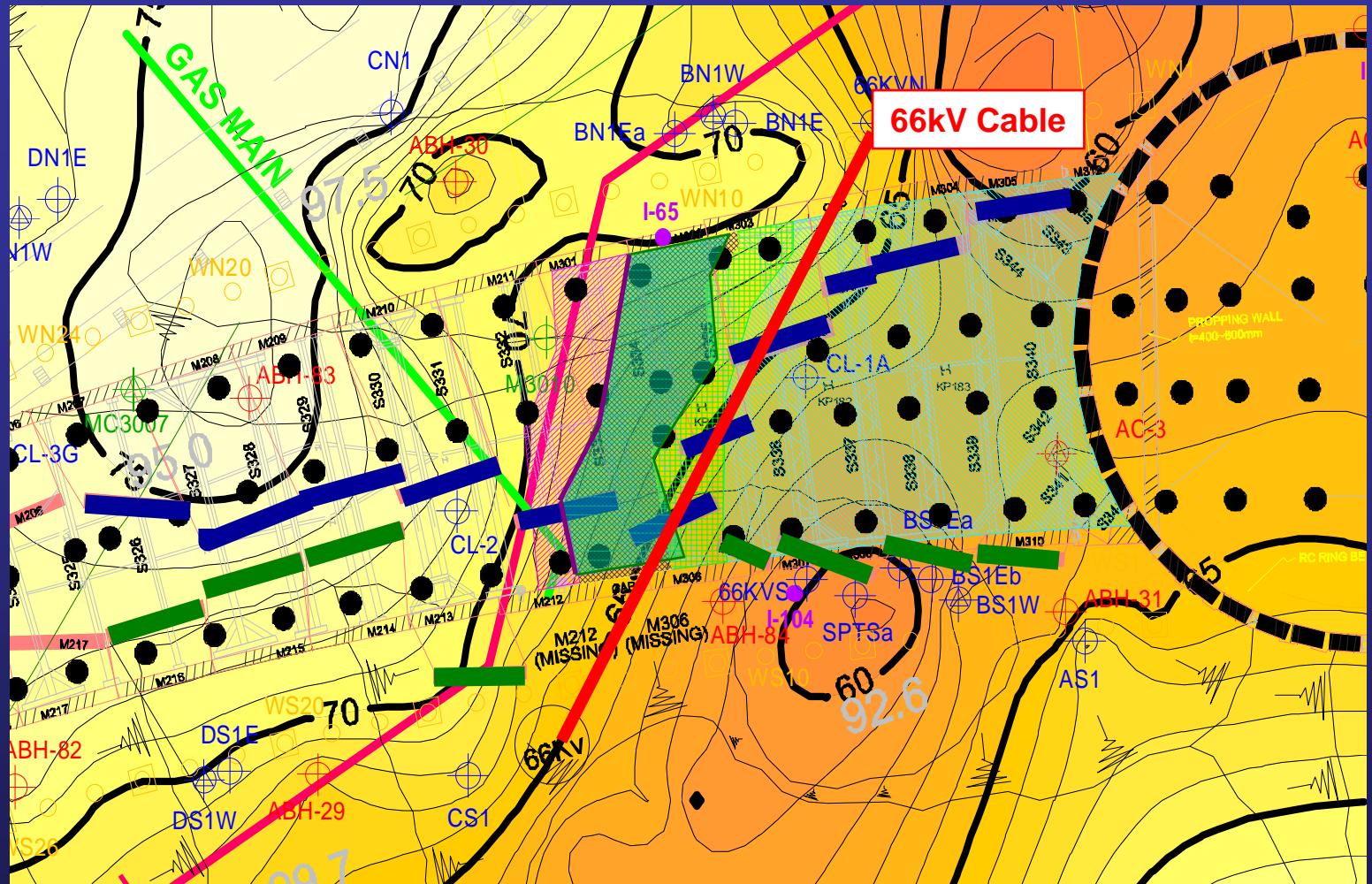


- There was a buried valley crossing the site of the collapse diagonally from south-west to north-east
- The presence and setting of the buried valley explain the asymmetric conditions and the different collapse on the north and south sides
- The buried valley coincides with the major ground distortion on the south side and was clearly influential in the collapse
- Below the Lower Marine Clay the buried valley was infilled with estuarine organic clays on the south side and fluvial clays on the north side
- Gas exsolution almost certainly occurred in the deep organic clays as a result of stress relief, reducing their strength further

*The buried valley*



# *Post-collapse geometry and sequence of excavation superimposed on buried valley*



## *Sequence of excavation in relation to buried valley*



- The buried valley was crossed without collapse developing
- Strut forces would have been a maximum in the buried valley and would have varied across the valley
- The collapse was not, therefore, inevitable
- An external influence (trigger) is required to explain the timing of the collapse and why it occurred after crossing the buried valley

*Significance of crossing the buried valley without collapse*



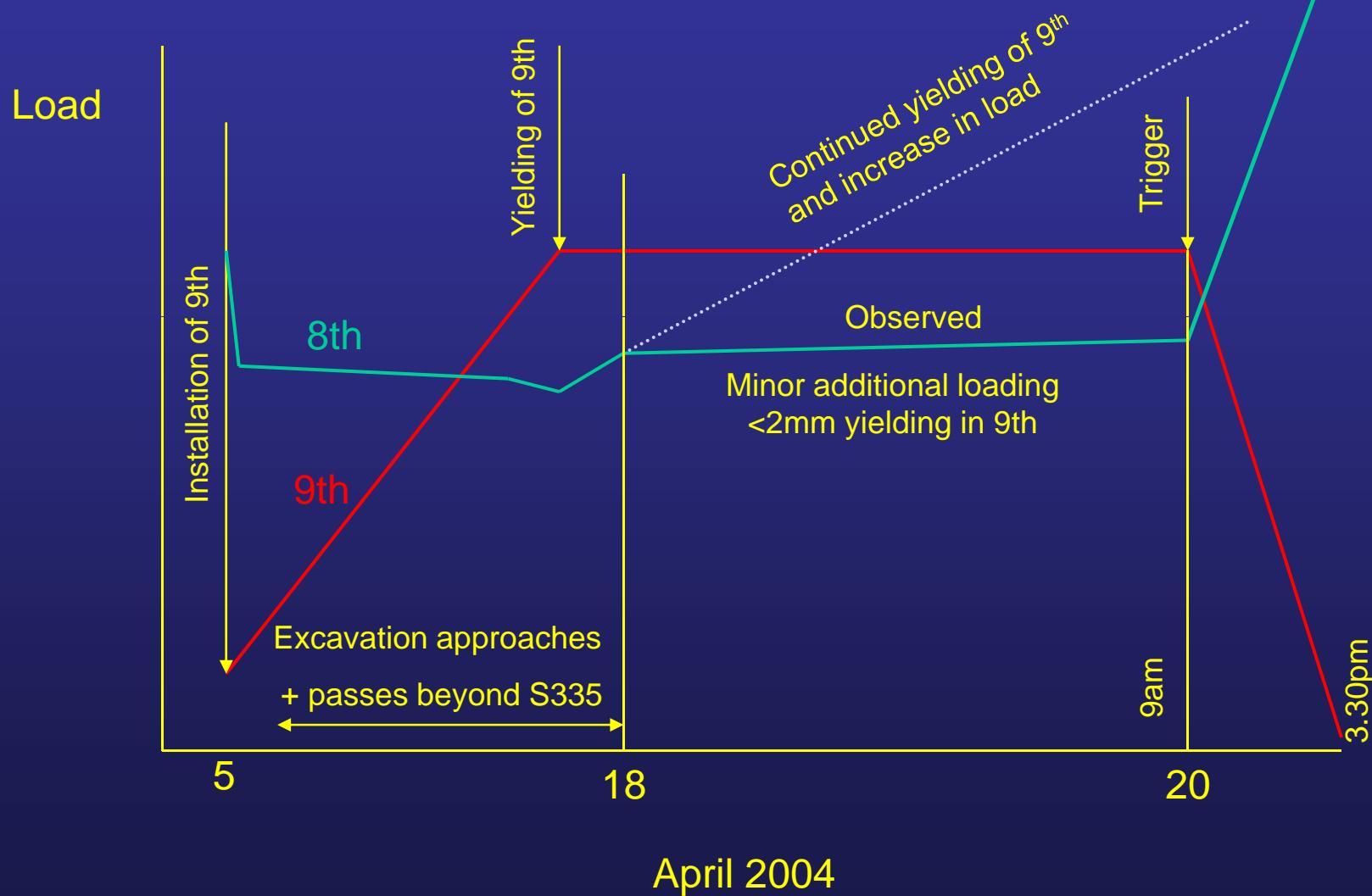
- S338-9 stood for 8 days under load and was 20m from excavation front
- S335-9 stood for 2.5 days under load and was over 8m from excavation front
- Both S335-9S & S338-9N buckled within 10 minutes
- Load in S335-8 and S335-9 was almost constant between 18 April and initiation of collapse
- All C-channel connections failed downwards at both ends
- The south wall was pushing the north wall back

*Key observations*



- 3D effects cannot explain why the collapse was initiated at 9am – S338 was 20-24m from the excavation face and had stood for 8 days without distress, S335 was 8-12m from the excavation face
- Time effects cannot explain why the collapse was initiated at 9am – there was no evidence of load increases in the monitoring

*Potential triggers*





*Post-collapse investigations*

Back analyses of the collapse



- Analyses by Dr Felix Schroeder and Dr Zeljko Cabarkapa using Imperial College Finite Element Program (ICFEP)
- 2D section through M307 (I104) and M302 (I65)
- Bored piles are not modelled (enhanced JGP)
- Upper and Lower Marine Clays, F2 and lower Estuarine Clay modelled using Modified Cam Clay
- Coupled consolidation
- Fill and OA sand modelled using Mohr Coulomb. OA-CZ clay/silt modelled as Tresca

*Geotechnical analyses*



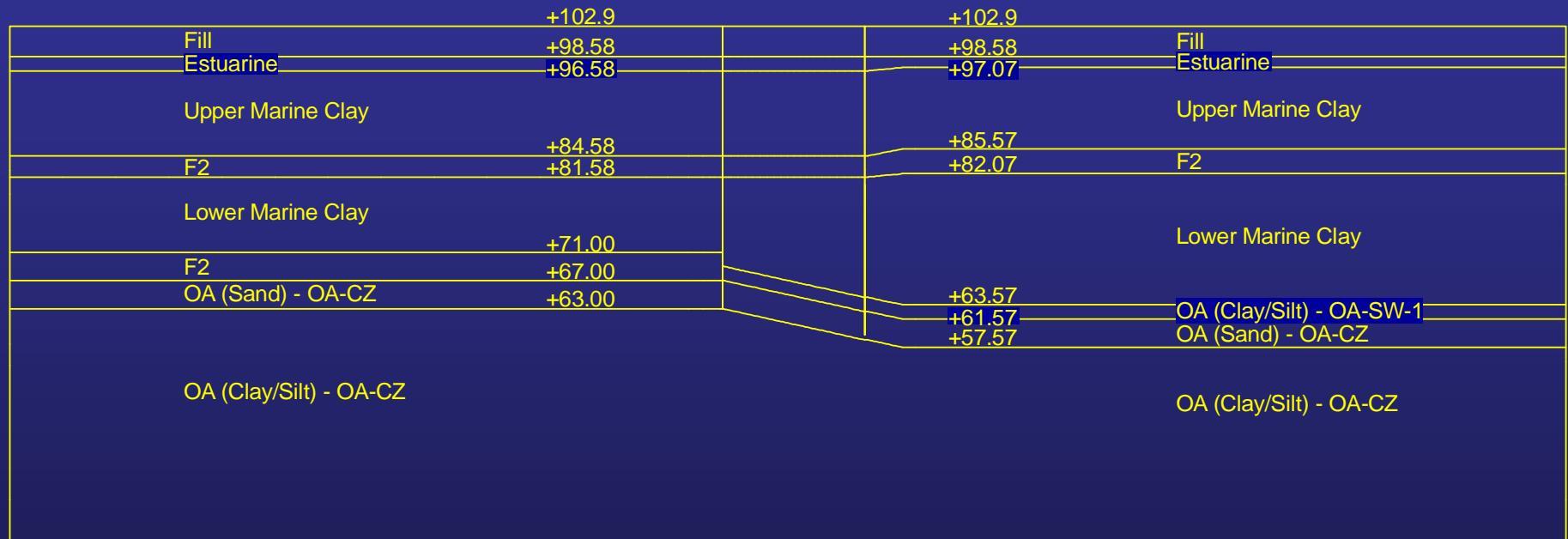
- Wall EI reduced to allow for cracking, based on reinforcement layout
- Bending moment capacities set according to reinforcement layout and ultimate strengths of steel and concrete as supplied
- JGP treated as brittle material
- 9<sup>th</sup> level strut capacity set and strut allowed to strain soften 72 hours after excavation to 10<sup>th</sup> level.

*Geotechnical analyses*

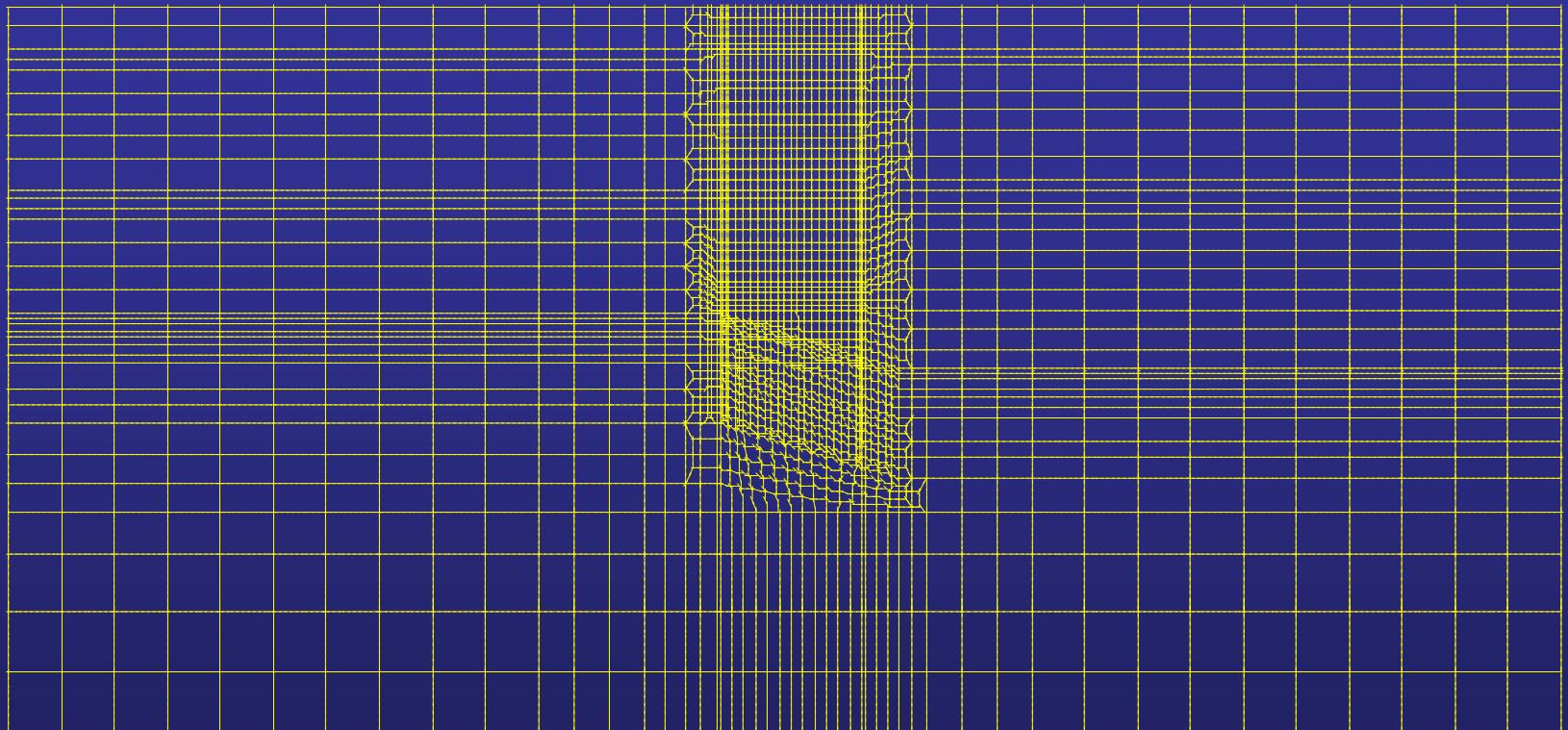


North

South



*Stratigraphy assumed for ICFEP analyses*

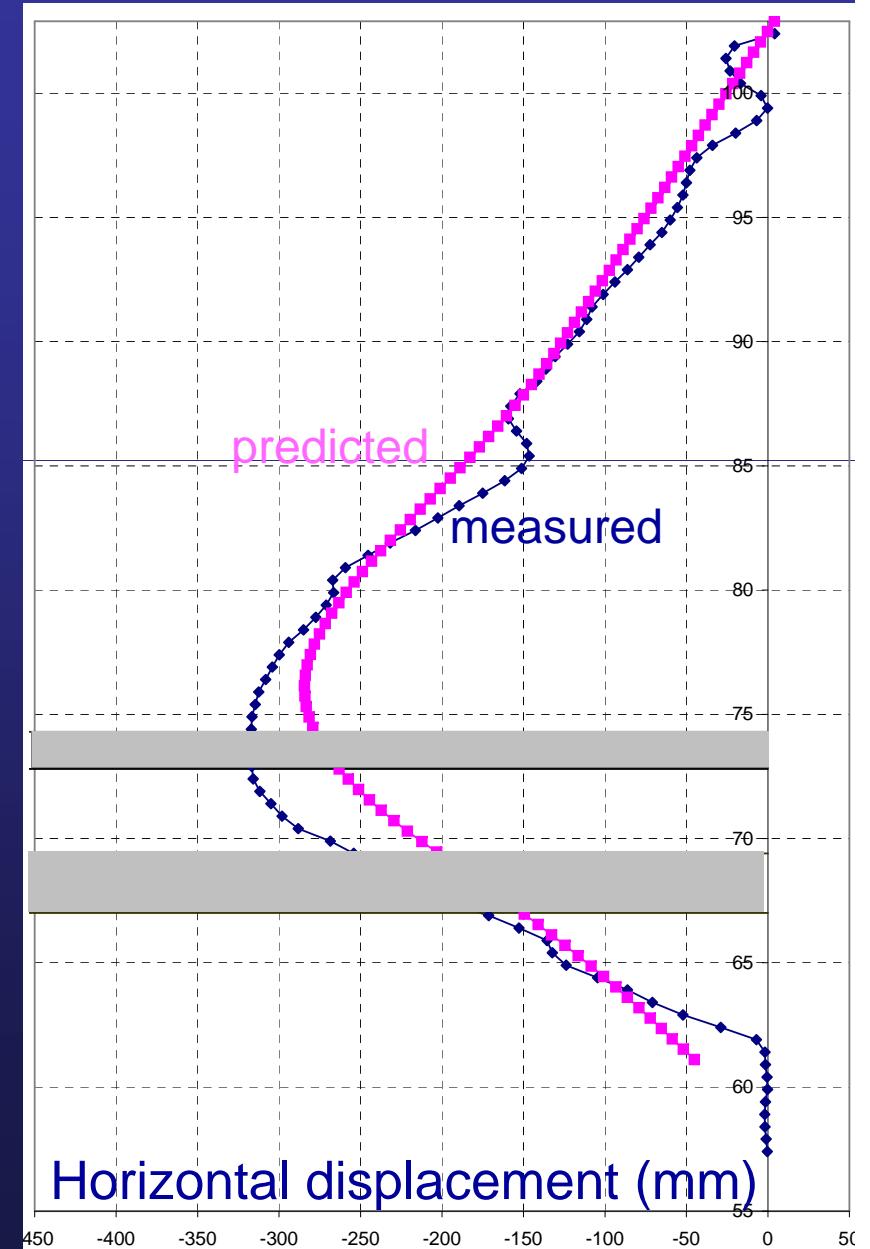
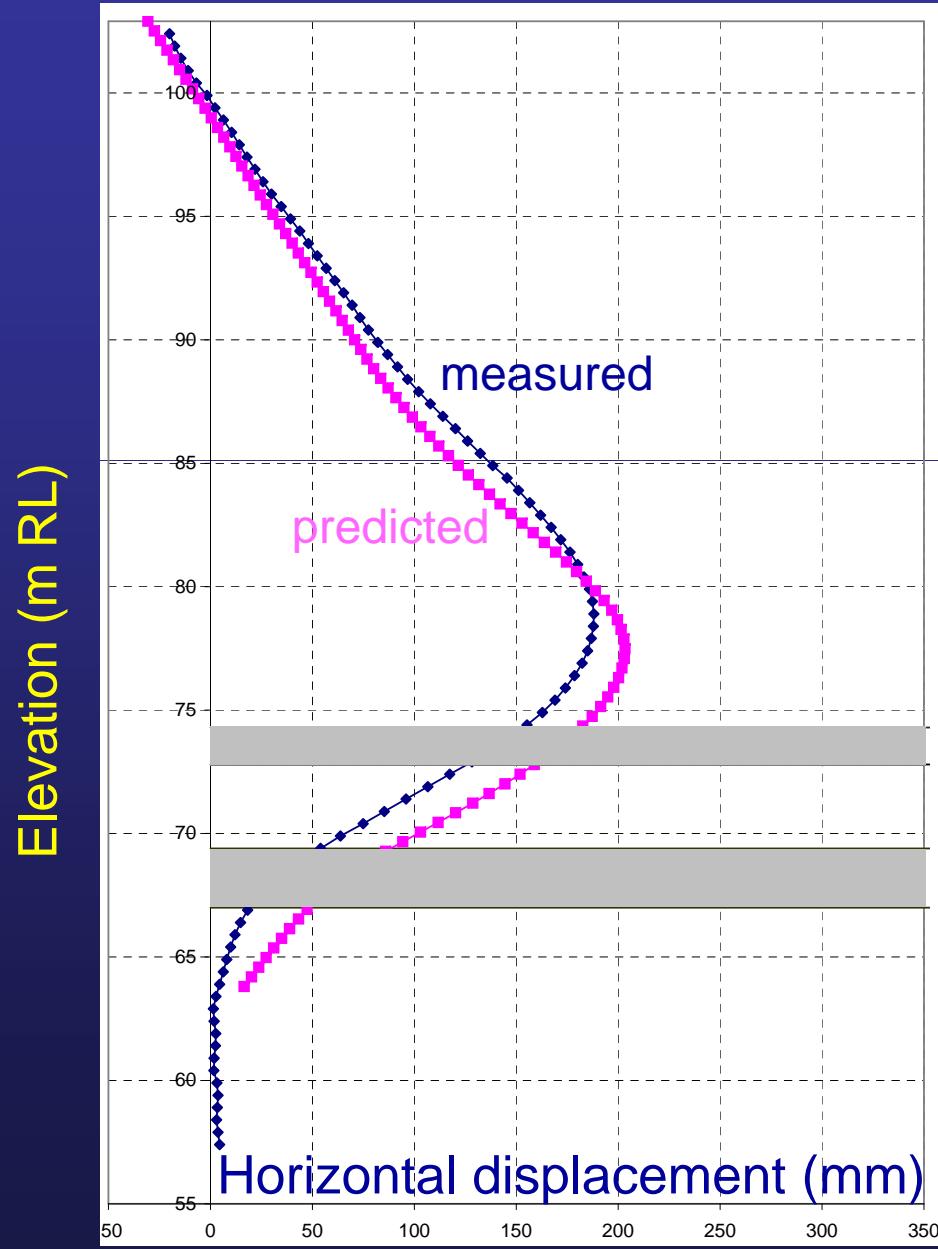




North wall

9th

South wall

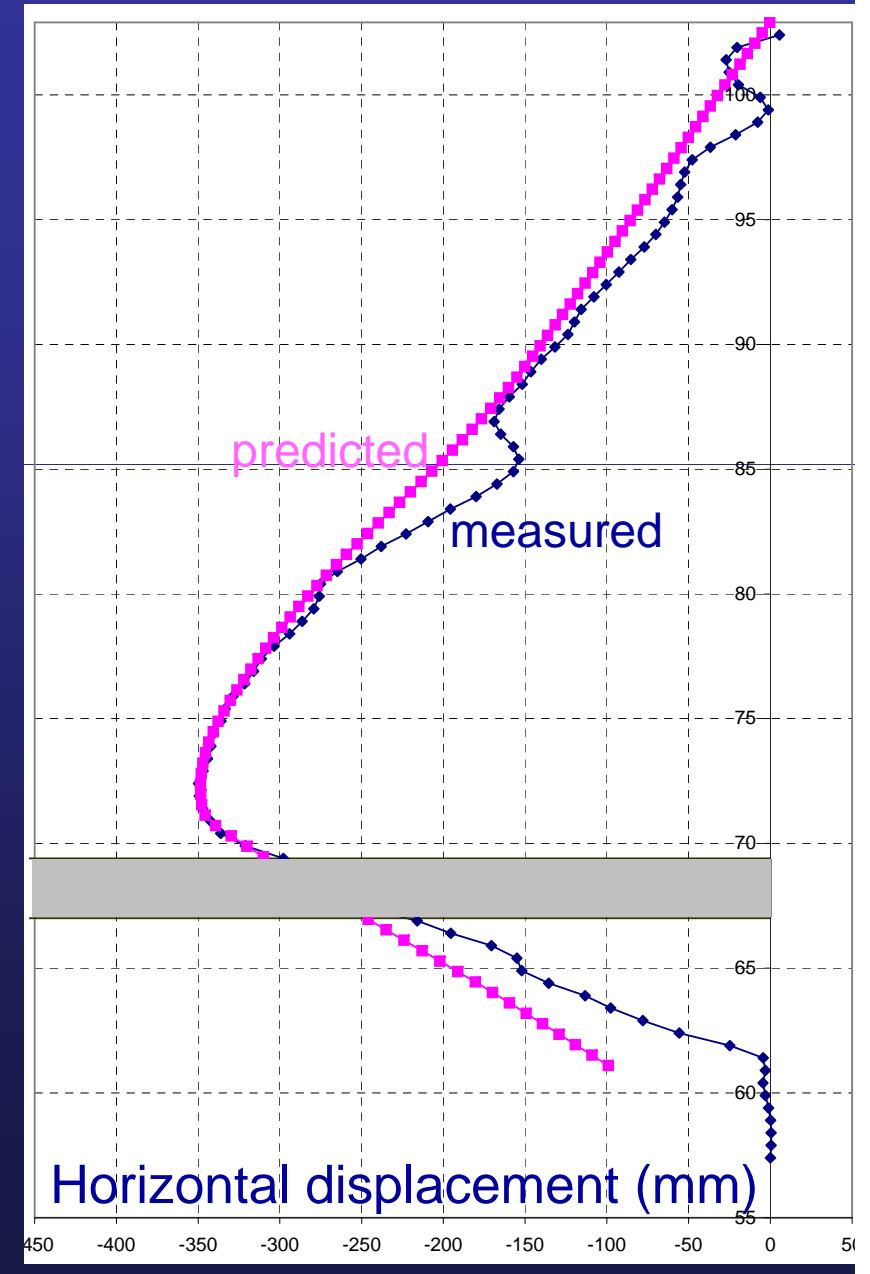
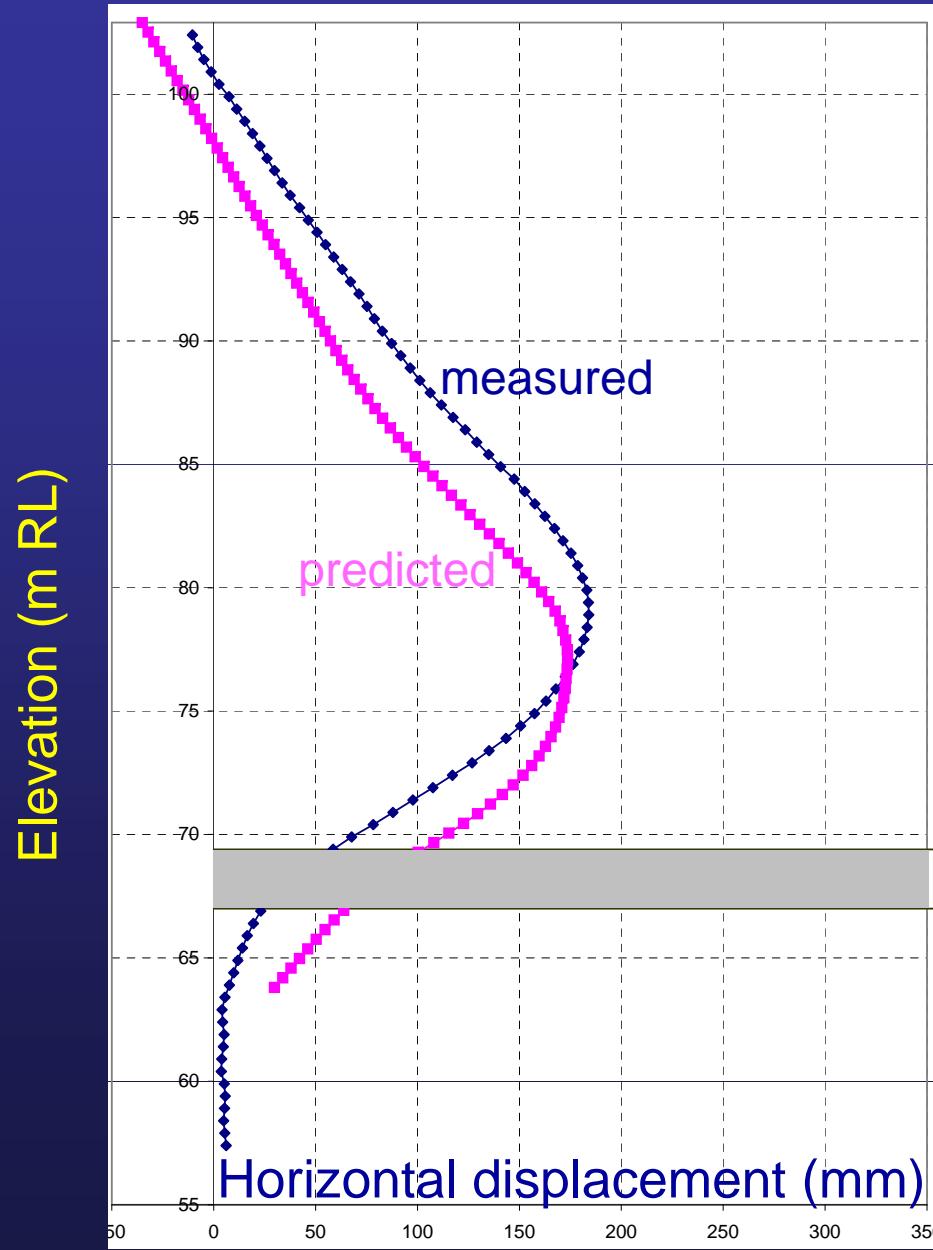




North wall

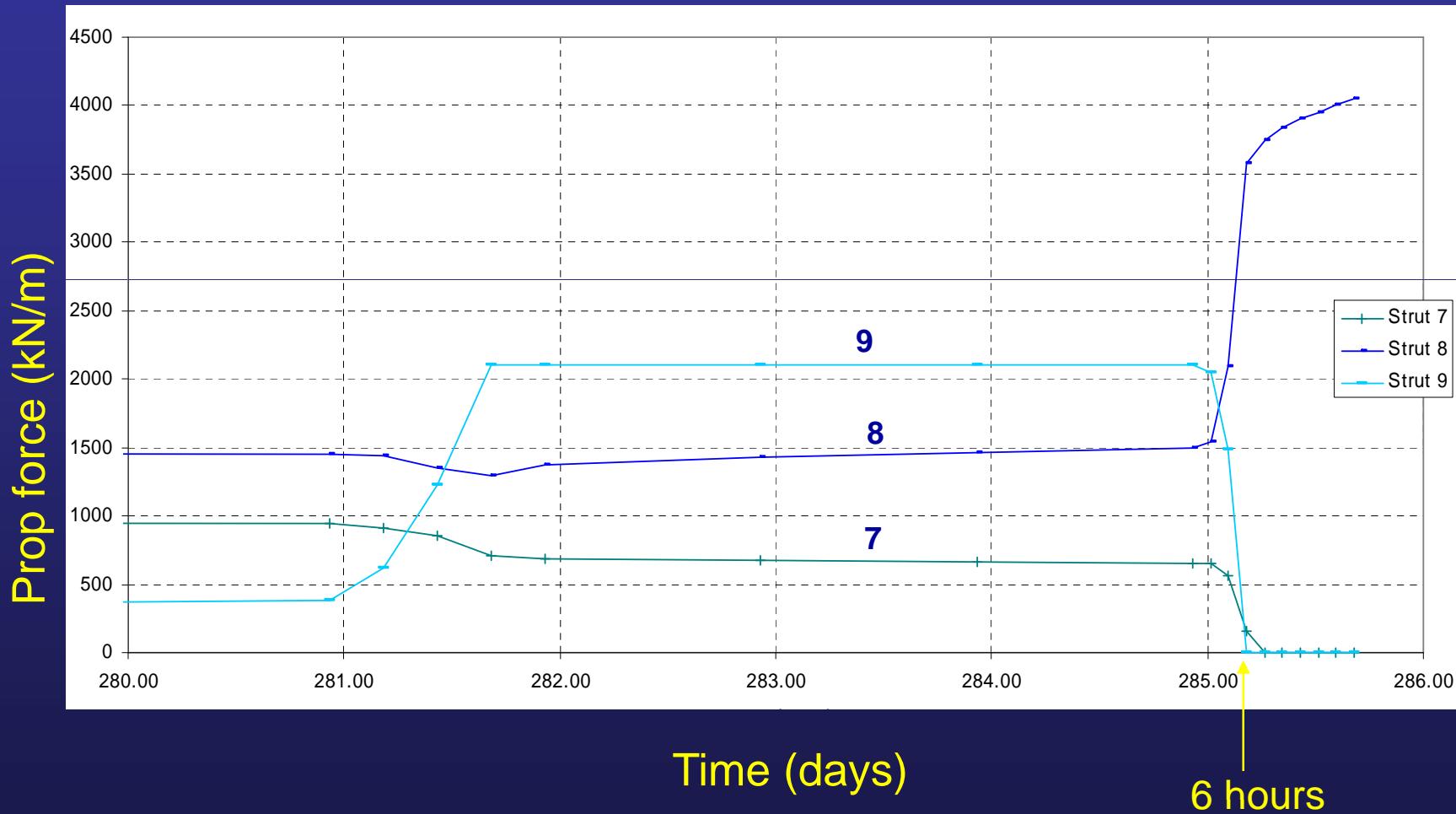
10th

South wall



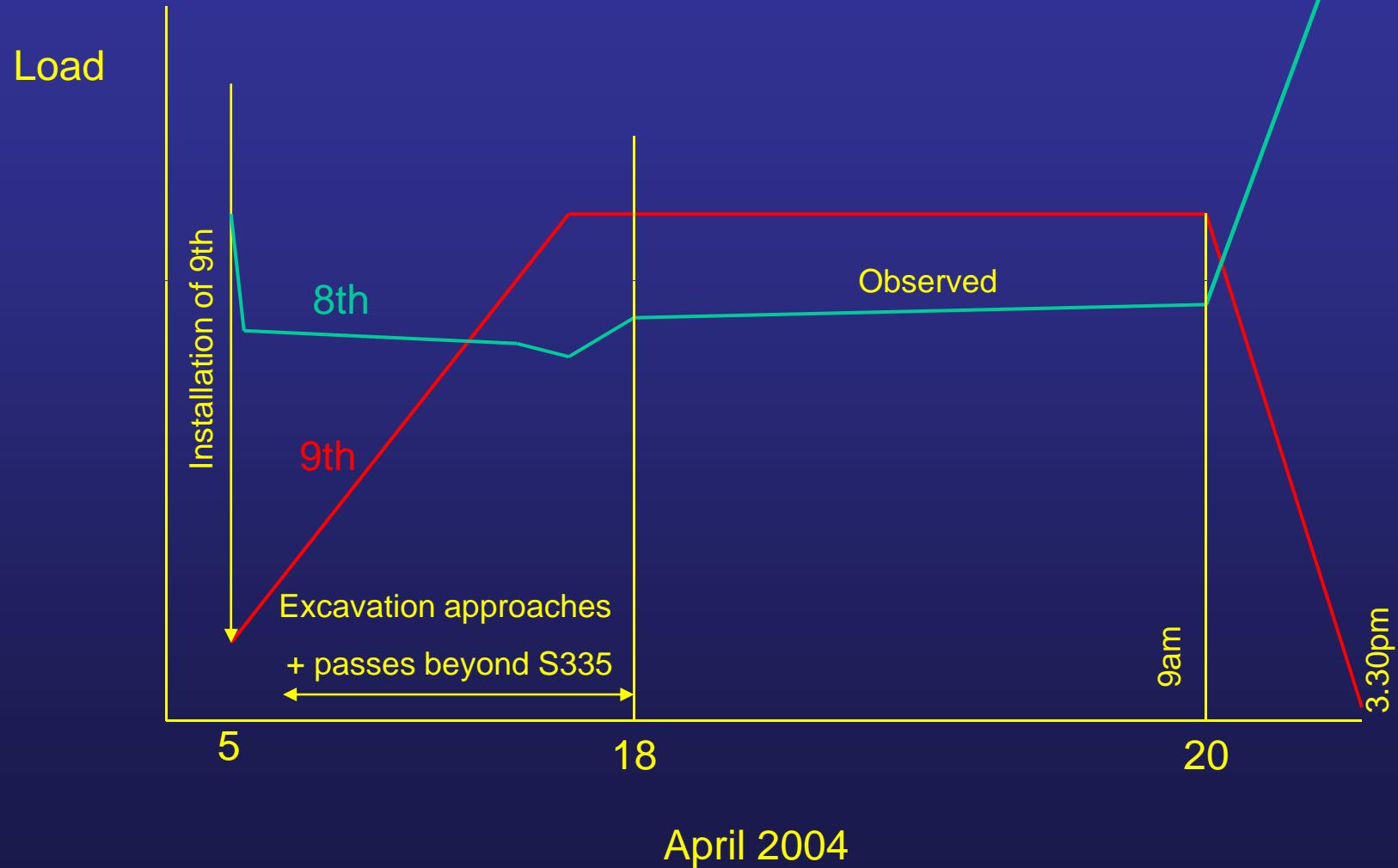


## *Predicted trends in 7<sup>th</sup>, 8<sup>th</sup> and 9<sup>th</sup> strut loads*





## Observed trends in 8<sup>th</sup> and 9<sup>th</sup> strut loads





- The analyses matched reasonably well the build up in horizontal wall movements, and the trends in the forces in the 7th, 8th and 9th level struts
- To match movements and forces at all stages it was necessary to model the jet grout as a brittle material
- The upper JGP was predicted to pass its peak strength during excavation to the 6th level and the lower JGP to pass its peak strength during excavation to the 9th level
- The 9th level strut reached its capacity during excavation to the 10th level

*Key findings from geotechnical analyses*



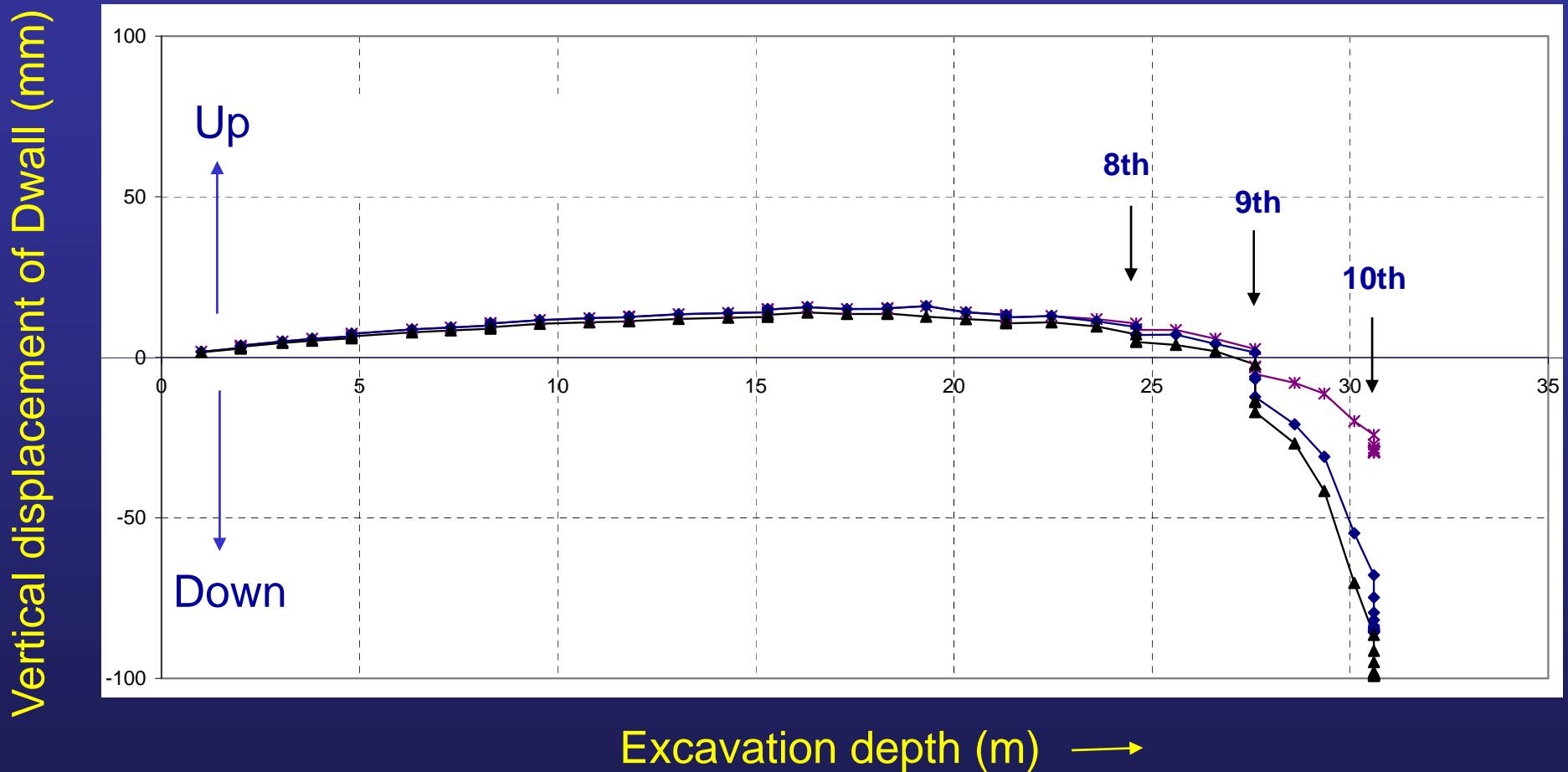
- The collapse had to be initiated by allowing the 9th level strut to strain soften – a ductile failure of the connection was not associated with a collapse
- The bending moment capacity of the south wall was reached on the first stage of excavation below the 9th level, but a hinge did not form in the wall until the sacrificial JGP layer had been removed

*Key findings from geotechnical analyses*

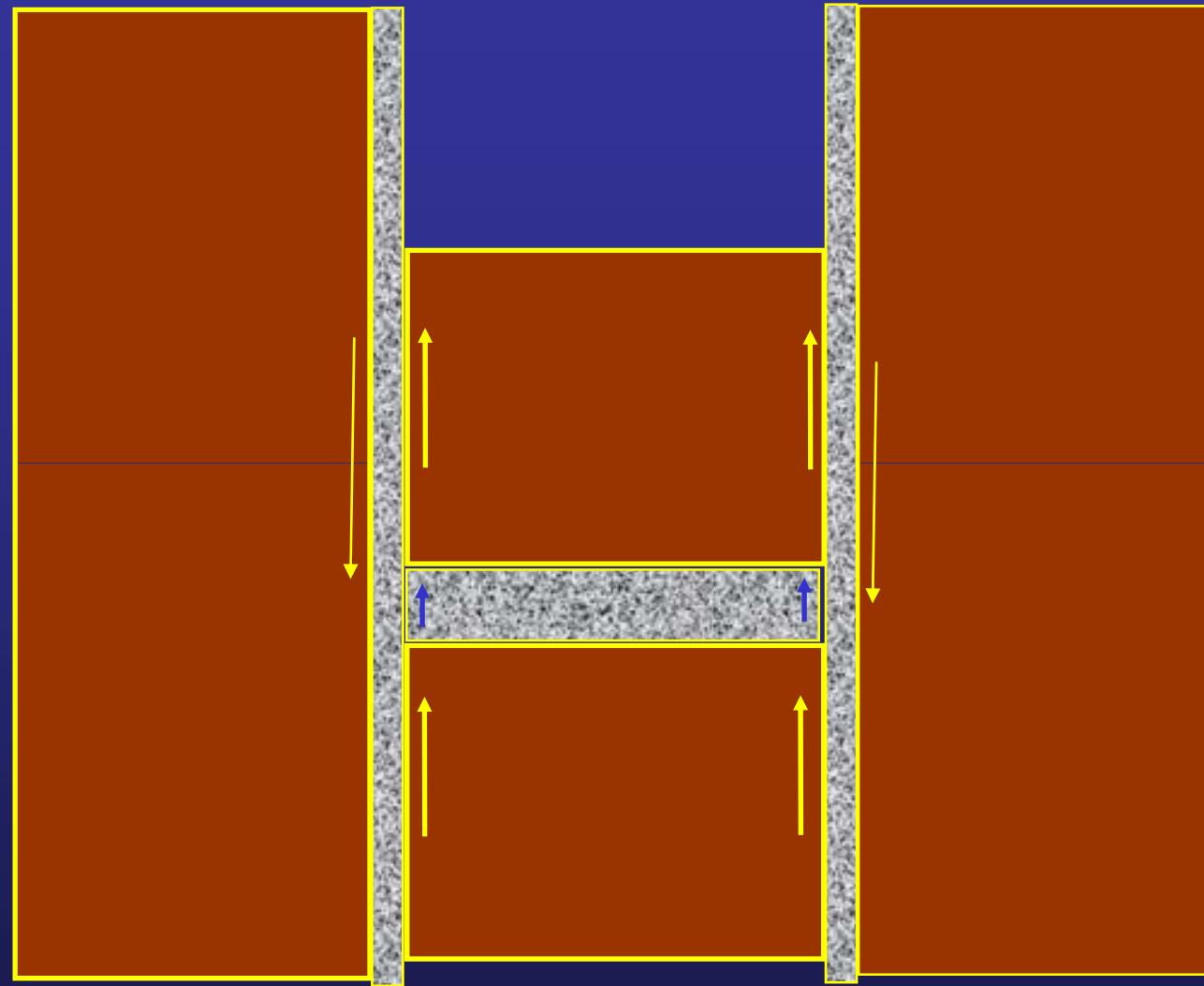


*Trigger required to initiate collapse*

Relative vertical displacement between  
the kingposts and Dwall panels

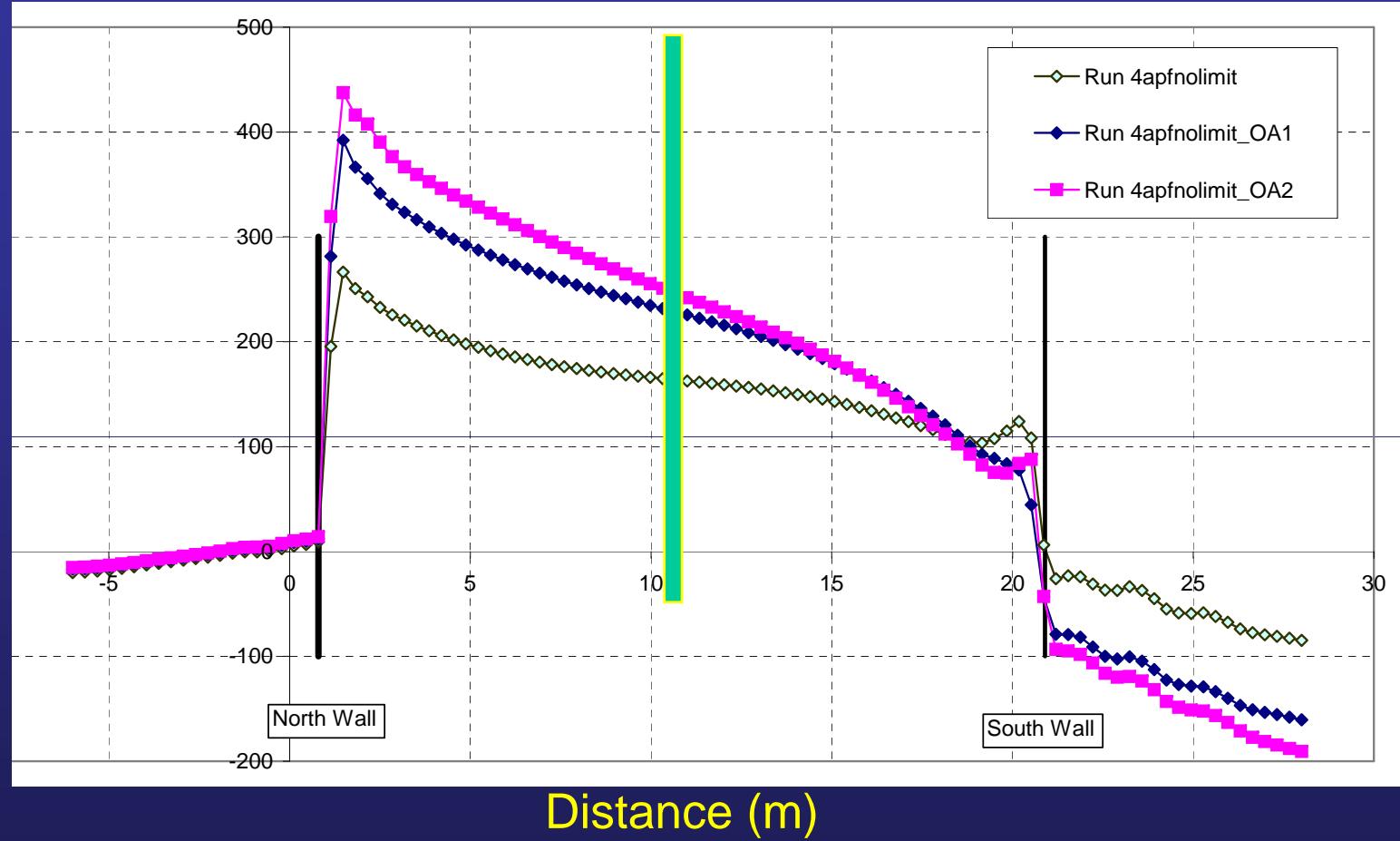


*Predicted settlement of south wall during excavation*





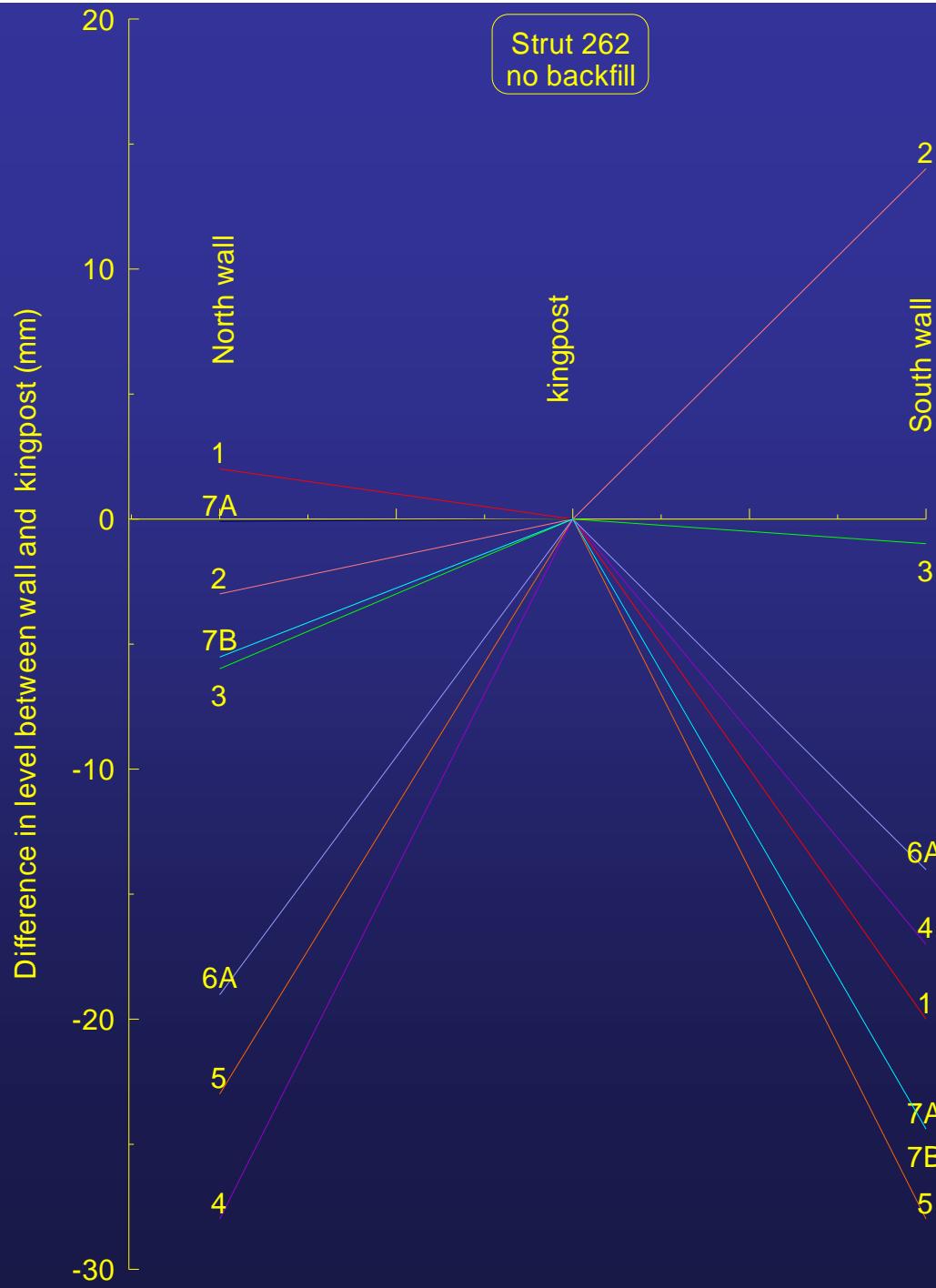
Vertical displacements (mm)



*Predicted vertical displacement of lower JGP layer  
after excavation to 10<sup>th</sup> level*



## Typical relative displacements of strut between walls and kingpost





- Calibrated FE analyses predict downward displacement of Dwall and upward displacement of kingpost when sacrificial JGP layer excavated
- Survey data supports upward vertical displacement of centre of strut relative to ends

*Relative vertical displacement*



9<sup>th</sup> level

Sacrificial JGP  
Excavation front

Lower JGP

*Kingposts in long section*

KP180

KP181

KP182

KP183

KP184

335

336

337

338

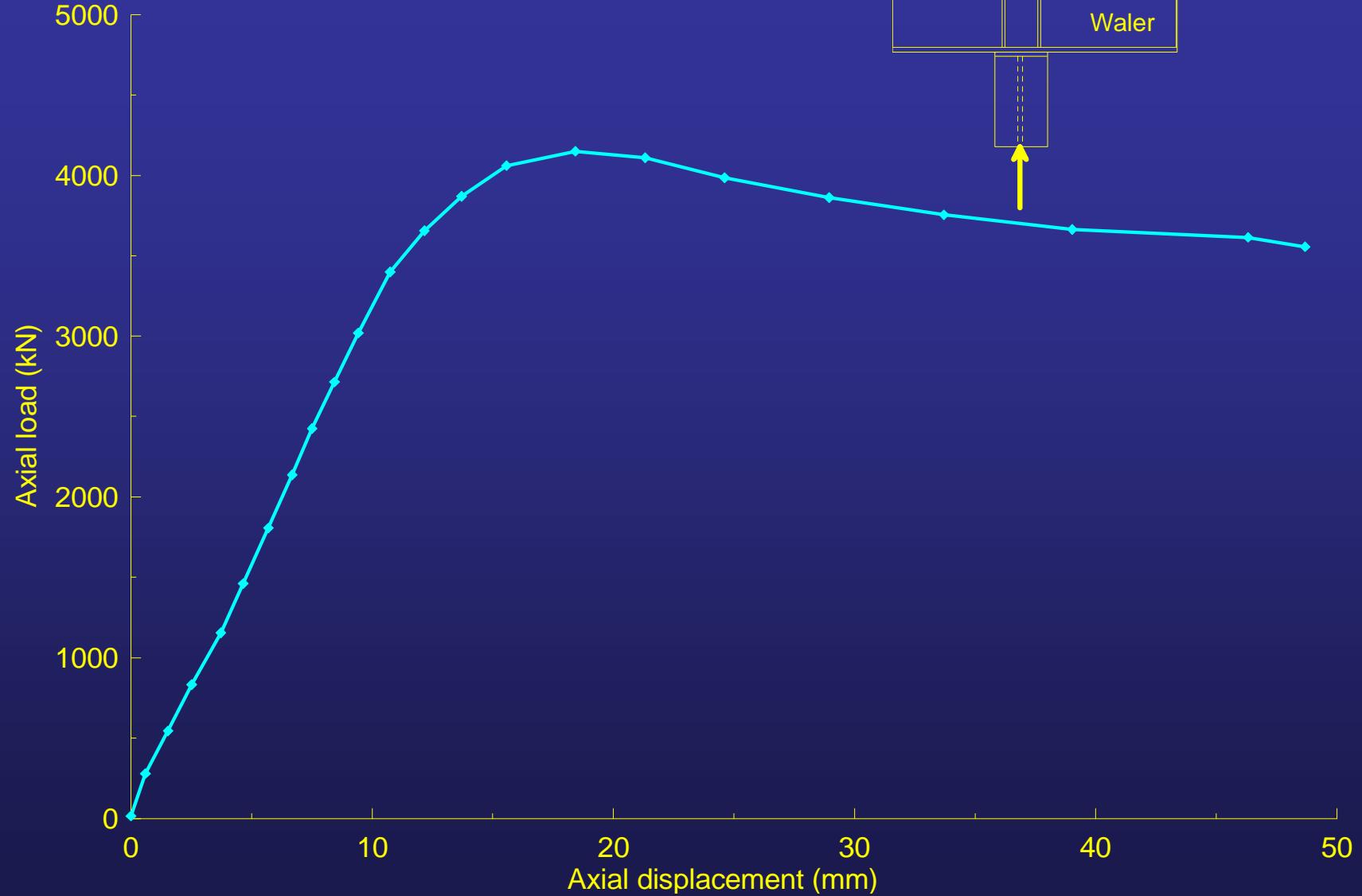
339

340

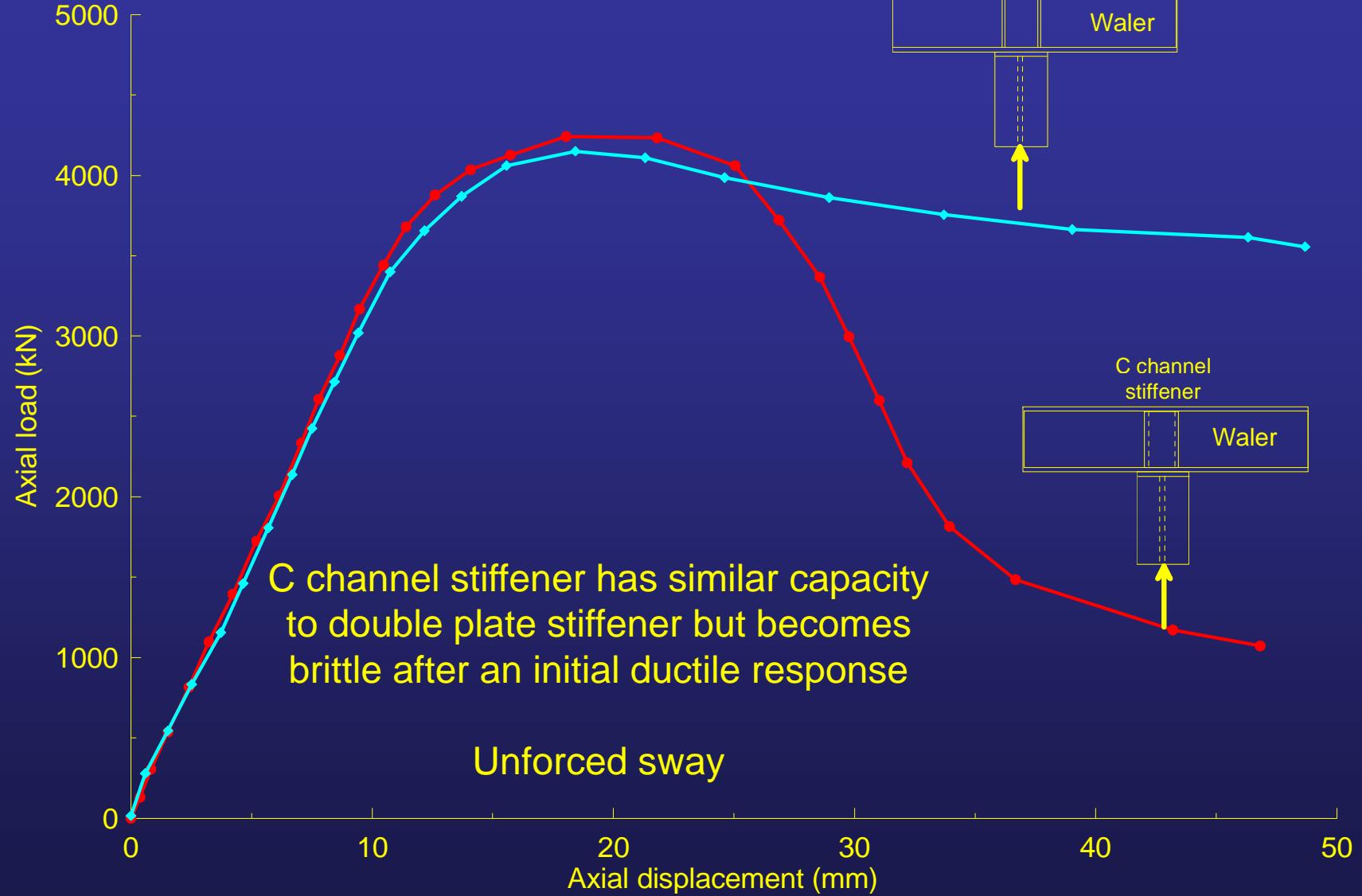


## *Post-collapse investigations*

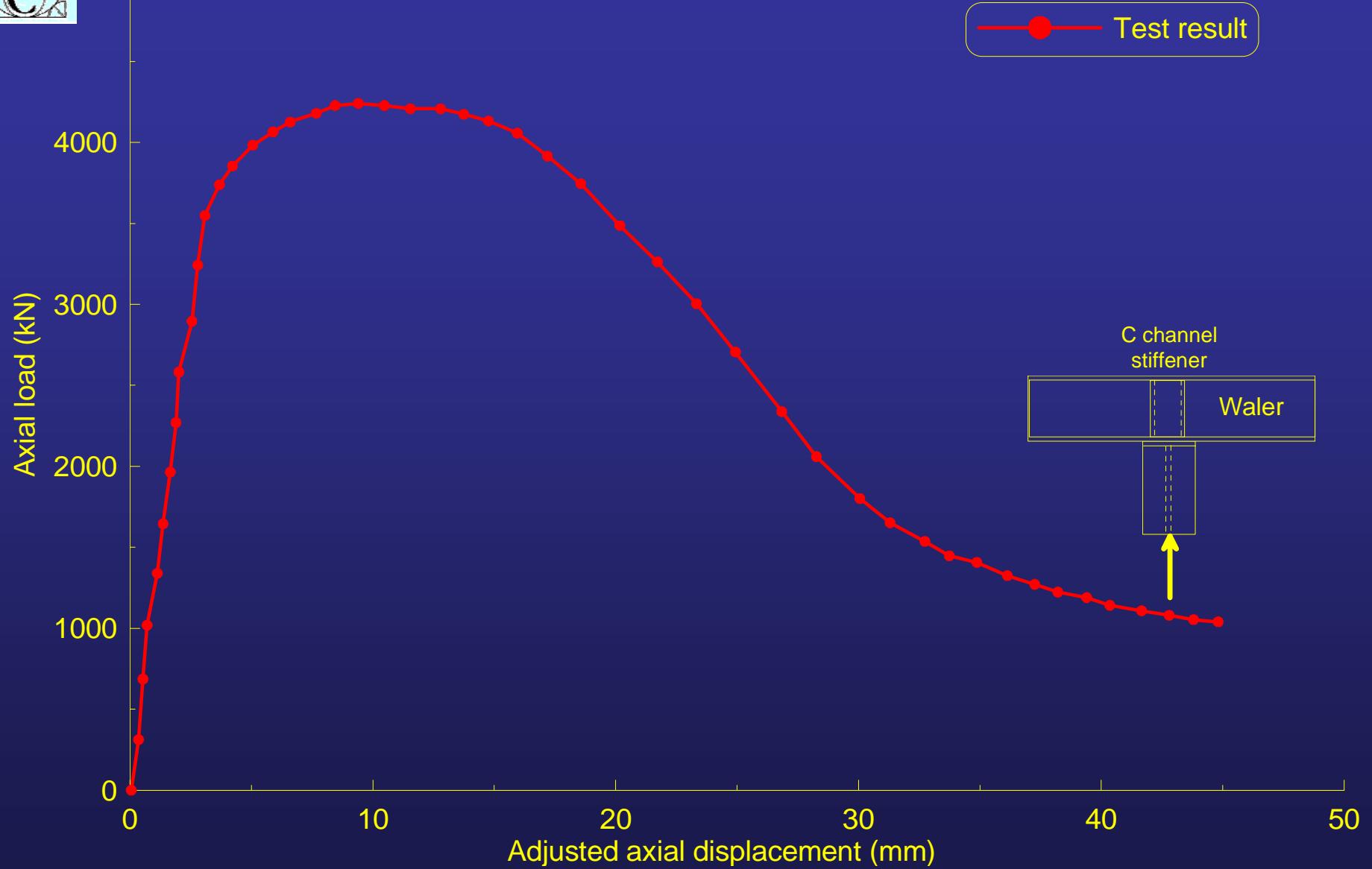
Structural steel physical tests  
and numerical analyses.  
The effect of relative vertical  
displacement



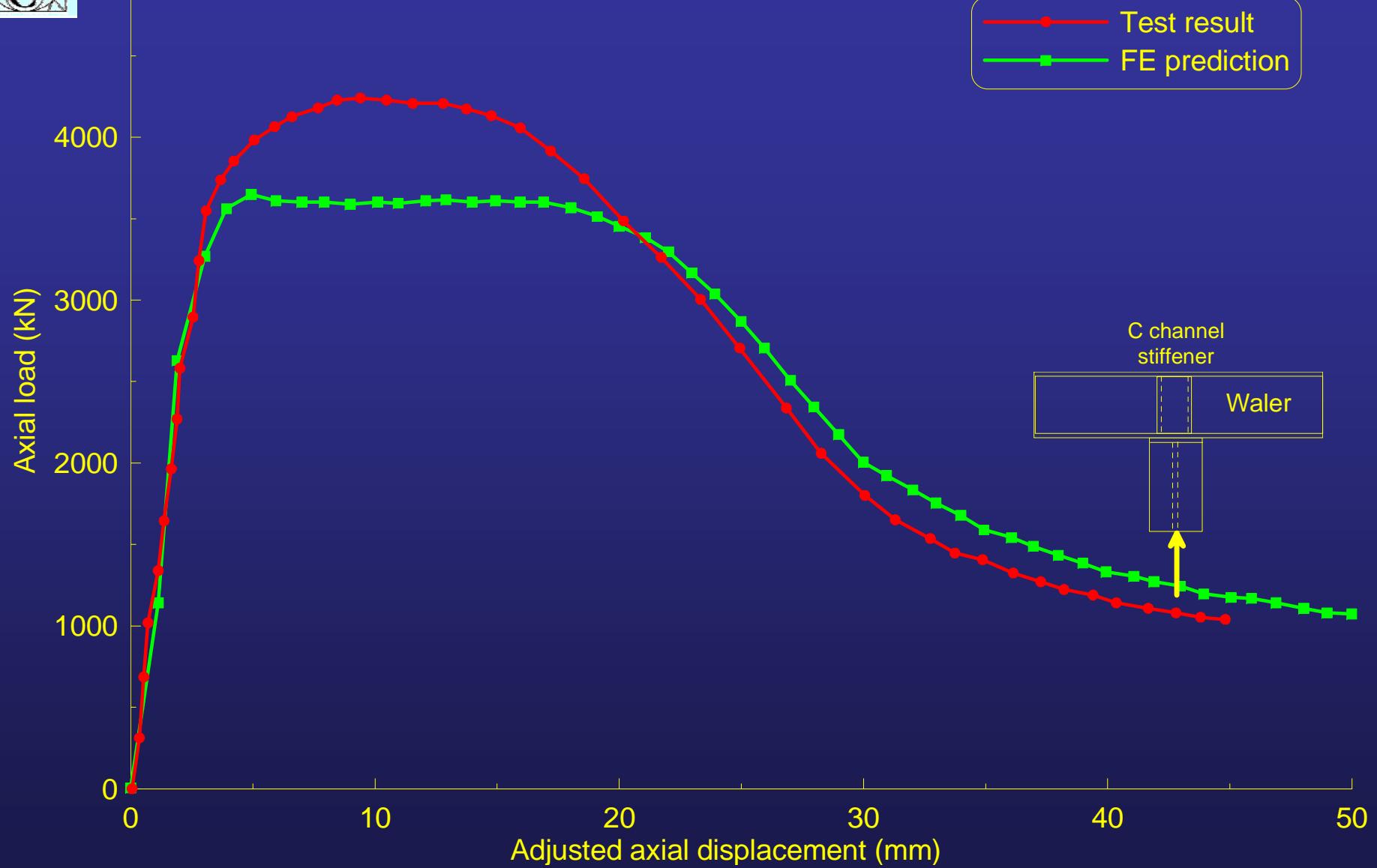
*Comparison of tests on connections with plate and C channel stiffeners*



*Comparison of tests on connections with plate and C channel stiffeners*



*Calibration of FE model of strut-waler connection*



*Calibration of FE model of strut-waler connection*



5000

Axial load (kN)

1000

0

Ductile plateau 10-15mm

Yield

Ductile plateau allows failure to develop at both ends

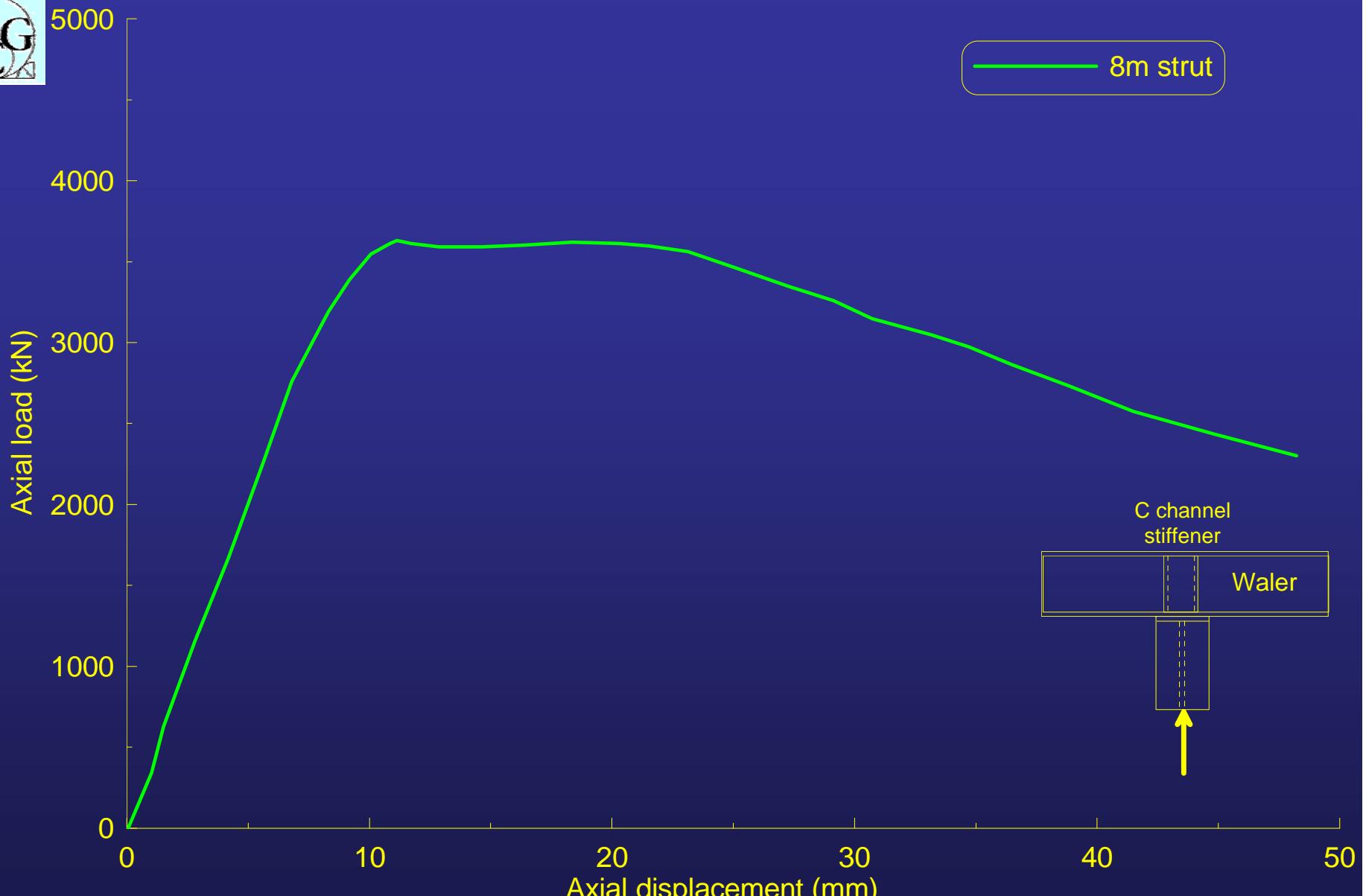
Test result  
FE prediction

C channel stiffener

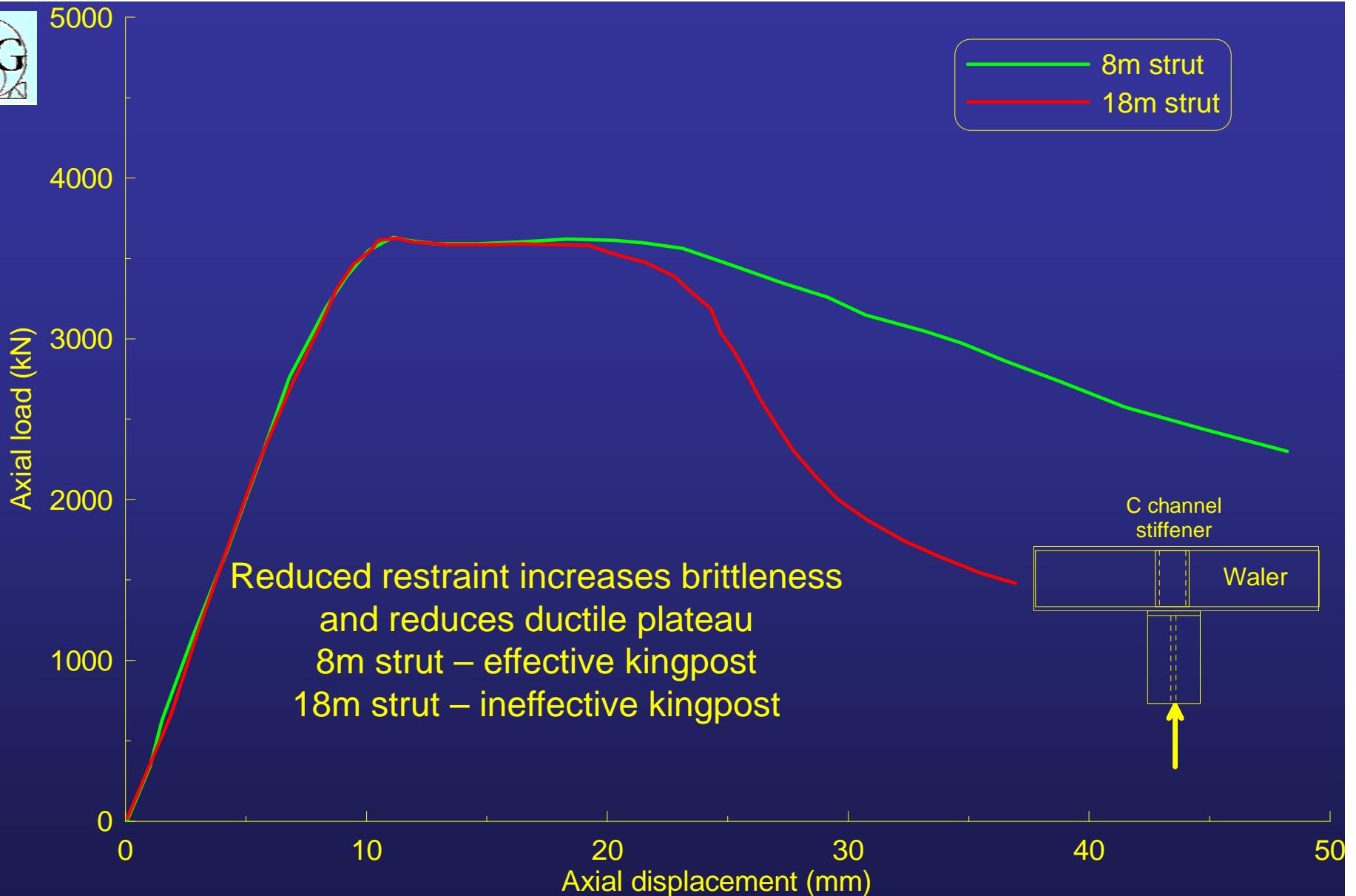
Waler

Adjusted axial displacement (mm)

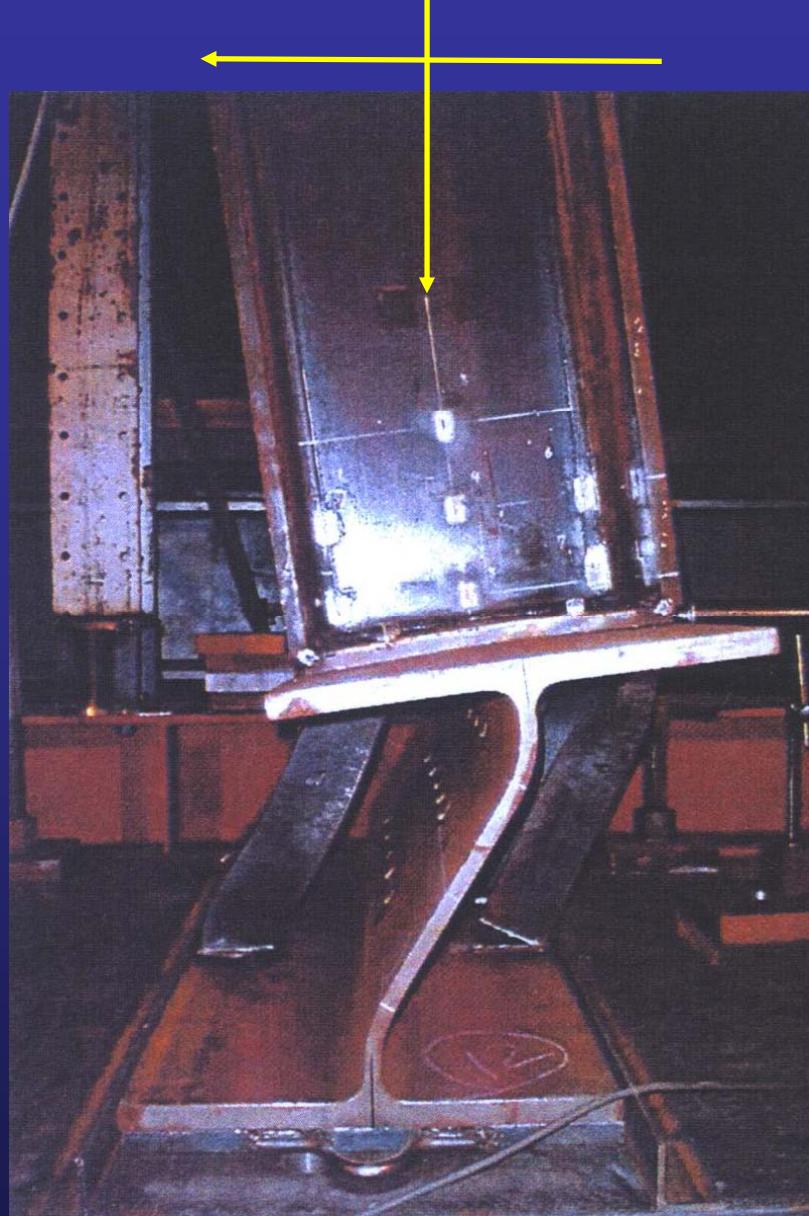
*Calibration of FE model of strut-waler connection*



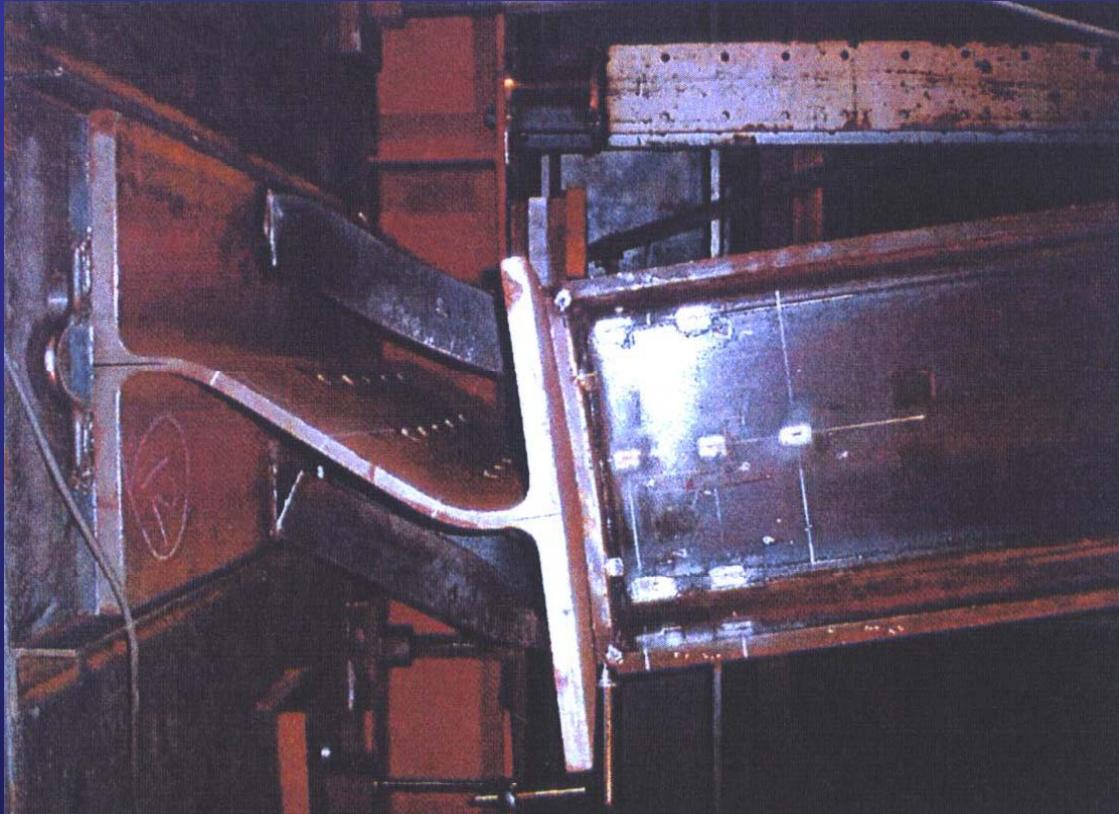
*Effect of strut length (bending restraint) on brittleness of connection*



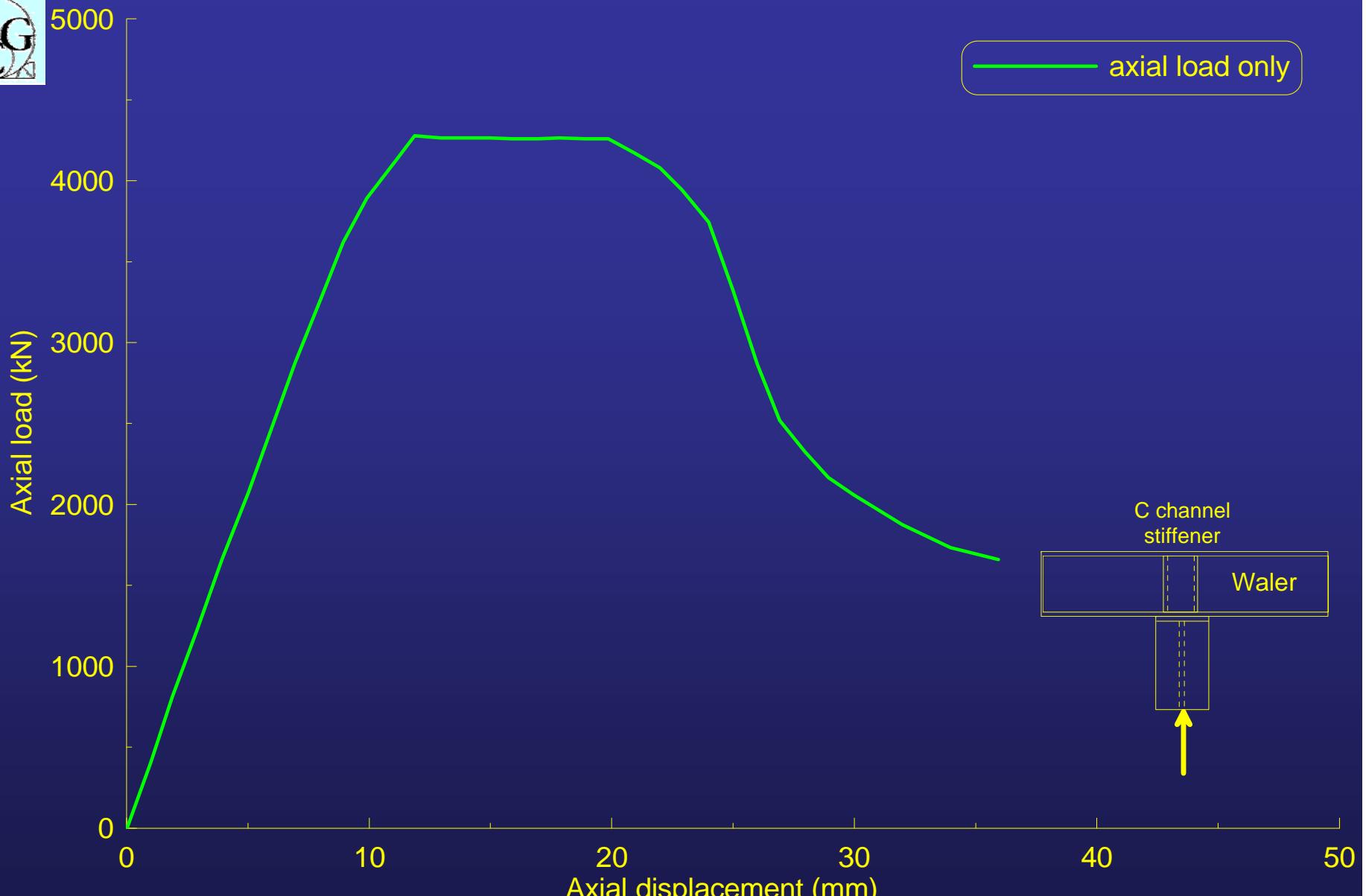
*Effect of strut length (bending restraint) on brittleness of connection*



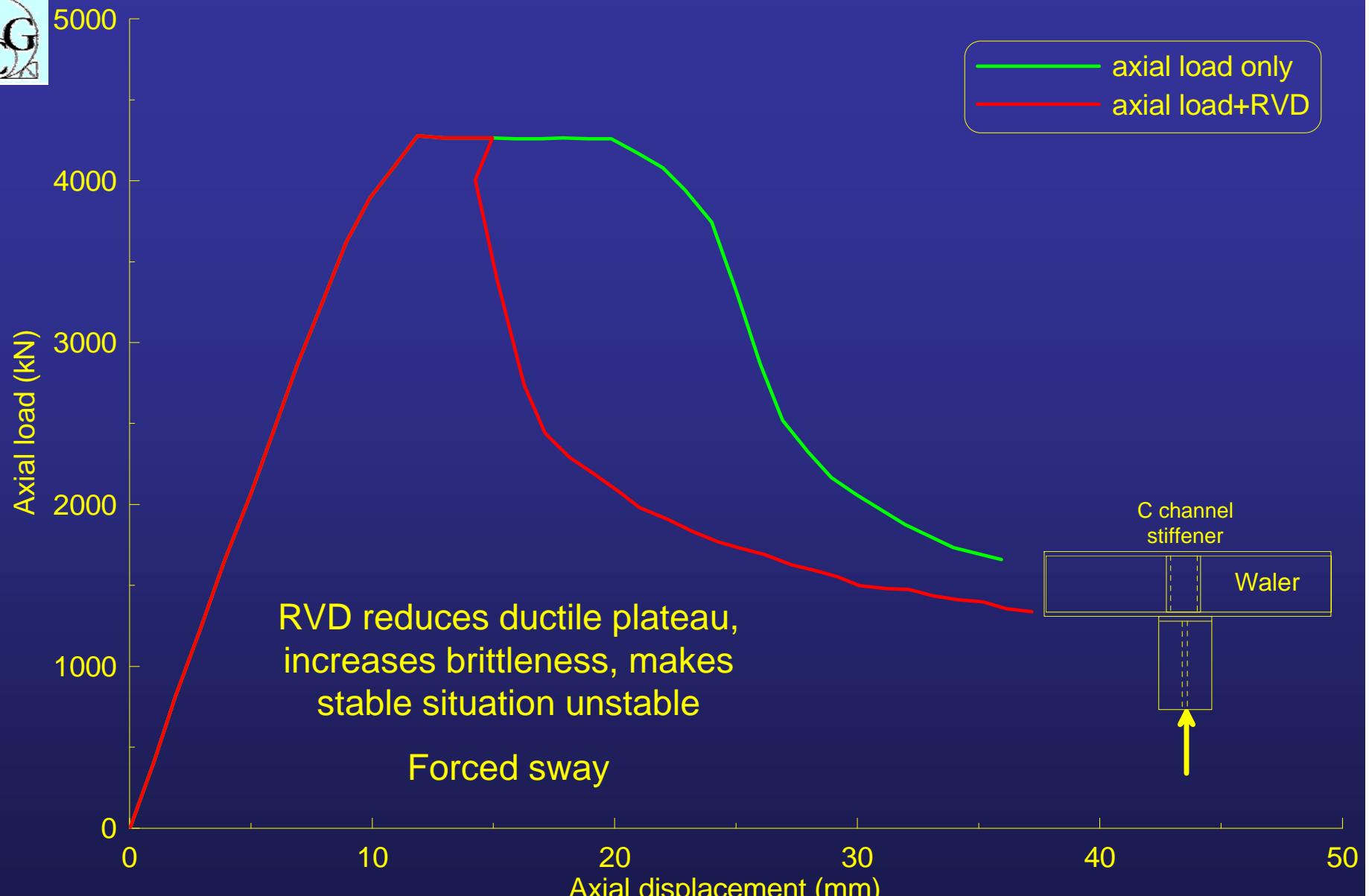
*Test on C channel stiffened connection by Nishimatsu*



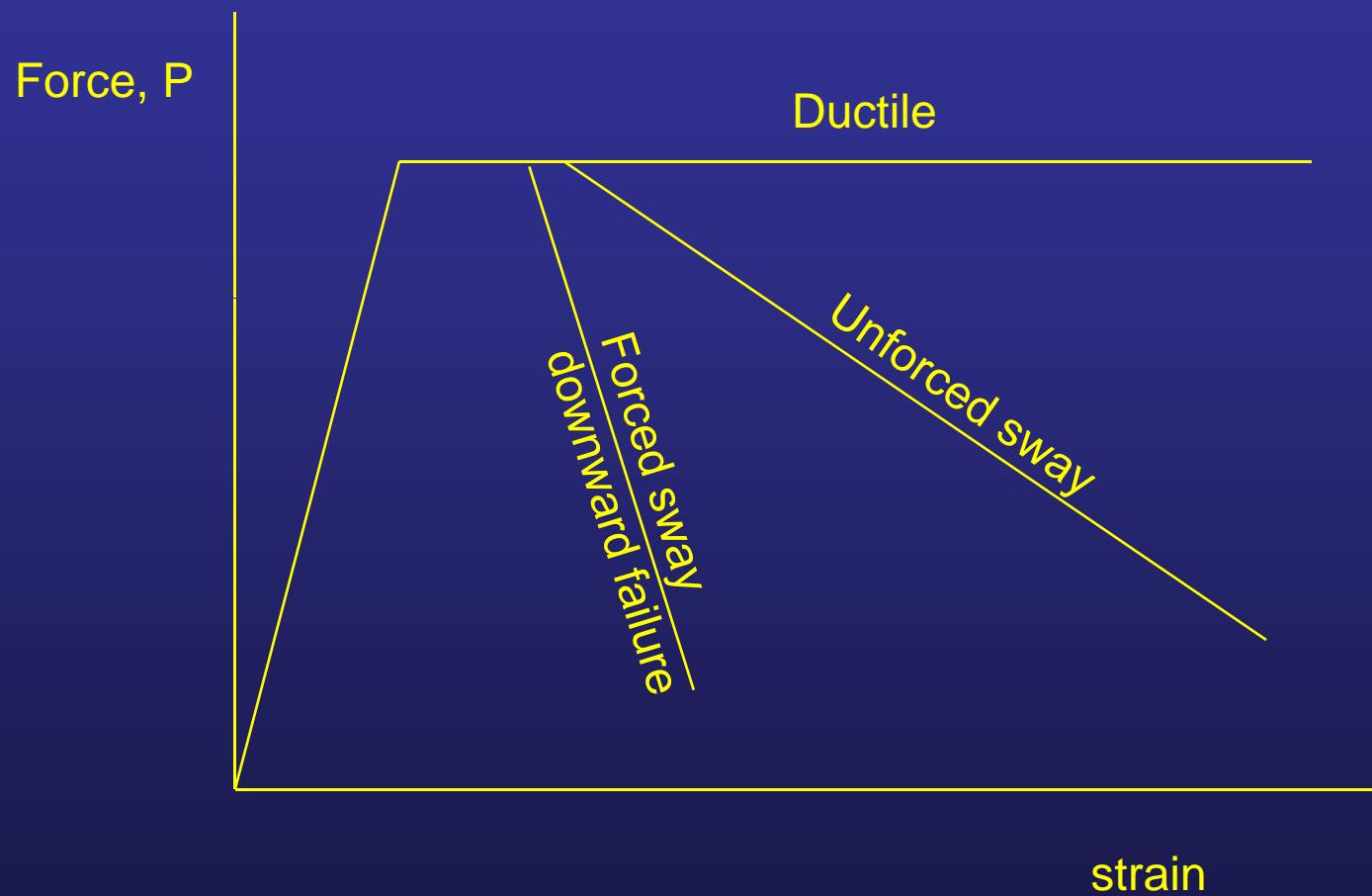
*Test on C channel stiffened connection by Nishimatsu*



*Effect of relative vertical displacement*

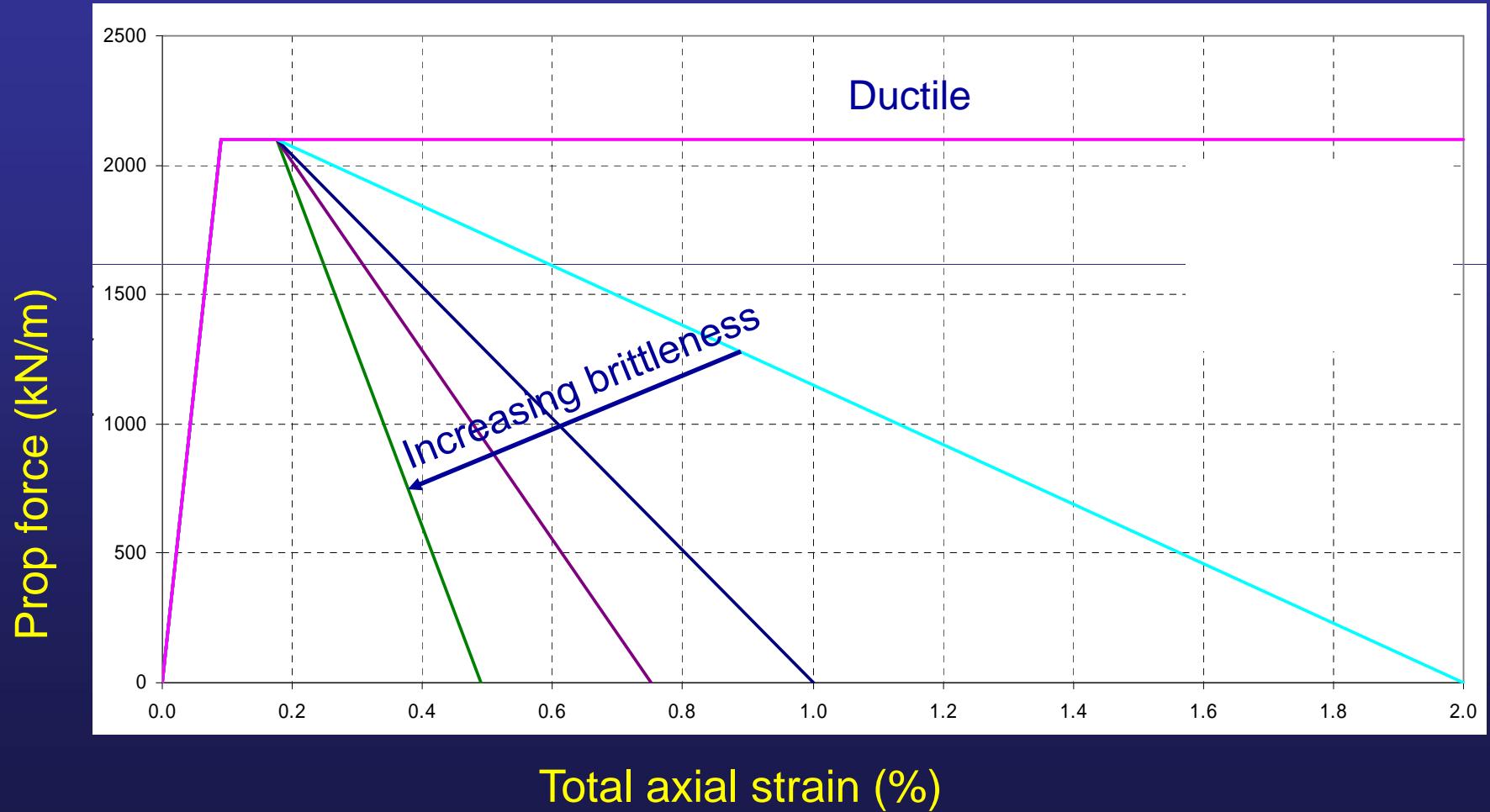


*Effect of relative vertical displacement*



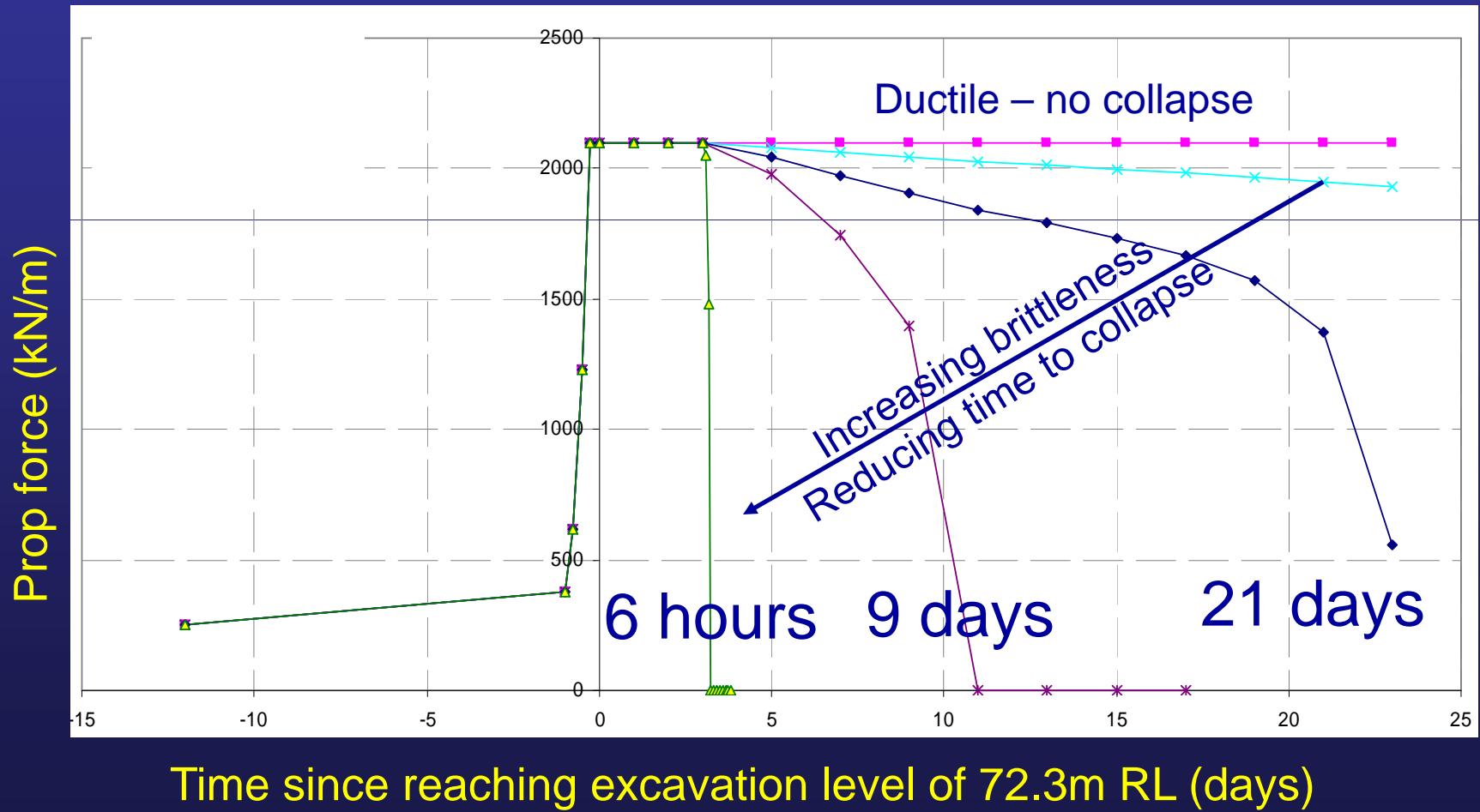


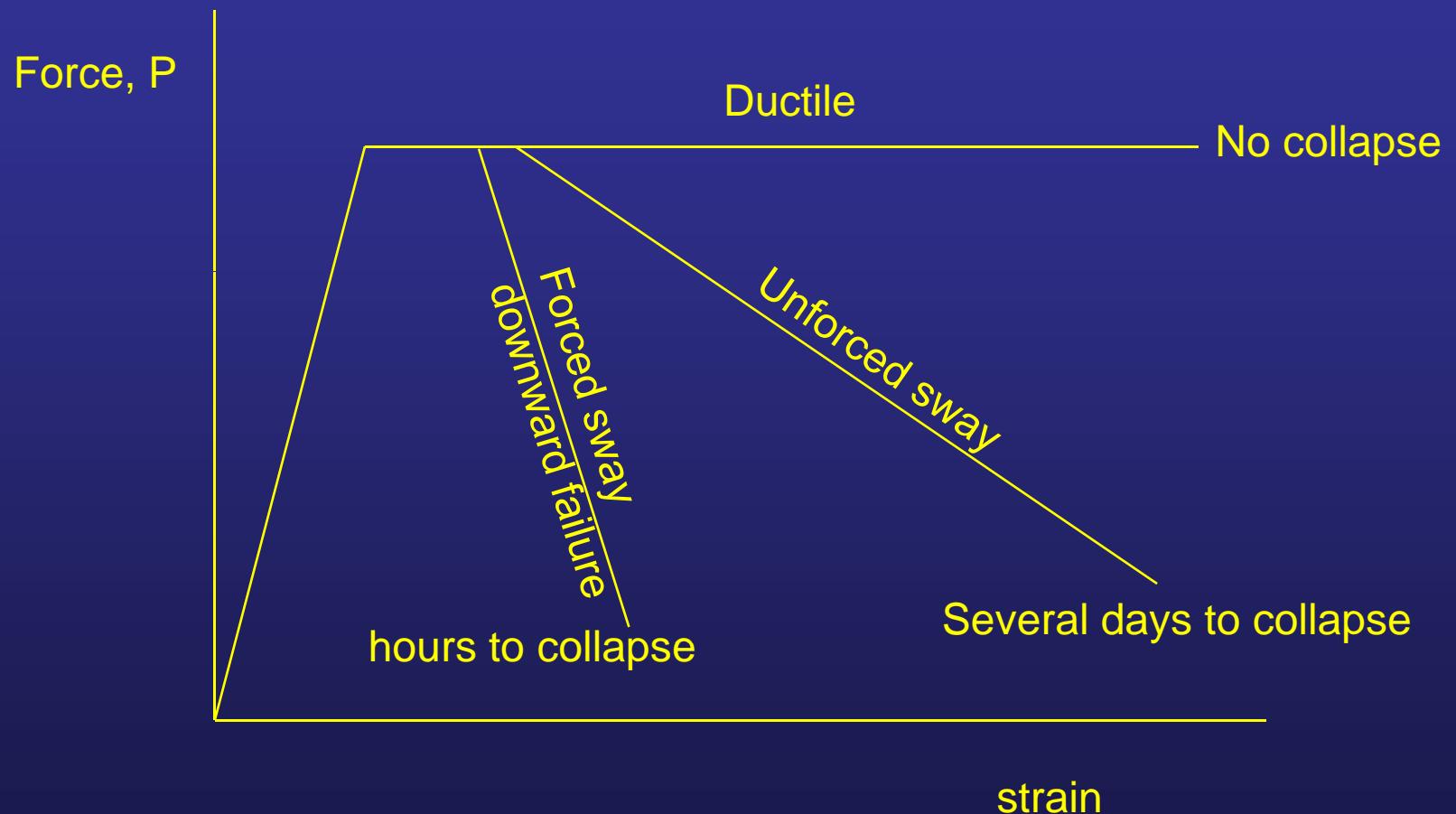
# *Effect of brittleness of strut to waler connection*





## *Effect of brittleness of strut to waler connection*







- There was relative vertical displacement between the diaphragm wall, which settled when the sacrificial JGP was removed, and the kingpost, which rose, i.e. relative vertical displacement between the ends and centre of the strut (RVD)
- The strut-waler connection was ductile-brittle. The ductile plateau explains why both ends could fail
- The brittleness of the connection determines the time taken for the collapse to develop

*Trigger required to initiate collapse*



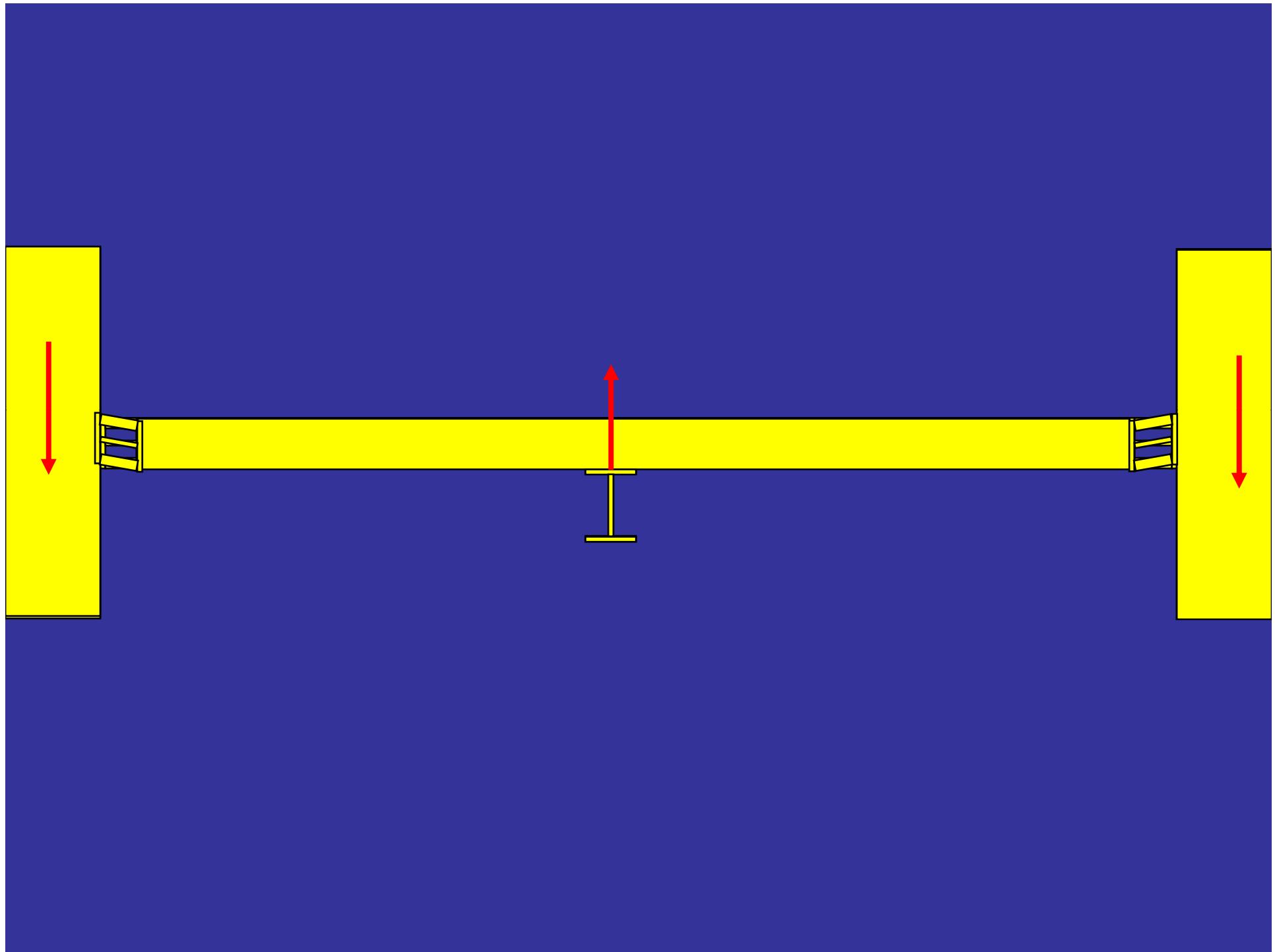
- RVD reduces the length of the ductile plateau and increases the brittleness
  - RVD can make a stable situation unstable
  - RVD can shorten the time to collapse
- 
- Why downward failure at both ends?
  - Why collapse after crossing the buried valley?

*Trigger required to initiate collapse*



- Free
- Fixed
- Forced sway

*Downward failure at both ends*



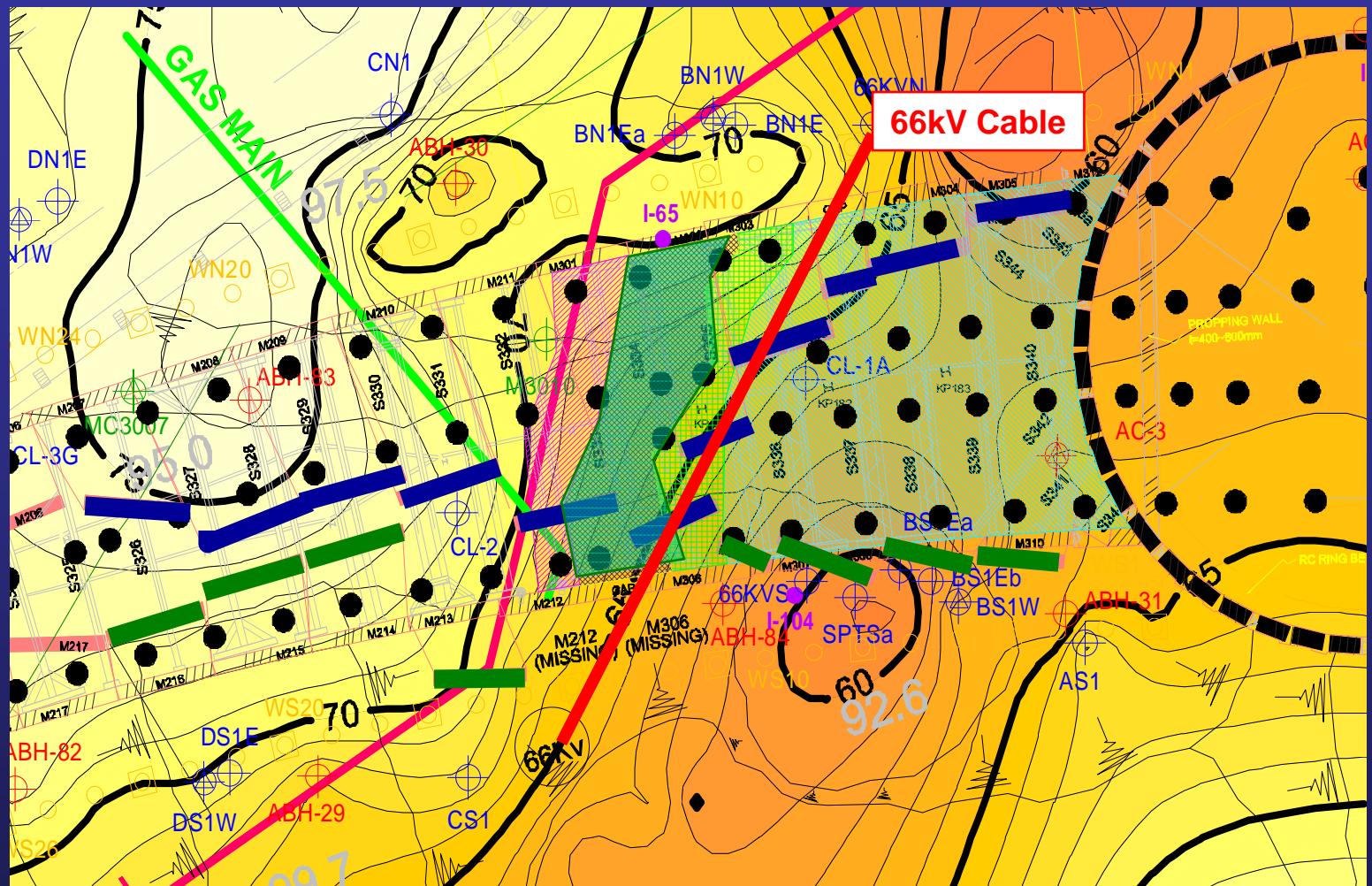


*Trigger required to initiate collapse*

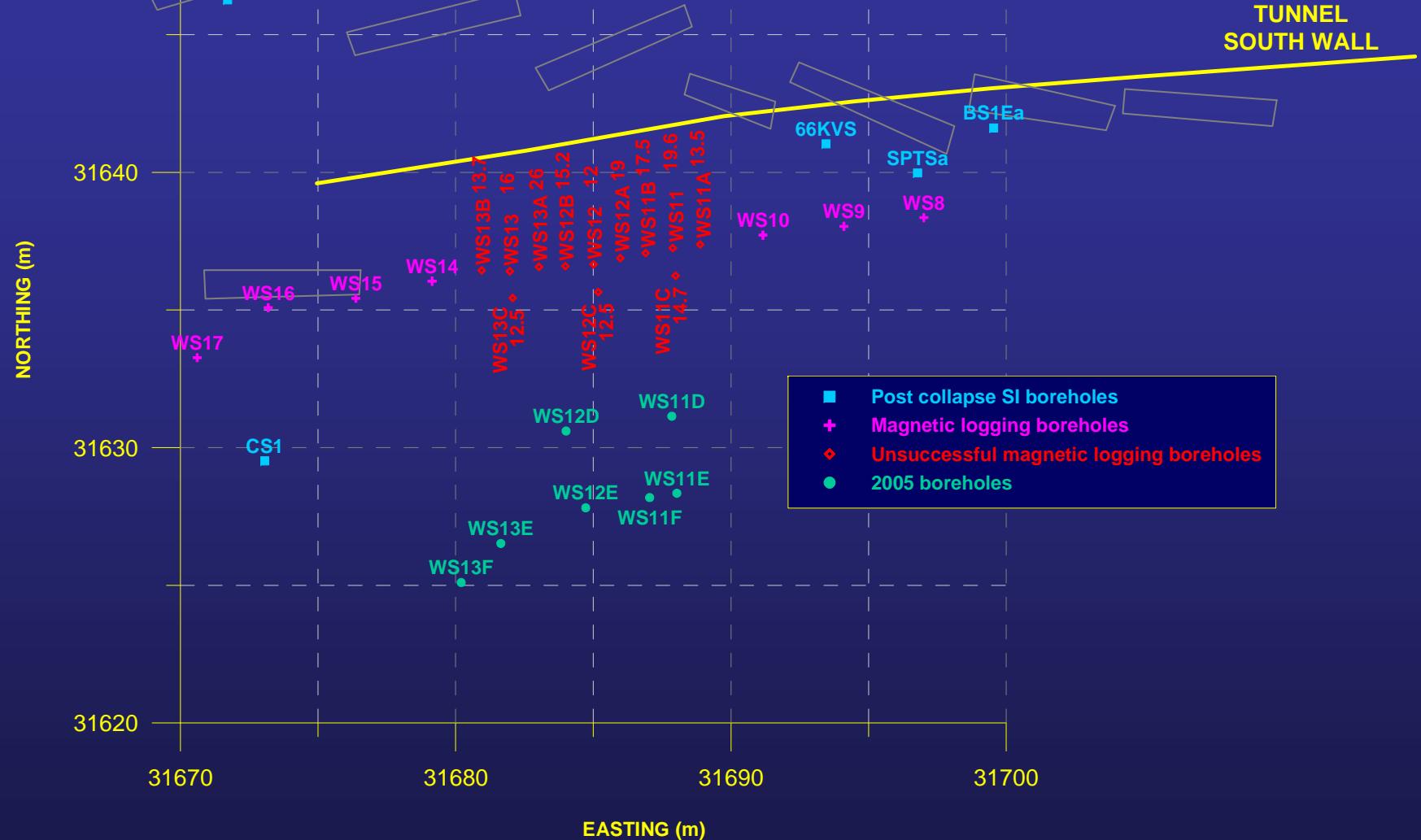
Post-collapse positions of the Dwall  
panels







# *Post-collapse geometry superimposed on buried valley*

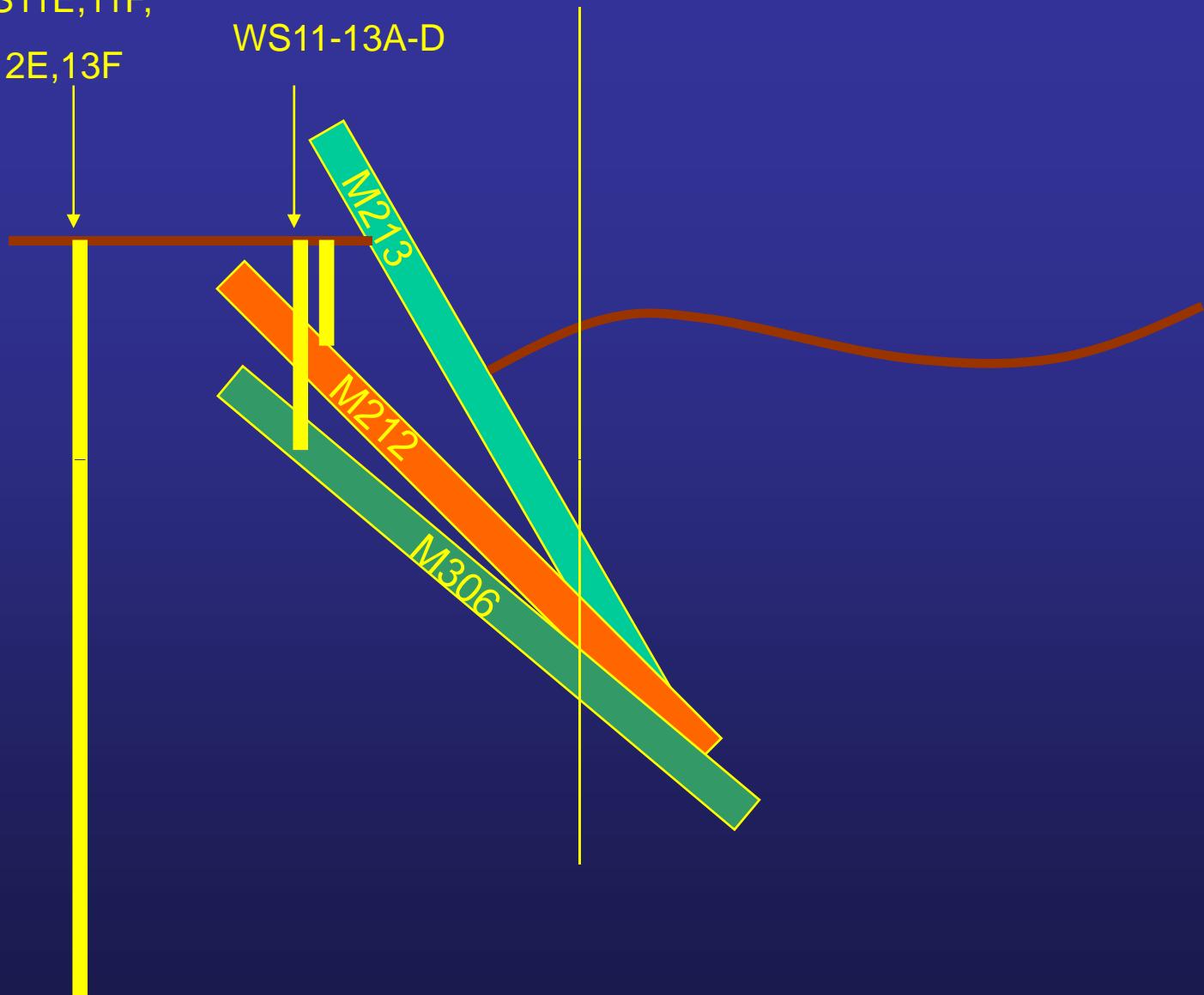


*Coincidence between inability to advance boreholes and missing Dwall panels*

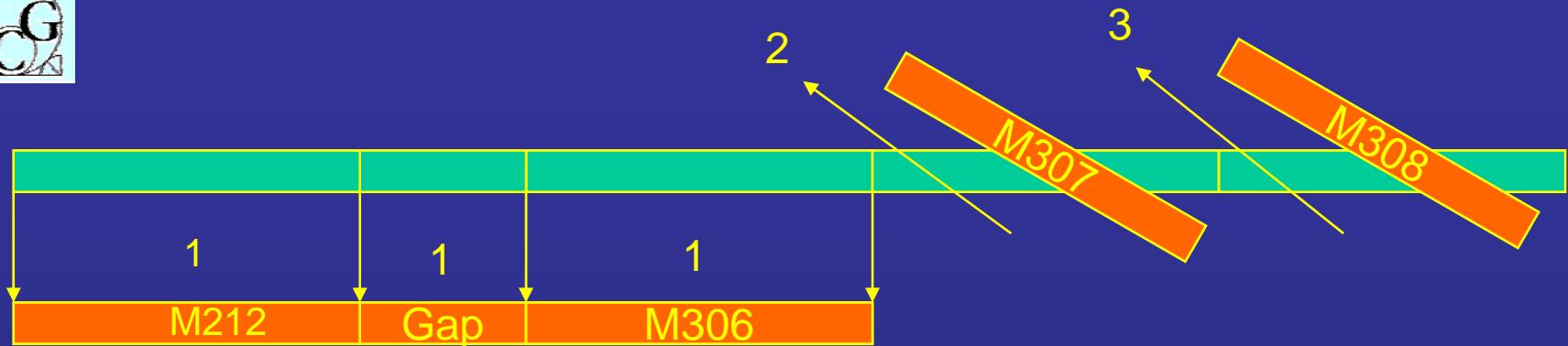


WS11E,11F,  
12E,13F

WS11-13A-D

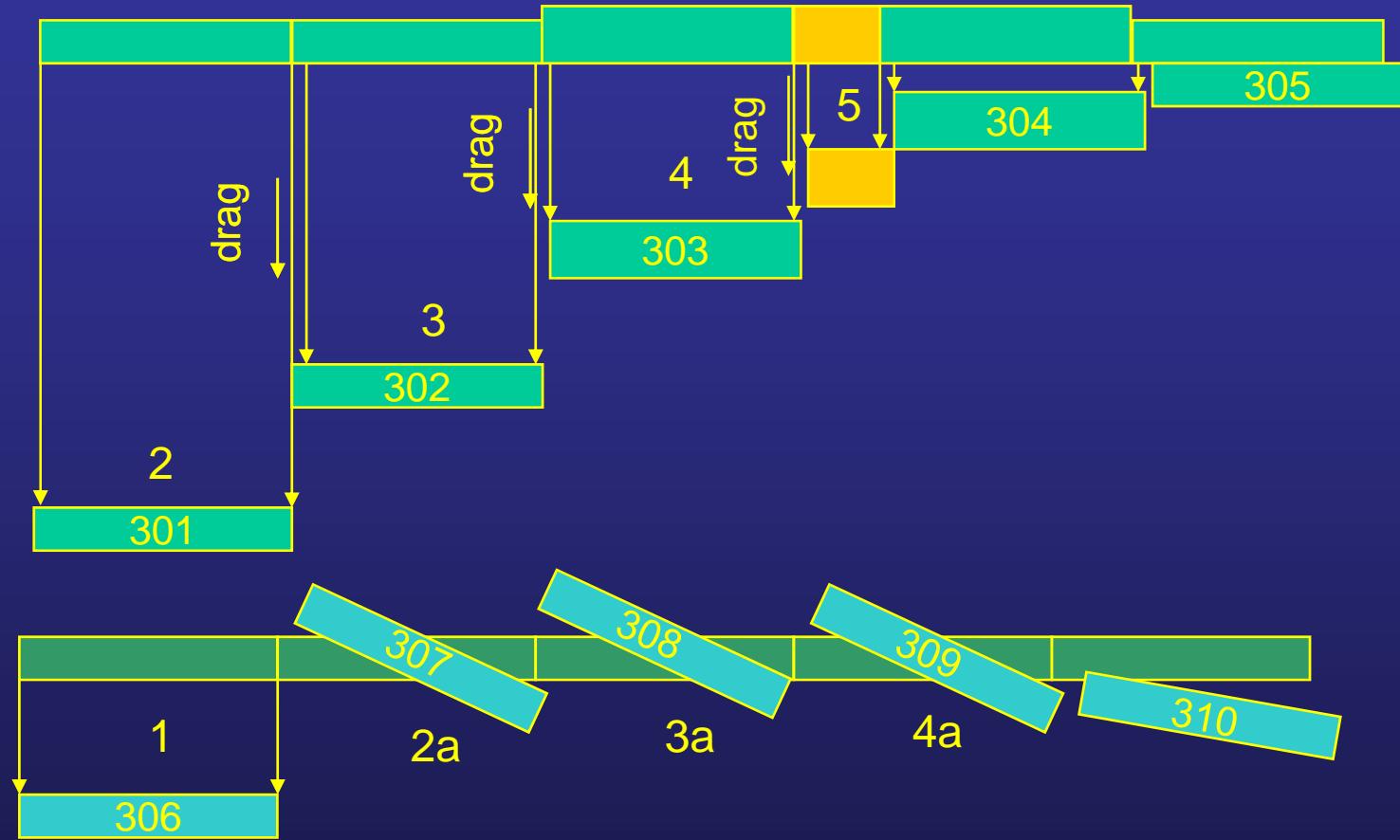


*Obstruction created by missing Dwall panels*



1. Panels M306 and M212, each side of the gap, and panel 213 fail by toe kick-in and rotate back.
2. Soil flows through resulting gap between M306 and M307, rotating panel 307.
3. Soil flows through resulting gap between M307 and M308, rotating panel 308, etc.

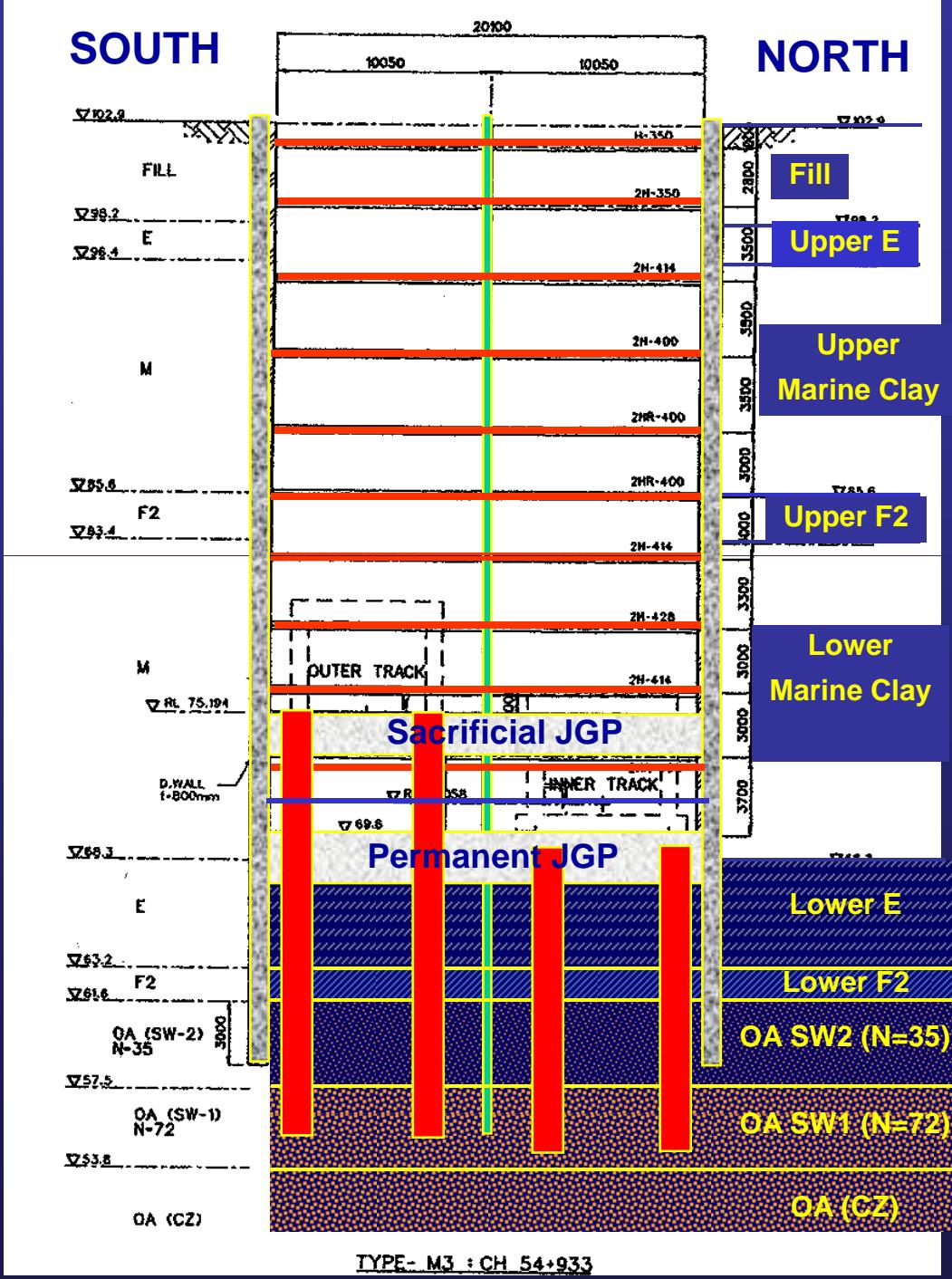
*Sequence of south wall panel movements*



*Sequence of south and north wall panel movements*



*Differing restraint imposed by bored piles at north and south walls*





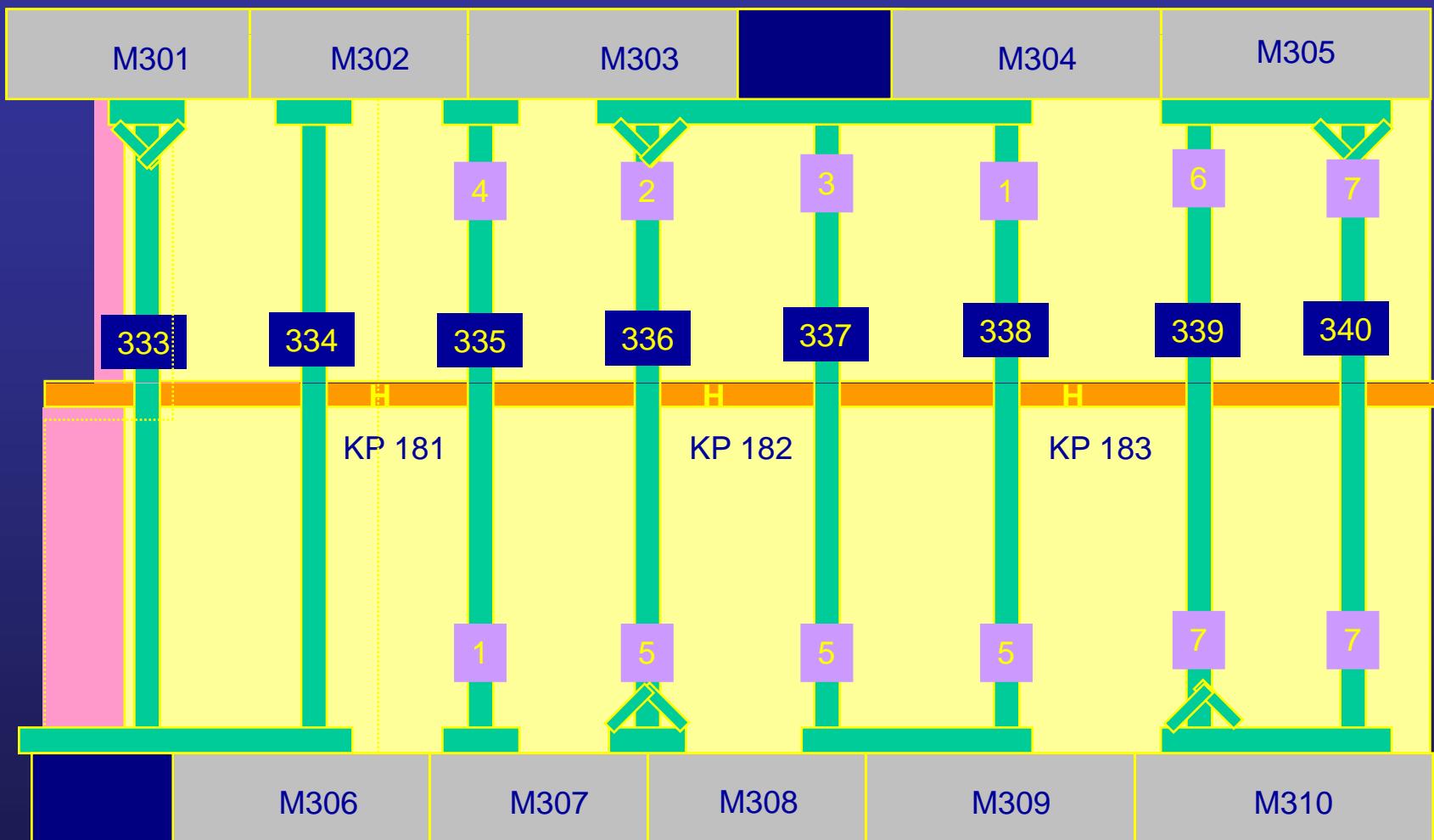
- The bored piles had a major influence on the displacements of the Dwall panels during the collapse and on their post-collapse positions
- The bored piles restricted toe movements on the south side and prevented failure as the buried valley was crossed
- Loads carried by the bored piles contributed to the under-reading of the strain gauges

*Significance of the bored piles*





## North wall



Order in which distortion to waler noted

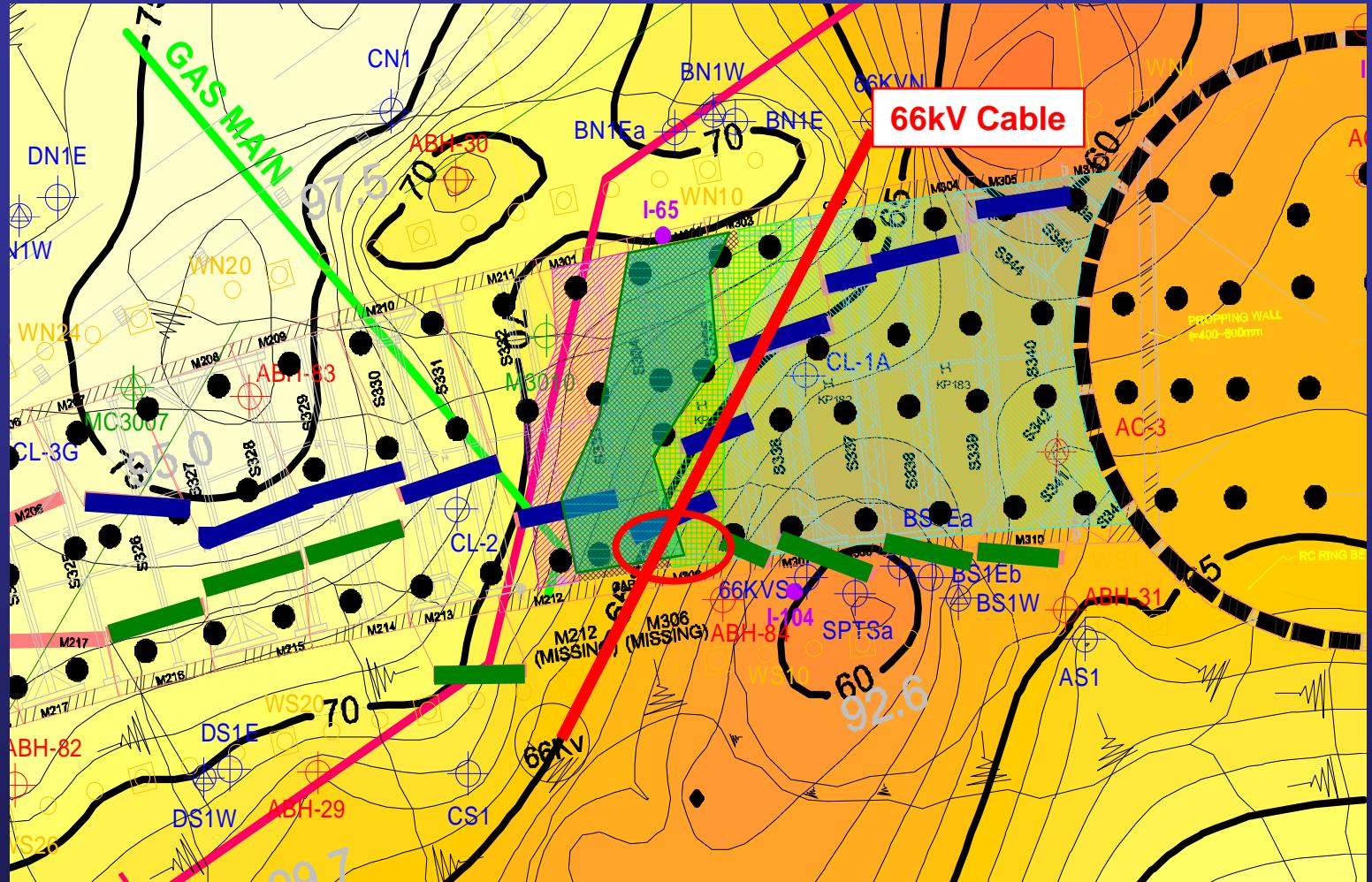


Excavation in progress



Excavation to 10<sup>th</sup> complete

Location of walers, splays and Dwall gaps



*Repositioned bored piles at 66kV crossing*



- Upward displacement of KP 180 and 181 accentuated by toe displacement of M306 and M212, where bored piles had been re-positioned and additional toe movement was possible
- Resulting RVD fed back into buried valley

*Relative vertical displacement*



KP180

KP181

KP182

KP183

KP184

335

336

335

337

338

339

340

9<sup>th</sup> level

Upper JGP  
Excavation front

Lower JGP

*Kingposts in long section*



- C channel stiffened connection undergoes brittle failure
- Critical length of strut and of load in strut result in minimal lateral restraint to connection
- Restraint from rising kingpost results in downward force on connection
- RVD results in reduction in ductility of connection and increase in brittleness
- RVD makes a stable situation with overstress unstable
- RVD results in downward failure of connection
- **RVD was the trigger for the failure**

*Failure mode of connection and RVD*



## *Overall conclusions*

- The use of Method A in the numerical analyses to model near normally consolidated soils is fundamentally incorrect
- Its use led to under-prediction of wall displacements and bending moments and so to a reduction in the redundancy in the system. The JGP was strained beyond its peak and a plastic hinge formed in the wall as excavation of the sacrificial JGP was underway



## *Overall conclusions*

- There were errors in the design of the strut-waler connection resulting in a design capacity that was 50% of the required capacity where splays were omitted
- The collapse initiated some time after the excavation crossed the buried valley, where forces on the under-designed strut-waler connections would have been a maximum
- An additional perturbation or trigger was necessary to explain the timing of the collapse, the downward failure of the walers at both ends and the trends in the monitoring data



## *Overall conclusions*

- The permanent bored piles in combination with the JGP played a significant role in preventing the collapse as the valley was crossed
- The collapse was triggered when working in the vicinity of the 66kV cable crossing
- At this location, the permanent bored piles had been repositioned and the JGP layout had been modified, allowing the wall toe to kick-in and cause additional uplift of the local kingposts



## *Overall conclusions*

- This additional upward displacement of the kingposts relative to the wall fed back into the system, introducing forced sway failure
- Downward movement of the walls has been predicted by analysis; the potential for relative upward movement of the kingposts has been confirmed by surveys
- Forced sway failure reduced the strain over which the connection remained ductile, increased the brittleness of the connection and allowed a stable situation to become unstable
- Forced sway failure can explain the timing of the collapse, the form of the observed distortions, the trends in the monitoring data, and the speed at which the collapse developed



## *Overall conclusions*

- The collapse was not caused by hydraulic base heave and was not related to poor workmanship
- Wall rotation, which had been linked with inadequate penetration of the wall into the OA, was not the cause of the collapse
- Several factors had to act in combination to cause the collapse



## *Unforgiving site*

- Deepest excavation in marine clay in Singapore –shortcomings in use of Method A not previously apparent because of depth dependence
- Ground conditions – buried valley in OA infilled with soft fluvial and organic clay, rapid variation in depth of marine clay along and across the excavation resulting in an asymmetric section
- Curvature of walls in plan requiring more frequent use of walings
- Presence of 66kVA crossing
- Need to adopt sacrificial JGP layer, removal of which caused step increase in 9th level strut load and step increase in wall settlement



## *Lessons learnt*

- JGP is a brittle material
- The mass properties of JGP need to be more carefully evaluated
- Coring of JGP is not an adequate check
- The use of numerical modelling of soils in design should be carried out by specialists and its incompatibilities with current codes needs to be removed
- The potential for brittle failure of C channel connections must be recognised



## *Lessons learnt*

- Temporary and permanent works should be subject to independent checks
- The effects of relative displacement between kingposts and walls should be considered in the design of struttied excavations
- Forced sway failure and its consequences should be recognised as a potential mechanism in design
- Monitoring did not warn of the impending collapse