WVTF IMWA 2024

Jones & Wagener
Engineering & Environmental Consultants

Hydrogeological Inputs to Stability Analysis of Tailings Storage Facilities

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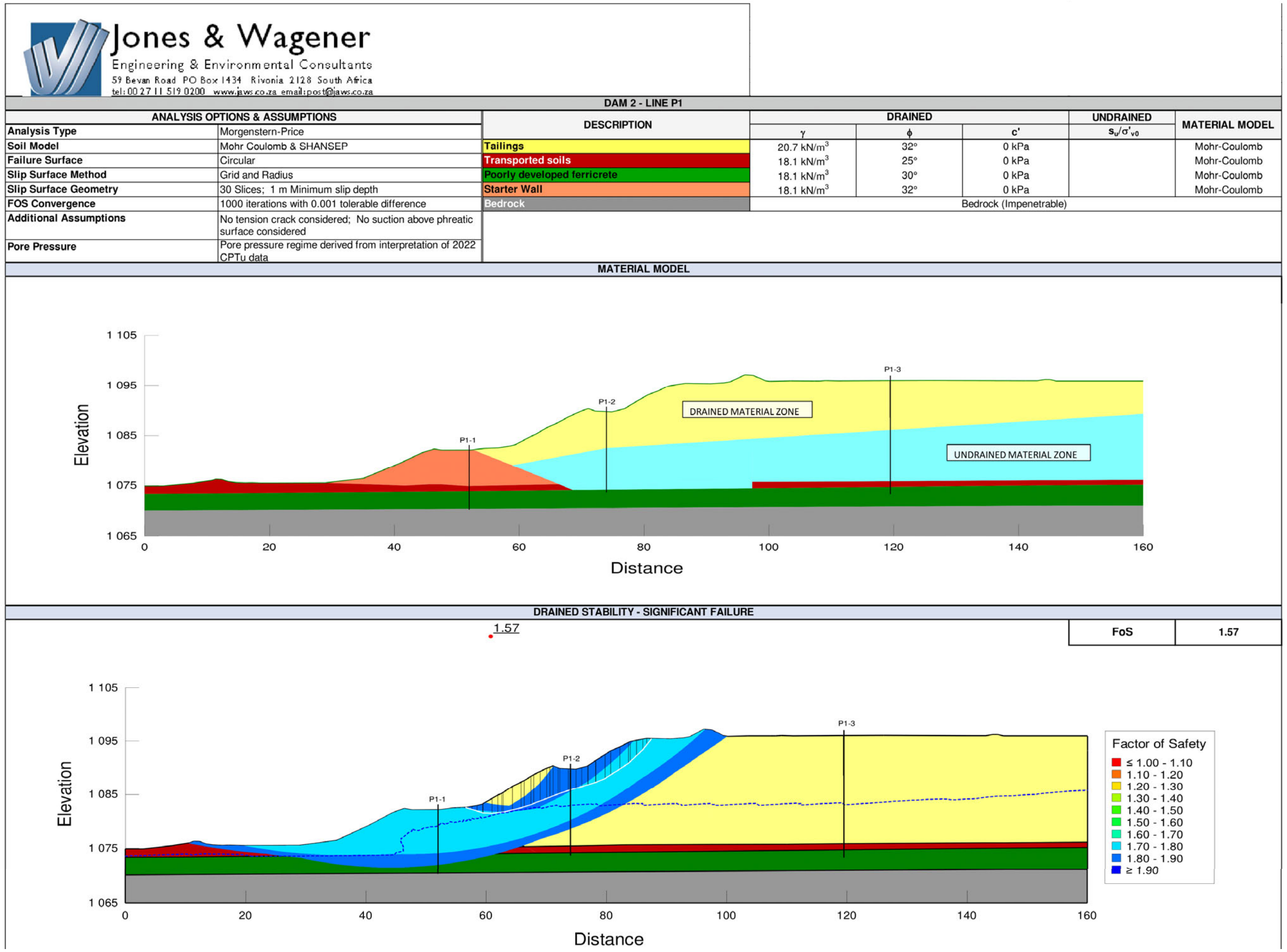
West Virginia Mine Drainage Task Force Symposium
&
15th International Mine Water Association Congress, 2024

Presentation Layout

- Introduction – Tailings Stability & Hydrogeology
- Methods – Stability Analysis and Flow Modelling
- Results & Discussion – Flow Modelling Results and Integration
- Conclusions

Introduction

- Traditional stability analyses of tailings storage facilities (TSFs) is usually two-dimensional.
- Relies heavily on visual inspection, piezometer data and CPTu data.
- Facility often isolated from aquifer systems.
- GISTM emergence – requires integrated approach.



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DAM 2 - LINE P1

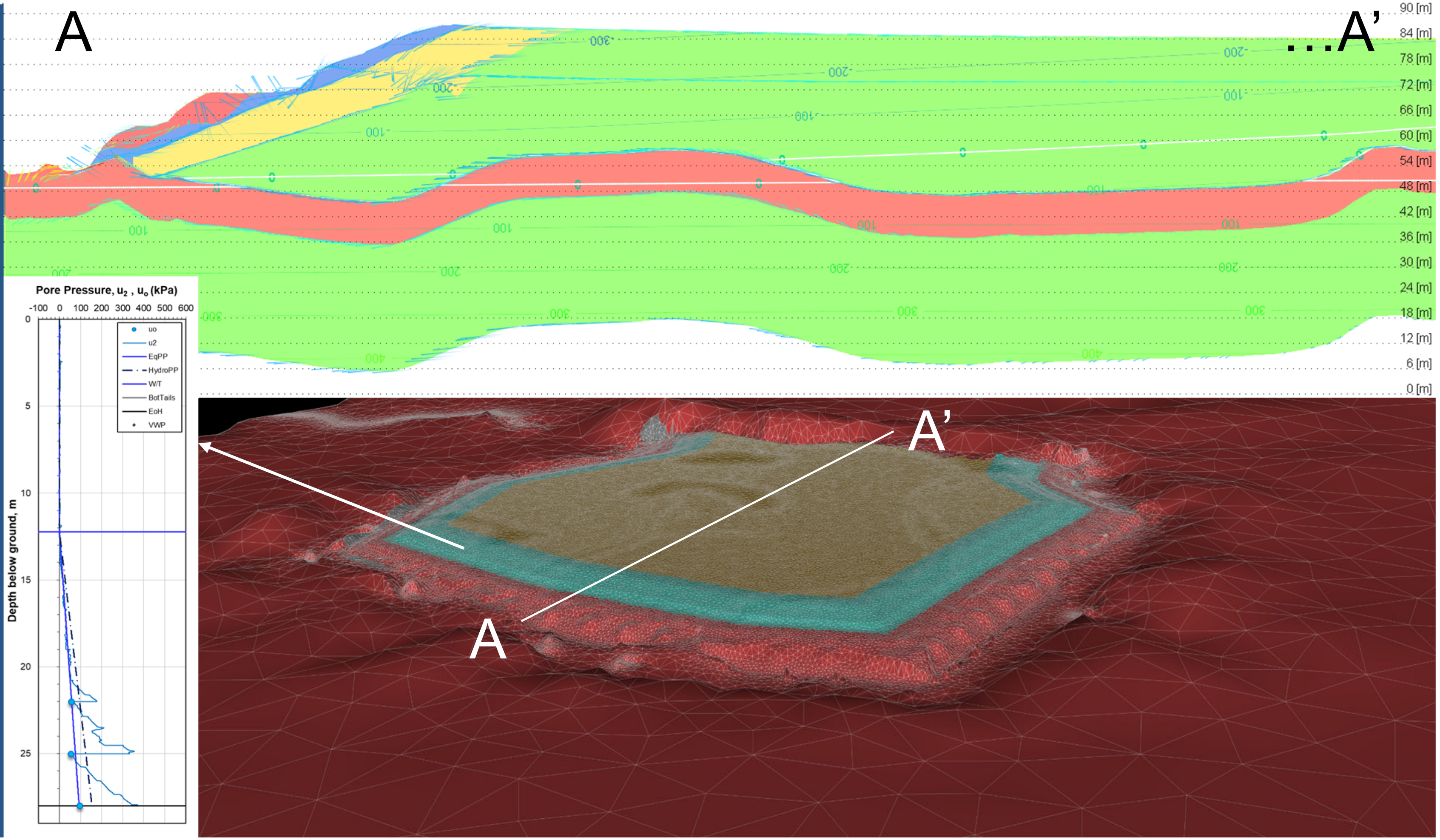
ANALYSIS OPTIONS & ASSUMPTIONS	
Analysis Type	Morgenstern-Price
Soil Model	Mohr Coulomb & SHANSEP
Failure Surface	Circular
Slip Surface Method	Grid and Radius
Slip Surface Geometry	30 Slices; 1 m Minimum slip depth
FOS Convergence	1000 iterations with 0.001 tolerable difference
Additional Assumptions	No tension crack considered; No suction above phreatic surface considered
Pore Pressure	Pore pressure regime derived from interpretation of 2022 CPTu data

DESCRIPTION	DRAINED			UNDRAINED	MATERIAL MODEL
	γ	ϕ	c'	s_u/σ'_{v0}	
Tailings	20.7 kN/m^3	32°	0 kPa		Mohr-Coulomb
Transported soils	18.1 kN/m^3	25°	0 kPa		Mohr-Coulomb
Poorly developed ferricrete	18.1 kN/m^3	30°	0 kPa		Mohr-Coulomb
Starter Wall	18.1 kN/m^3	32°	0 kPa		Mohr-Coulomb
Bedrock	Bedrock (Impenetrable)				

MATERIAL MODEL

DRAINED STABILITY - SIGNIFICANT FAILURE

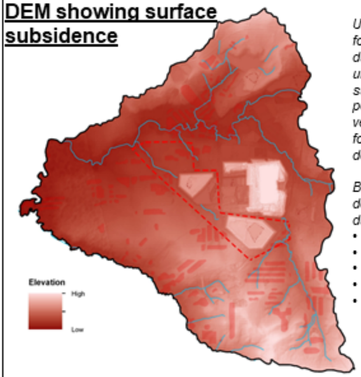
FoS	1.57


A
…A'
90 [m]
84 [m]
78 [m]
72 [m]
66 [m]
60 [m]
54 [m]
48 [m]
42 [m]
36 [m]
30 [m]
24 [m]
18 [m]
12 [m]
6 [m]
0 [m]
-300
-200
-100
0
100
200
300
400
Pore Pressure, u_2 , u_o (kPa)
-100
0
100
200
300
400
500
600
Depth below ground, m
0
5
10
15
20
25
uo
u2
EqPP
HydroPP
W/T
BotTails
EoH
VWP
A
A'

Methods

- Numerical flow modelling utilised to bridge the gaps between inspection areas.
- Illustrates areas of flow convergence and potential instability.
- Full hydrogeological characterisation of the TSF and underlying aquifers.
- ERT, Rotary Core- and Percussion Drilling, Packer Testing and Pumping Tests, CPTu.
- Data integration with slope stability analysis

DEM showing surface subsidence

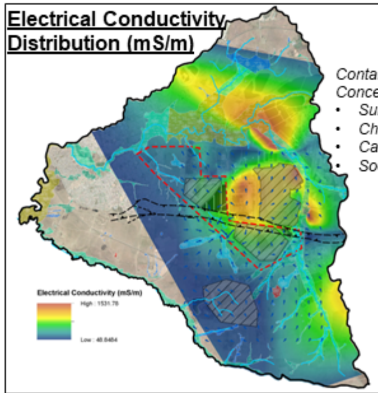


Underground mining led to the formation of surface subsidence due to the collapse of underground workings. This subsidence can lead to the ponding of water or promote vertical groundwater flow and form localized cones of depression.

Boreholes exhibiting evidence of decreased groundwater levels due to subsidence:

- *BP10*
- *BP6*
- *HP12D*
- *REGM-122*
- *REGM-133*
- *REGM-238D*
- *REGM-43*
- *TBD01*
- *TBD03*

Electrical Conductivity Distribution (mS/m)



Contaminants of Concern include:

- *Sulfate (SO_4)*
- *Chloride (Cl)*
- *Calcium (Ca)*
- *Sodium (Na)*

TSF 5

A: *Seepage – 8.1 x 10^{-5} m^3/s per m^2*
Soil Profile – TP5A/1 (1.8-3.0m)
Gravel: 2% Silt: 49%
Sand: 24% Clay: 25%

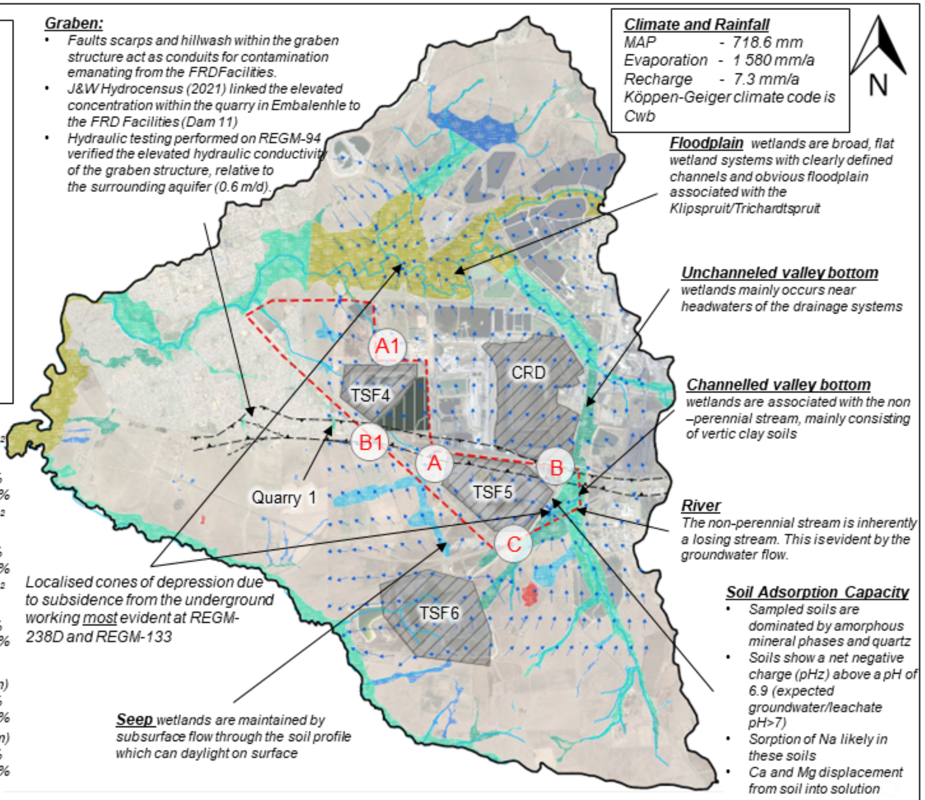
B: *Seepage – 8.2 x 10^{-7} m^3/s per m^2*
Soil Profile – TP5C/1 (0.3-1.0m)
Gravel: 0% Silt: 25%
Sand: 37% Clay: 38%

C: *Seepage – 9.2 x 10^{-7} m^3/s per m^2*
Soil Profile – TP5E/1 (1.2-3.1m)
Gravel: 6% Silt: 13%
Sand: 71% Clay: 10%

TSF 4

A1: *Soil Profile – TP4A/1 (1.7-3.1m)*
Gravel: 1% Silt: 17%
Sand: 38% Clay: 44%

B1: *Soil Profile – TP5C/1 (0.3-1.0m)*
Gravel: 0% Silt: 21%
Sand: 44% Clay: 35%



Graben:

- *Faults scarps and hillwash within the graben structure act as conduits for contamination emanating from the FRDFacilities.*
- *J&W Hydrocensus (2021) linked the elevated concentration within the quarry in Embalenhle to the FRD Facilities (Dam 11)*
- *Hydraulic testing performed on REGM-94 verified the elevated hydraulic conductivity of the graben structure, relative to the surrounding aquifer (0.6 m/d).*

Climate and Rainfall
MAP - 718.6 mm
Evaporation - 1 580 mm/a
Recharge - 7.3 mm/a
Köppen-Geiger climate code is Cwb

Floodplain *wetlands are broad, flat wetland systems with clearly defined channels and obvious floodplain associated with the Klipspruit/Trichardtspruit*

Unchanneled valley bottom *wetlands mainly occurs near headwaters of the drainage systems*

Channelled valley bottom *wetlands are associated with the non –perennial stream, mainly consisting of vertic clay soils*

River
The non-perennial stream is inherently a losing stream. This is evident by the groundwater flow.

Soil Adsorption Capacity

- *Sampled soils are dominated by amorphous mineral phases and quartz*
- *Soils show a net negative charge (pHz) above a pH of 6.9 (expected groundwater/leachate pH>7)*
- *Sorption of Na likely in these soils*
- *Ca and Mg displacement from soil into solution*

Localised cones of depression due to subsidence from the underground working most evident at REGM-238D and REGM-133

Seep *wetlands are maintained by subsurface flow through the soil profile which can daylight on surface*

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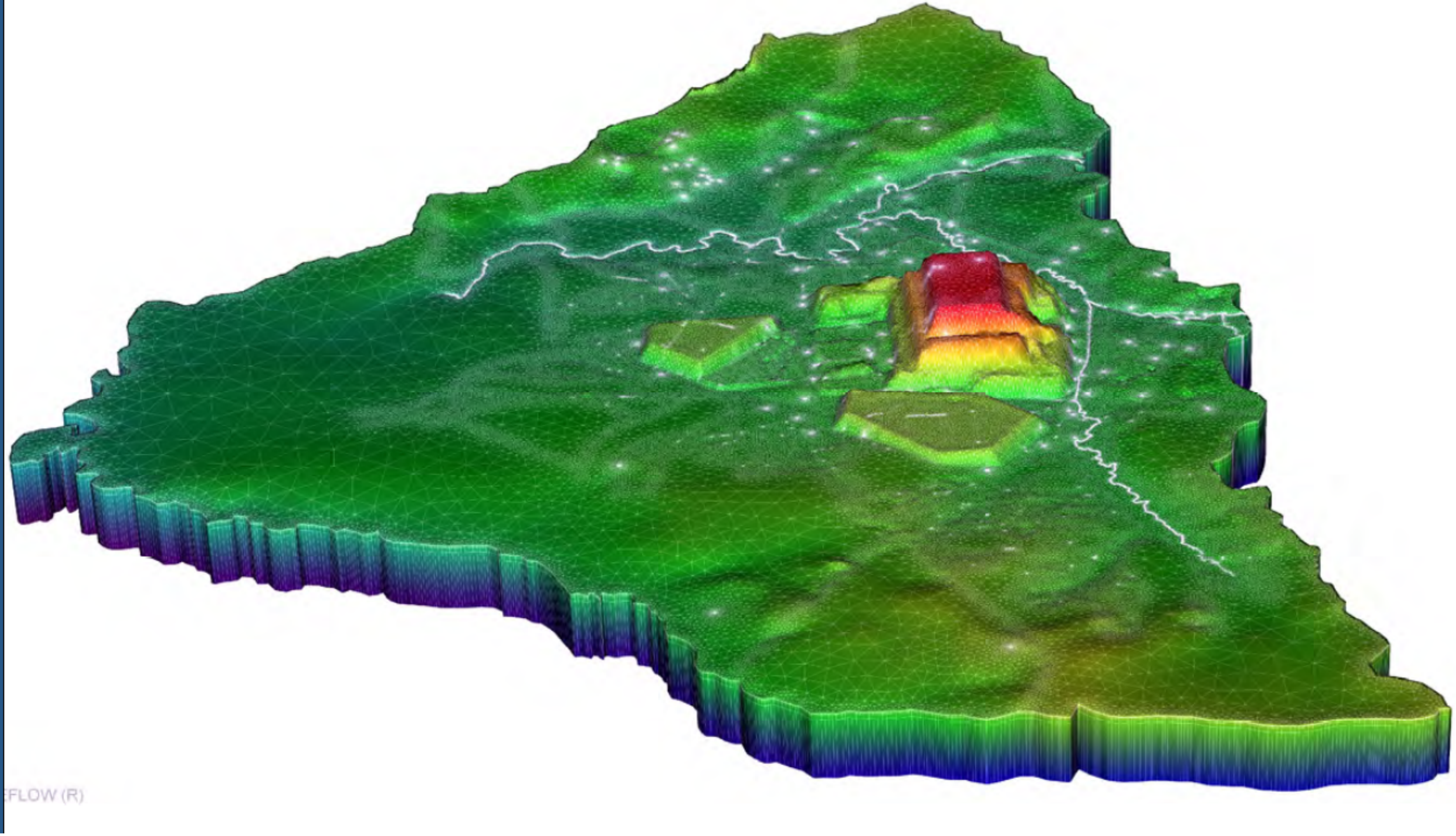
Conceptual Site Model

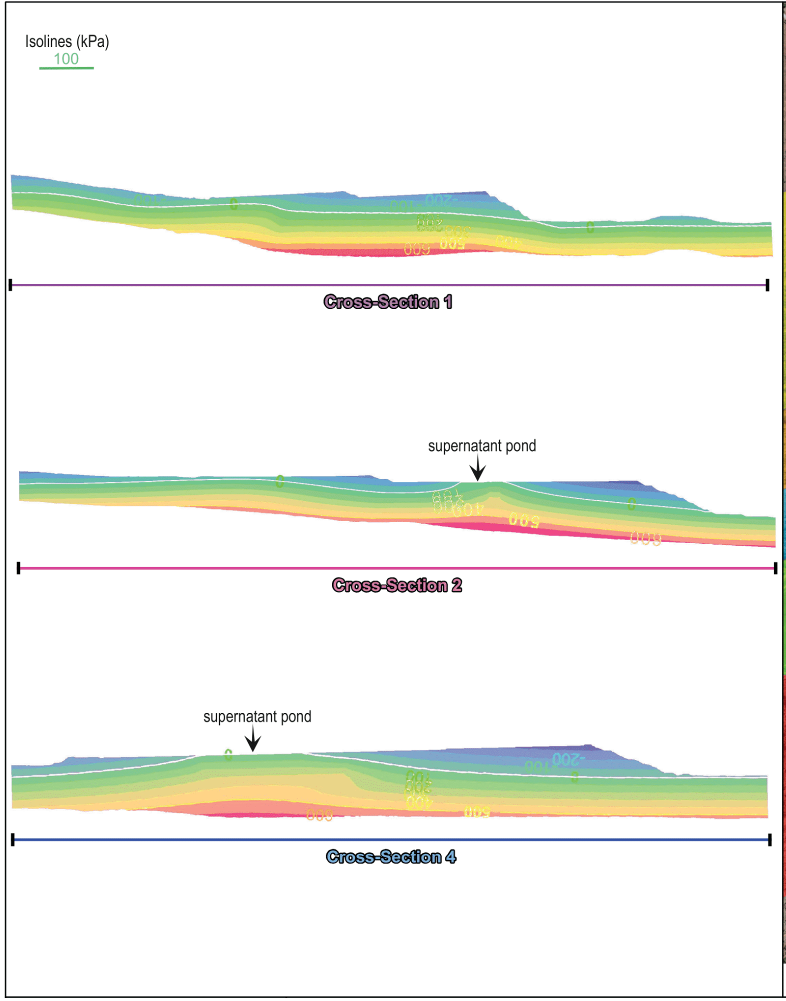

FLOW (R)

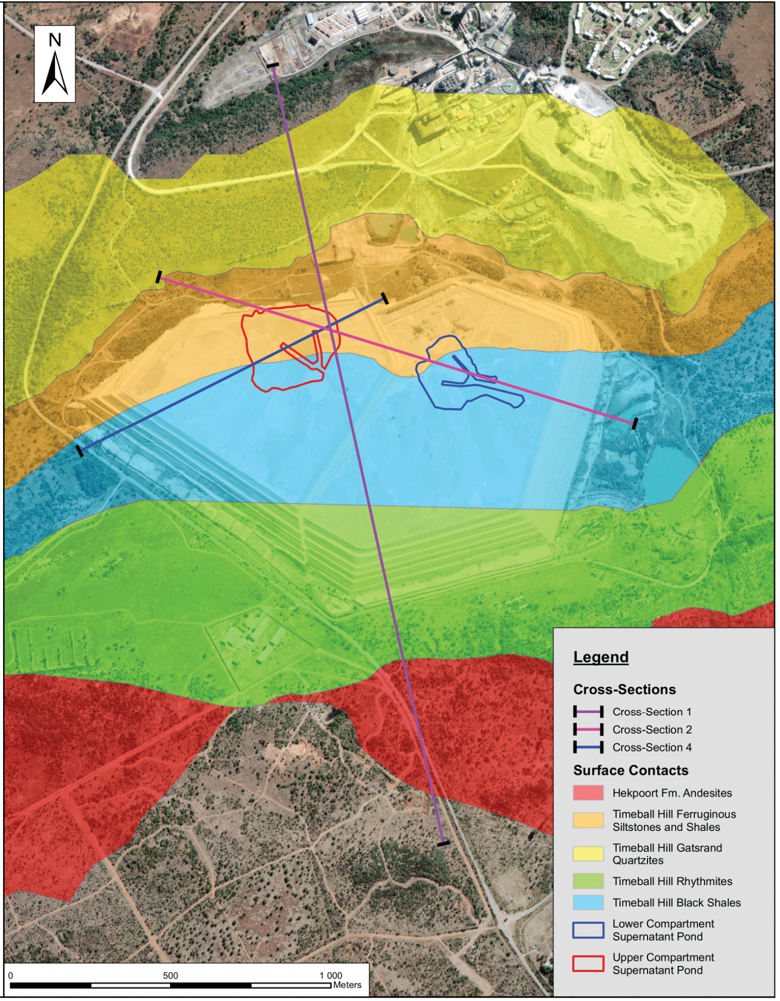
Results and Discussion

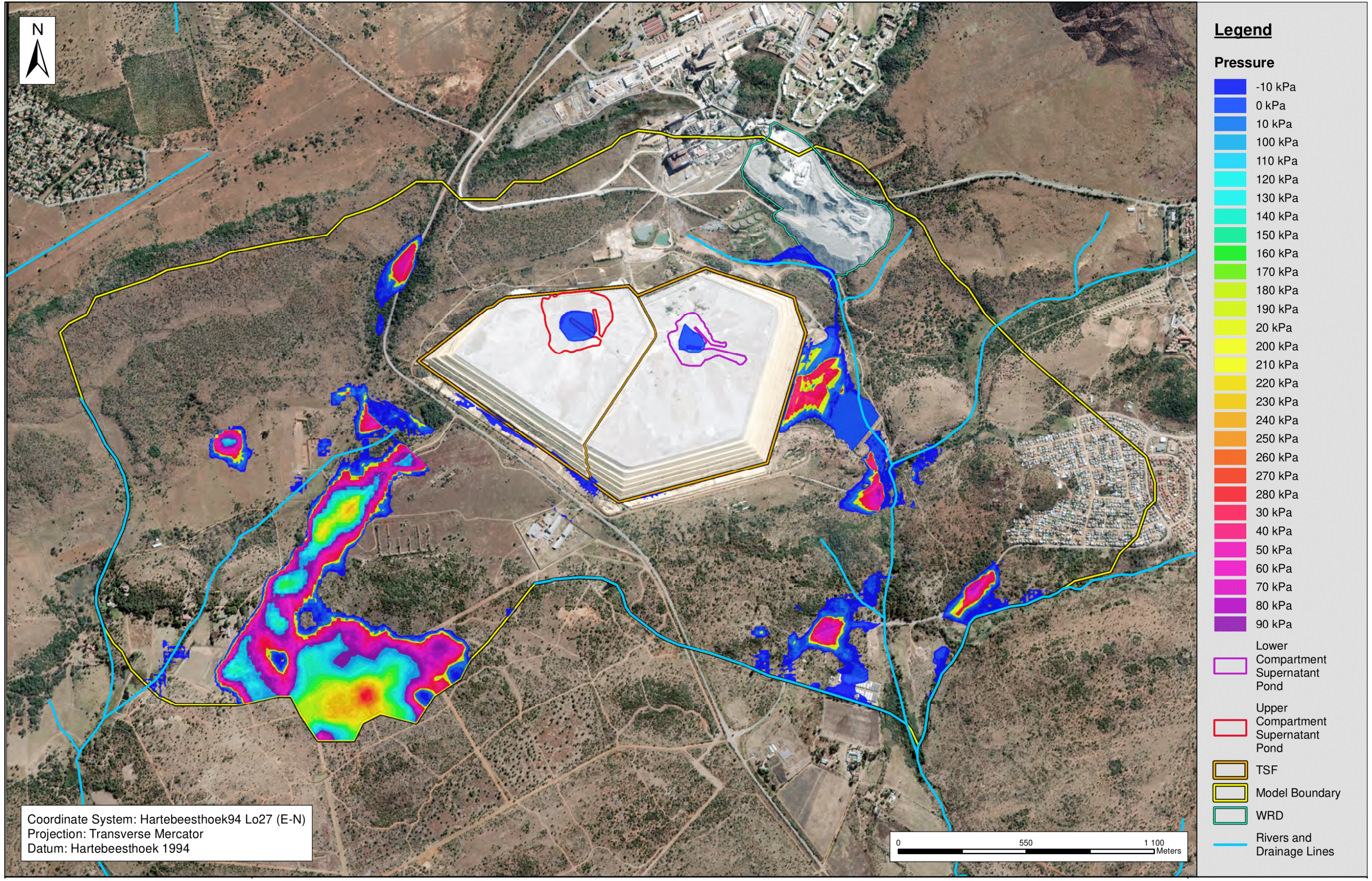
- Geometric- and material data integration shows a hydraulic continuum in many cases.
- Calculated phreatic surface elevation error ranged between 1 – 6%.
- Integration of regolith is crucial to seepage- and pressure zone identification.
- Components contributing to seepage in the TSF can successfully be identified in flow budgets.

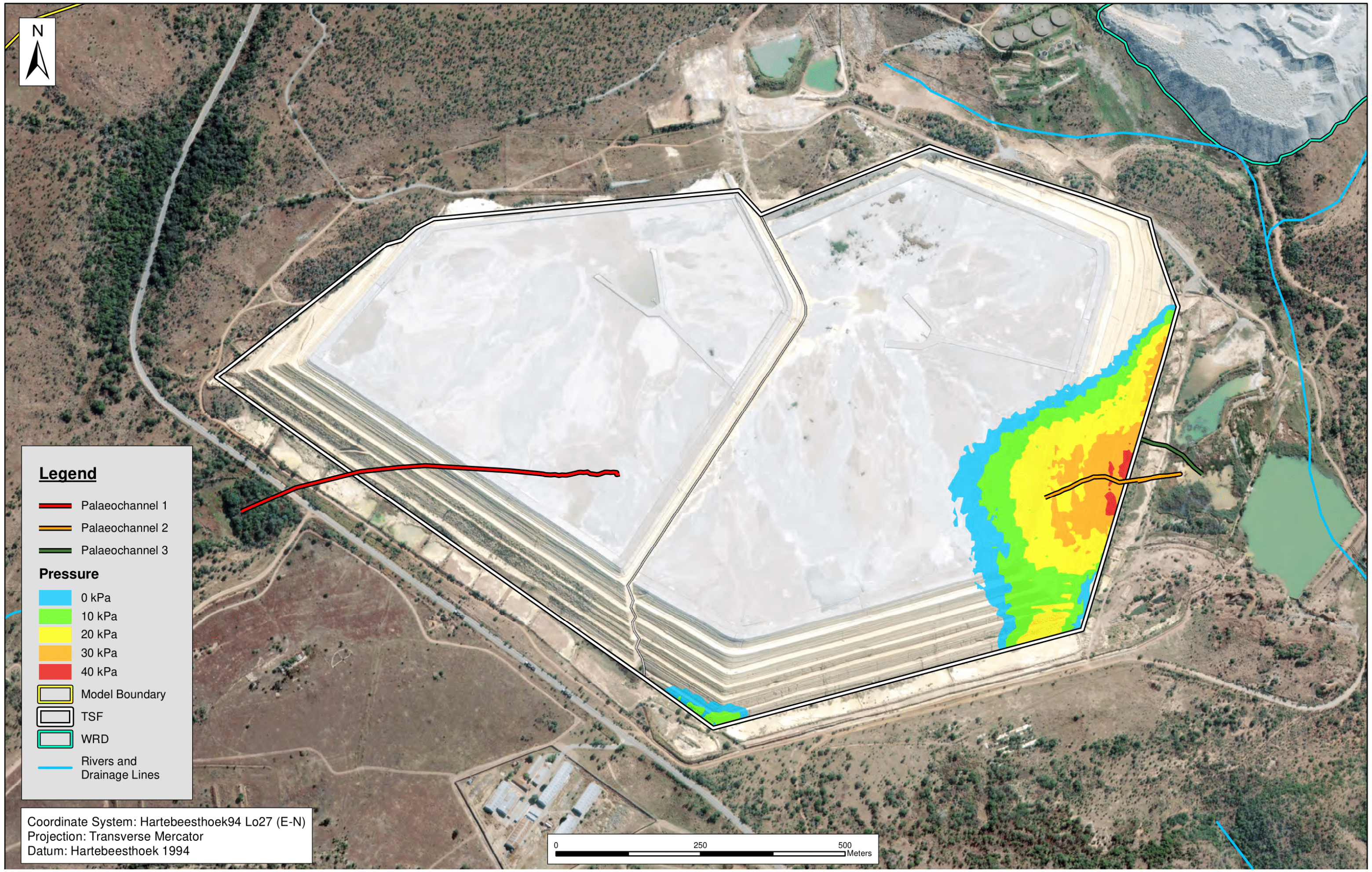
Results and Discussion

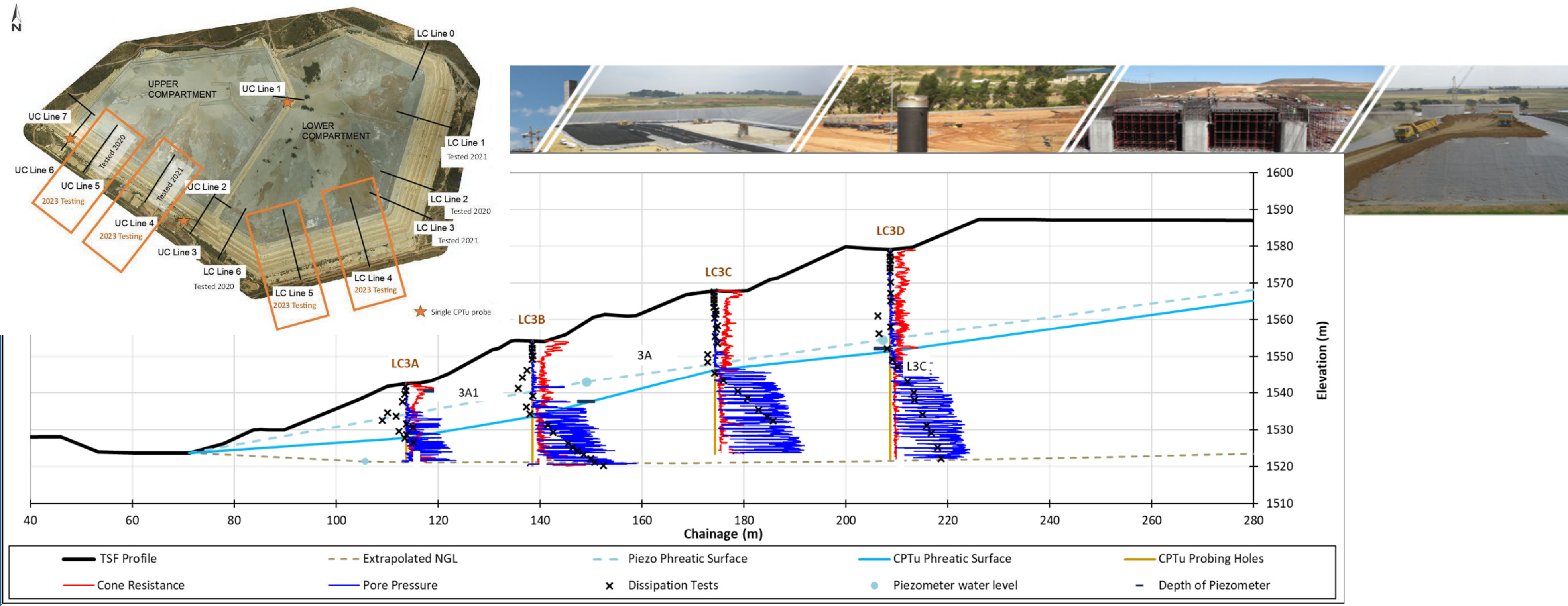
- Potential risk zones were consistently and successfully identified.
- Calculated phreatic surfaces were used to perform stability analyses for identified risk zones.
- Potential leakage zones and clogged underdrainage zones could be identified.
- Unsaturated flow parameters provide insight to flow mechanisms.

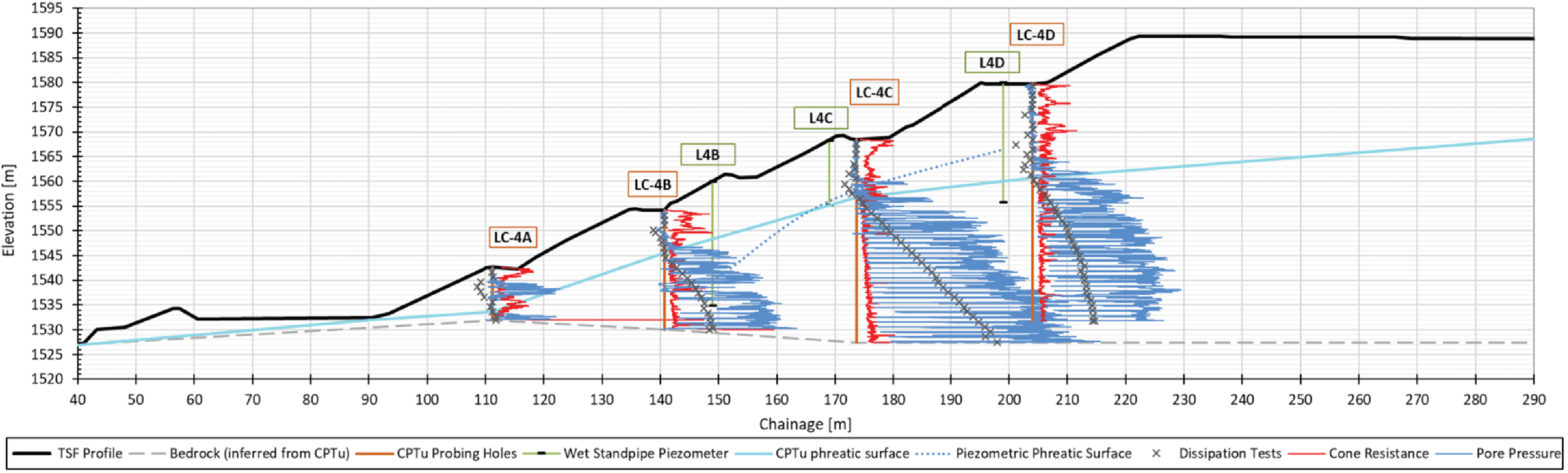

Isolines (kPa)
100
0
200
300
400
500
600
Cross-Section 1
supernatant pond
Cross-Section 2
supernatant pond
Cross-Section 4


N
0
500
1 000
Meters
Legend
Cross-Sections
Cross-Section 1
Cross-Section 2
Cross-Section 4
Surface Contacts
Hekpoort Fm. Andesites
Timeball Hill Ferruginous Siltstones and Shales
Timeball Hill Gatsrand Quartzites
Timeball Hill Rhythmites
Timeball Hill Black Shales
Lower Compartment Supernatant Pond
Upper Compartment Supernatant Pond


N
Legend
Pressure
-10 kPa
0 kPa
10 kPa
100 kPa
110 kPa
120 kPa
130 kPa
140 kPa
150 kPa
160 kPa
170 kPa
180 kPa
190 kPa
20 kPa
200 kPa
210 kPa
220 kPa
230 kPa
240 kPa
250 kPa
260 kPa
270 kPa
280 kPa
30 kPa
40 kPa
50 kPa
60 kPa
70 kPa
80 kPa
90 kPa
Lower Compartment Supernatant Pond
Upper Compartment Supernatant Pond
TSF
Model Boundary
WRD
Rivers and Drainage Lines
Coordinate System: Hartebeesthoek94 Lo27 (E-N)
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
0
550
1 100
Meters


N
Legend
Palaeochannel 1
Palaeochannel 2
Palaeochannel 3
Pressure
0 kPa
10 kPa
20 kPa
30 kPa
40 kPa
Model Boundary
TSF
WRD
Rivers and Drainage Lines
Coordinate System: Hartebeesthoek94 Lo27 (E-N)
Projection: Transverse Mercator
Datum: Hartebeesthoek 1994
0
250
500
Meters


N
LC Line 0
UPPER COMPARTMENT
UC Line 1
LOWER COMPARTMENT
LC Line 1
Tested 2021
UC Line 7
Tested 2020
UC Line 6
UC Line 5
2023 Testing
Tested 2021
UC Line 2
LC Line 2
Tested 2020
LC Line 3
Tested 2021
UC Line 4
2023 Testing
UC Line 3
LC Line 6
Tested 2020
LC Line 5
2023 Testing
LC Line 4
2023 Testing
Single CPTu probe
LC3A
LC3B
LC3C
LC3D
3A1
3A
L3C
1600
1590
1580
1570
1560
1550
1540
1530
1520
1510
Elevation (m)
40
60
80
100
120
140
160
180
200
220
240
260
280
Chainage (m)
TSF Profile
Extrapolated NGL
Piezo Phreatic Surface
CPTu Phreatic Surface
CPTu Probing Holes
Cone Resistance
Pore Pressure
Dissipation Tests
Piezometer water level
Depth of Piezometer


LC-4A
LC-4B
L4B
L4C
LC-4C
L4D
LC-4D
1595
1590
1585
1580
1575
1570
1565
1560
1555
1550
1545
1540
1535
1530
1525
1520
Elevation [m]
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
Chainage [m]
TSF Profile
Bedrock (inferred from CPTu)
CPTu Probing Holes
Wet Standpipe Piezometer
CPTu phreatic surface
Piezometric Phreatic Surface
Dissipation Tests
Cone Resistance
Pore Pressure

Conclusions

- Groundwater numerical models – a useful, integrative tool to generate inputs used for tailings stability analysis (especially under unsaturated conditions.
- Integration of natural- and anthropogenic aquifers consistently yielded reliable model results.
- Identify potential zones of leakage, groundwater inflow, instability, liquefaction, and contaminant release.

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