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Heat Transfer and Thermal Stresses in the Singapore Cable Tunnel

Transfert de chaleur et effets thermiques dans le tunnel immergé à Singapour

Wärmeleitung und thermische Spannungen im Untersee -Kabeltunnel in Singapur

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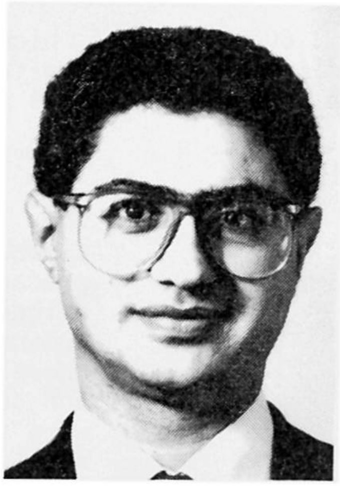

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SUMMARY
In 1986 a 2.6 km long undersea cable tunnel in Singapore was completed. The heat generated by the power circuits is removed from the tunnel by means of a cooling water system and a ventilation system. Heat transfer calculations were carried out and formed the basis for the structural stress analysis.

RÉSUMÉ
En 1986, la construction d'un tunnel immergé de 2,6 km de longueur a été achevée à Singapour. La chaleur produite par les câbles haute – tension a été éliminée du tunnel du moyen d'une installation de refroidissement par eau et d'un système de système d'aération. Les calculs de ce transfert de chaleur ont formé la base de l'analyse des contraintes dans le tunnel.

ZUSAMMENFASSUNG
Im Jahre 1986 wurde der 2,6 km lange Untersee-Kabeltunnel in Singapur fertiggestellt. Die Abwärme aus dem Transport elektrischer Energie wird mittels eines Kühlwassersystems und einer Lüftungsanlage aus dem Tunnel entfernt. Wärmeleitungsberechnungen bildeten die Grundlage der Spannungsanalysen für den Tunnel.

1. INTRODUCTION

In April 1985, the Public Utilities Board of Singapore (PUB) awarded to Christiani & Nielsen A/S a contract for the design and construction of an immersed cable tunnel from Pulau Seraya across the Jurong Strait to Mainland Singapore.

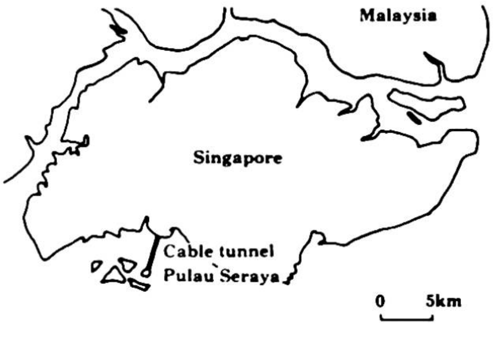

Fig. 1 Tunnel Location

At the time of award, a 1750 MW power station was under construction on Pulau Seraya. This station has now been commissioned, supplying electrical power to Singapore since January 1987.

The construction of the immersed tunnel, two terminal buildings, mechanical and electrical installations was completed by the end of 1986.

The contract was awarded as a result of international tendering based on an outline design and specifications prepared by Mott, Hay & Anderson Asia Pte. The detailed design of the immersed tunnel and the planning of the construction methods were done by Christiani & Nielsen while Ove Arup and Partners, London were engaged for the design of the terminal buildings, the mechanical/electrical installations and ancillary services in the tunnel.

2. THE SUBMERGED CABLE TUNNEL

The immersed cable tunnel is 2,600 m long of which 1,800 m has a floor level 23 metres or more below main sea level. The tunnel consist of 26 nos. 100 metres long elements with overall dimensions of 6.50 m wide x 3.70 m high.

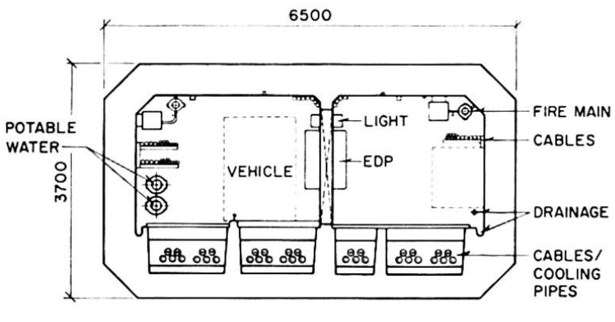

Fig. 2 Cross-section of cable tunnel

The 100 metres long tunnel elements were made up of 29 precast segments. These were aligned and prestressed longitudinally on a marine lift where 80% of the mechanical and electrical installations were also fitted. After launching from the marine lift, each element was towed into position, sunk, founded and backfilled.

3. COOLING SYSTEMS

3.1 Cable Loading and Troughs

The maximum normal cable loading is established as being a total of continuous load of the power station at 2000 MVA and 230 kV. There are seven cable circuits each designed for 500 MVA.

The power circuits and associated cooling pipes are arranged in flat formation in troughs which are back-filled by a lean mix concrete of 0.8 W/m°K thermal conductivity. The west bore, Figure 3, houses four circuits which generate 365 W/m heat at full load. The east bore houses two troughs, one containing a single circuit with heat generation of 89 W/m and the other containing two circuits with heat generation of 181 W/m when operating at full load. Any number of the seven circuits can be loaded in any combination at full or part load subject to the maximum total continuous load.

3.2 Water Cooling System

Each power circuit is associated with two piped cooling water circuits, each pipe designed for a flow rate of 3 kg/s at maximum outlet temperature of 40°C. The cooling water is pumped from Pulau Seraya Terminal cooling towers to the tunnel cable through pipework to extract heat from power circuits. The heated water is then discharged at the Pandan Road Terminal cooling towers. The water is cooled and pumped back to the cable troughs in the tunnel. The cycle is continuously repeated. The cooling equipment is provided with 100% standby and situated at the two terminals. Equipment at each terminal is designed for 50% of the total cooling requirements.

Power circuits generate heat which is primarily removed by cooling water. The rate of heat removal, q, as advised by the cable contractor depends on the loading of cables. The maximum values are 52, 121 and 261 W/m for a single circuit, two circuits in one trough and four circuits in the same bore respectively. The excess heat which cannot be removed by the cooling water system dissipates by ventilating air and by transmission to the tunnel structure, sea and seabed.

3.3 Tunnel Ventilation

The tunnel ventilation system provides environmental control of the tunnel atmosphere whilst unmanned, during maintenance occupation and in an emergency.

Six axial flow, vertical mounted, two speed, two stage, contra rotating, reversible fans are located in the Pulau Seraya terminal building. The fans operate in two banks, one bank per bore. Each bank is operated in various fan, stage and speed combinations to suit the three conditions. There are three modes of fan operatin for each bore.

i) A single fan operates continuously at low speed with one stage working to achieve the minimum air velocity of 1 m/s required for heat dissipation, whilst maintaining a tunnel air temperature not exceeding 40°C. Ambient air at maximum temperature of 33°C is drawn into each bore via the Pandan Road terminal building. It is then passed via segregated shafts into the respective bores. The fans extract the vitiated air from the tunnel and exhaust it to atmosphere at the Seraya terminal building.

ii) Two fans operate at low speed with both stages working to achieve the minimum tunnel air velocity of 2.5 m/s, required for ventilation with the tunnel occupied and all services in operation and with maximum normal operating condition at the power circuits.

iii) The fans are capable of being manually set in the high speed and reverse modes from the fireman's control panels situated at either end of the tunnel for smoke removal. The fans either extract smoke from the tunnel in the normal direction or are reversed to draw in air and exhaust instead through the Pandan Road terminal. Two fans operate at high speed with both stages working to achieve tunnel air velocities of 5 M/s in the normal mode or 4.5 m/s in the reverse mode.

4.0 THE HEAT TRANSFER MODEL

4.1 Objective and Assumptions

The heat transfer model is developed to check that the ventilation system corresponding to the different modes of operation will maintain a tunnel air temperature of less than 40°C when any combination of power circuits are under maximum normal load, and to investigate the temperatures that will result along the tunnel at various surfaces of the tunnel cross section.

The steady state heat balance equations for air and two cable cores in the west and east bores have been solved to arrive at air temperature distribution along the tunnel. Assumptions have been made that, (i) the heat conduction and convection coefficients are constant along the tunnel, (ii) axial and peripheral conduction is negligible, (iii) at any cross section, the air temperature in each bore and temperature of each cable core are constant.

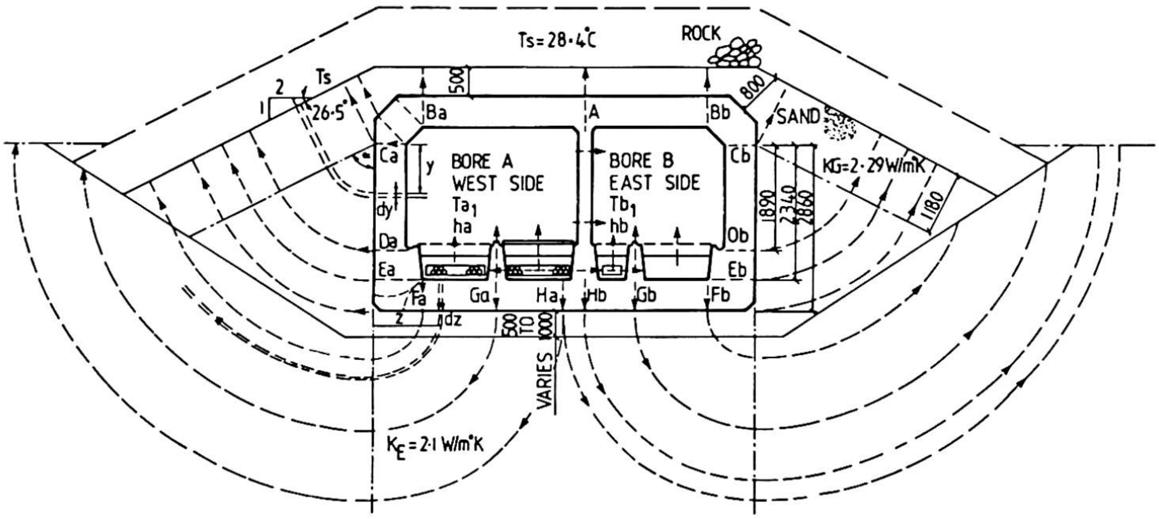

Fig. 3 Heat Conduction Model

4.2 The Heat Conduction Model

Figure 3 shows the heat conduction model at a cross section of the tunnel. The perimeter of the tunnel has been divided into a number of section, as AB, BC, CD, etc. on Figure 3, for which a set of uniform heat-flow path is designated. In mapping the path, attention has been given to experimental studies in [1] and [2], and it is assumed that the internal and external concrete surfaces for each section are isotherms. The paths in each section have then been used for calculating the heat conductance (W/°K) per unit length of the tunnel.

The conductances of appropriate sections have been added to find the total conductances corresponding to the heat transfer between cable cores, air and sea.

4.3 Energy Balance Equations

Referring to Figure 3, the heat balance equations for air, Cable Core 1 (Outer trough) and Cable Core 2 (Inner trough) at a discrete length ΔL, m, along the tunnel are:

Bore A

$$(MC)_a \frac{\Delta Ta}{\Delta L} + K_{a1}(T_a - T_s) + K_{ab1}(T_a - T_b) = K_{a21}(T_{ca1} - T_a) + K_{a22}(T_{ca2} - T_a) \quad (1)$$

$$K_{a21}(T_{ca1} - T_a) + K_{a31}(T_{ca1} - T_s) + K_{a4}(T_{ca1} - T_{ca2}) = q_{a1} \quad (2)$$

$$K_{a22}(T_{ca2} - T_a) + K_{a32}(T_{ca2} - T_s) + K_{a4}(T_{ca2} - T_{ca1}) + K_{ab2}(T_{ca2} - T_{cb2}) = q_{a2} \quad (3)$$

Bore B

$$(MC)_b \frac{\Delta Tb}{\Delta L} + K_{b1}(T_b - T_s) + K_{ab1}(T_b - T_a) = k_{b21}(T_{cb1} - T_b) + K_{b22}(T_{cb2} - T_b) \quad (4)$$

$$K_{b21}(T_{cb1} - T_b) + K_{b31}(T_{cb1} - T_s) + K_{b4}(T_{cb1} - T_{cb2}) = q_{b1} \quad (5)$$

$$K_{b22}(T_{cb2} - T_b) + K_{b32}(T_{cb2} - T_s) + K_{b4}(T_{cb2} - T_{cb1}) + K_{ab2}(T_{cb2} - T_{ca2}) = q_{b2} \quad (6)$$

Where M and C are mass flow rate and specific heat of air and T is temperature. Subscripts a, b and c refer to bore A, bore B and cable core respectively. Conductance, K(W/m) is defined as follows:

K_1 Air and Sea, K_{21} Air and Cable Core 1 (the outer trough), K_{22} Air and Cable Core 2 (the inner trough) and sea, K_4 The Two Adjacent Cable Cores in each bore, K_{ab1} Air in Two Bores, K_{ab2} The two Adjacent Cable Cores in Two bores. Heat transfer coefficient inside the tunnel has been calculated from:

$Nu = 0.023\ Pr^{.3}\ Re^{.8}$, Where, $Re = (VD/\nu)$, $Nu = (hD/k)$, and Pr is the Prandtl number. At each discrete interval, it is assumed that:

$\Delta T_a = (T_{a2} - T_{a1})/2$, $\Delta T_b = (T_{b2} - T_{b1})/2$, $T_a = (T_{a2} + T_{a1})/2$,
$T_b = (T_{b2} + T_{b1})/2$

Where (T_{a1}, T_{b1}) and (T_{a2}, T_{b2}) denote the air temperatures at inlet and outlet of a discrete length respectively. Boundary conditions at the tunnel ends are:

$T_{a1} = T_{b1} = T_{ambient}$ at $x = 0$ and $T < 40^oC$ at $x = 2600$ m

T_a, T_b, T_a and T_b are substituted into equations 1 to 6 and the resulting equations have been solved for the unknown parameters T_{a2}, T_{b2}, T_{ca1}, T_{ca2}, T_{cb1} and T_{cb2} at each intervals. Computation has been carried out on a micro computer for different modes of operation and cable loading.

The model provides the average temperatures that will result along the tunnel at various surfaces of the tunnel cross section together with the air and cable core temperature.

The analysis indicates that the surface of the inner trough in he west bore can reach to a maximum temperature of 64^oC at the "unmanned" mode of operation when three power circuits in the west bore (two circuits in the inner trough) and one single circuits in the inner trough of the east bore are loaded at 2000 MVA.

The model does not account for the effect of moisture evaporation from the tunnel walls. Therefore, the results obtained for dry air are conservative in regard to the amounts of heat transferred between the air and the tunnel, as the effect of evaporation is to decrease the temperatures of air and tunnel surfaces from those predicted for dry air conditions.

A separate model for periodic analysis based on the modified method in [3] indicates that the variation of maximum temperature due to changes in the ambient temperature would be minor.

5.0 STRESS-ANALYSIS

In the longitudinal direction the bending moments and shear forces were calculated by use of a soil-structure interaction model and from this the number of tendons were determined.

The stress calculation results fulfil the stress requirement for normal operation condition with minimum compression stress 2 Mpa and extreme operation condition with minimum stress 0.0 Mpa. The number of tendons were governed by the two conditions, both conditions included temperature loads.

After sinking, the element is backfilled and locked with an initial axial compression force due to the water pressure. The heat generation from the power circuits will increase the temperature inside the tunnel and thereby cause an increase in the axial compression force already built into the tunnel element.

The non-uniform temperature increase over the cross section due to the position of the circuits at the bottom of the tunnel, following maximum gradients and temperature differences was achieved from the heat transfer calculations

- Gradient roof 2.5^{o}C
- Gradient bottom 1.0^{o}C
- Temperature different roof and bottom 10.9^{o}C

The gradients and the temperature different cause a tension stress in the roof of 2.2 Mpa which was taken into account during the determination of the number of the tendons.

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