Catalogue of Notable Tunnel Failure Case Histories (up to December 2008)

Prepared by Mainland East Division
Geotechnical Engineering Office
Civil Engineering and Development Department
Foreword

This catalogue of notable tunnel failures is primarily based on published information. Both overseas and local cases involving collapse or excessive deformation of the ground are included. For contractual and other reasons, there are relatively few cases reported in technical publications, and those reported are usually of such scale or seriousness that they have received public attention. Even for the cases reported, usually only limited information is available. Apart from the cases included, readers can find other information on tunnel failure in the list of General References given at the end of this catalogue.

This catalogue is a live document that will be updated from time to time as further information becomes available.
Foreword

The main purpose of the catalogue is to disseminate information and promote awareness on tunnel failures which could pose a danger to life and property. The possible causes of the failures, the geotechnical problems and the lessons learnt, where these are known, are outlined in the catalogue. Readers should refer to the source reference documents quoted for details. Clients and works agents are advised to implement effective geotechnical risk management measures in the planning, investigation, design and construction of their tunnel projects.
Foreword

The first edition of the catalogue was issued in February 2007 and was put together by Mr W Lee, supervised by Mr K J Roberts. This second edition was prepared by Ms L Y Pau, supervised by Mr L P Ho. GEO staff, members of the Hong Kong Institution of Engineers Geotechnical Division Working Group on Cavern and Tunnel Engineering and other individuals have contributed to this Catalogue. All contributions are gratefully acknowledged.
Foreword

If any information in this catalogue is found to be inaccurate or out-of-date, please contact the Chief Geotechnical Engineer/Mainland East of the Geotechnical Engineering Office, Civil Engineering and Development Department, 101 Princess Margaret Road, Ho Man Tin, Kowloon, Hong Kong.

P. L. R. Pang
Chief Geotechnical Engineer/Mainland East
Geotechnical Engineering Office
Civil Engineering and Development Department
March 2009
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Overseas Cases
Green Park, London, UK, 1964

• **Background**
  - Tunnel (Green Park to Victoria) driven through London Clay using drum-digger shield

• **The failure**
  - Inflow of sand and gravel, burying most of the shield

Clay & Takacs (1997)
Green Park, London, UK, 1964

• Possible cause of failure
  • The crown of the shield penetrated through the London Clay layer into sand and gravel

• Source
  • Clay & Takacs (1997)

• Background
  • Tunnel (300m long and 3.7m internal diameter) driven through London Clay using hand-shield and lined with cast-iron segments under a disused railway marshalling yard

• The failure
  • Inflow of sand and gravel

Clay & Takacs (1997)

- Possible cause of failure
  - The shield was ineffective in supporting the overlying ground

- Source
  - Clay & Takacs (1997)
Southend-on-Sea Sewage Tunnel, UK, 1966

• **Background**
  • Tunnel driven through London Clay (40m long and 1.35m in diameter)

• **The failure**
  • Water inflow into the tunnel

Clay & Takacs (1997)
Southend-on-Sea Sewage Tunnel, UK, 1966

• Possible cause of failure
  • The tunnel intersected the bottom of an abandoned 600mm diameter well

• Source
  • Clay & Takacs (1997)
Orange-fish Tunnel, South Africa, 1970

• **Background**
  • Tunnel designed to carry irrigation water from the Orange River (80km long and 5.3m in diameter, 1,200m above sea level)
  • Tunnelling using the rail-mounted drill and blast method and lined with insitu concrete

• **First failure – Heavy water inflow**
  • Water inflow of about 55,000 litres/min into the tunnel at 14 bars
  • Entire 1.6km tunnel section flooded within 24 hours

• **Possible cause of failure**
  • The tunnel passed through a shallow anticline and intersected a fissure, about 75mm wide, almost perpendicularly
Orange-fish Tunnel, South Africa, 1970

• Second failure – Fire
  • Methane gas ignited by a blast
  • No explosion occurred as the gas did not reach the explosive concentration
  • The fire burnt for about 6 month

• Possible cause of failure
  • Methane gas from a methane bearing fissure entered the tunnel during excavation

• Source
  • Clay & Takacs (1997)
Munich Underground, Germany, 1980

Construction Today (1994b)
Munich Underground, Germany, 1980

• **Background**
  - New Austrian Tunnelling Method (NATM) construction of twin 6m diameter tunnels

• **The failure**
  - 10m wide, 14m deep sinkhole

• **Possible causes of failure**
  - Local variation in geology with reduction in marl cover to 1-1.5m and led to overstressing of the sprayed concrete temporary lining
Munich Underground, Germany, 1980

- **Consequences**
  - Delay to works

- **Remedial Measures**
  - Void was backfilled with crushed rock and cement and pressure grouted

**Source**
- Construction Today (1994b)
Gibeı Railway Tunnel, Romania, 1985

- **Background**
  - Railway tunnel 2.21km long and 9m in diameter

- **The failure**
  - “Compact” fissured clay layer failed suddenly, allowing water inflow >600 litres/min into the tunnel

Clay & Takacs (1997)
Gibei Railway Tunnel, Romania, 1985

- **Possible cause of failure**
  - The tunnel penetrated a lens of waterlogged fine-grained sand just above the crown

- **Source**
  - Clay & Takacs (1997)
Moda Collector Tunnel, Istanbul Sewerage Scheme, Turkey, 1989

- **Background**
  - Tunnel constructed by Tunnel Boring Machine (TBM)

- **The failure**
  - Fine soil flowed into the tunnel forming a hole in the road as the TBM went through the rock into the soft ground

Clay & Takacs (1997)
Moda Collector Tunnel, Istanbul Sewerage Scheme, Turkey, 1989

• Possible cause of failure
  • The tunnel intersected a hidden area of soft clay

• Source
  • Clay & Takacs (1997)
Seoul Metro Line 5 - Phase 2, Korea, 17 Nov. 1991

Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 17 Nov. 1991

- **Background**
  - Construction of Seoul Metro tunnel near Majang by drill and blast method

- **The failure**
  - After blasting: daylight collapse up to ground surface, involving the embankment of a river
  - 20m x 15m and 4m deep crater at the ground surface
  - Water from river flowed into the tunnel

- **Possible cause of failure**
  - Thin weathered rock cover
  - Inflow of soil and groundwater
Seoul Metro Line 5 - Phase 2, Korea, 17 Nov. 1991

- **Consequences**
  - Roads collapse and gas mains fractured

- **Remedial measures**
  - Backfilling the crater with soil followed by cement grouting and chemical grouting

- **Lessons learnt**
  - Insufficient ground investigation
  - Unexpected groundwater inflow
  - No tunnel face stability analysis
  - No consideration of blasting effects closed to weathered zone with shallow cover

Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 17 Nov. 1991

- **Source**
  - Madrid (1996)
Seoul Metro Line 5 - Phase 2, Korea, 27 Nov. 1991

Lee & Cho (2008)
South Metro Line 5 - Phase 2, Korea, 27 Nov. 1991

- **Background**
  - Construction of Seoul Metro tunnel near Dangsan by drill and blast method

- **The failure**
  - 27 November 1991
    - 10:40am: blasting
    - 4:00pm: rock falls at the tunnel face
    - 10:00pm: soil and groundwater inflow into the tunnel
  - 28 November 1991
    - 3:20am: substantial daylight collapse up to ground surface forming a 25m diameter crater
Seoul Metro Line 5 - Phase 2, Korea, 27 Nov. 1991

- **Possible cause of failure**
  - Weathered granite at the face and high permeability soil

- **Consequences**
  - Three buildings collapsed
  - Several water mains, gas pipes and sewerage were broken

- **Remedial measures**
  - Backfilling the crater with soil followed by cement grouting and chemical grouting

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Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 27 Nov. 1991

• Lessons learnt
  • Insufficient ground investigation
  • Unexpected groundwater inflow
  • No tunnel face stability analysis
  • No consideration of blasting effects closed to weathered zone with shallow cover

• Source
  • Lee & Cho (2008)
  • Madrid (1996)
  • Shin et al (2006)
Seoul Metro Line 5 - Phase 2, Korea, 11 Feb. 1992

Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 11 Feb. 1992

• Background
  • Construction of Seoul Metro tunnel near Youido by road header

• The failure
  • Significant inflow of groundwater
  • About 4.5 tonnes of soil flowed into tunnel
  • 38m wide x 6m deep crater at the ground surface
Seoul Metro Line 5 - Phase 2, Korea, 11 Feb. 1992

• **Possible cause of failure**
  - Weathered granite at the tunnel face and high permeability soil

• **Remedial measures**
  - Backfilling the crater with soil followed by cement grouting and chemical grouting

• **Lessons learnt**
  - Insufficient ground investigation
  - Unexpected groundwater inflow
  - No tunnel face stability analysis

Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 11 Feb. 1992

- **Source**
  - Madrid (1996)
Seoul Metro Line 5 - Phase 2, Korea, 7 Jan. 1993

Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 7 Jan. 1993

• **Background**
  • Construction of Seoul Metro tunnel near Yongdungpo by drill and blast method

• **The failure**
  • Tunnel collapsed after removing spoil
  • Tunnel collapsed starting from the left side of the crown
  • 900m³ of loose material flowed into the tunnel and water inflow of up to 300 litres/min recorded
Seoul Metro Line 5 - Phase 2, Korea, 7 Jan. 1993

- Possible cause of failure
  - Weathered granite at the tunnel face
  - High groundwater pressure

- Remedial measures
  - Backfilling the crater with soil followed by cement grouting and chemical grouting
Seoul Metro Line 5 - Phase 2, Korea, 7 Jan. 1993

• Lessons learnt
  • Insufficient ground investigation
  • Unexpected groundwater inflow
  • No tunnel face stability analysis
  • No consideration of blasting effects closed to weathered zone with shallow cover

• Source
  • Lee & Cho (2008)
  • Madrid (1996)
  • Shin et al (2006)
Seoul Metro Line 5 - Phase 2, Korea, 1 Feb. 1993

Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 1 Feb. 1993

• **Background**
  - Construction of Seoul Metro tunnel near Anyangcheon by road header

• **The failure**
  - Daylight collapse when weathered granite found at the tunnel face
  - Groundwater flowed into the tunnel
  - 60m wide oval shaped area subsided
Seoul Metro Line 5 - Phase 2, Korea, 1 Feb. 1993

- **Possible cause of failure**
  - Weathered granite and alluvium at the tunnel face
  - High groundwater pressure

- **Consequences**
  - Six heavy plants buried

- **Remedial measures**
  - Backfilling the crater with soil followed by cement grouting and chemical grouting

Lee & Cho (2008)
Seoul Metro Line 5 - Phase 2, Korea, 1 Feb. 1993

- Lessons learnt
  - Insufficient ground investigation
  - Unexpected groundwater inflow
  - No tunnel face stability analysis

- Source
  - Madrid (1996)
Motorway Tunnels, Austria, 1993-95

• Background
  • Tunnel constructed in sandstone and shale with fault zones by the drill & blast method
  • Tunnel divided into 4 sections, namely T1 – T4
  • T1 - 376m long; T2 - 562m; T3 – 2,760m and T4 – 1,230m

• Failures at T4 in 1993
  • About 130 overbreak incidents with total volume of 1,461m³, maximum deformation of 120mm measured in the tunnel
  • 200m³ of loose material collapsed after a blast, resulting in water inflow of up to 450 litres/min
Motorway Tunnels, Austria, 1993-95

- **Two failures at T3 in 1995**
  - 650m$^3$ of loose material flowed into the tunnel, water inflow of up to 1,500 litres/min recorded
  - Radial movement of rib of about 300mm occurred and water inflow of up to 1,500 litres/min recorded

- **Source**
  - Clay & Takacs (1997)
Heathrow Express Tunnel, UK, 21 Oct. 1994

Ground Engineering (2008)

ICE (1998b)
Heathrow Express Tunnel, UK, 21 Oct. 1994

• **Background**
  • NATM in London Clay

• **The failure**
  • 10m diameter crater formed

ICE (1998b)
Heathrow Express Tunnel, UK, 21 Oct. 1994

- **Possible cause of failure**
  - A series of design and management errors combined with poor workmanship and quality control

- **Consequences**
  - Differential settlement induced at adjacent buildings
  - Services Terminal 4 halted for one month
  - Remedial measures caused chaos at Heathrow Airport
  - Recovery cost £150M (3 times original contract sum)
Heathrow Express Tunnel, UK, 21 Oct. 1994

GROUND SURFACE CONTOURS

LEGENDS

- Blue: 0 to +0.5m
- Green: 0 to -1m
- Yellow: -1 to -2m
- Red: -2 to -3m
- Orange: > -3m

Central Terminal Area Settlement Contours
Heathrow Express Tunnel, UK, 21 Oct. 1994

- Remedial measures
  - Backfilled with 13,000m$^3$ concrete
Heathrow Express Tunnel, UK, 21 Oct. 1994

• **Lessons learnt**
  - Measures to ensure safety must be planned
  - Do not lose sight of critical technical issues in the pursuit of time and cost reduction
  - Whilst a number of factors contributed to the collapse, half of them were matters of management
  - However much engineers are pressured to build quickly and cheaply, the industry will be judged by its own failures

• **Sources**
  - Ground Engineering (2000)
  - ICE (1998b, 1999)
Heathrow Express Tunnel, UK, 21 Oct. 1994

1996 report
Safety of New Austrian Tunnelling Method (NATM) Tunnels
A review of sprayed concrete lined tunnels with particular reference to London clay

2000 report
The collapse of NATM tunnels at Heathrow Airport
A report on the investigation by the Health and Safety Executive into the collapse of New Austrian Tunnelling Method (NATM) tunnels at the Central Terminal Area of Heathrow Airport on 20/21 October 1994

Civil Engineering and Development Department
Hong Kong Special Administration Region Government
Munich Underground, Germany, 27 Sept. 1994

• Background
  • 7m diameter tunnel supported by sprayed concrete lining
  • The tunnel was assumed to be beneath a clay layer overlying water-bearing gravel and groundwater would not be drawn down

• The failure
  • Quick inflow of water and ground materials
  • Large subsidence crater quickly filled with groundwater
  • 20m wide, 18.5m deep crater

Construction Today (1994a)
Munich Underground, Germany, 27 Sept. 1994

- **Possible causes of failure**
  - Layer of marl separating groundwater bearing layers was much thinner than originally assumed
  - Sand-infilled cracks in the marl layer acted as preferential pathways for water

- **Consequences**
  - Bus fell into the crater
  - Three passengers killed
  - 30 people injured

Construction Today (1994a)
Munich Underground, Germany, 27 Sept. 1994

- Remedial measures
  - Bored-pile wall to form a shaft
  - Excavation inside the shaft for rescue
  - Tunnel driven again using compressed air

- Sources
  - Construction Today (1994a)
  - Ground Engineering (1994)
Los Angeles Metro, USA, 22 June 1995

• Background
  • Re-mining/remedial works to realign an existing TBM tunnel (6.7m diameter, 25m deep), which had been bored off line
  • Hard siltstone overlain by alluvium with groundwater level 10-12m below surface

• The failure
  • 25m deep sinkhole caused by collapse of south bore
  • Serious cracking observed in temporary lining of north bore
Los Angeles Metro, USA, 22 June 1995

• **Possible causes of failure**
  • Failure occurred during removal of segmental lining in tunnel roof and relining of tunnel to correct the horizontal alignment
  • Unexpected ground conditions in the alluvium
  • Fractured water mains (unconfirmed)

• **Consequences**
  • 30m length of a four lane road (Hollywood Boulevard) affected leading to road closure
  • Collapsed 250mm water main possibly contributing to failure
  • Broken gas pipe
  • Evacuation of local residents
Los Angeles Metro, USA, 22 June 1995

• Remedial measures
  • Steel rings installed in tunnel either side of the collapse
  • 3,300m³ of grout to fill void and stabilise area
  • Road resurfacing

• Source
  • Civil Engineer International (1995)
Docklands Light Rail, UK, 23 Feb. 1998

ICE (2004)

A crater 22m wide and 7m deep was created by the blast in the grounds of George Green school.

ICE (1998a)

The compressed air blast left a huge crater in a Docklands school playing field.
Docklands Light Rail, UK, 23 Feb. 1998

• Background
  • Tunnel constructed for Docklands Light Rail (diameter 5.2m) by earth pressure balance TBM

• The failure
  • 22m wide and 7m deep crater formed in the grounds of George Green School
Docklands Light Rail, UK, 23 Feb. 1998

• Possible causes of failure
  • Insufficient overburden above the tunnel
  • High pressure within tunnel causing blow out failure

• Consequence
  • Windows up to 100m away broken by the shower of mud and stones released
Docklands Light Rail, UK, 23 Feb. 1998

• Lesson learnt
  • To require specific assessments / calculations to demonstrate the adequacy of factor of safety against blow out failure

• Sources
  • ICE (1998a)
  • ICE (2004)

• **Background**
  
  - Construction of the Olympic Metro under a turnkey contract (estimated cost about 2 billion ECUs)
  - Construction started in November 1991 and operation in 1998
  - TBM (by Mitsubishi) used for construction of 11.7km long, 9.5m diameter tunnels located at a depth of 15-20m (with penetration rate ranging from 1.6m to 18m per day based on 18-hour-per-day shift, depending on the ground conditions)
  - Cut and cover, supported by soldier piles, struts and prestressed anchor tiebacks for 6.3km long tunnels and stations
  - NATM for other short auxiliary tunnels and oval-shaped stations where existence of buried antiquities precluded open excavation

• The failures
  • Roof collapses of appreciable size often occurred
  • Large and occasionally uncontrollable overbreaks for TBM

• Possible causes of failure
  • Ravelling of the ground seems to be due to insufficient strength in the intensely weathered and highly tectonised zones of Athenian schist (which is a flysch-type sediment consisting of thinly bedded clayey and calcareous sandstones with alterations and subjected to intense folding, thrusting, faulting and fracturing)
  • Large muck openings of the TBM cutterhead which cannot adequately control muck-flow (the cutterhead operates in the open air, i.e. under atmospheric pressure)

• Consequence
  • Major delay in TBM tunnelling

• Remedial measures
  • Cavities caused by the TBM overbreaks was backfilled by grout (which sometimes reached the ground surface)

• Source
  • IMIA
  • IMS
  • Kavvadas et al (1996)
  • Mihalis & Kavvadas (1999)
Sewage Tunnel, Hull, UK, 1999


Civil Engineering and Development Department
Hong Kong Special Administration Region Government
Sewage Tunnel, Hull, UK, 1999

• **Background**
  • Construction of a 10.5km long underground sewer by earth pressure balance TBM (diameter 3.85m) supported by reinforced concrete segmental lining

• **The failure**
  • Water and sand ingress
  • Tunnel subsided by 1.2m causing serious subsidence at surface

• **Possible cause of failure**
  • Fluctuation of groundwater level caused by tidal effects resulting in vertical movement of the tunnel tube causing opening of joints
Sewage Tunnel, Hull, UK, 1999

- **Consequences**
  - Damage to buildings, roads and utility lines
  - TBM had to be abandoned

- **Emergency and remedial measures**
  - Ground freezing
  - Reconstruction of tunnel using sprayed concrete

- **Source**
Taegu Metro, South Korea, 1 Jan. 2000

Taegu Metro, South Korea, 1 Jan. 2000

- **Background**
  - Construction of underground Taegu Metro

- **The failure**
  - Failure of diaphragm wall
  - Excavation pit caved in

- **Possible causes of failure**
  - Rapid fluctuation of groundwater level caused movement of unidentified gravel and sand strata
  - Additional loading on diaphragm wall was not considered in design
Taegu Metro, South Korea, 1 Jan. 2000

• Consequences
  • Bus buried and bus driver seriously injured
  • Three passengers killed
  • Neighbouring buildings suffered considerable damage

• Remedial measures
  • Excavation pit backfilled
  • Subsoil grouted and diaphragm wall strengthened

• Source
CTRL infilled the hole with concrete on Saturday night.
### Channel Tunnel Rail Link, UK, Feb. 2003

**Background**
- Tunnelling using TBM (diameter 8.2m)
- Boring at a depth of 21m

**The failure**
- 10m diameter and 20m deep void formed in the ground behind a row of houses

**Possible cause of failure**
- The vibration from the TBM may have caused the nearby wells (30m deep and 1.8m diameter) to collapse
Channel Tunnel Rail Link, UK, Feb. 2003

• Consequence
  • Three uncharted wells collapsed

• Remedial measures
  • The voids were backfilled with grout

• Source
  • ICE (2003)
Météor Metro Tunnel, France, 14 Feb. 2003

Dubois & Rat (2003)
Météor Metro Tunnel, France, 14 Feb. 2003

• Background
  • Construction of Météor Metro Tunnel in Paris

• The failure
  • About 3,000m$^3$ of sedimentary deposits collapsed underneath a school, occupying an area of 400m$^2$ on plan

Dubois & Rat (2003)
Météor Metro Tunnel, France, 14 Feb. 2003

- **Possible cause of failure**
  - Not known

- **Consequences**
  - No casualty
  - The school had to be closed for a year affecting 900 students

- **Source**
  - Dubois & Rat (2003)
Shanghai Metro, China, 2003

Shanghai Metro, China, 2003

• **Background**
  - Expansion of the Shanghai Metro (上海地铁) Line 4 crossing beneath the Huangpu River (黄埔江)
  - Two parallel tunnel tubes constructed by earth pressure balance TBM

• **The failure**
  - Failure occurred during construction of a cross passage
  - Massive ingress of water and material at the face at a depth of 35m
  - Several metres ground subsidence
Shanghai Metro, China, 2003

• **Possible cause of failure**
  • Failure of ground freezing unit

• **Consequences**
  • High rise office buildings seriously damaged
  • Flood protection dyke on the river badly damaged

• **Source**
Hsuehshan Tunnel, Taiwan, 1991-2004

TANEEB (2005)
Hsuehshan Tunnel, Taiwan, 1991-2004

• Background
  • Construction of 12.9km long and 4.8m diameter Hsuehshan Tunnel in Taiwan (雪山隧道)
  • Works commenced in 1991 and completed in 2004
  • Comprised 2 main tunnels (East & Westbound) and a pilot tunnel
  • Eastbound by TBM method (July 1993 to Sept. 2004)
  • Westbound by TBM method (July 1993 to April 2004)
  • Pilot tunnel by drill & blast method (July 1991 to Oct. 2003)
Hsuehshan Tunnel, Taiwan, 1991-2004

• The failures
  • Eastbound
    • 28 collapses occurred
  • Westbound
    • TBM badly damaged due to tunnel collapse and groundwater inflow of 45,000 litres/min into the tunnel
  • Pilot Tunnel
    • 8 collapses occurred

• Possible causes of failure
  • Unexpected difficult geology with fractured rock and massive inflows of water
  • 6 major faults found along the tunnel alignment
Hsuehshan Tunnel, Taiwan, 1991-2004

- **Consequences**
  - Eastbound
    - Failure in May 1993 affected 56 buildings and 73 families
  - Westbound
    - 11 men died
  - Pilot Tunnel
    - 13 stoppages

- **Source**
  - TANEEB (2005)
Stormwater Management and Road Tunnel (SMART), Malaysia, 2003 - 2006

Stormwater Management and Road Tunnel (SMART), Malaysia, 2003 - 2006

- **Background**
  - 9.7km long and 13.26m diameter tunnel driven through karst formation by slurry shield TBM

- **The failure**
  - 37 incidents within 8 km of tunnel excavation

- **Possible cause of failure**
  - Adverse geology and karst conditions
Stormwater Management and Road Tunnel (SMART), Malaysia, 2003 - 2006

Stormwater Management and Road Tunnel (SMART), Malaysia, 2003 - 2006

McFeat-Smith (2008)
Stormwater Management and Road Tunnel (SMART), Malaysia, 2003 - 2006

• Source
  • Siow, M. T. (2006)
  • McFeat-Smith (2008)
Guangzhou Metro Line 3, China, 1 April 2004

Guangzhou Metro Line 3, China, 1 April 2004

• **Background**
  - Construction of a 58.5km long underground metro in which 45.6km is a single-tube shield TBM

• **The failure**
  - Failure of a diaphragm wall

• **Possible cause of failure**
  - Rapid fluctuation of groundwater level due to the heavy rainfall
  - Complicated geology including a layer of swelling soil
Guangzhou Metro Line 3, China, 1 April 2004

- **Consequences**
  - A three-storey building collapsed and sunk into the ground
  - Collapse of nearby underground water mains

- **Remedial measures**
  - Backfilled with crushed rock and cement

- **Source**
  - Soufun (2004)
Singapore MRT, 20 April 2004

• Background
  • An open cut tunnel excavated for Singapore MRT’s new Circle Line
  • Design and build
  • Excavated trench of 15m wide and 33m deep mainly in marine clay with some fluvial clay supported by 0.8-1.0m thick diaphragm wall which is 35-45m deep without rock socket
  • Steel struts: 4-5m horizontal and 3m vertical spacing
  • Bottom-up construction
  • Jet grouted base slabs
    • Layer 1-1.5m thick at 28.5m below ground
    • Layer 2-3m thick at 33.5m below ground (Layer 2 not yet constructed when collapse occurred)
Singapore MRT, 20 April 2004

• The failure
  • 9th level of struts being installed when collapse took place
  • Unusual cracking and groaning noises heard early in the morning (6 hours)
  • Loud cracking noise heard in the afternoon, 15 minutes before collapse
  • Collapse plan area was 100m by 130m
  • Settlement up to 15m
  • Diaphragm walls displaced
  • Steel struts mangled

Government of Singapore (2005)
Civil Engineering and Development Department
Hong Kong Special Administration Region Government
Possible causes of failure

- Under-design of the strut-waler connection in the strutting system
- Incorrect use of Finite Element Method
- No proper design reviews
- Disregard of different warnings, for example, excessive wall deflections and surging inclinometer readings
- Poor construction quality
- Ineffective instrumentation and monitoring system
- Failure to implement risk management
Consequences

- Part of Nicoll Highway, Singapore’s major east-west harbour-front road, destroyed
- Four workers killed
- Several others injured
- 15,000 people and 700 businesses affected
- Three offices and retail towers at risk from further ground movement
- Damage of a gas service line, resulting in an explosion and fire
- A storm drain damaged
Singapore MRT, 20 April 2004

- **Remedial measures**
  - Rescue and backfilling
  - Structurally disconnected the Merdeka Bridge
  - All contracts of the Circle Line put on hold
  - All contracts to carry out checks and review of design and construction of temporary works
  - All Professional Engineers to confirm in writing the adequacy of their designs
  - All designs to be independently checked by the Building & Construction Authority
Lessons learnt

- This is a need for robust design, risk management, design review and independent checking, purposeful back analysis, an effective instrumentation, monitoring and interpretation regime, an effective system of management of uncertainties and quality during construction, corporate competencies and safety management.
- The safety of temporary works is as important as that of permanent works and should be designed according to established codes and checked by competent persons.

Main Source

- Government of Singapore (2005)
Kaohsiung Rapid Transit, Taiwan, 10 Aug. 2004

• **Background**
  - Construction of the Kaohsiung Rapid Transit Blue & Orange Lines in Kaohsiung City

• **The failures**
  - First collapse on 29 May 2004 underneath a street
  - Second collapse in mid June 2004
  - Third collapse on 13 July 2004 with formation of a large sinkhole
  - Fourth collapse on 10 Aug 2004

Taiwan Info (2004)
Kaohsiung Rapid Transit, Taiwan, 10 Aug. 2004

• **Possible cause of failure**
  • Possible adverse ground and groundwater conditions

• **Consequences**
  • First collapse - Several buildings affected and 100 people evacuated
  • Third collapse - Three residential buildings evacuated and significant disruption to water/electricity supply
  • Fourth collapse - No casualty, one building affected and part of the works suspended

• **Source**
  • Taiwan Info (2004)
Barcelona Metro, Spain, 27 Jan. 2005
Barcelona Metro, Spain, 27 Jan. 2005

• Background
  • Tunnel for Barcelona Line Five Metro Extension
  • Tunnelling using NATM

• The failure
  • 30m wide and 32m deep crater formed

• Possible cause of failure
  • A “hidden” vertical fault located 1m behind the sprayed concrete lining
Barcelona Metro, Spain, 27 Jan. 2005

- **Consequences**
  - 2 five-storey buildings and a smaller one demolished
  - More than 50 families made homeless

- **Remedial measures**
  - The void was backfilled with grout of about $2,000m^3$

- **Source**
  - European Foundations (2005)
Lausanne M2 Metro, Switzerland, 22 Feb. 2005

Extent of the cavity with shotcrete applied to the walls to stabilise them and inset, view of the conditions at the face.

Tunnels & Tunnelling (2005)
Lausanne M2 Metro, Switzerland, 22 Feb. 2005

• **Background**
  - Tunnel (6km long, approximately 10m wide x 7m high) for Lausanne Metro M2 Project (cost US$472M) in Switzerland
  - Tunnelling using an Eickhoff ET 380-L roadheader

• **The failure**
  - Collapse in area of soft ground (lake deposits)
  - 50m$^3$ of material displaced into the tunnel at a depth of 12m, leading to a crater at the surface

• **Possible cause of failure**
  - Tunnel driven through a pocket in the glacial moraine, causing sudden inflow of groundwater
Lausanne M2 Metro, Switzerland, 22 Feb. 2005

• **Consequences**
  • People in two buildings, a supermarket and a food outlet in commercial district evacuated when their cellars collapsed
  • No injuries reported

• **Remedial measures**
  • A curtain of 11 piles constructed ahead of the collapsed face with grouting to strengthen the ground and limit further flow of material into the tunnel
  • The void was backfilled with 800m$^3$ of glass-sand (recycled glass)

• **Source**
  • Tunnels & Tunnelling (2005)
Lane Cove Tunnel, Australia, 2 Nov. 2005
Lane Cove Tunnel, Australia, 2 Nov. 2005

• Background
  • Twin NATM tunnels (7m high, 8.1 wide and 3.6km long) constructed under Lane Cove Tunnel Project in Sydney

• The failure
  • Collapse occurred during breakout for a ventilation tunnel from the running tunnel
  • A 10m by 10m, 25m deep crater formed in the ground between a 3-storey high residential building and a highway exit ramp
Lane Cove Tunnel, Australia, 2 Nov. 2005

• Possible causes of failure
  • Possible “rock slippage”
  • Ground investigation did not identify dyke at the tunnel intersection
  • Under designed rock bolts due to increased effective span at intersection of adit and tunnel

• Consequences
  • A 3-storey building partially collapsed and 47 residents evacuated
  • A water main burst
  • Citybound road closed
Lane Cove Tunnel, Australia, 2 Nov. 2005

- **Remedial measures**
  - The void was backfilled with 1,400m$^3$ of concrete
  - Continual monitoring

- **Sources**
  - Golder (2005)
  - Ground Engineering (2005)
  - Ground Engineering (2006a)
  - Ground Engineering (2006b)
  - ICE (2006)
  - NNN (2005)
  - SMH (2005)
Kaohsiung Rapid Transit, Taiwan, 4 Dec. 2005

• **Background**
  - Construction of Kaohsiung Rapid Transit (KRT) Orange Line at the junction of Chungcheng Road and Tashun Road in Kaohsiung City

• **The failure**
  - Failure occurred during excavation of an underground sump pit at a cross passage (33m below ground) underneath an existing reservoir
  - A 30m by 20m, 4m deep trench initially formed on 4 Dec. 2005 and was collapsed to form a 50m by 30m, 10m deep crater at the road surface
  - This was the 10th reported failure of the KRT project
  - Another crater (10m diameter, 7m deep) formed at another location on 10 Dec. 2005
Kaohsiung Rapid Transit, Taiwan, 4 Dec. 2005

- Possible cause of failure
  - Massive water seepage from a reservoir
Kaohsiung Rapid Transit, Taiwan, 4 Dec. 2005

• **Consequences**
  - Chungcheng Road (a major trunk road) closed for a week
  - The nearby Linkang railway line temporarily suspended
  - A 100m long section of tunnels and utilities damaged
  - Cracks found at 20 nearby residential buildings

• **Remedial measures**
  - The crater was backfilled with about 2,800m$^3$ of soil/rock and concrete 20 hours after the accident
  - The damaged sections of the KRT tunnels needed to be re-constructed
  - Cost of the remedial measures estimated to be up to NT$500M (US$15M) excluding reconstruction of the damaged sections of the KRT tunnels
Kaohsiung Rapid Transit, Taiwan, 4 Dec. 2005

- Sources
  - TVB News (2005)
  - TT (2005)
  - SP (2005)
  - ST (2005)
  - Sun (2005)
  - WWP (2005)
  - OD (2005)
  - TKP (2005)
  - MP (2005)
Sao Paulo Metro Station, Brazil, 15 Jan. 2007
Sao Paulo Metro Station, Brazil, 15 Jan. 2007

• Background
  • New Austrian Tunnelling Method (NATM) was used to excavate a 18.5m diameter 45m long section station tunnel
  • The tunnel failure occurred close to a junction with a 40m diameter, 40m deep access shaft

• The failure
  • Collapse of the station tunnel and partial damage to the access shaft
  • The rate of settlement at the tunnel crown increased rapidly and reached 15mm to 20mm two to three days before the failure
Sao Paulo Metro Station, Brazil, 15 Jan. 2007

• Possible cause of failure
  • Failed to account for the geology of the site; fractured rock located over the excavation
  • The lack of sufficient supports in the roof and side walls of the excavation

• Consequences
  • Several vehicles dropped into the 30m-deep hole
  • Seven persons killed

• Remedial measures
  • Stabilized the section of tunnel with extensive reinforcement
  • A system of anchors extending 32m into the soil was put in place and the excavation through the section was performed after pre-grouting
Sao Paulo Metro Station, Brazil, 15 Jan. 2007

• Source
  • ICE (2008)
  • Gulp (2007)
Guangzhou Metro Line 5, China, 17 Jan. 2008

AD (2008)

Sina (2008a)
Guangzhou Metro Line 5, China, 17 Jan. 2008

• Background
  • Construction of a cross passage between two tunnel boring machine tunnels

• The failure
  • Collapse of the cross passage tunnel

• Possible cause of failure
  • Groundwater flowed into the tunnel

• Consequences
  • Cave-in at the road, about 100m² on plan
  • No injury
Guangzhou Metro Line 5, China, 17 Jan. 2008

• Remedial measures
  • Crater backfilled with concrete

• Source
  • AD (2008a)
  • Sina (2008a, 2008b)
Circle Line 4 Tunnel, Singapore, 23 May 2008

Property Highlights of Singapore (2008)

Civil Engineering and Development Department
Hong Kong Special Administration Region Government
Circle Line 4 Tunnel, Singapore, 23 May 2008

• Background
  • Construction of Circle Line 4 tunnel by 6m diameter slurry mixshield TBM

• The failure
  • Cave-in at Holland Road approximately 8m diameter x 3m deep

• Possible cause of failure
  • Loose ground
Circle Line 4 Tunnel, Singapore, 23 May 2008

- **Consequences**
  - Temporary suspension of water supply

- **Remedial measures**
  - Crater backfilled with concrete

- **Source**
  - Property Highlights of Singapore (2008)
Hangzhou Metro Tunnel, China, 15 Nov. 2008
Hangzhou Metro Tunnel, China, 15 Nov. 2008

• **Background**
  • Construction of Hangzhou Metro

• **The Failure**
  • Failure of a series of continuous walls of 800mm thick constructed by cut-and-cover method forming a 21m wide x 16m deep excavated area

• **Consequences**
  • A 75m long section of road collapsed and 11 vehicles fell into the 16m deep excavation
  • A 600mm diameter water main was broken
  • Water from the nearby river flowed into the collapsed area
Hangzhou Metro Tunnel, China, 15 Nov. 2008

• Consequences
  • Three 3-storey buildings seriously damaged and needed to be demolished
  • Two 110kV cables were damaged
  • 8 persons died, 13 persons missing (as of 19 Nov. 2008) and 11 persons injured
Hangzhou Metro Tunnel, China, 15 Nov. 2008

Civil Engineering and Development Department
Hong Kong Special Administration Region Government
Hangzhou Metro Tunnel, China, 15 Nov. 2008

XINHUANET (2008)

XINHUANET (2008)

XINHUANET (2008)
Hangzhou Metro Tunnel, China, 15 Nov. 2008

• Source
  • AD (2008b)
  • Beijing Review (2008)
  • CNS (2008)
  • NCE (2008)
  • XINHUANET (2008)
Hong Kong Cases
MTR Modified Initial System, Prince Edward Station, Nathan Road, 12 Sept. 1977

• **Background**
  • A running tunnel (5m in diameter) being constructed from Prince Edward Station by the drill and blast method
  • Ground above the tunnel strengthened

• **The failure**
  • A wall section of the running tunnel under Nathan Road collapsed
  • The subsidence did not affect the road surface
Possible causes of failure

Gap existed between the ground treatment above the station tunnel and that above the running tunnel allowing the soil to flow into the tunnel.

MTR Modified Initial System, Prince Edward Station, Nathan Road, 12 Sept. 1977

after Clay & Takas (1997)
MTR Modified Initial System, Prince Edward Station, Nathan Road, 12 Sept. 1977

• **Consequences**
  • Nathan Road between Argyle Street and Arran Street closed as a safety measure
  • Three buildings (Nos. 745, 745A and 745B Nathan Road) involving 100 people evacuated
  • Closure Order issued for nearby shops and a petrol station

• **Source**
  • Clay & Takacs (1997)
  • SCMP (1977)
MTR Island Line, 22 Hennessy Road, 1 Jan. 1983
MTR Island Line, 22 Hennessy Road, 1 Jan. 1983

• **Background**
  • Tunnelling from Admiralty to Causeway Bay for MTR Island Line using the drill and blast method
  • Tunnel formed by the drill and blast method

• **The failure**
  • Water-bearing fill flowed into the tunnel, opening a hole at the road above
  • 1,500m$^3$ of material flowed into the tunnel creating a void of an area of 100m$^2$ and 30m deep beneath the road surface
MTR Island Line, 22 Hennessy Road, 1 Jan. 1983

• Possible cause of failure
  • Misinterpretation of the geology by the Contractor
  • Blasting went too far, resulting in the tunnel penetrating the rock into soft ground

after Clay & Takas (1997)
MTR Island Line, 22 Hennessy Road, 1 Jan. 1983

• **Consequences**
  - Cracks found in the granite masonry of the outside wall of a building at 22 Hennessy Road
  - At least 21 timber piles beneath an adjacent building of 22 Hennessy Road exposed
  - More than 150 people in 18-22 Hennessy Road evacuated
  - The building at 18-20 Hennessy Road reopened 3 hours after the incident and the building at 22 Hennessy Road 6 days later
Remedial measures
- The void was backfilled by grout
- The floor slab of the building at 22 Hennessy Road pushed up by the grouting works by 50-75mm

Sources
- Clay & Takacs (1997)
- SCMP (1983)
成安街路陷出现巨洞
两幢楼宇四百人疏散
其中一幢大厦地基有下陷现象

MP (1983a)
MTR Island Line, Shing On Street, Shau Kei Wan, 23 July 1983

- **Background**
  - Tunnelling from Tai Koo Station to Sai Wan Ho Station for MTR Island Line

- **The failure**
  - 13m x 1m void formed
MTR Island Line, Shing On Street, Shau Kei Wan, 23 July 1983

• Consequences
  • Section of Shau Kei Wan Road closed
  • Building at 122-124 Shau Kei Wan Road settled more than 100mm and tilting observed
  • More than 80 families (400 people) evacuated & a woman injured
  • Water main damaged due to the settlement
  • Water and gas supplies stopped

• Source
  • MP (1983a)
MTR Island Line, 140-168 Shau Kei Wan Road
16 Dec. 1983

附件楼宇結構無礙

附近楼宇結構已穩定

食水今將恢復

受路陷影響楼宇
MTR Island Line, 140-168 Shau Kei Wan Road
16 Dec. 1983

• Background
  • Construction of Sai Wan Ho Station for MTR Island Line

• The failure
  • More than 40mm of ground settlement
  • About 150m³ of soil flowed into the tunnel leaving a void between Shau Kei Wan Road and the tunnel
MTR Island Line, 140-168 Shau Kei Wan Road
16 Dec. 1983

• Consequences
  • Section of Shau Kei Wan Road closed
  • Water supply stopped

• Source
  • MP (1983b)
Kowloon Southern Link Contract KDB 200, Canton Road, 21 Oct. 2006
Kowloon Southern Link Contract KDB 200, Canton Road, 21 Oct. 2006

• Background
  • Twin railway tunnels between Jordan Road and East Tsim Sha Tsui Station constructed by a slurry TBM
  • Incident of ground loss occurred at TBM launch area

• The failure
  • 3m(W) x 3.5m(L) x 3m(D) sinkhole formed reaching the ground surface

• Possible cause of failure
  • Slurry leakage and loss of slurry support pressure
Kowloon Southern Link Contract KDB 200, Canton Road, 21 Oct. 2006

- **Consequences**
  - Crater formed at the ground surface closed to a busy road and a gas main

- **Remedial measures**
  - Backfilling of the sinkhole with stockpile materials and sub-base materials

- **Source**
  - GEO File Information
Kowloon Southern Link Contract KDB 200, Salisbury Road, 3 June 2007
Background

• Twin railway tunnels between Jordan Road and East Tsim Sha Tsui Station constructed by a slurry TBM

The failure

• 2m x 3m sinkhole reaching the ground surface

Possible cause of failure

• Sudden air pressure loss through the interface between CDG/HDG and overlying marine sand during a compressed air intervention, resulting in loss of face support and subsequent formation of sinkhole
Kowloon Southern Link Contract KDB 200, Salisbury Road, 3 June 2007

- **Consequences**
  - Crater formed at the ground surface, with associated settlement
  - Temporary closure of a busy road lane
  - A low pressure gas main and a 1200 mm stormwater drain were affected

- **Remedial measures**
  - Backfilling of sinkhole with granular fill

- **Source**
  - GEO File Information
References


AD (2008b). 杭州地鐵地盤塌陷增至2死19傷


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