Design and construction failures caused Singapore tunnel collapse

INADEQUATE TEMPORARY works and 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 last week.

The collapse hit a 110m section of tunnel being constructed for Singapore Mass Rapid Transit’s new Circle Line, adjacent to the six lane Nicoll Highway. Four workers died when steel struts supporting the excavation’s diaphragm walls failed, causing the tunnel to cave in on 20 April last year. Part of the highway was also destroyed. The disaster was triggered by the failure of a connection between horizontal struts and waling beams, which between them supported the diaphragm walls, the inquiry heard last week.

The explanation was given as part of a summary of evidence submitted to the Committee of Inquiry in Singapore.

The general causes of the collapse were agreed last month 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.

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 told the inquiry into the Nicoll Highway collapse.

Finite element analysis of ground conditions used the mechanical properties of drained soil - known as Method A. For deep excavation of the Nicoll Highway tunnel in the highly plastic marine clays found on site, NLC should have used data for undrained soils, Shanmugam 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 onto 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 led to strut-water connections being under-strength by a factor of two, he told the inquiry.

LTA claimed that the problem was compounded by NLC’s substitution of C-channel shaped steel sections for plate stiffeners to strengthen the strut-wafer connection.

NLC cut 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 light of stiffener plate buckling.”

The situation worried NLC, but it sought to suppress information to prevent LTA interfering in its construction schedule, Shanmugam claimed. By April 2004 NLC had S$25M (£83M) 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 had to bear the costs of delay or its own.”

Even after struts failed at two adjacent NLC sites the contractor maintained that 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...”
Unforeseen downward movement in diaphragm walls triggered the Nicoll Highway tunnel collapse, main contractor Nishimatsu-Lum Chang jv (NLC) claimed before the public inquiry last week.

A sudden drop in the height of the wall relative to king posts supporting the temporary struts altered the angle at which struts connected with the walers. This caused them to deform rapidly, leading to "sway failure", the contractor said.

Sway failure happens when the junctions between the flanges and web of an I-beam act as hinges, causing the beam to flatten under heavy loading.

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

Movement of diaphragm walls relative to king posts had been observed on other sections of Singapore’s Circle Line cut and cover excavation. But there was no evidence of this at Nicoll Highway, said the contractor. "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.

Although the struts were close to the limit at which they could fail, there was no evidence that loads exceeded the ultimate capacity of the temporary works, he added. "There was no evidence of a build up of loads before 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 the diaphragm walls apart during cut and cover tunnel works. These connected with horizontal walers running along the tunnel walls (see box overleaf).

The catastrophic failure started at the ninth level strut-waler connections, 30m below ground, and only 3m above formation level, the Committee of Inquiry heard. Yielding of the level nine connections allowed the diaphragm wall to deform.

NLC dismissed the importance attached by the client LTA to the use of drained soil data in finite element analysis of ground conditions on site.

It said this 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, NLC claimed LTA accepted that deflections measured on site were close to those anticipated using Method A finite element analysis, Jeyaretnam said.

NLC’s independent engineer Dr Andy Pickles of consultant CPG had briefed LTA on the soil analysis in May 2002 and LTA’s supervising engineer had described alternative analysis models as over-cautious, he added.

What went wrong: the contractor’s view

Unforeseen downward movement in diaphragm walls triggered the Nicoll Highway tunnel collapse, main contractor Nishimatsu-Lum Chang jv (NLC) claimed before the public inquiry last week.

A sudden drop in the height of the wall relative to king posts supporting the temporary struts altered the angle at which struts connected with the walers. This caused them to deform rapidly, leading to "sway failure", the contractor said.

Sway failure happens when the junctions between the flanges and web of an I-beam act as hinges, causing the beam to flatten under heavy loading.

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

Movement of diaphragm walls relative to king posts had been observed on other sections of Singapore’s Circle Line cut and cover excavation. But there was no evidence of this at Nicoll Highway, said the contractor. "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.

Although the struts were close to the limit at which they could fail, there was no evidence that loads exceeded the ultimate capacity of the temporary works, he added. "There was no evidence of a build up of loads before 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 the diaphragm walls apart during cut and cover tunnel works. These connected with horizontal walers running along the tunnel walls (see box overleaf).

The catastrophic failure started at the ninth level strut-waler connections, 30m below ground, and only 3m above formation level, the Committee of Inquiry heard. Yielding of the level nine connections allowed the diaphragm wall to deform.

NLC dismissed the importance attached by the client LTA to the use of drained soil data in finite element analysis of ground conditions on site.

It said this 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, NLC claimed LTA accepted that deflections measured on site were close to those anticipated using Method A finite element analysis, Jeyaretnam said.

NLC’s independent engineer Dr Andy Pickles of consultant CPG had briefed LTA on the soil analysis in May 2002 and LTA’s supervising engineer had described alternative analysis models as over-cautious, he added.
overloading struts in levels above, causing them to buckle. This triggered a progressive collapse of the tunnel walls. The failure was rapid. Only an hour elapsed between failure of the first strut-waler connection and total collapse of the excavation. Overloading of the temporary works coincided with the excavation of a sacrificial prop installed using jet grouting methods just below the ninth level struts. NLC admitted to the inquiry that failure of the temporary works resulted from underdesign and inappropriate detailing of the strut-waler connections. NLC’s design engineers misinterpreted building code BS5950, said counsel for NLC Philip Jeyaretnam. This resulted in the adoption of smaller than required steel sections for the struts, reducing redundancy in the design.

The collapse was the result of under-designed temporary works.

Problems with the temporary works

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 Kallang river.

The collapsed cut and cover section was on a curve in an area of reclaimed land, consisting of 6m of made ground 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 the 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-grouted slabs before excavation got under way.

The lower slab formed the tunnel base while the upper one was sacrificial, located 6m above the base slab. It was installed to provide temporary support to the diaphragm walls. The sacrificial slab was to

![Diagram](image-url)
But this design deficiency was made drastically worse by omission of load spreading splays at the ends of the struts during construction (see diagram).

The contractor’s failure to include these crucial structural components in the strut-waler connection was not picked up during routine works supervision the inquiry heard.

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

Forces of 4,000kN to 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.

Overloading of the connections led to buckling of the NLC replaced waler web plate stiffeners with a C-channel stiffening detail - a "C" shaped piece of steel commonly used in Nishimatsu’s home country Japan.

All parties agreed that the sudden failure of this detail on the 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, is expected to reach a decision on who was to blame for the collapse later this month.

Andrew Mylius, in Singapore • 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 NCEI’s Megatunnels conference, Wednesday 18 May.


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.

Level nine struts had been installed and work on level 10 excavation, including breaking out the sacrificial jet-grouted prop, was under way when the collapse occurred.

Strutting in the area of the collapse was unlike that being used on neighbouring cut and cover tunnel sections where the alignment was straighter.

The inquiry was told NLC was fixing struts directly to the 6m wide diaphragm wall panels over most of the excavation. Struts were at 4m centres.

Struts were connected to diaphragm wall panels symmetrically to prevent uneven forces being applied.

Asymmetrical wall panel loading would have introduced rotational moments that could have undermined the structure’s integrity.

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 in the curved section were to be further distributed by 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 400mm by 400mm I-sections.