Slope stabilization of an embankment on the West Coast Main Line, UK

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INTRODUCTION

Lancaster to Carlisle line (West Coast Mainline, UK) – constructed 1840s

Site is an embankment section, 300 m in length, constructed on natural sidelong ground – embankment slope on Up-line side, 13 m in height, 30 degree slope, densely vegetated

Currently comprises two tracks (Up-line and Down-line) with 25 kV overhead electrification

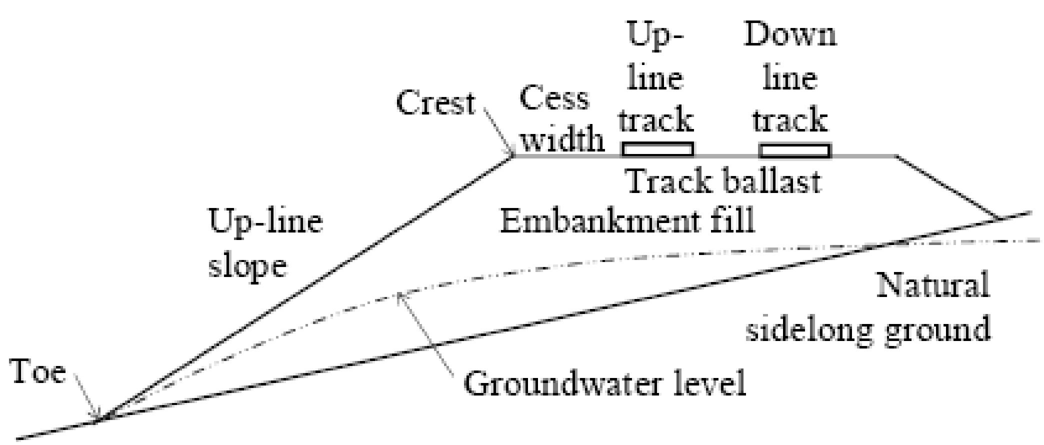


Figure 2. Terminology associated with twin-track railway.


Figure 3. View southwards along Up-line slope.

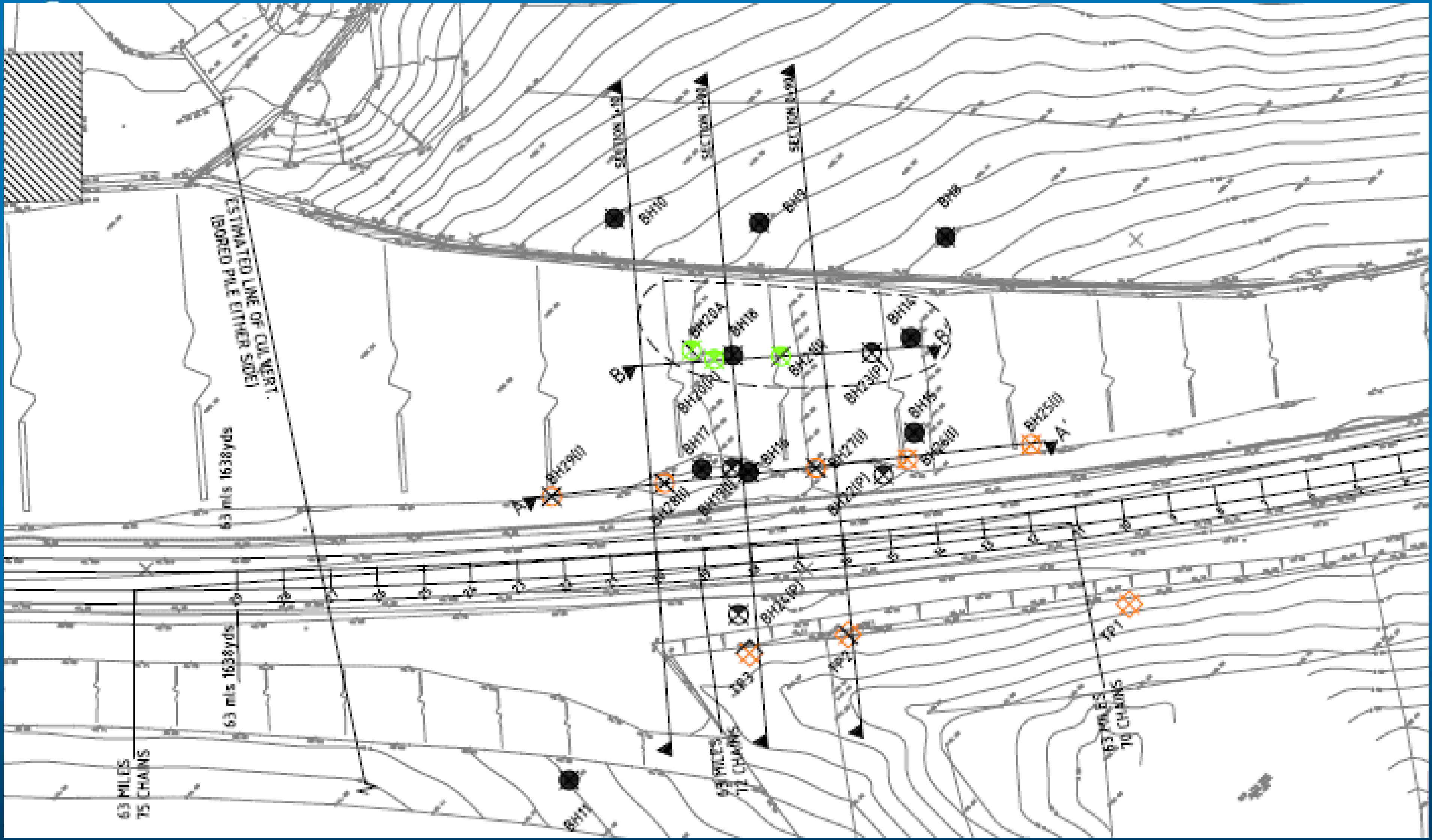
- Area of previous slope instability
  - Site inspections (leaning gantry; seepage, waterlogged ground conditions and bulging along Up-line toe); tilting of boundary fence installed four years previously
  - Track monitoring (adverse movement of rail tracks)

- Paper presents geotechnical design and construction of upgrade works to reduce future movement of track and improve stability of critical embankment section

- Ground investigation (21 cable percussive boreholes + 3 trial pits) and instrumentation (3 standpipe-piezometers + 7 inclinometers) along Up-cess and at embankment mid-height

River Petterill located 200 m northeast of site

Tributary Gill Beck culverted beneath north end of site



Area former railway tip (Wreay ash tip) in 1900s
Lower embankment section constructed using glacial till
Undrained shear strength determined from SPT blow counts indicated frequent loose zones

Solid geology Penrith Sandstone (poorly silicified red-brown sandstone)

Table 1. Stratigraphy beneath embankment centreline.

Stratum	Description	Thickness (m)
Ballast		0.3 to 0.5
Made ground	Loose to medium-dense ash, slag and cinders	3.8 to 4.4
Embankment fill	Very soft to firm silty sandy clay with some loose silty clayey sand	2.7 to 6.4
Glacial till	Firm to stiff glacial till with fine sand lens (ground foundation)	Not proven

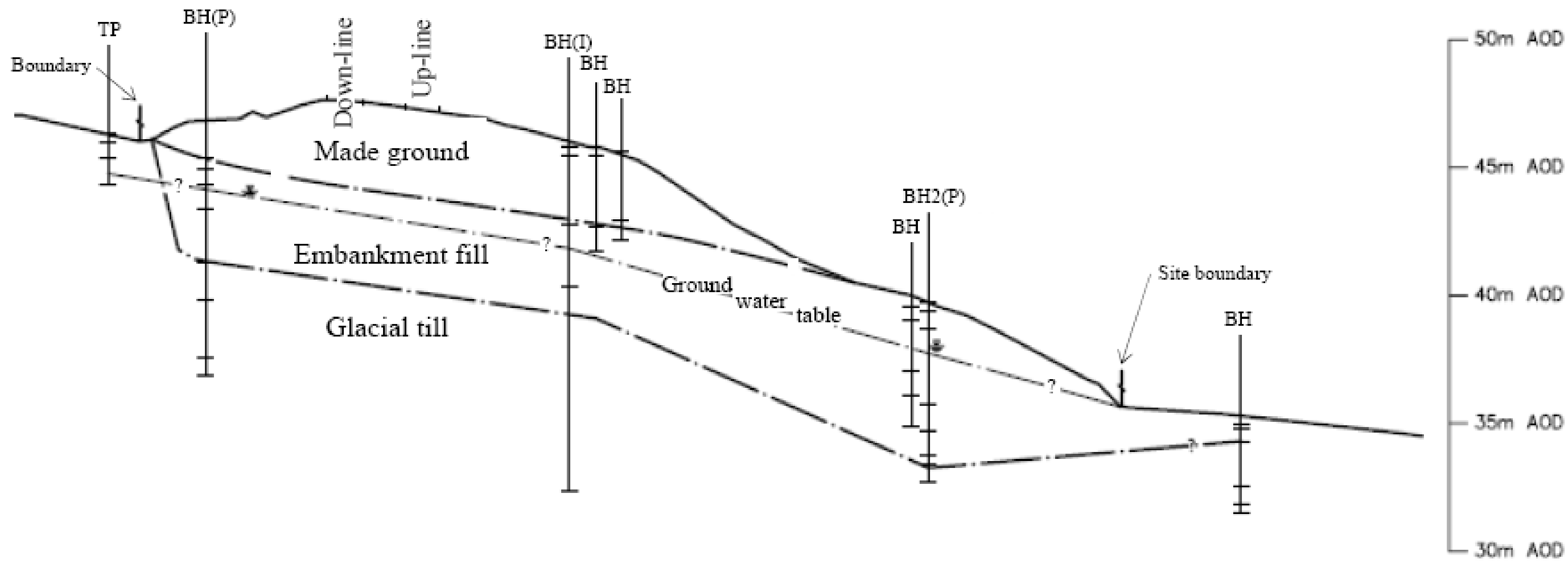


Figure 4. Geological profile at section AA in Figure 1. Note: BH, borehole; TP, trial pit; (P), includes piezometer.

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Piezometers monitored over one year period – relatively high groundwater table fluctuated seasonally (substantial rise between September and October 2001) within reworked glacial till

Groundwater table coincident with ground surface at embankment toe; no seepage observed from slope face

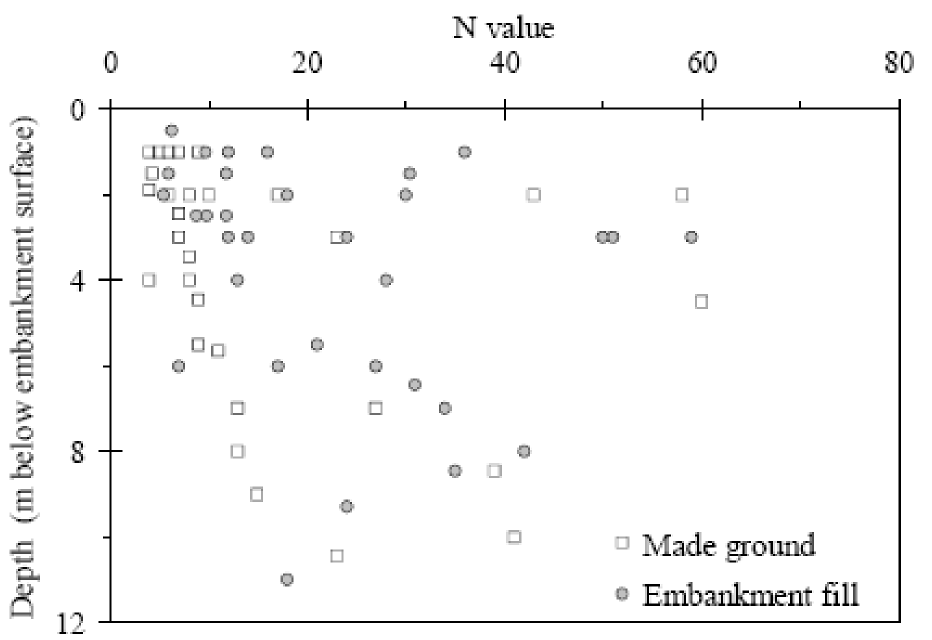

Figure 5. Standard Penetration test data.

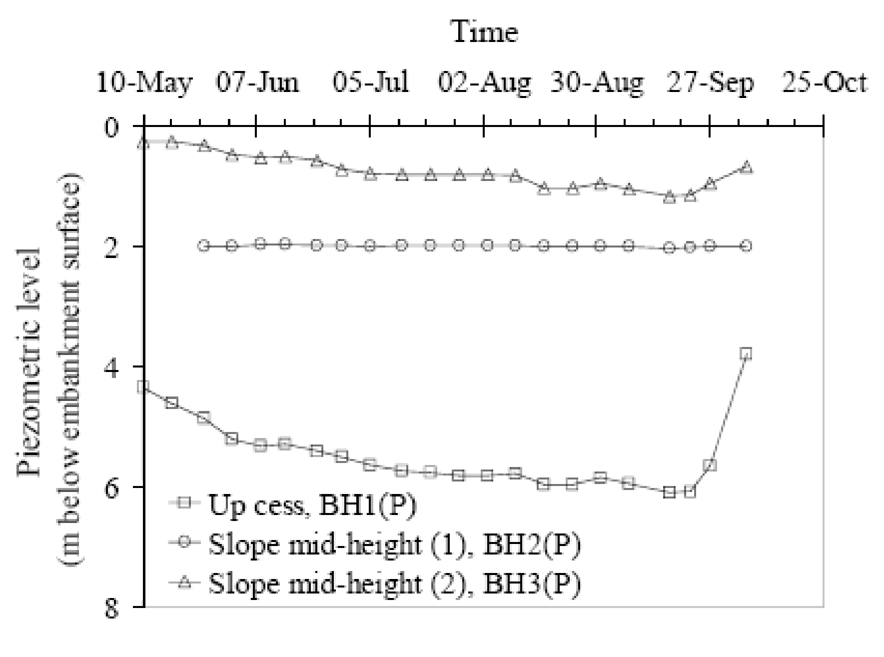

Figure 6. Groundwater levels within the embankment core.

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- Inclinometers indicated embankment moving laterally along shear zone located between 2.0 and 5.0 m below track level (within made ground and embankment fill) with up to 30 mm movement between April and September 2001

- Monitoring of track distortion and 22 target-monitoring points undertaken on weekly basis between June 2001 and May 2002

- Settlement trough identified over full length of site although degree of track distortion still within acceptable limits – up to 16 mm settlement recorded between July and September 2001

- Mobilized effective stress shear strength parameter values determined from slope stability back-analysis using *SLOPE W* assuming limiting equilibrium condition
  - Initial input data from ring shear (peak), shearbox and CU triaxial compression tests with pore water pressure measurement Sensitivity analysis considered FOS values mobilized for most probable and most unfavourable ground conditions and effects of variations in groundwater levels
- CONCLUSION : Upper embankment slowly but progressively moving along rotational slip surface located within embankment core (from Up-line cess and day-lighted at embankment toe) Critical slip surface activated during transient rises in groundwater level within embankment fill during torrential rainstorm events

Table 2. Design values from *SLOPE W* back analysis.

Stratum	Bulk unit weight (kN/m^3)	Effective cohesion c' (kPa)	Effective friction angle, ϕ' (degree)
Made ground	18	0	27
Embankment fill	20	3	22
Glacial till	21	3	32

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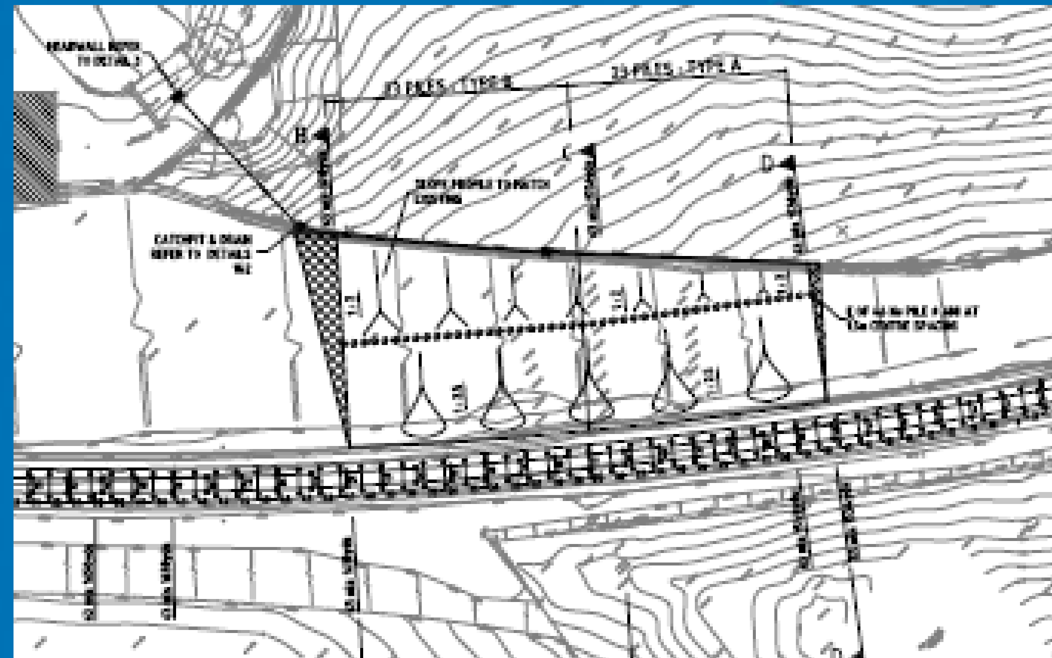
Upgrade works :

Construct pile retaining wall along mid-height embankment slope;

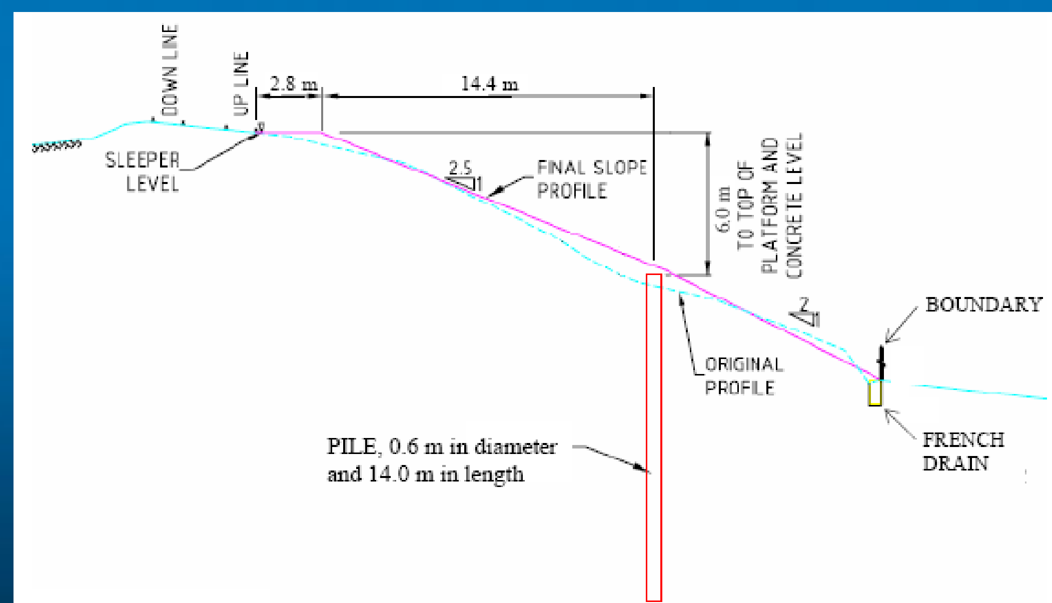
Re-grading of slope face (one vertical in 2.5 horizontal above wall and 2.0 horizontal below)

Construct 2.8 m wide cess walkway along Up-line and toe drain to reduce high groundwater table/water-logging near toe



Location of pile row at slope mid-height most efficient and caused least disruption to rail operations

Pile row installed through embankment and penetrating full depth of glacial till, founded in underlying glacial sands



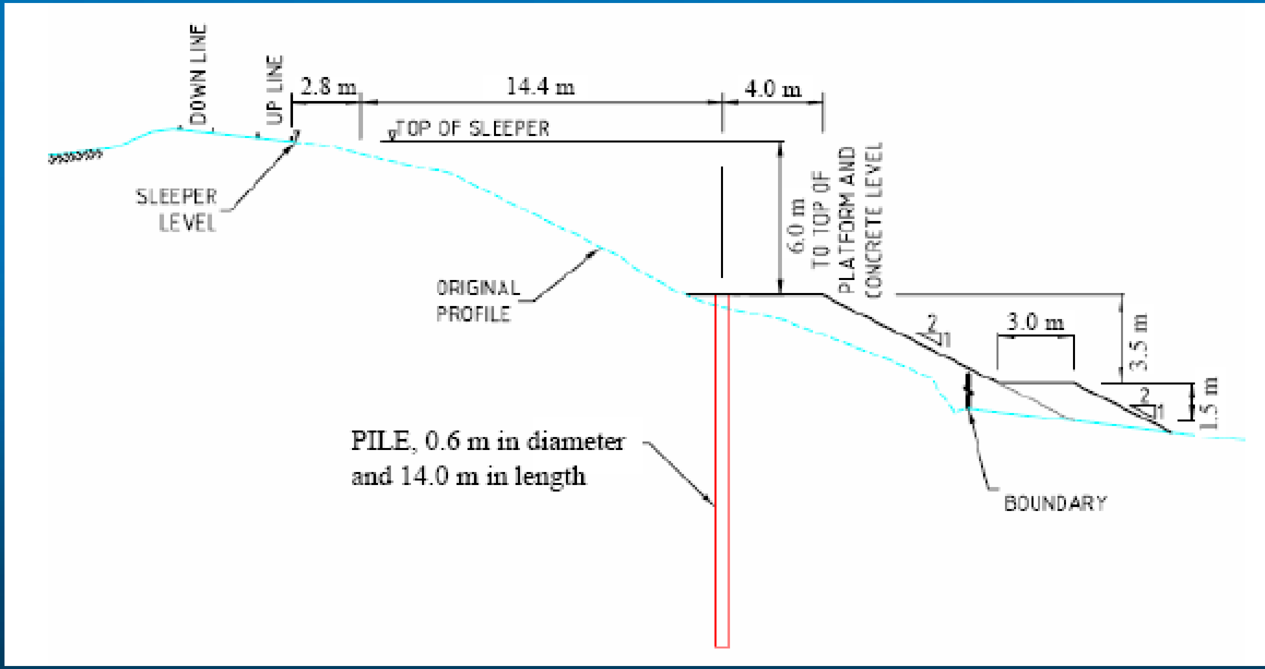
- Alternative solutions ultimately rejected as possession of rail track not possible and concerns that excessive slope movements would occur during excavation works for toe retaining structure/counterfort drains

- *Pile wall design :*
  - FOS value against reactivation of critical slip surface increased from unity to 1.3
  - *SLOPE W* analysis, and with vertical stress of 50 kPa applied along twin tracks, indicated pile row capable of exerting horizontal resistance of 200 kN/m run at embankment mid-height necessary
  - All potential shallower slips day-lighteding just upslope of retaining wall also had FOS values greater than 1.3
- Pile design based on plane-strain analysis of retaining wall using *WALLAP* assuming loss of passive support of up to 1.0 m in depth in event of slip failure occurring further down slope

- Row of 46-number cantilevered piles (600 mm in diameter and 12.4 to 14.0 m in length) capable of providing necessary horizontal resistance
  - Piles spaced 1.5 m centres – easy migration of groundwater through wall
  - Glacial till foundation provided lateral resistance to piles (FOS value of 2.0 against rotation failure)
  - Steel reinforcement (10 number T40 mm diameter main steel bars, 75 mm cover) and 40 N concrete

Construction

- Piling platform, 5.0 m in width, constructed at mid-height embankment slope using granular fill by progressively benching into lower embankment slope to reach 1.3 m above pile cut-off level
- Bored piles installed through platform using CFA technique – pile heads trimmed after hardening – integrity tested – piles sound
- Upper section of embankment slope regraded – unsuitable fill removed in benches and replaced with Class 6B granular fill – slope face covered with Class 6F2 capping layer



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- Piling platform removed followed by regrading lower embankment slope
- French drain constructed along boundary fence near toe with outfall to Gill Beck stream – excavated in short lengths and backfilled without delay with Type B filter material
- Geo-matting and seeding placed over entire embankment slope

POST CONSTRUCTION

- Periodic monitoring of track indicated negligible movement had occurred at track-bed level during construction works and following three-month period
- Six-month review of site indicated no discernable deficiencies or defects in tracks
- Interestingly, all inclinometers located above embedded retaining wall recorded ground movements of up to 10 mm upslope, towards track
  - Postulated ground movements up slope were due to stress relief following removal of pile platform and slope regrading works

SUMMARY

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- Ground investigation, monitoring and numerical analysis indicated upper section of embankment was slowly but progressively moving (limiting equilibrium) along rotational slip surface located within embankment core
  - Groundwater level within embankment was relatively high due to site topography (steeply sloping sidelong ground)
  - Critical slip surface activated by transient rises in groundwater within embankment core during torrential rainstorm events
- Upgrade works comprised construction of stabilising piles (shear dowels) at embankment mid-height, regrading of slope face to prevent secondary shallow slips near embankment crest and construction of toe drain
- Stabilising piles had desired effect of preventing lateral movement of embankment core, thereby reduced future movement at track level to acceptable amount
  - 600-mm diameter piles at 1.5 m centres provided necessary horizontal resistance to increase FOS value against slope instability from unity to at least 1.3

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Thank you