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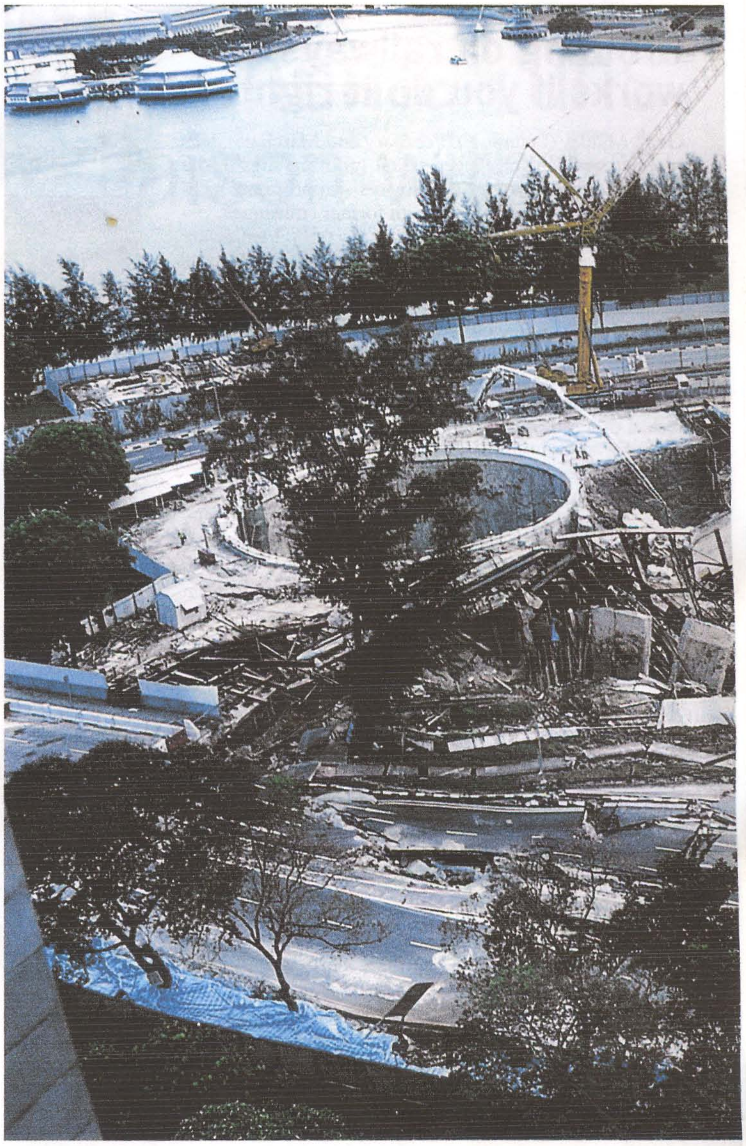
NEWS FEATURE

Singapore parties dispute blame for "Nicoll" collapse

The public inquiry into the Nicoll Highway disaster has identified how the tunnel failed. Now everyone awaits the judge's decision on who was to blame. Andrew Mylius reports.



INADEQUATE TEMPORARY works design and construction errors led to the fatal collapse of Singapore's deepest ever cut and cover tunnel, the public inquiry into the disaster heard at the end of March.

A 110m section of tunnel being built for Singapore Mass Rapid Transit's new Circle Line, adjacent to the six lane Nicoll Highway, collapsed on 20 April last year (GE May 2004).

Four workers died when steel struts supporting the excavation's diaphragm walls failed, causing the tunnel to cave in. Part of the highway was also destroyed.

The disaster was triggered by deformation of a connection between the horizontal struts and waling beams running horizontally along the diaphragm walls, according to part of the summary of evidence submitted to the Committee of Inquiry in Singapore on 31 March.

The general causes of the collapse were agreed by client the Land Transport Authority (LTA), main contractor Nishimatsu-Lum Chang joint venture (NLC), NLC's designer Maunsell Asia, NLC project engineer Paul Broome, base slab subcontractor L&M, strutting subcontractor Kori, diaphragm walling subcontractor Bachy Soletanche, project insurer Aviva, LTA project directors Ng Seng Yoong and Sripathy and Singapore's Ministry of Manpower.

But details are being disputed by the main contractor and the LTA (see boxes).

The collapse occurred east of the planned Nicoll Highway station in a section of cut and cover tunnel adjoining a large diameter reinforced concrete shaft.

This had been built in preparation for the launch and extraction of a tunnel boring machine, which was to drive a section of tunnel under

The client's case

Main contractor Nishimatsu-Lum Chang (NLC) was negligent, reckless and dishonest during design and construction of the collapsed section of tunnel, client the Land Transport Authority (LTA) claimed.

NLC's catalogue of design errors started with the use of inappropriate soil analysis during the early stages of temporary works design, LTA's counsel K Shanmugam said.

Finite element analysis of ground conditions used the mechanical properties of drained soil – known as Method A. NLC should have been using data for undrained soils for deep excavation in the site's highly plastic marine clays, he stated.

"Use of Method A was grossly erroneous. It was a substantial error. Use of Method A led to serious underprediction of the forces acting on the temporary works, and hence led to underdesign in the temporary works in general.

"This was an error which bedevilled the entire design, and consequently the entire system had insufficient capacity to cater for the loads coming on to it."

NLC's soil analysis meant that as excavation got deeper, deflections of the diaphragm wall increasingly exceeded those predicted.

Shanmugam insisted that "NLC knew from the outset in 2001 that there would be potential problems with Method A, but recklessly and dishonestly persisted in using it and refused to change."

Combined with further errors in temporary works design, this contributed to strut-waler connections being understrength by a factor of two.

LTA claimed the problem was compounded by NLC's substitution of C-channel stiffeners for plate stiffeners at the strut-waler connection.

NLC sought to save costs by using "scrap material to replace stiffener plates which they had run out of", Shanmugam stated. "NLC ignored its own risk analysis which stated that a fundamental reassessment had to be done in the light of stiffener plate buckling."

NLC was worried by the situation, but sought to suppress information to prevent LTA interfering in its construction schedule, Shanmugam claimed.

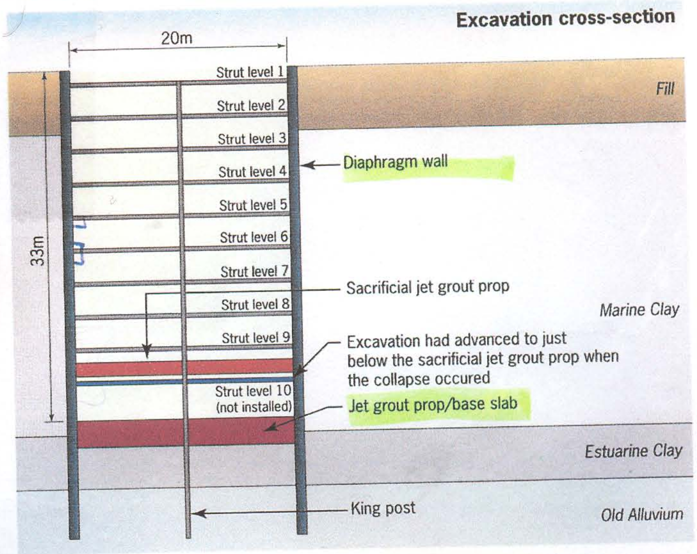
By April 2004 NLC had S$25M (£8.3M) against it in claims for late delivery against schedule.

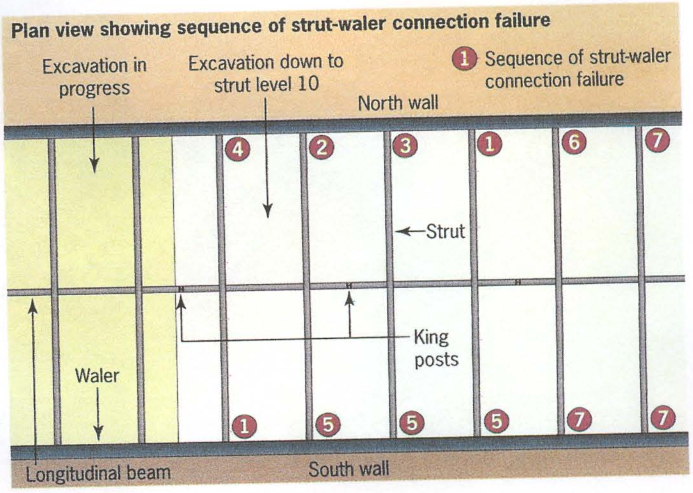
"If LTA knew that NLC's design had serious defects, and that NLC was concerned and uncomfortable about its own design, the LTA would probably have stopped work, and in these circumstances NLC would have to bear the costs of delay on its own."

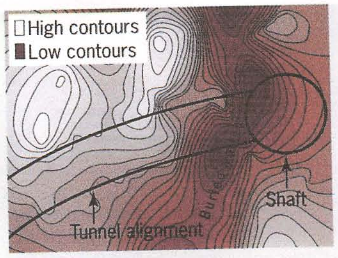
Even after struts failed at two adjacent NLC sites, the contractor maintained its temporary works designs were satisfactory, and pressured LTA to allow it to resume work, Shanmugam said.

NLC breached its legal duties to reveal key information, he added. "LTA never had sufficient material information from NLC to justify exercising its contractual powers to stop work."

LTA refuted NLC's claim that an unforeseen trigger would have been required to set off the sequence of collapse.







The contractor's case

Unforeseen relative movement between the diaphragm walls and king posts triggered the Nicoll Highway tunnel collapse, main contractor Nishimatsu-Lum Chang JV (NLC) has claimed.

The sudden change in relative level altered the angle at which struts bore on to the walers, causing them to deform rapidly, and leading to "sway failure".

Sway failure describes a mechanism in which the junctions between the flanges and web of an I-beam act as hinges, with one flange moving downwards relative to the other.

NLC has coined the term "forced sway failure" to describe the violent forcing of this mode of collapse.

Movement of diaphragm walls relative to the king posts had been observed on other sections of Circle Line cut and cover excavation, but there was no evidence of this at Nicoll Highway.

It is thought that downward movement of diaphragm walls happens when they deflect, allowing soils behind to relax, so reducing pore water pressure. This contributes to a reduction in skin friction between the wall and surrounding ground.

"Collapse was not inevitable. The collapse occurred because the forced sway mechanism dramatically reduced the time in which it developed," claimed NLC counsel Philip Jeyaretnam.

Though close to the limit there was no evidence to show that loads exceeded the temporary works' ultimate capacity, he added – "there was no evidence of a build-up of loads prior to 20 April".

"If the loads exceeded actual capacity the connections would have failed as excavation beneath each strut reached the 10th level, or as loads built up with time after completion of excavation. There was no evidence from the monitoring trends of significant build up in loads with time.

"Strain gauge readings gave no indication of a build-up of load, nor even that the loads were high," he said.

NLC was dismissive of the importance attached by the Land Transport Authority (LTA) to the use of drained soil data in finite element analysis of ground conditions on site (Method A).

It said use of drained soil data was appropriate as, at shallower depths, it tends to give conservative results, although there was no precedent for such deep excavation using Method A in Singapore.

During the early stages of construction, LTA accepted deflections measured on site were close to those anticipated using Method A finite element analysis, Jeyaretnam said.

LTA had been briefed on the soil analysis by NLC's independent engineer in May 2002, and LTA's supervising engineer had described alternative analysis models as over-cautious, he added.

NLC discovered a buried channel in the old alluvium, which was filled with deep, soft, organic clay. There was also a bowl of soft estuarine clay below the marine clay. Neither had been detected during the site investigation.

The temporary works had not been designed for these conditions, and had to be adapted, Jeyaretnam said.

Design errors resulted from the application of engineering judgement, not negligence.

"It is completely clear that NLC's engineers did not realise the structural design errors, or the potential brittleness introduced by the C-channels [stiffeners used in the strut-waler connections]."

Jeyaretnam maintained LTA had been kept abreast of issues at the Nicoll Highway site and had appeared to agree NLC's design would allow safe construction.

Strutting arrangement

Strutting in the collapsed section was different to that being used on neighbouring cut-and-cover sections where the alignment was straighter.

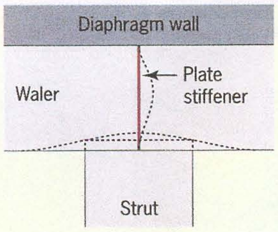
On the straight sections NLC fixed struts at 4m centres to the 6m wide diaphragm wall panels. Struts were connected symmetrically to prevent uneven forces being applied. Asymmetrical wall panel loading would have introduced rotational moments that could have undermined the structure's integrity.

An alternating connection pattern was applied along each diaphragm wall: two struts were connected to the outer edges of one panel and a single strut to the centre of the next panel.

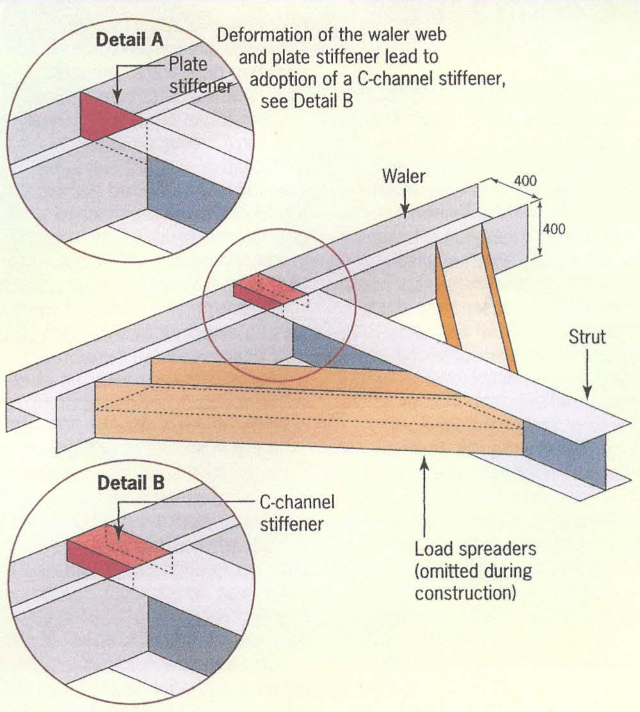
But the curved tunnel alignment near the TBM launch shaft forced a radial arrangement of struts. This disrupted the symmetry of the strut to panel connection pattern, and would have resulted in uneven loading of diaphragm wall panels.

A more flexible strutting system was therefore designed, with struts connected to horizontal waling beams which spread loads over a larger area.

Strutting forces were to be further distributed by the installation of I-section spreaders, branching from the strut-ends at 45°. Struts were supported mid-span by king posts connected by longitudinal stringer beams. Struts, waling beams and king posts were 400mm² I-sections.



Typical waler web and plate stiffener deflection



the nearby Kallang River.

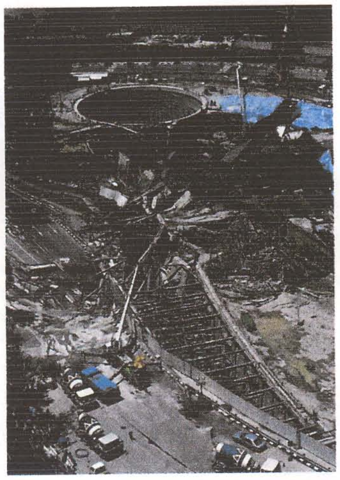
The collapsed cut and cover section curved through an area of reclaimed land, comprising 6m of fill over 27m of soft marine clay and 5m of estuarine clay. It was unusually deep, with a base slab at 33m below ground level. This was to accommodate LTA's plans to build a future road tunnel above the rail tunnel.

Construction involved the installation of reinforced concrete diaphragm walls and two deep level jet-grout slabs before excavation began.

The lower slab, 33m below ground, was to form the permanent base of the excavation. It also acted as a major structural component, resisting earth pressure behind the diaphragm walls after excavation had been completed.

The upper slab, or "sacrificial jet grout prop", 6m above, was installed to provide temporary support to the diaphragm walls. It was to be broken out and replaced with steel struts as excavation advanced.

In all, 10 levels of struts were to be installed between the base slab and the surface during construction. These connected with horizontal walers running along the diaphragm walls in the curved section (see box).



Excavation was in its final stages – at 30m, just 3m above formation level – when collapse began. With level nine struts in place and working from the launch shaft end, the contractor began breaking out the sacrificial jet grout prop to allow excavation to continue.

But before the final level of struts could be installed, the level nine struts became overloaded and their connections with the waler beams yielded. This allowed the walls to deform, in turn causing overloading of struts above. This triggered progressive collapse of the walls.

Failure was rapid. Only an hour elapsed between failure of the first strut-waler connection and total collapse of the excavation.

NLC admitted to the inquiry that failure of the temporary works resulted from under-design and inappropriate detailing of the strut-waler connections.

NLC's design engineers misinterpreted building code BS5950, NLC's counsel Philip Jeyaretnam said. This resulted in the adoption of smaller than required steel sections, reducing the amount of redundancy in the design.

But this design deficiency was made drastically worse by omission of load spreading splays at the ends of the struts during construction. The contractor's failure to include these crucial structural components in the strut-waler connection was not picked up during routine works supervision.

Consequently, the entire axial load of each strut was directed into the waling beam through a single point of contact.

Forces of 4,000kN-4,600kN were being channelled through a detail designed with a capacity of 2,551kN. Laboratory testing and finite element analysis of identical strut-waler connections after the collapse revealed an actual ultimate capacity of 4,030kN-4,260kN.

The resultant overloading of the connections led to buckling of the waler web in several locations before the collapse occurred.

NLC replaced waler web plate stiffeners with a C-channel stiffening detail – commonly used in Nishimatsu's home country Japan.

All parties have agreed the sudden failure of this detail on level nine strut-waler connections caused the collapse.

But there is intense disagreement between the parties over why this detail should have failed so suddenly and dramatically.

Head of the Committee of Inquiry Judge Richard Magnus was expected to reach a decision on who was to blame for the collapse at the end of April, soon after *GE* went to press.

● The Land Transport Authority's expert witness, Benaim director of geotechnical engineering Richard Davies, will be speaking about the Nicoll Highway collapse and inquiry at *New Civil Engineer's* Megatunnels conference on 18 May. For more details visit www.megatunnels.com or tel +44 (0)20 7505 6944.