



SOLETANCHE BACHY

Slope Stabilisation for the Thirlmere Aqueduct at Nab Scar

David Preece, Design Manger, Bachy Soletanche, UK

International Society for Micropiles, 23 September 2010, Washington DC

Introduction

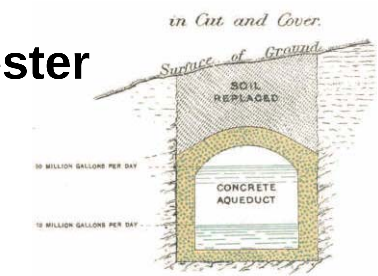
- History of Thirlmere Reservoir and Aqueduct
- Original construction of conduit at Nab Scar
- Aqueduct issues at Nab Scar
- Requirements & restrictions
- Selected solution
- Design of spaced piles
- Effectiveness of works

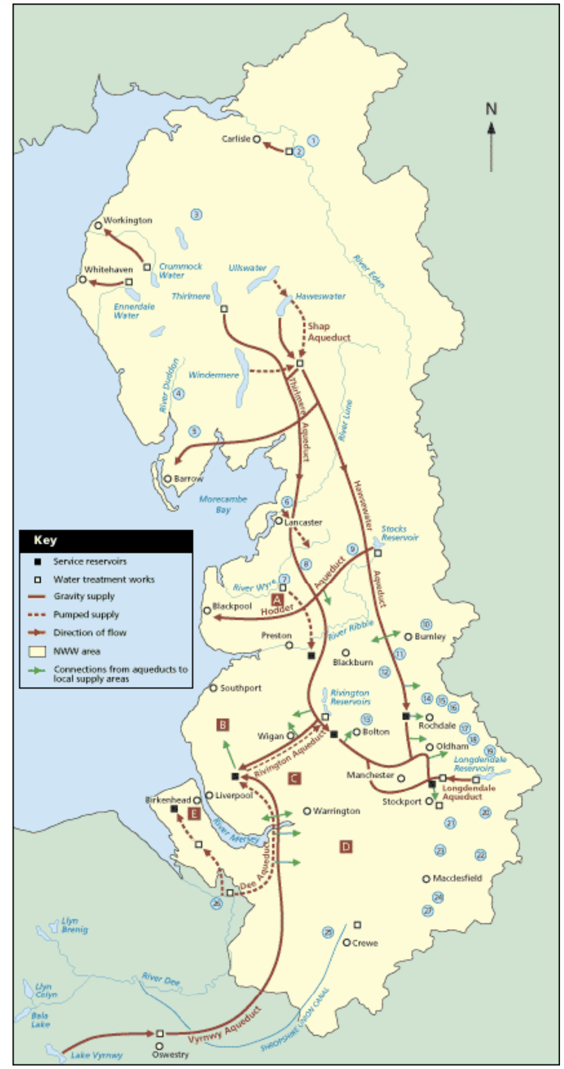
History of Thirlmere Reservoir and Aqueduct

- **Man made reservoir**
- **Water to support industrial revolution in Manchester**

History of Thirlmere Reservoir and Aqueduct

- **Connection established in 1894**
- **Mass unreinforced concrete**
- **95 miles in length**
- **180m @Thirlmere to 110m @Manchester**
- **Gradient 450mm to 1km (1 in 2200)**
- **220 million litres of water per day**
- **Water speed 3 to 5 kph**



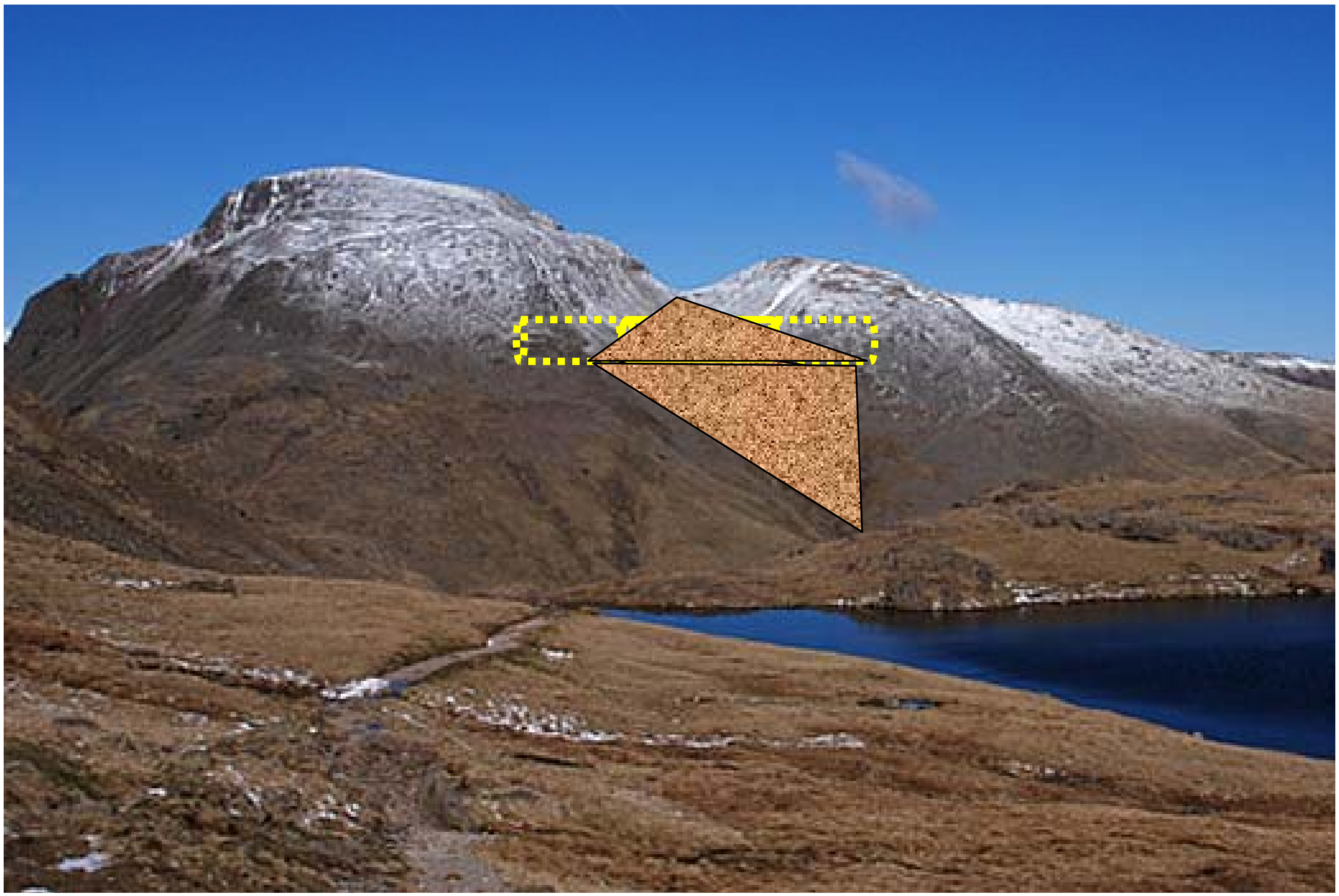


Original construction of conduit at Nab Scar

Original construction of conduit at Nab Scar

Original construction of conduit at Nab Scar

Original construction of conduit at Nab Scar

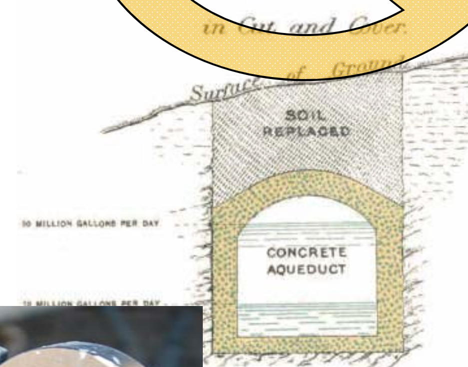


Aqueduct issues at Nab Scar

- **Inspections & investigations since 2005**
- **Series of spiral crack observed within the conduit & around arch barrel**
- **Opening of joint between slab and walls**
- **Torsional movement considered due to the movement of ground over top of conduit**

Requirements & Restrictions

- **No direct loading of the conduit**
- **Minimal vibration techniques**
- **No slope loading**
- **Monitoring of conduit and slope throughout works:**
  - Hillside surface & ground at depth
  - Conduit position
  - Conduit internal cracks



Selected Solution

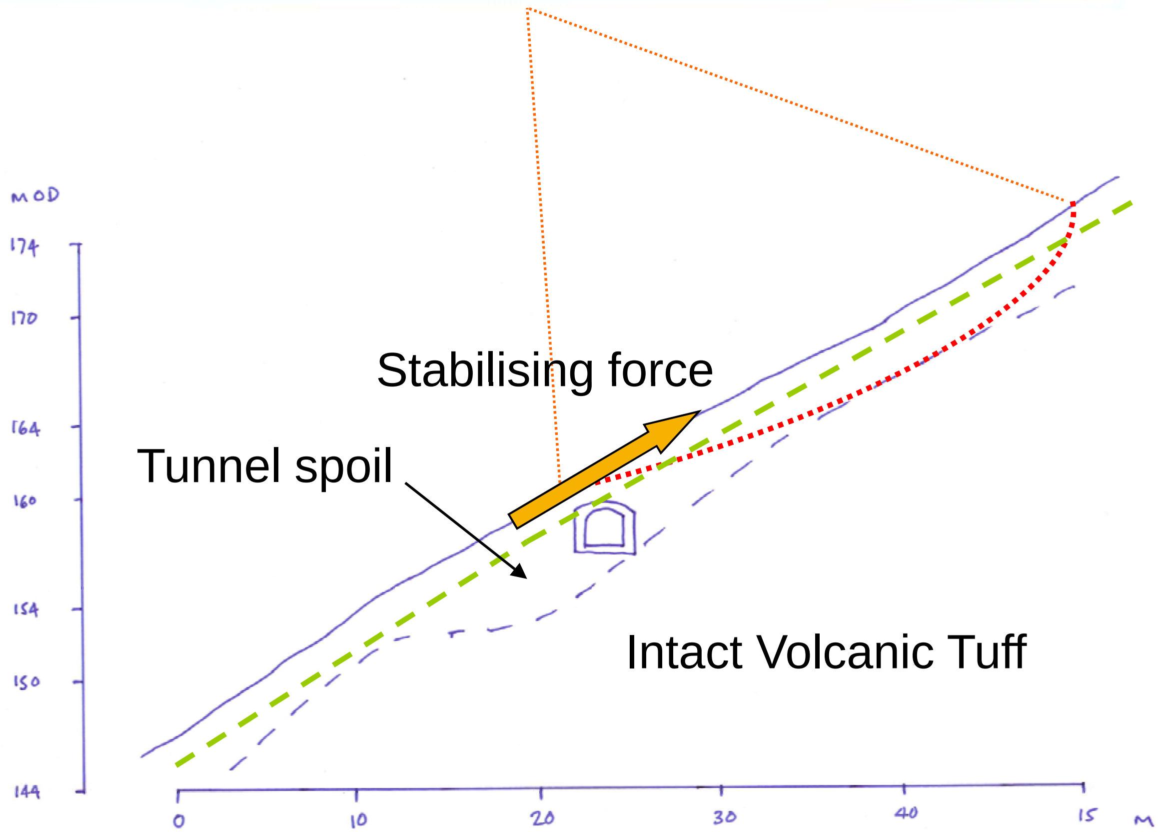
- **All about construct-ability**

Design of spaced piles

- **Determination of required stabilising force**
- **Determination of pile loads to provide required stabilising resistance force**
- **Layout of stabilisation works**
- **Development of load on A-frames**
- **Analysis results considering different models**
- **Micropile & cap dimensions**

Design of spaced piles: determination of stabilising resistance force

- **Slope stability analysis**
- **Circular slip and infinite slope analysis**
- **Back calculate soil and ground water parameters**
- **Establish required restoring force to provide increase stability FoS = 1.3**



FoS = 1.0; Slip depth: 2.5m, $\phi' = 45^{o}$, ground water: 1m b.e.g.l

FoS = 1.3; restoring force = 250kN per m run of slope

Design of spaced piles: determination of stabilising resistance force

- **Infinite slope & finite slope eqns**
- **FoS = 1.0 for existing case**
- **FoS = 1.3 with 250kN/m restoring force**

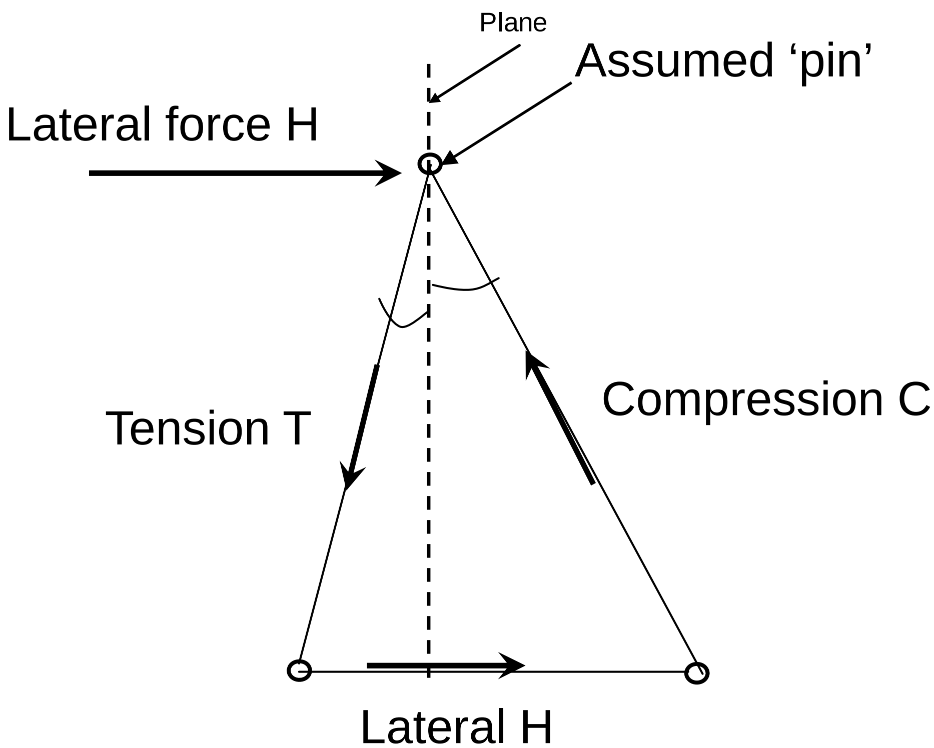
saturated soil unit weight	γ_{sat}	20	kN/m³
unit weight of water	γ_w	10	kN/m³
angle of friction	ϕ	45	o
slope angle to horizontal	β	34	o
cohesion	c	0	kPa
depth to slip surface, z		2.5	m
depth to groundwater surface, z_w		1	m
slope length, l		38	m
Restoring force parallel to slope, H		250	kN per m
$m = (z-z_w)/z$		0.6	

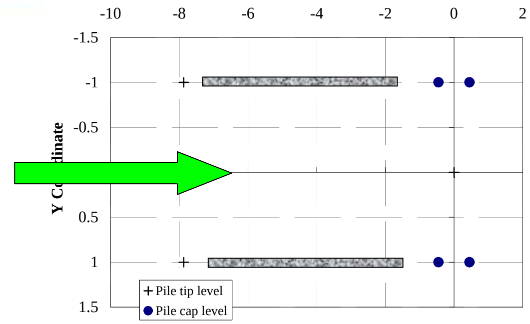
$$F = [c/(\gamma_{sat}.z.\sin\beta.\cos\beta)]+[(\gamma_{sat}-\{\gamma_w.m\})/\gamma_{sat}].[\tan\phi/\tan\beta]$$

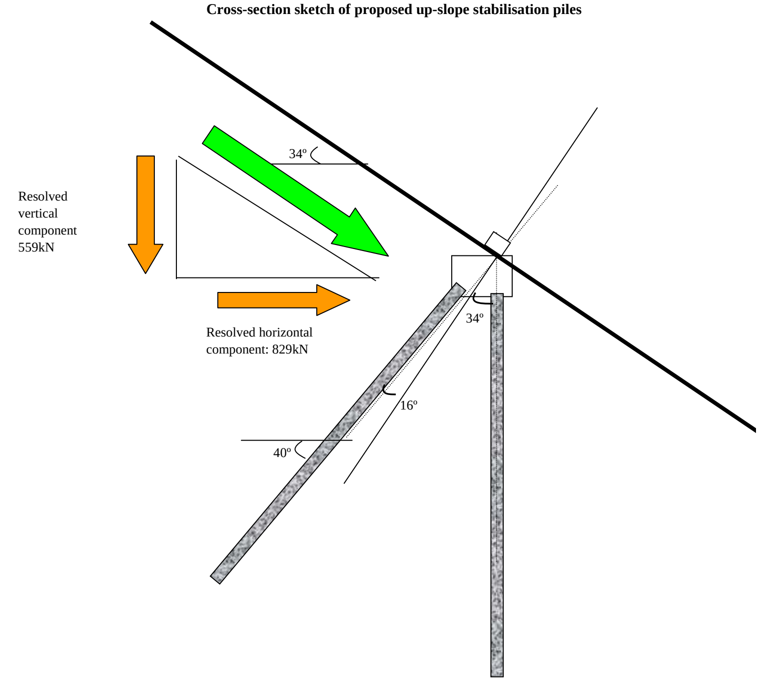
$$F = \frac{c.l}{\gamma_{sat}.l.z.\sin\beta.\cos\beta} + \frac{(\gamma_{sat}.l.z.\cos^2\beta - \gamma_{\omega}.m.z.l.\cos^2\beta).\tan\phi + H}{\gamma_{sat}.l.z.\sin\beta.\cos\beta}$$

Design of spaced piles: Determination of pile loads to provide required stabilising resistance force

- **Structural frame model & elastic continuum model using Piglet**

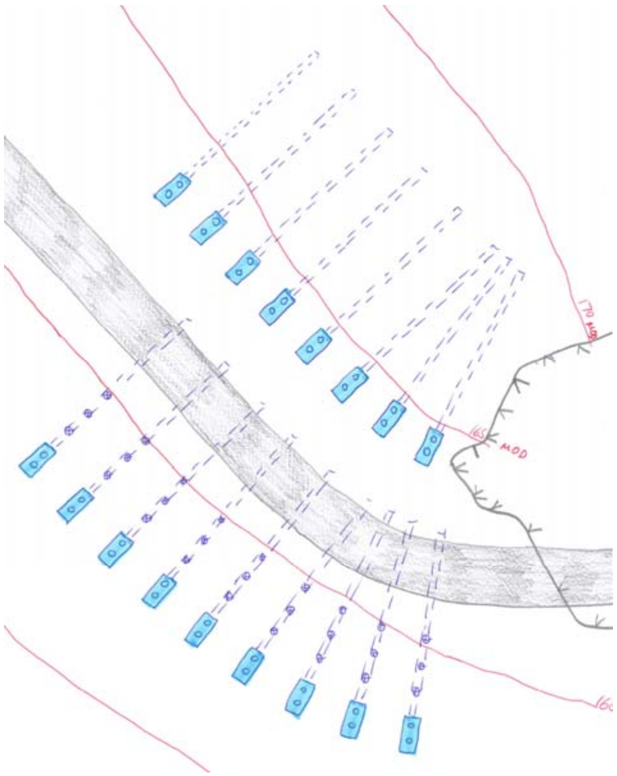




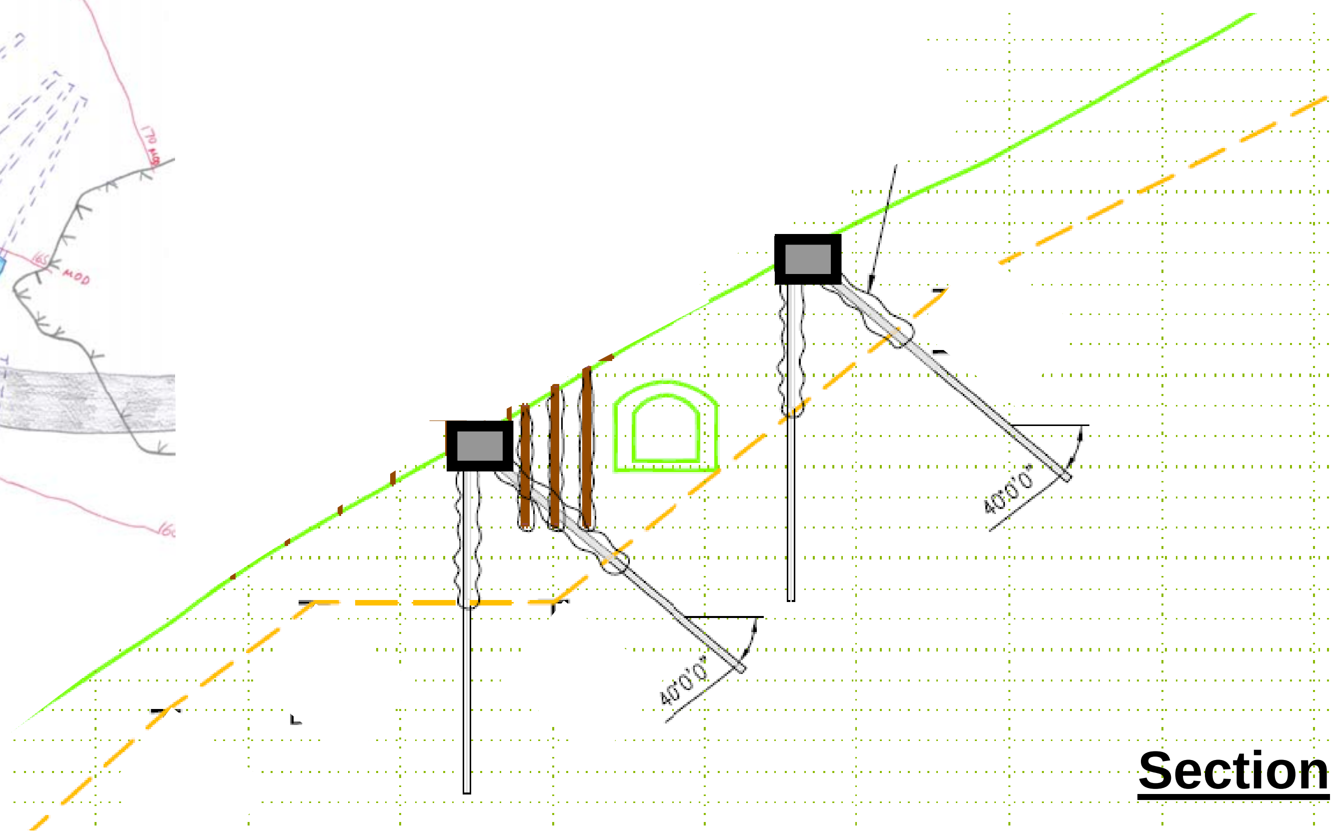


Design of spaced piles: Layout of stabilisation works

- **Pairs of spaced ‘A-frame’ micropiles to provide restoring force**
- **Targeted permeation grouting**



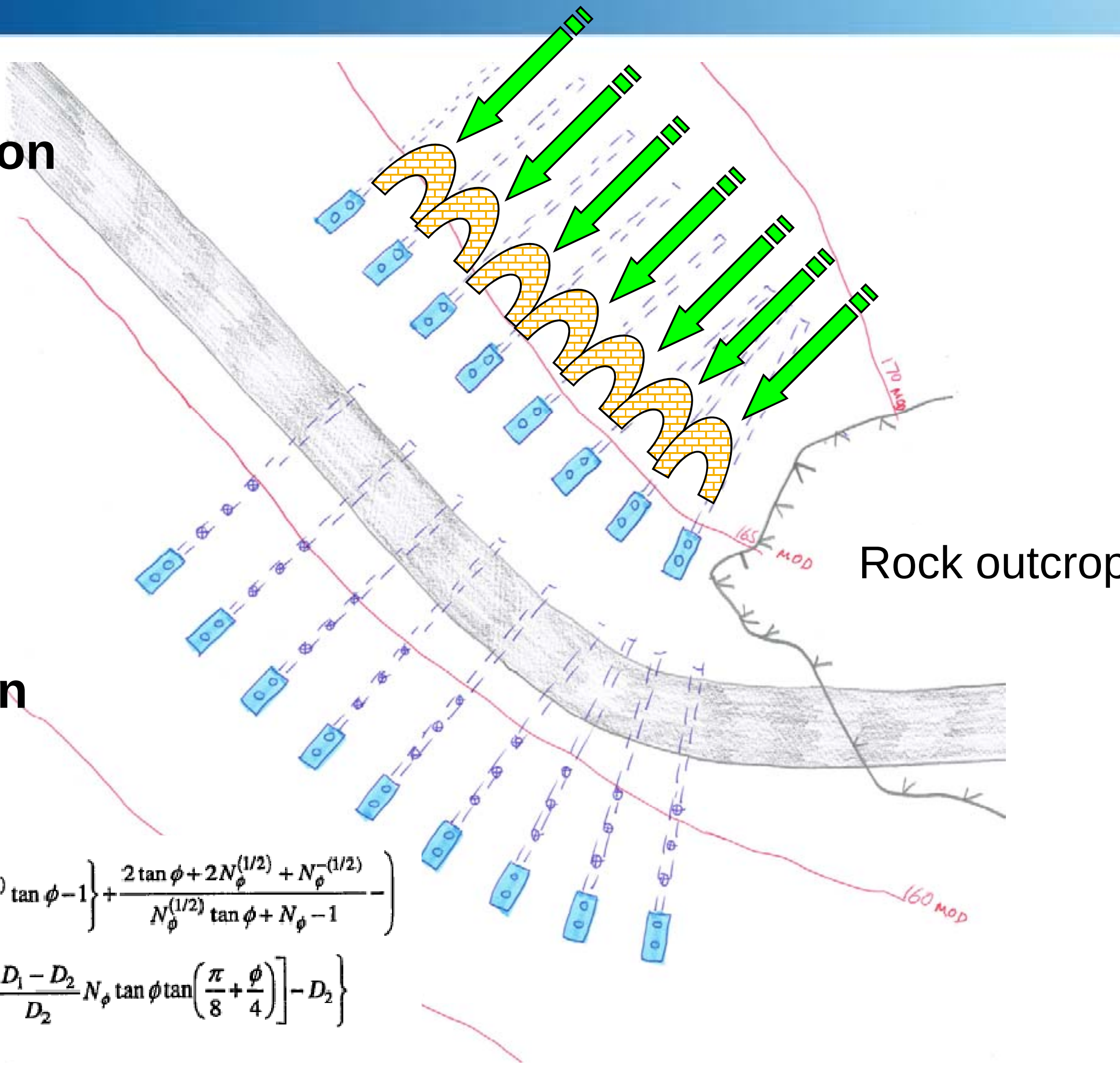
Plan



Section

Design of spaced piles: Development of load on A-frames

- **Arching check & development of load on spaced A-frames in response to hillside movement**
- **Function of:**
  - Spacing
  - Cap width/pile diameter
  - ϕ'; c'; slip depth z
- **Output: lateral load on pile cap & piles**



$$p = cA\left(\frac{1}{N_\phi \tan\phi}\left\{\exp\left[\frac{D_1 - D_2}{D_2} N_\phi \tan\phi \tan\left(\frac{\pi}{8}+\frac{\phi}{4}\right)\right] - 2N_\phi^{(1/2)} \tan\phi - 1\right\} + \frac{2\tan\phi + 2N_\phi^{(1/2)} + N_\phi^{-(1/2)}}{N_\phi^{(1/2)}\tan\phi + N_\phi - 1} - \right)$$

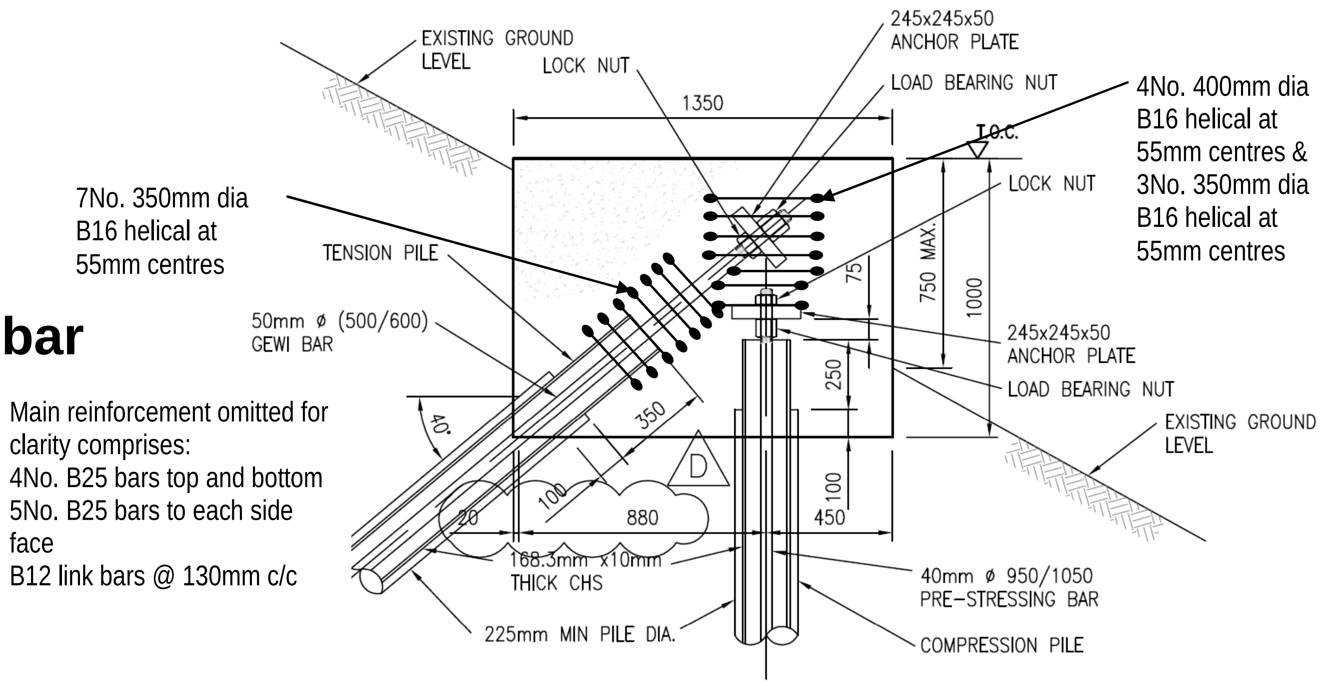
$$-c\left(D_1 \frac{2\tan\phi + 2N_\phi^{(1/2)} + N_\phi^{-(1/2)}}{N_\phi^{(1/2)}\tan\phi + N_\phi - 1} - 2D_2 N_\phi^{-(1/2)}\right) + \frac{\gamma z}{N_\phi}\left\{A\exp\left[\frac{D_1 - D_2}{D_2} N_\phi \tan\phi \tan\left(\frac{\pi}{8}+\frac{\phi}{4}\right)\right] - D_2\right\}$$

Design of spaced piles: Analysis results considering different models

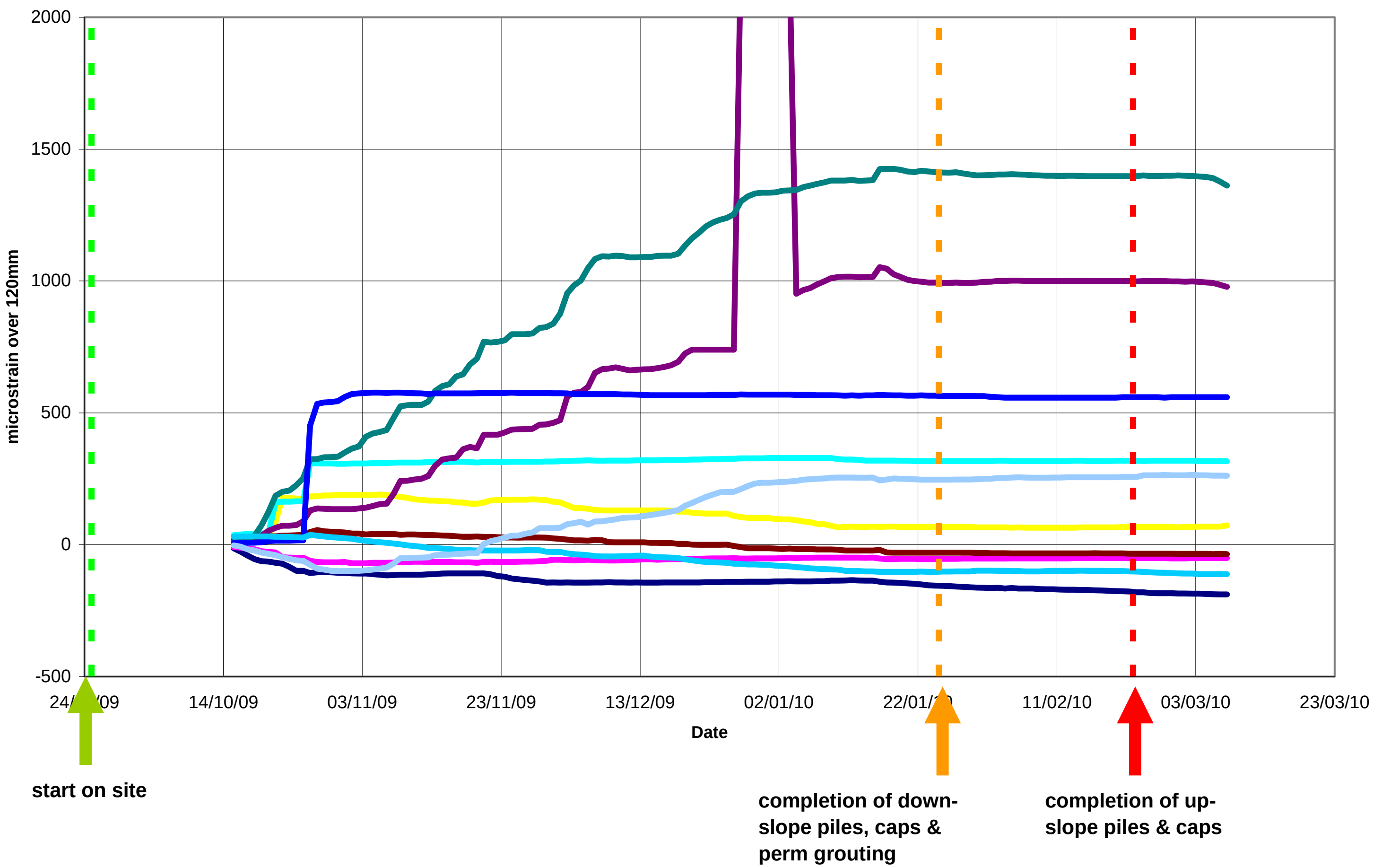
Analysis	Tension pile force	Compression on pile force	Individual pile bending moment / shear force	Pile cap moment
Based on providing required restoring force of 250kN per m run:				
Slope restoring force structural frame model	541kN	628kN	--	--
Slope restoring force elastic continuum model (Piglet)	531kN	635kN	27kNm / 20kN	784kNm
Based on applied slope movement loads according to Ito & Matsui:				
Slope movement induced forces on pile caps: structural frame model	623kN	401kN	--	--
Slope movement induced forces on pile caps: elastic continuum model (Piglet)	623kN	422kN	25kNm / 18kN	663kNm

Design of spaced piles: Micropile & cap dimensions

- **225mm diameter micropiles 6.5m rock socket**
- **168.3 x 10mm CHS from cap to 1m into competent rock**
- **Tension pile: 50mm Gewi bar**
- **Compression pile: 40mm pre-stressing bar**
- **40N/mm^2 grout**



Effectiveness of works: Strain gauge results from inside conduit



Finished works

Conclusion

- **A vital section of water infrastructure has been stabilised**
- **Early indications show the works to be effective**
- **Water continues to flow at Queen Victoria Jubilee Fountain in Manchester**