ANALYSIS BY CROSS PLOT METHOD FOR ANTICIPATING SEEPAGE DURING OPERATION OF UNLINED UNDERGROUND STORAGE CAVERNS

GEOSTOCK

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ABSTRACT N° 2396

CONTENT

- Mined caverns and Hydrodynamic Containment Principle
- Final seepage prediction based on construction data
- Monitoring parameters: Hydraulic Margin & Seepage
- Cross plot analysis: seepage versus Hydraulic margin
- Seepage vs Hydraulic margin for different stages:
  - Full Size Hydraulic Test of the Water curtain system: FSHT
  - Access Tunnel flooding
  - Cavern acceptance Test : CAT
- Analysis
- Conclusions

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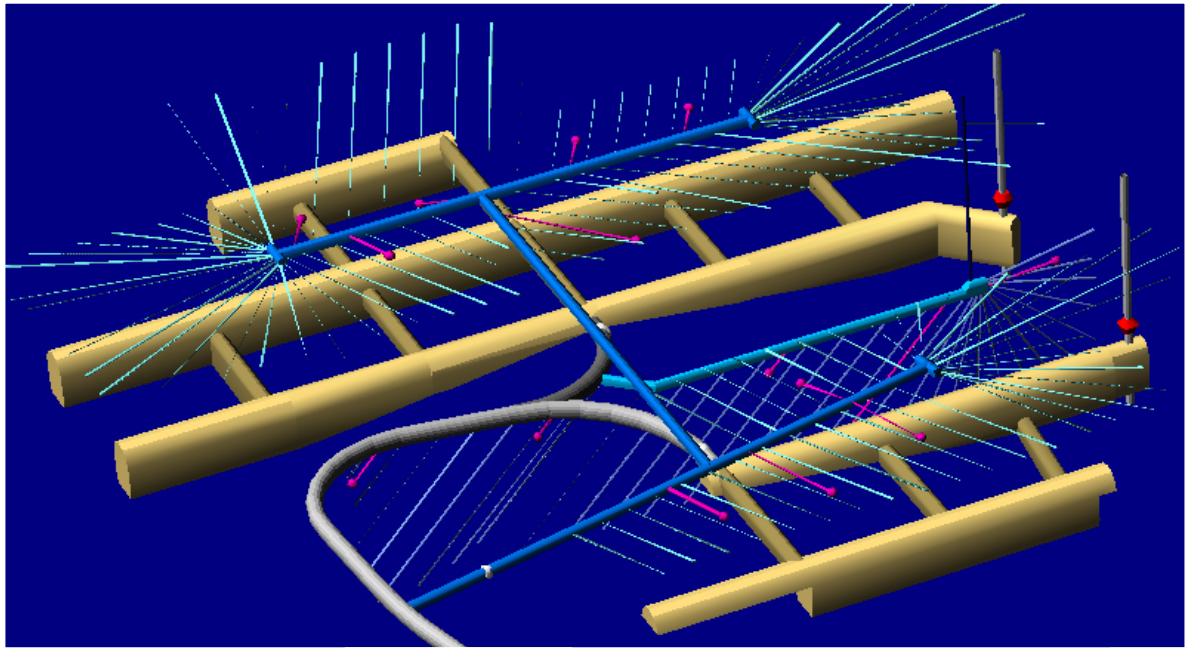
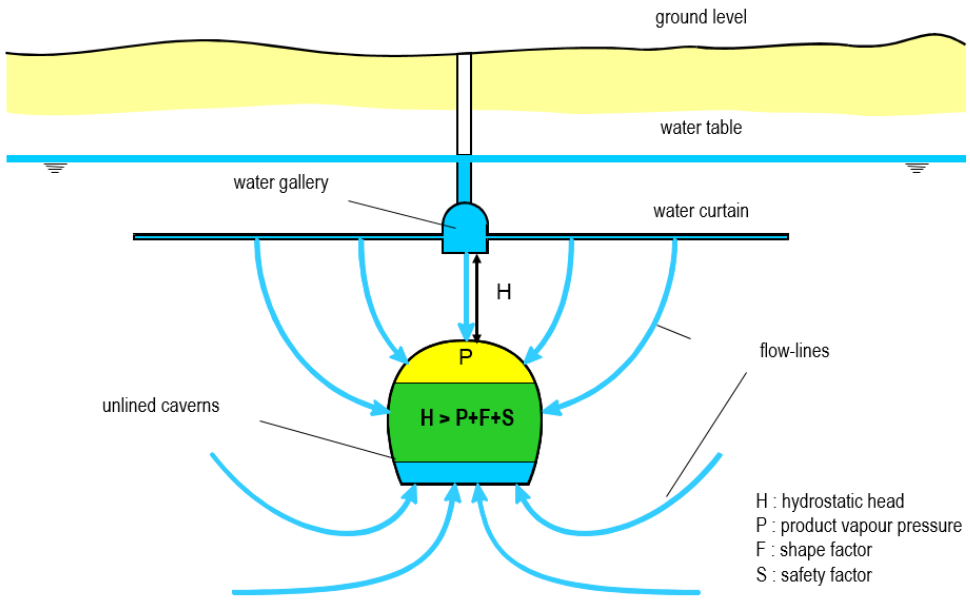
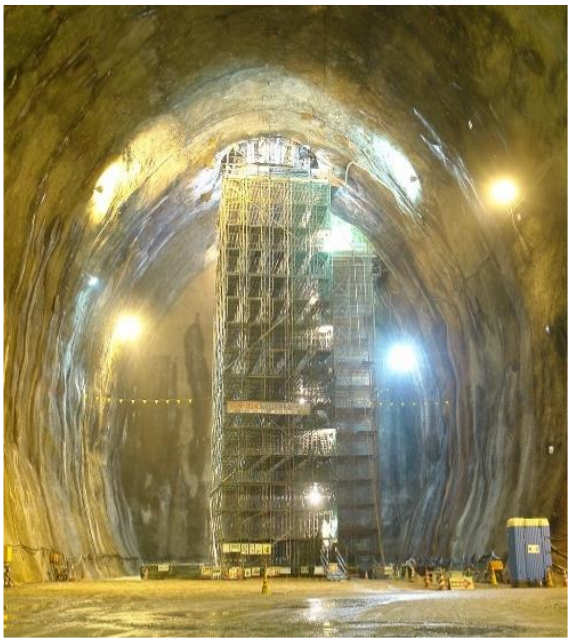
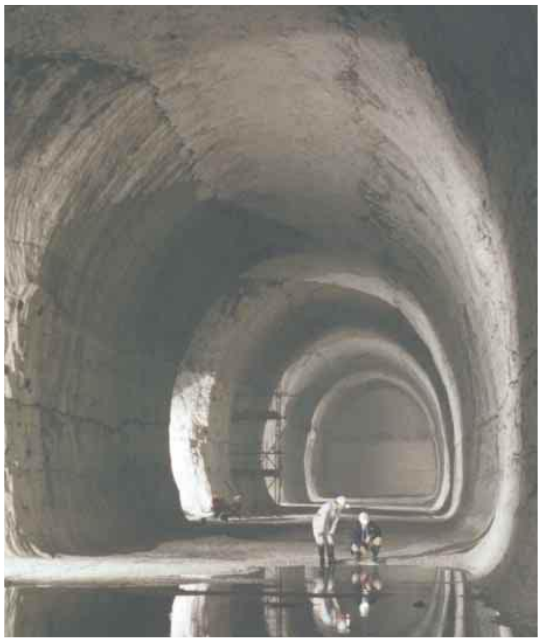
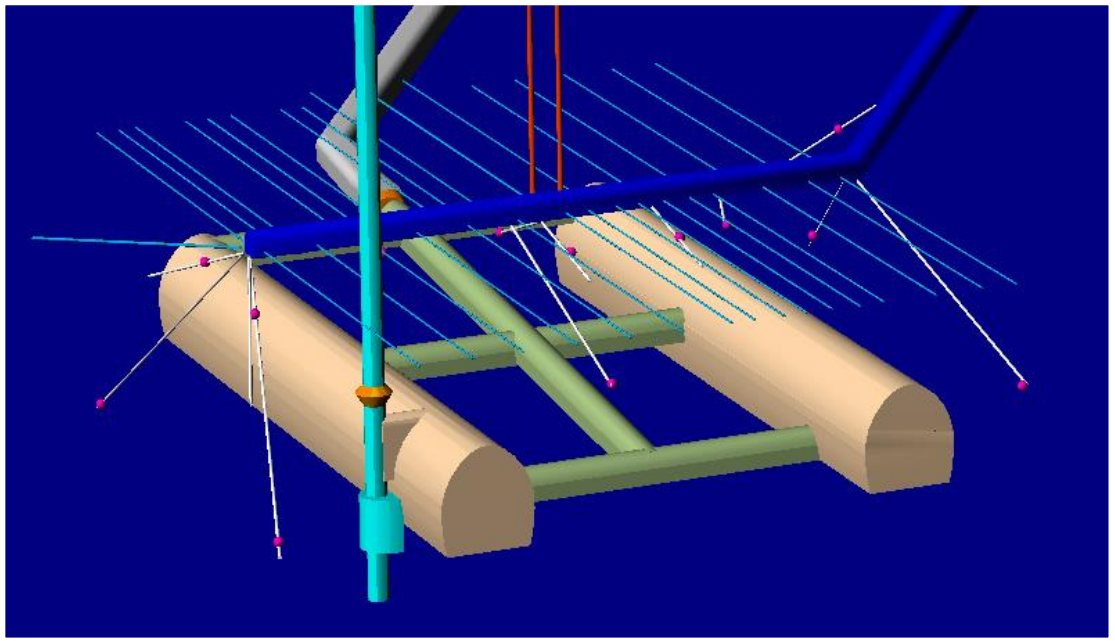
MINED CAVERNS AND HYDRODYNAMIC CONTAINMENT PRINCIPLE





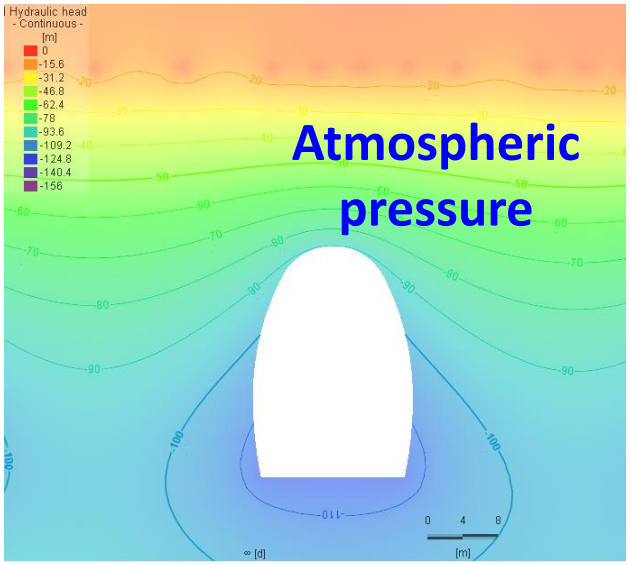


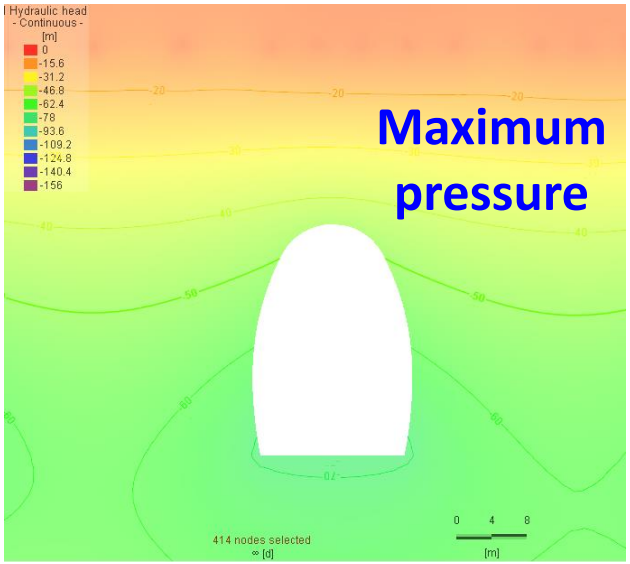




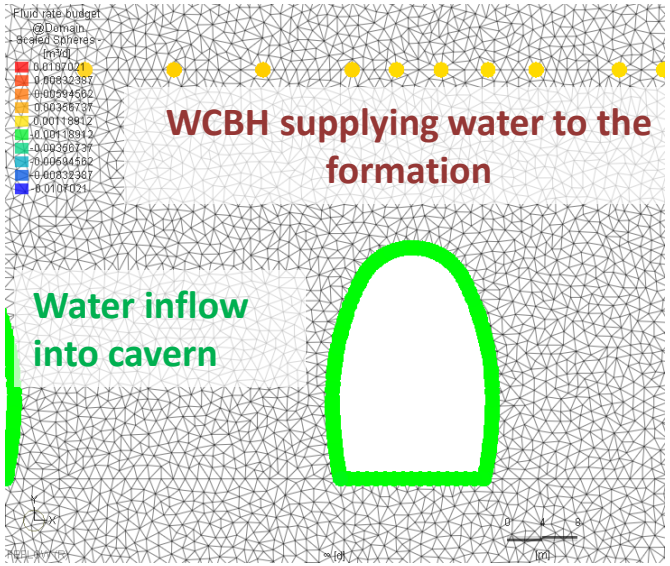
MINED CAVERNS AND HYDRODYNAMIC CONTAINMENT PRINCIPLE

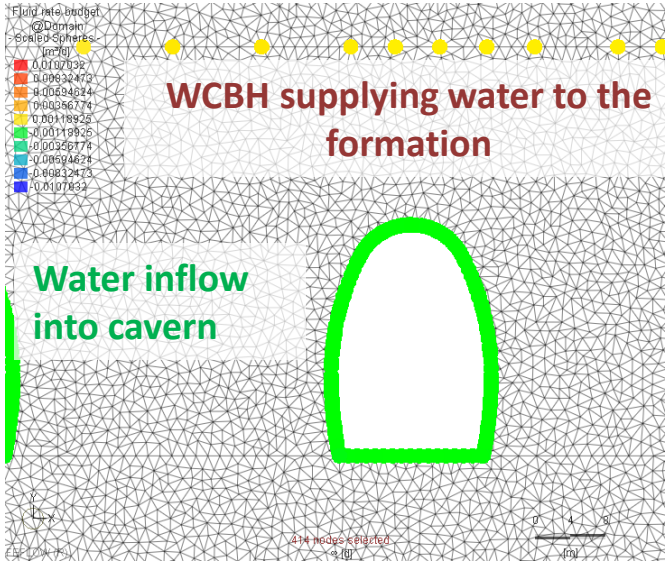
Isopotential lines



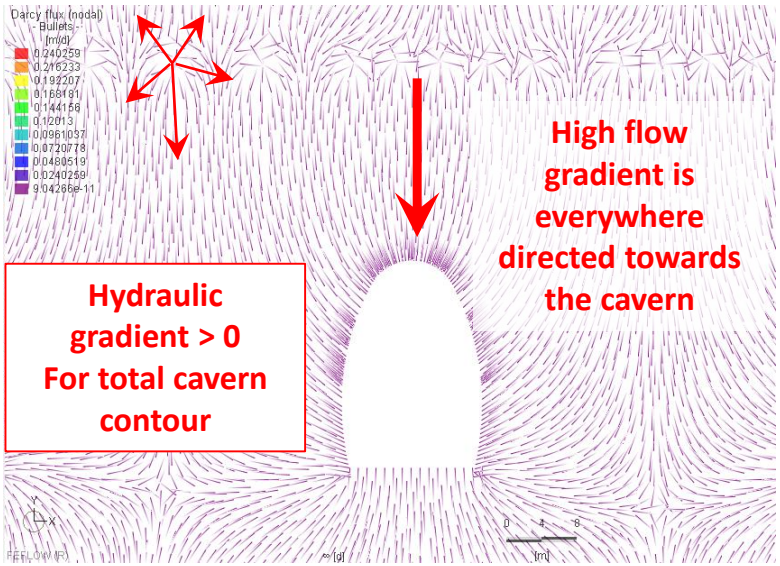


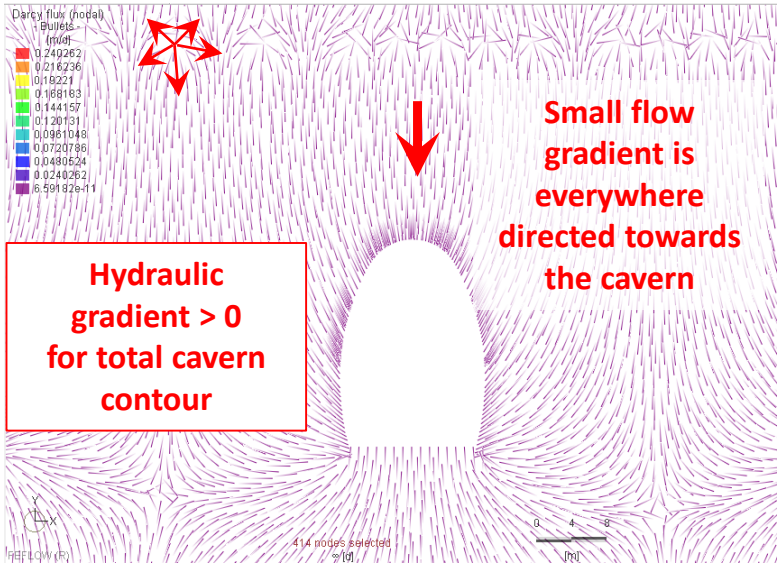
Flow directions for Boundary conditions





Flow lines in the formation





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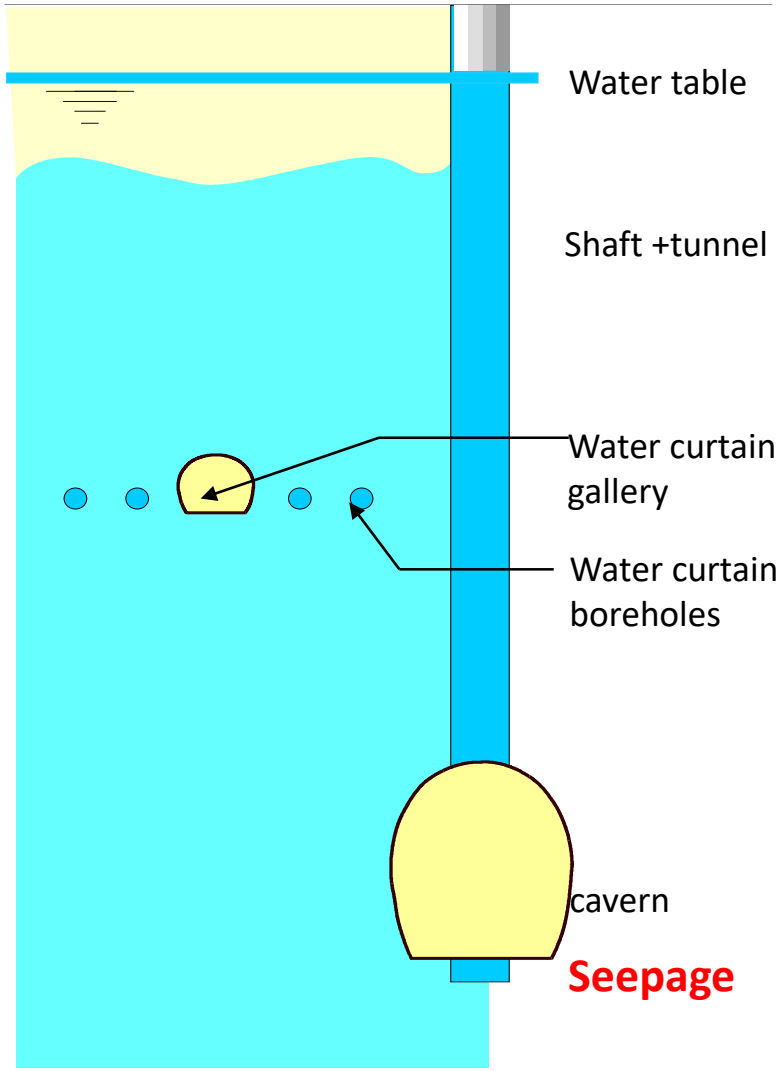
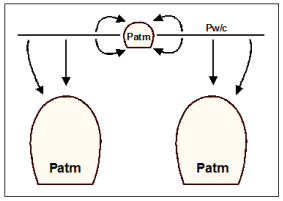
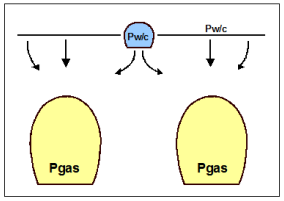
FINAL SEEPAGE PREDICTION BASED ON CONSTRUCTION DATA

Seepage water evaluation

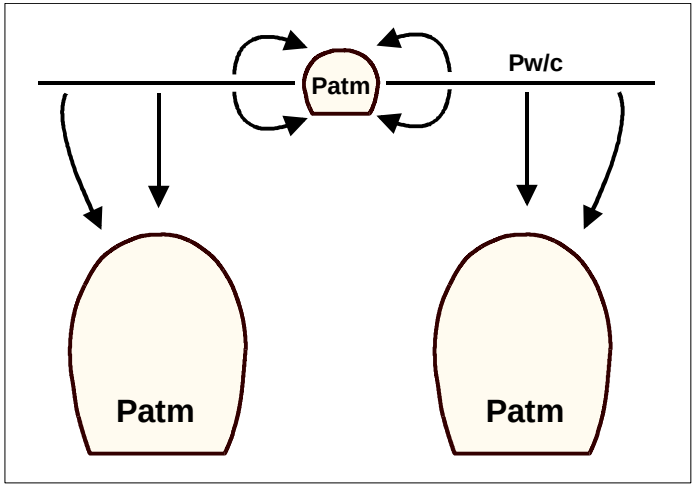


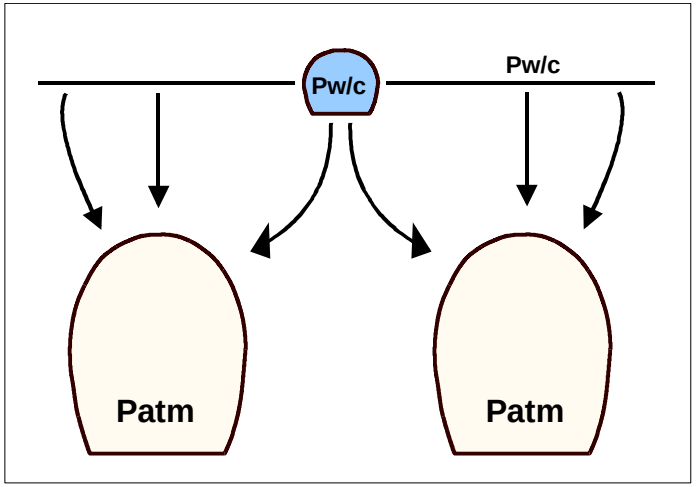
	Construction	Operation
	draw down due to drainage	Recovery after initial transient phase
	P atm	Flooded Φ max
	P atm	Flooded Φ max
	• P injection depends on supply system + formation permeability	Flooded Φ max
	• Progressive activation upon finishing of boreholes 	
	P atm	P min ; P max
	Increases with excavation progress Varies with grouting and WCS efficiency	How to anticipate accurately

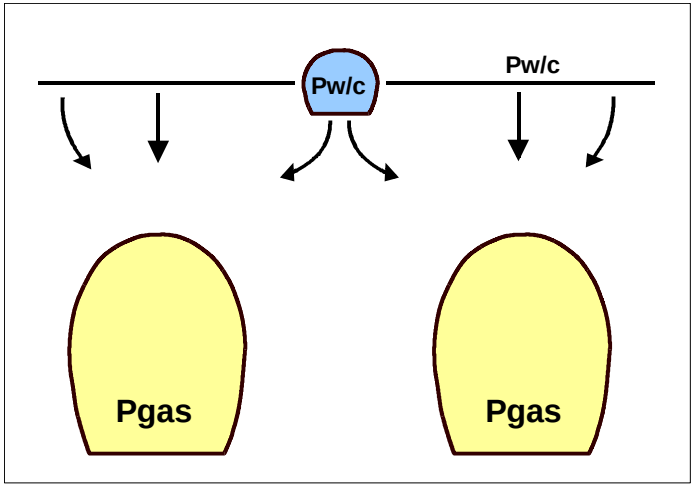
How to evaluate final seepage for operation based on seepage rate measurements during construction ?

Final seepage prediction based on construction data

Hydraulic boundary conditions during different stages of construction, testing and commissioning







Construction:

- Cavern, access tunnel, water curtain tunnel are all at atmospheric pressure.
- The water curtain boreholes are supplied at a given pressure

Full Size Hydraulic Test:

- Cavern, access tunnel are at atmospheric pressure.
- Water curtain tunnel is flooded
- The water curtain boreholes are supplied at the same pressure as the water curtain tunnel

Cavern Acceptance Test And Operation:

- Cavern is pressurised
- Water curtain tunnel, access tunnel and shaft are flooded
- The water curtain boreholes are supplied at the same pressure as the water curtain tunnel

FINAL SEEPAGE PREDICTION BASED ON CONSTRUCTION DATA

Seepage:

- How to evaluate as early as possible the **final seepage for operation**: allowing for finalising the seepage pump sizing

- How to distinguish between:
  - **Favourable low seepage** due to **lower permeability** than evaluated during investigation
  - **Favourable low seepage** due to **efficient grouting** works, and
  - **Unfavourable low seepage** due to **local desaturation** resulting in **insufficient hydrodynamic containment**

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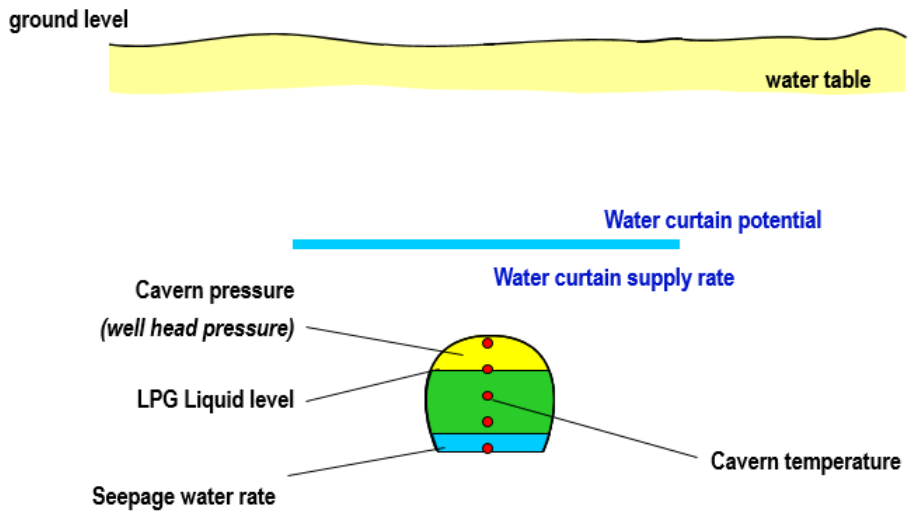
MONITORING PARAMETERS : HYDRAULIC MARGIN & SEEPAGE

Facility parameters

Storage Cavern

- Cavern pressure
- Liquid level in cavern
- Cavern temperature
- Seepage rate

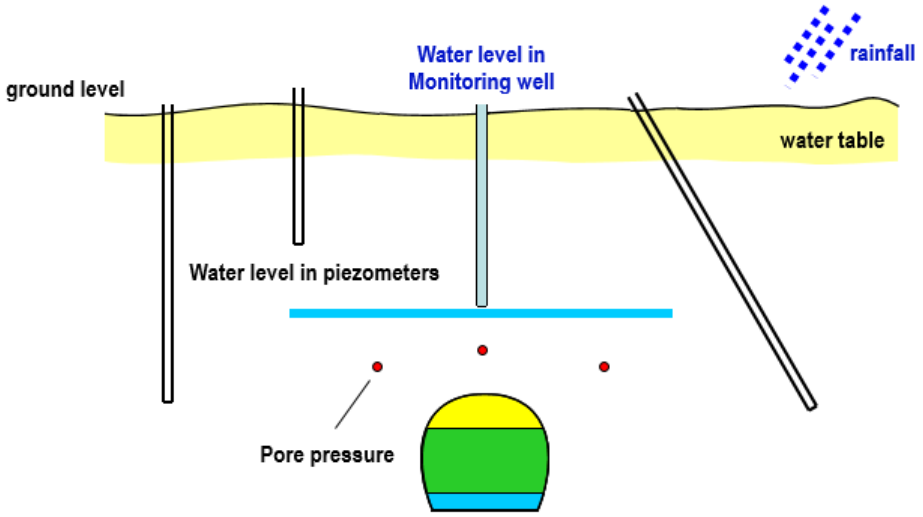


Water Curtain System

- Hydraulic potential of water curtain system
- Supply rate to water curtain system

Formation parameters

- Hydraulic potential for pore pressure cells located between the cavern and the water curtain system
- Hydraulic potentials for piezometers located beyond the water curtain system
- Rainfall
- Tidal effects
- Others: nearby pumping, ongoing works, …



MONITORING PARAMETERS : HYDRAULIC MARGIN & SEEPAGE

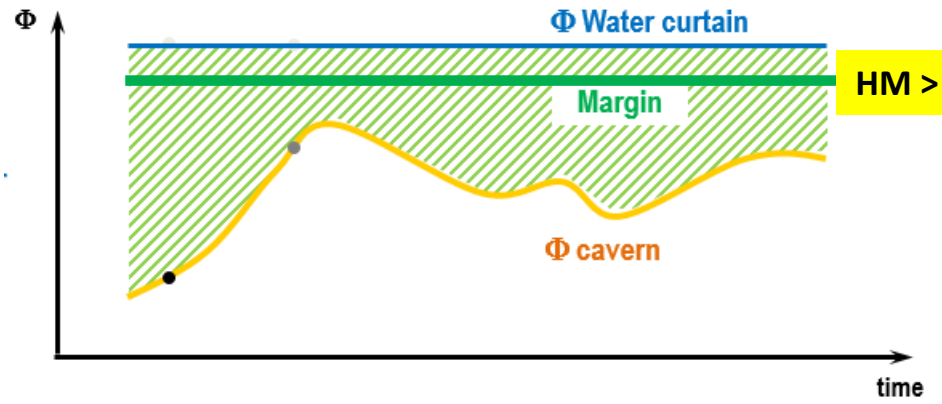
Hydraulic margin

=

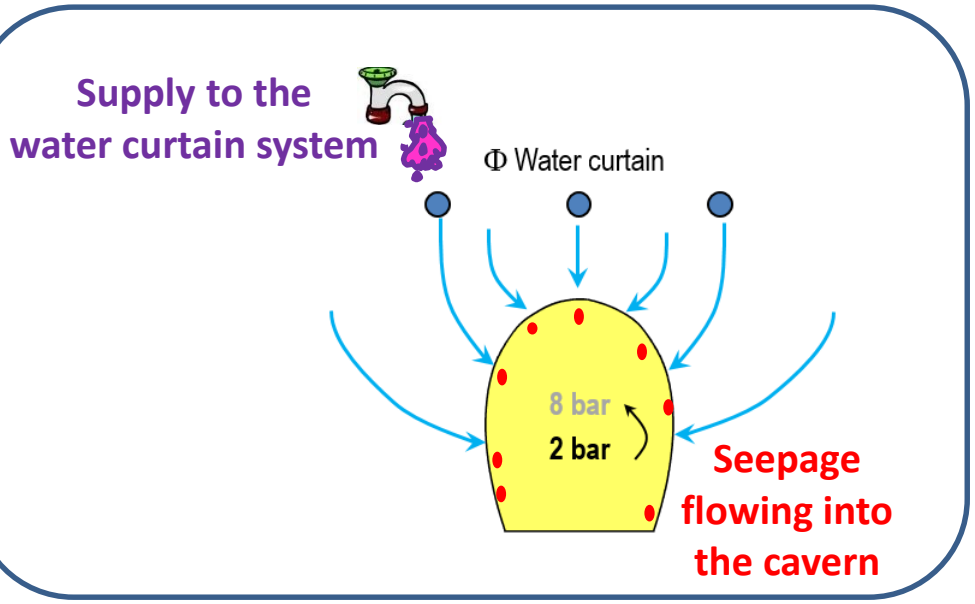
Hydraulic potential of the upstream boundary condition: the water table or the water curtain system

-

Hydraulic potential of the cavern



HM > criteria



Hydraulic margin > Critical value

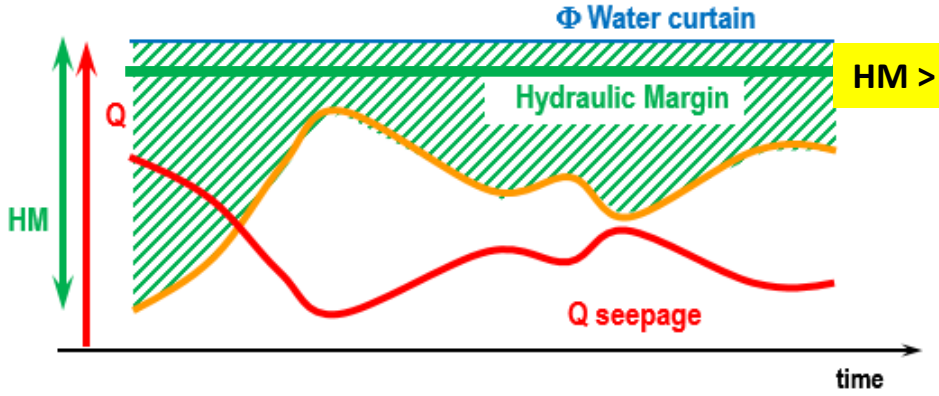
Based on shape factor and safety margin

Darcy's law:

For a given hydraulic conductivity and a given geometry (area and length):

->

The discharge rate is proportional to the head difference (hydraulic margin)



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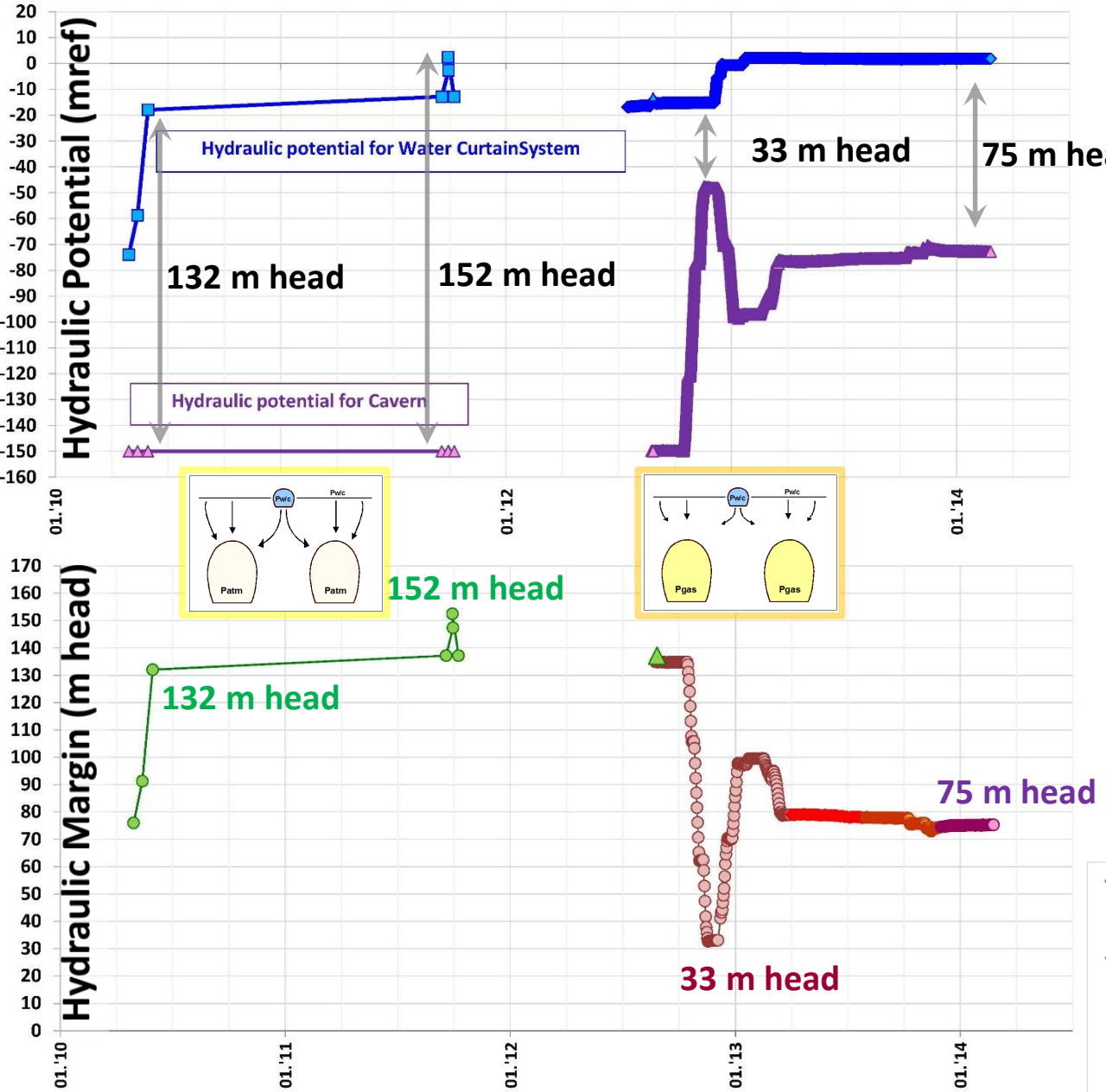
Cross plot analysis : Seepage versus Hydraulic Margin



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Hydraulic margin

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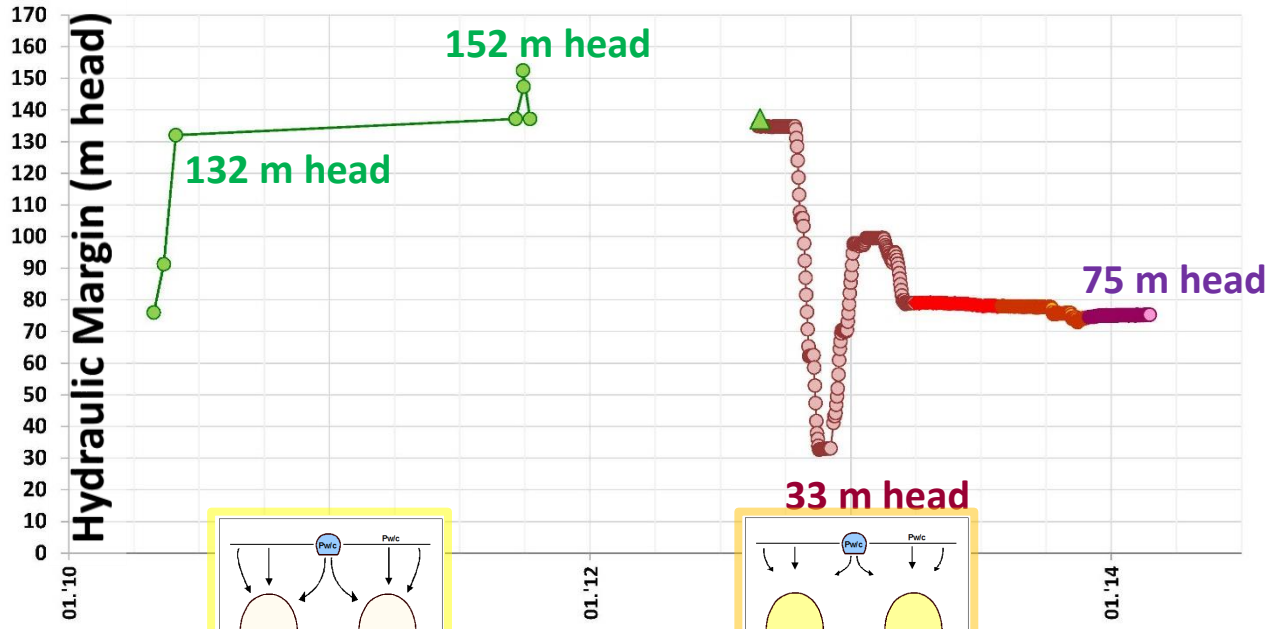

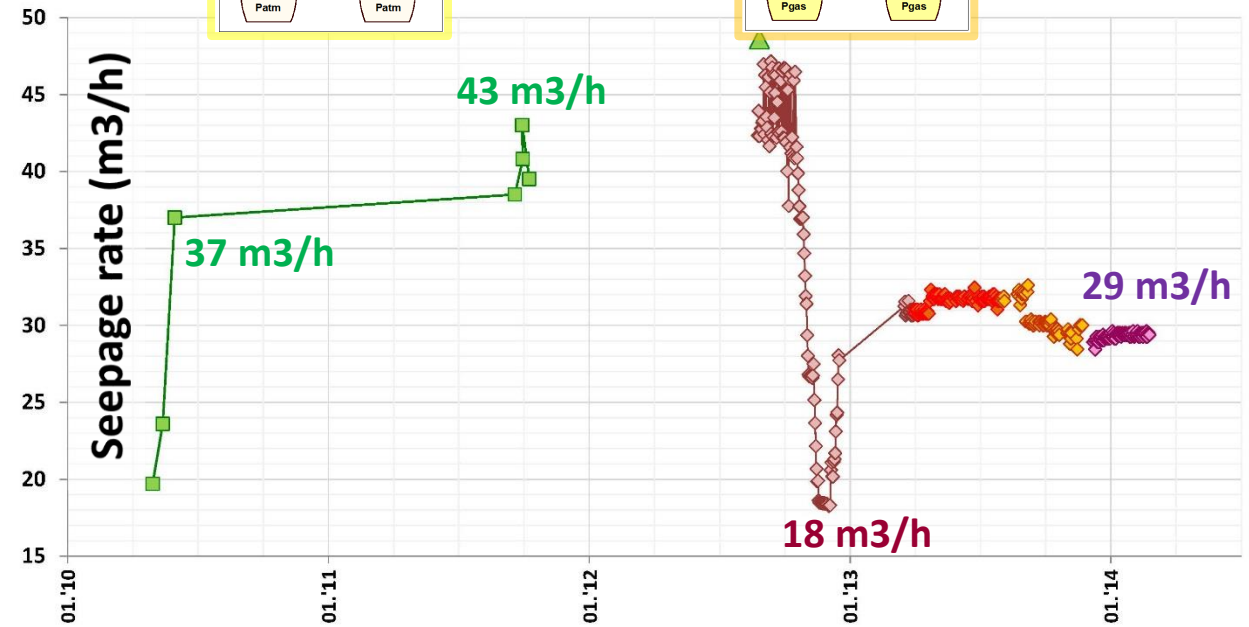

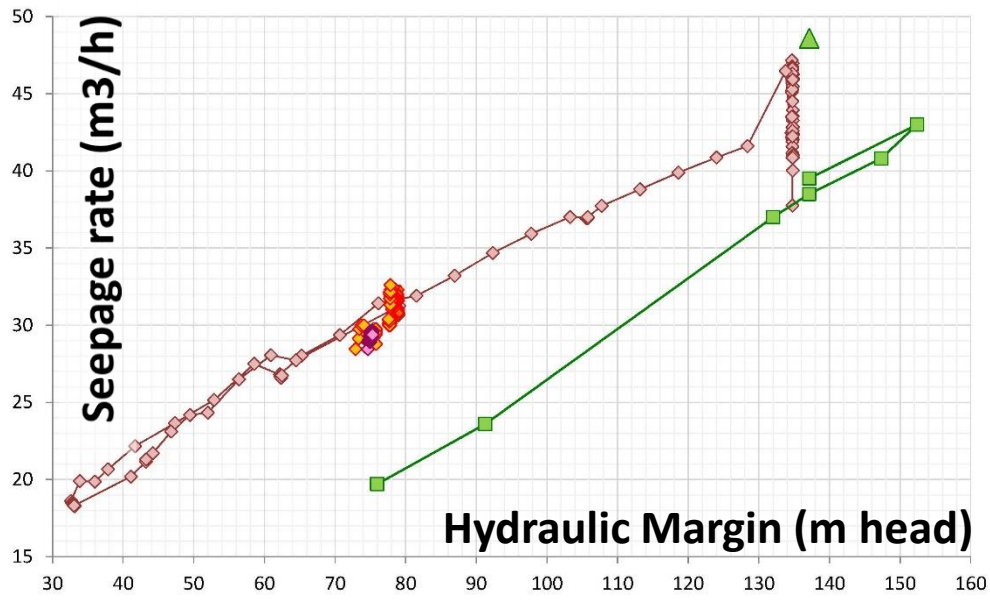

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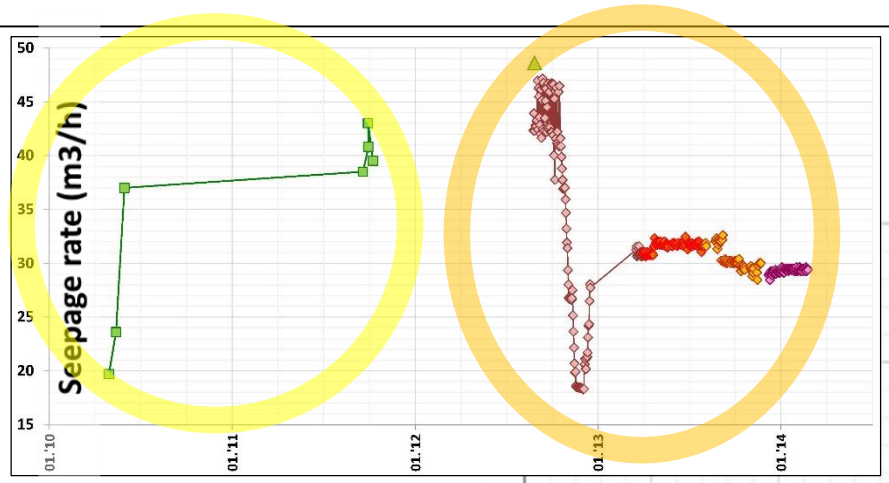
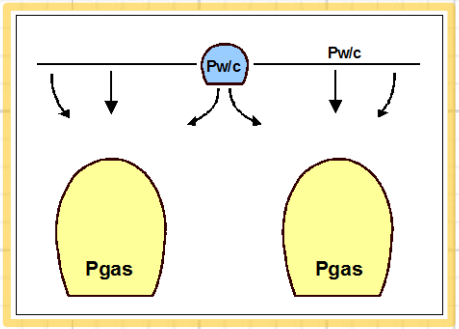
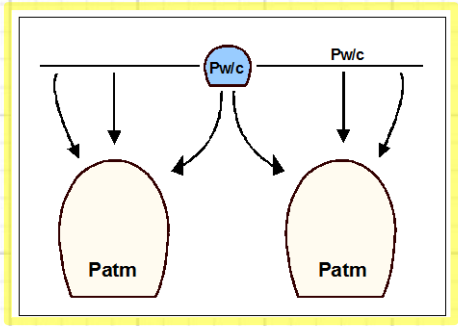
SEEPAGE VERSUS HYDRAULIC MARGIN : SUCCESSIVE PHASES OF CONSTRUCTION



Linear correlation during FSHT lower by 6 to 10 m3/h compared to the linear correlation for CAT

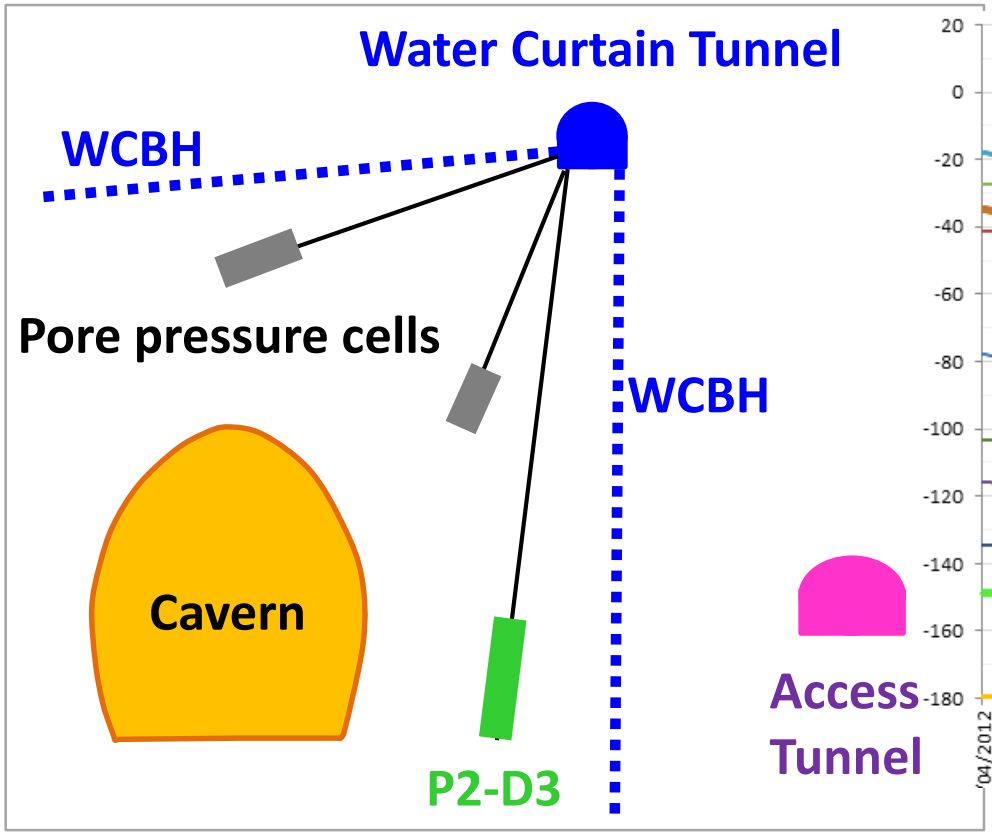


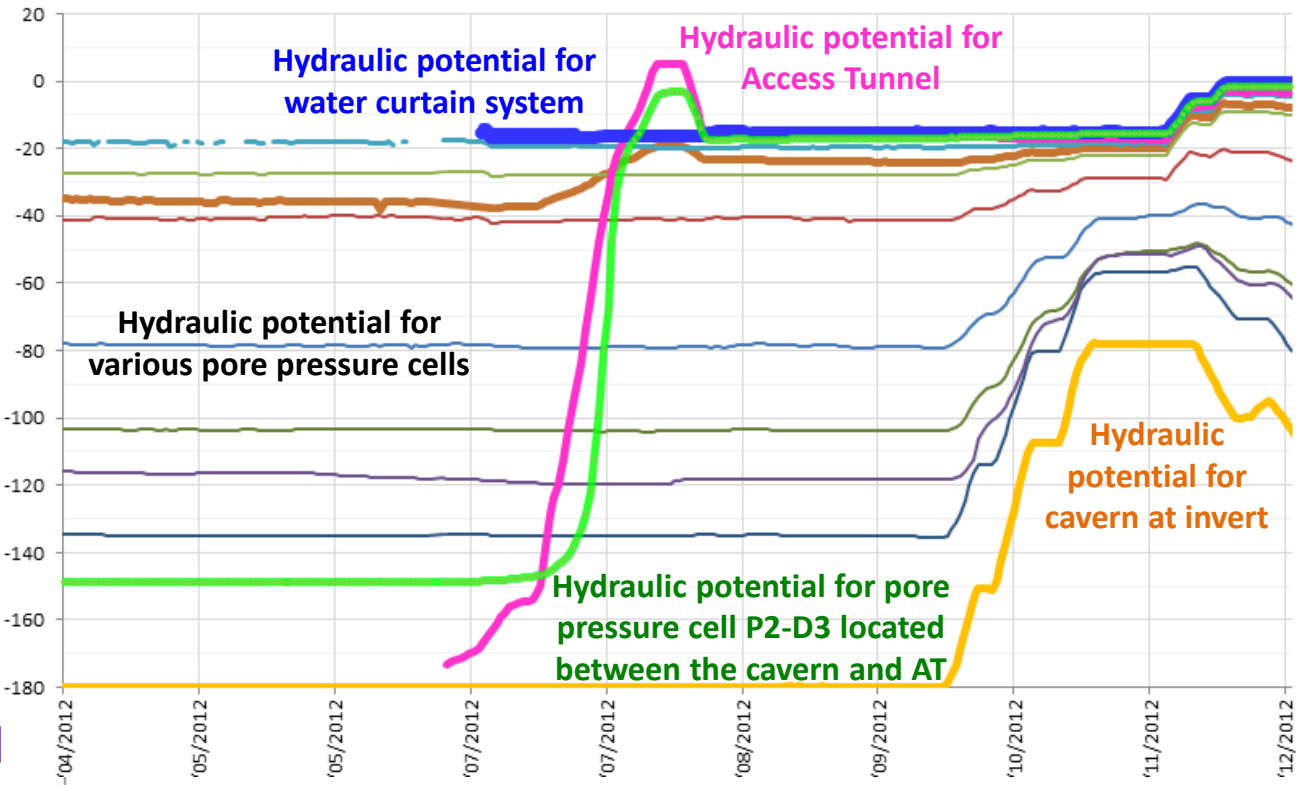


SEEPAGE VERSUS HYDRAULIC MARGIN : SUCCESSIVE PHASES OF CONSTRUCTION

Most **pore pressure cells** display hydraulic potential evolution in correlation with the variation in hydraulic potential for both the **water curtain system** and **cavern**.

Some pore pressure cells display a rising hydraulic potential during **access tunnel flooding**. Pressure cell **P2-D3** displays a significant rise with AT flooding, **suggesting a direct connection between P2-D3 and access tunnel bypassing the water curtain system**: additional seepage to cavern.





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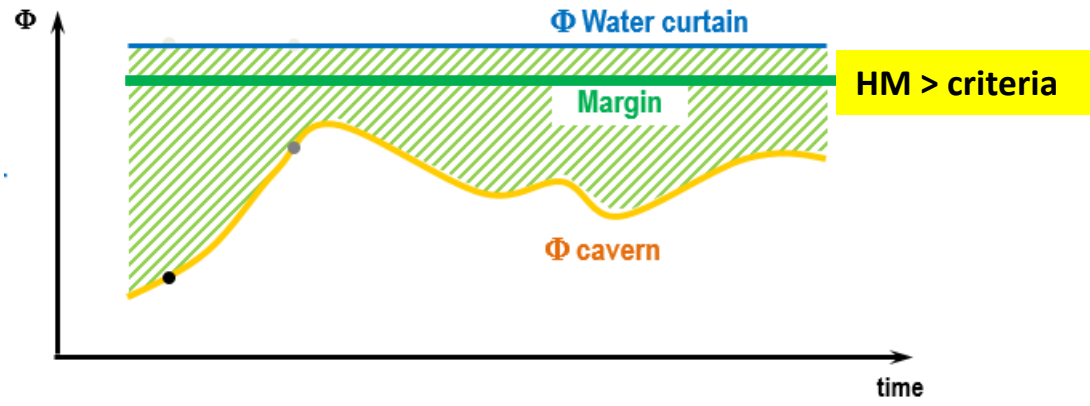
SEEPAGE VERSUS HYDRAULIC MARGIN : ANALYSIS

As mentioned earlier:

hydraulic margin > critical value

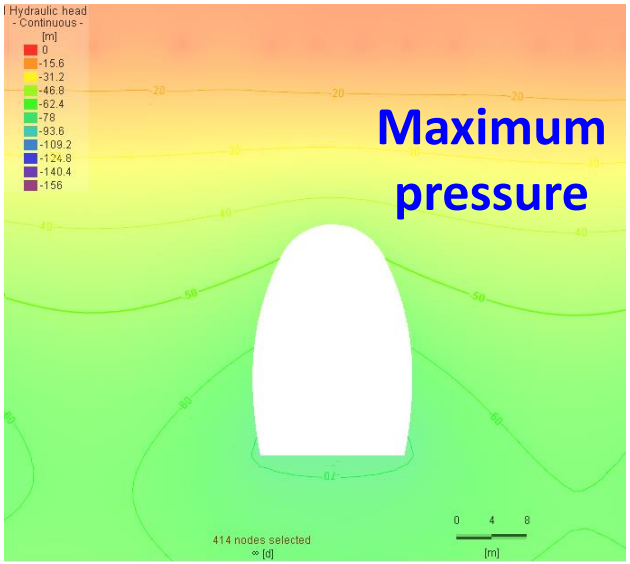


For HM = critical value

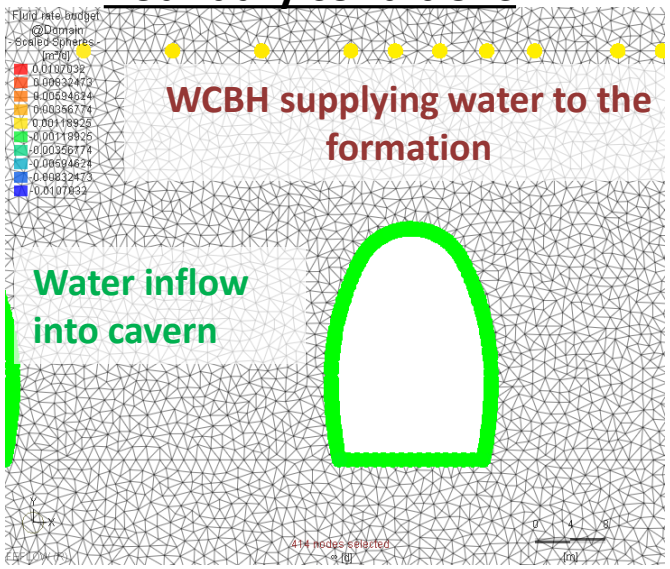
⇒ **Hydraulic gradient directed towards the cavern for the total cavern contour**

⇒ **Seepage > 0**

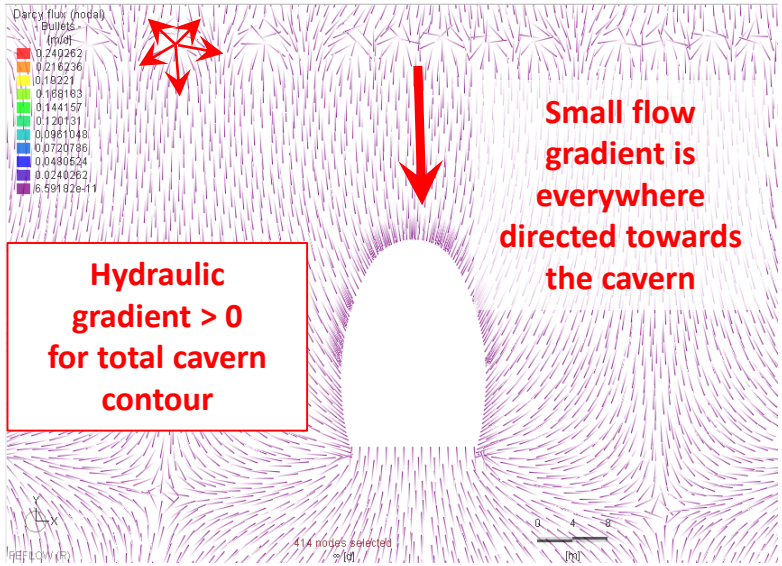
Isopotential lines



Flow directions for Boundary conditions



Flow lines in the formation



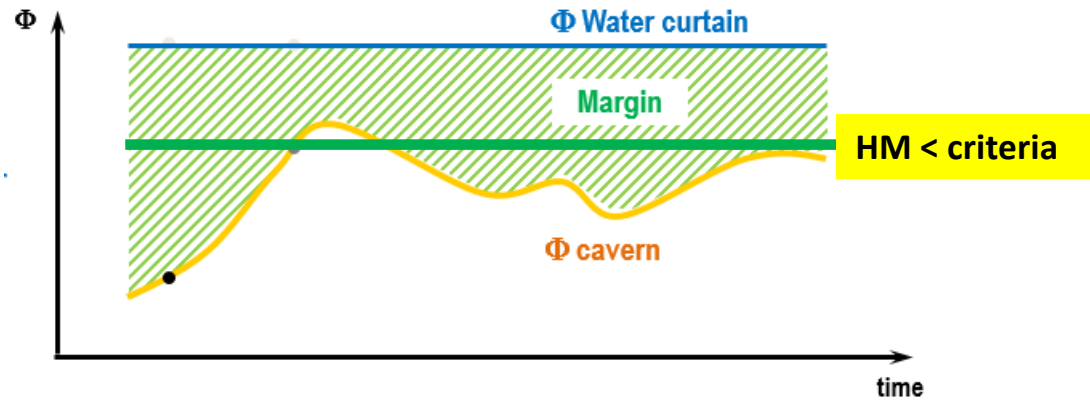
SEEPAGE VERSUS HYDRAULIC MARGIN : ANALYSIS

For HM < critical value

⇒ **Hydraulic gradient inversion along part or total cavern contour**

⇒ **In case of partial gradient inversion there is still some seepage**

⇒ **In case of total gradient inversion seepage drops to zero**



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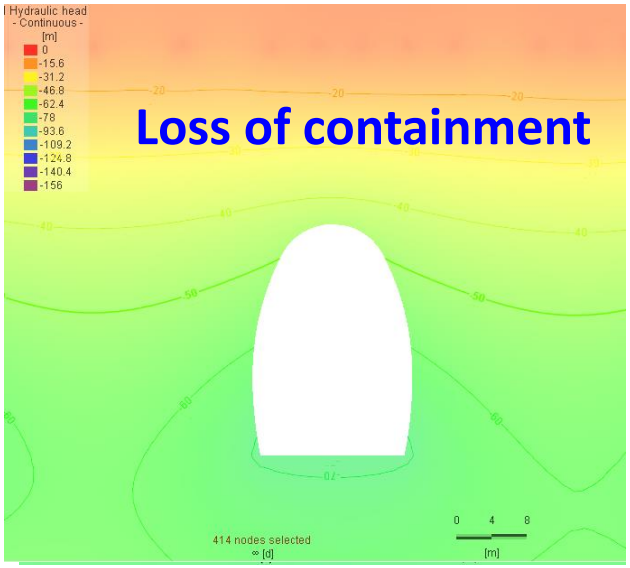

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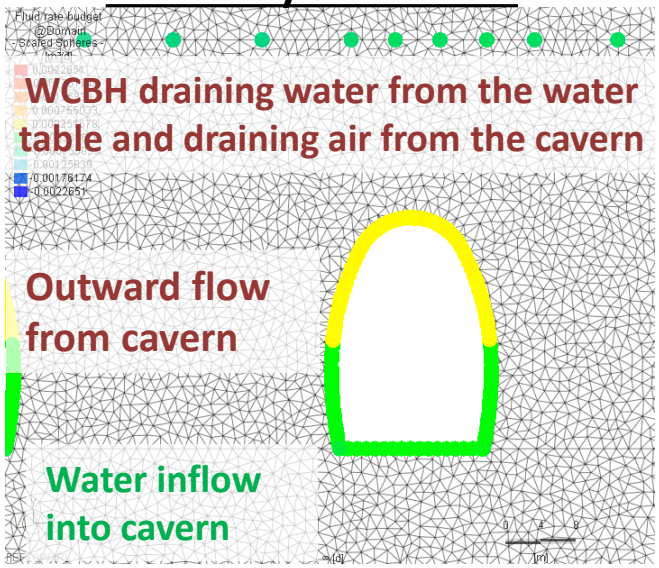

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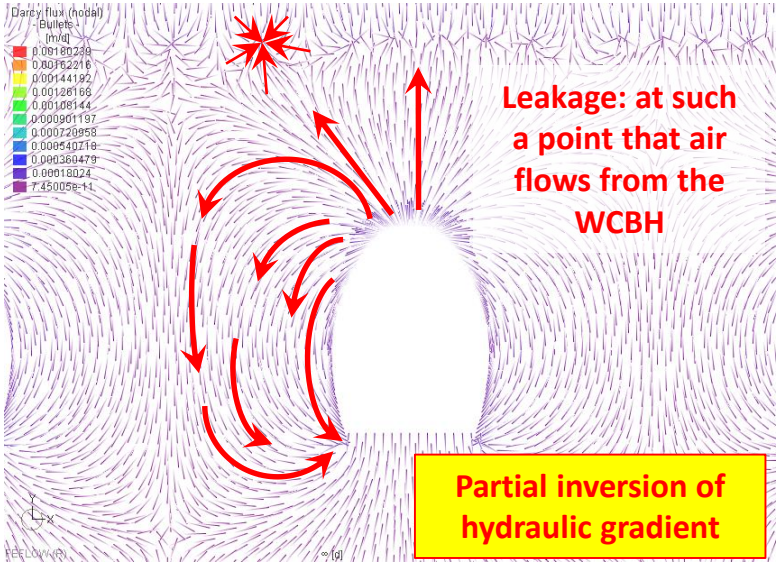

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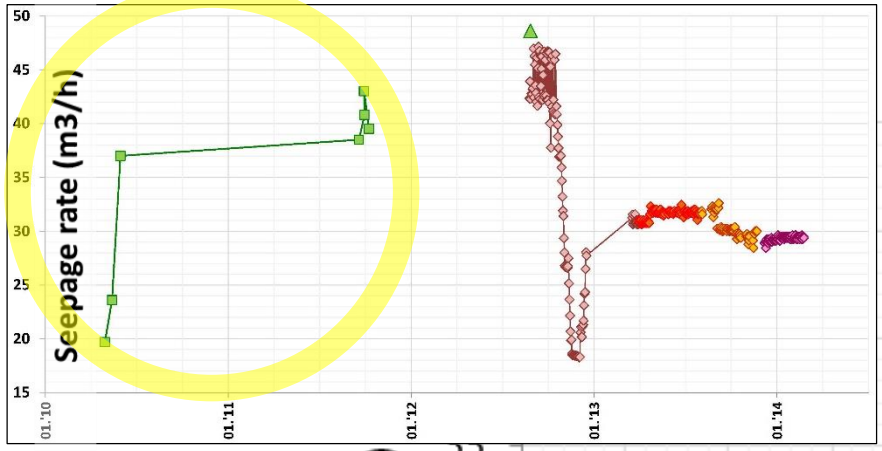
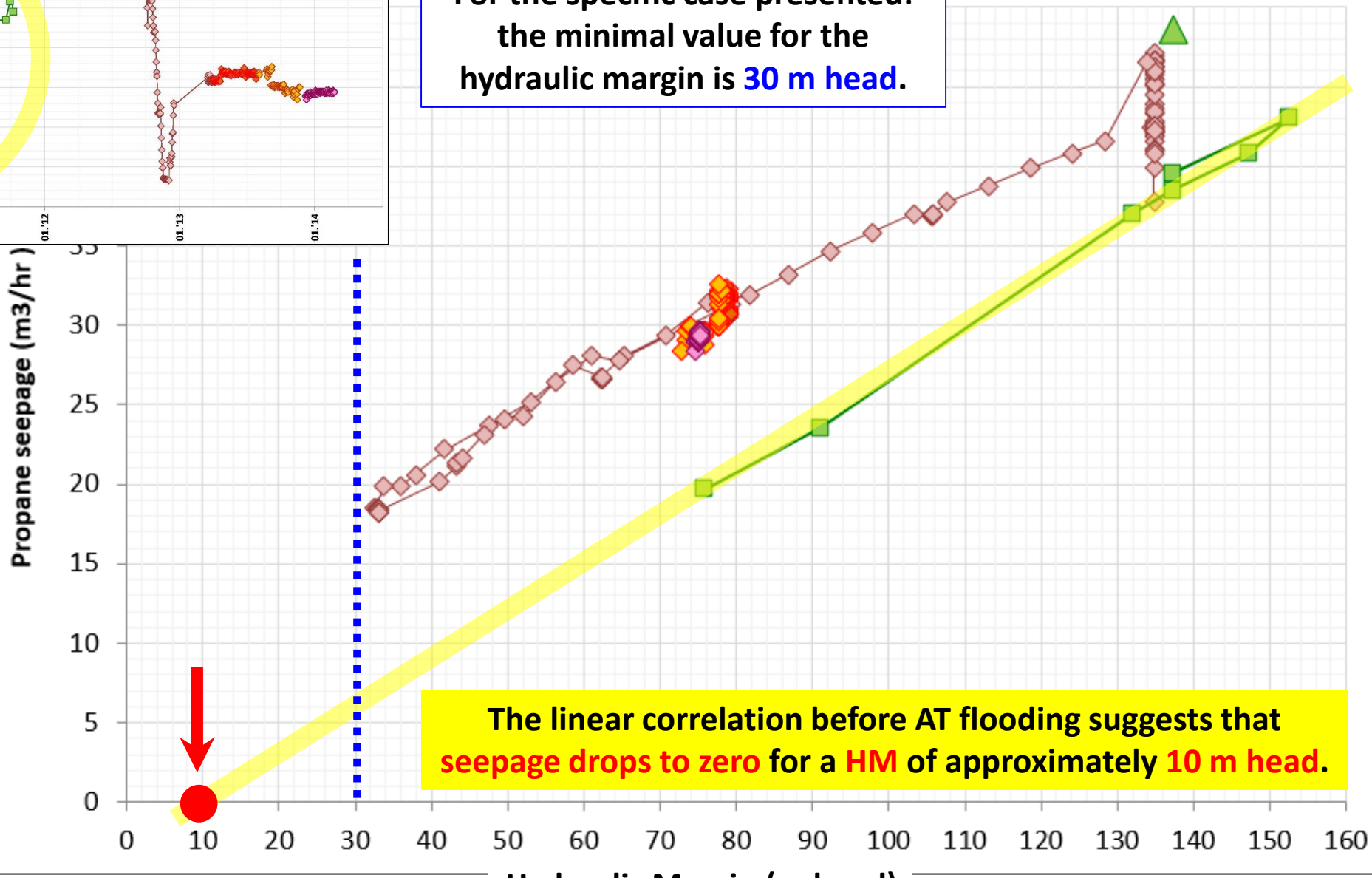


For the specific case presented: the minimal value for the hydraulic margin is **30 m head**.



The linear correlation before AT flooding suggests that **seepage drops to zero** for a **HM** of approximately **10 m head**.

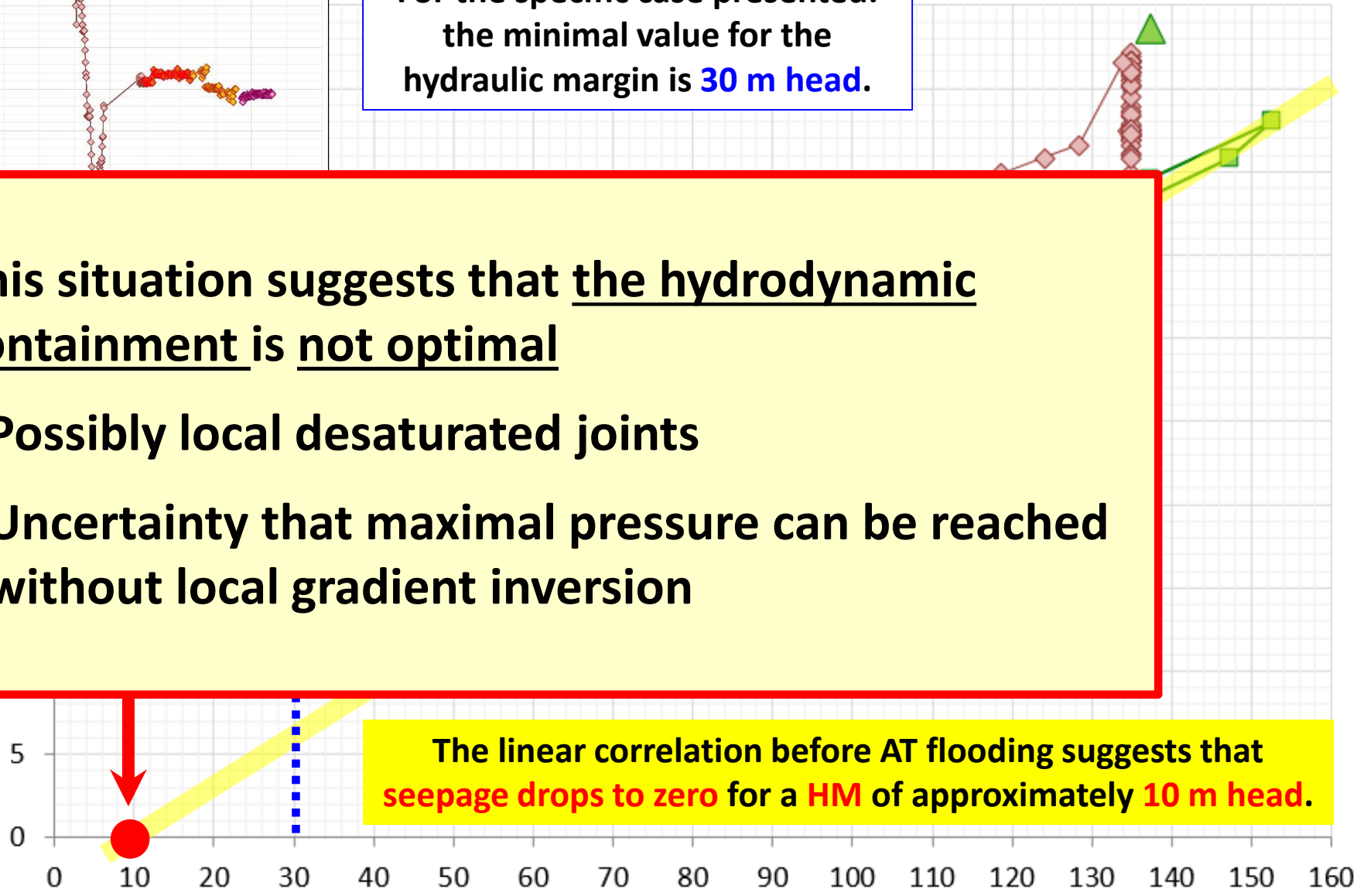
Seepage versus Hydraulic Margin : Analysis

For the specific case presented: the minimal value for the hydraulic margin is 30 m head.

This situation suggests that the hydrodynamic containment is not optimal

- Possibly local desaturated joints
- Uncertainty that maximal pressure can be reached without local gradient inversion

The linear correlation before AT flooding suggests that seepage drops to zero for a HM of approximately 10 m head.



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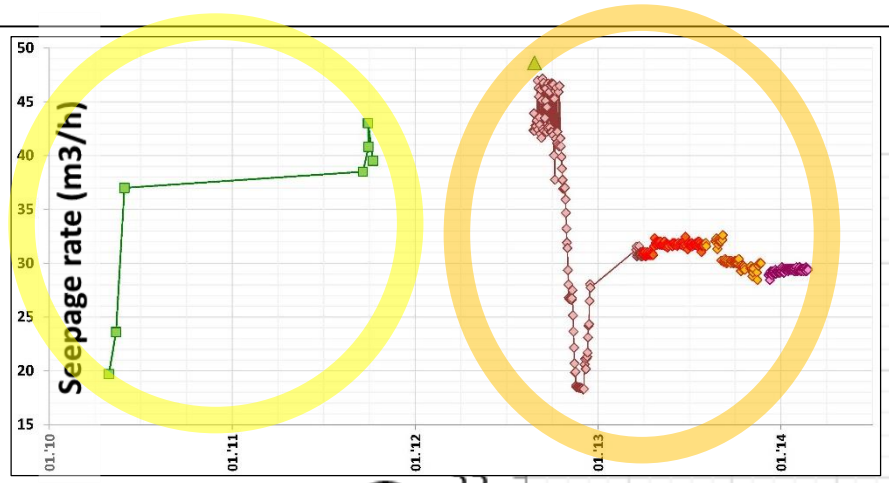

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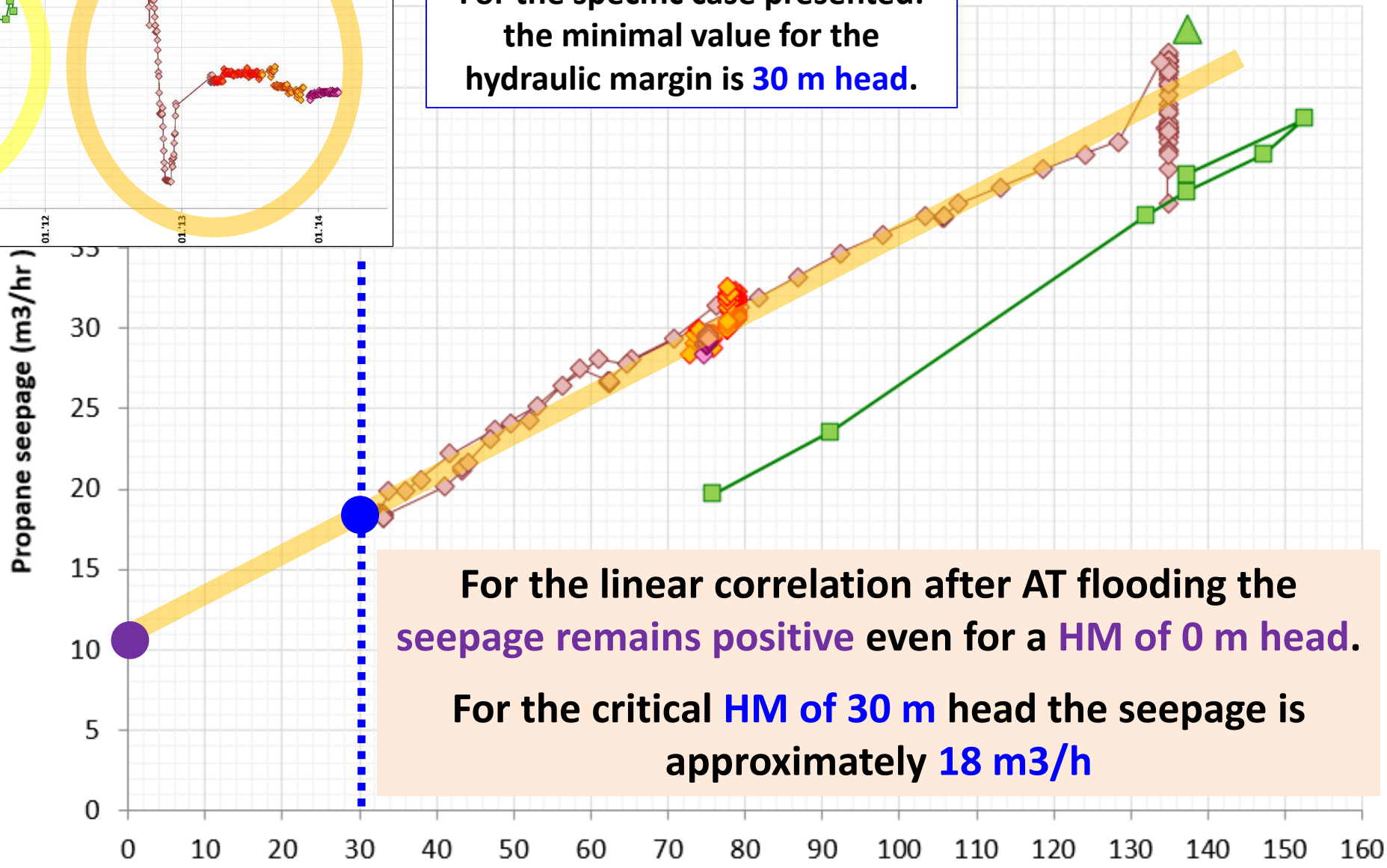

For the linear correlation after AT flooding the **seepage remains positive** even for a **HM of 0 m head**.

For the critical **HM of 30 m** head the seepage is approximately **18 m3/h**

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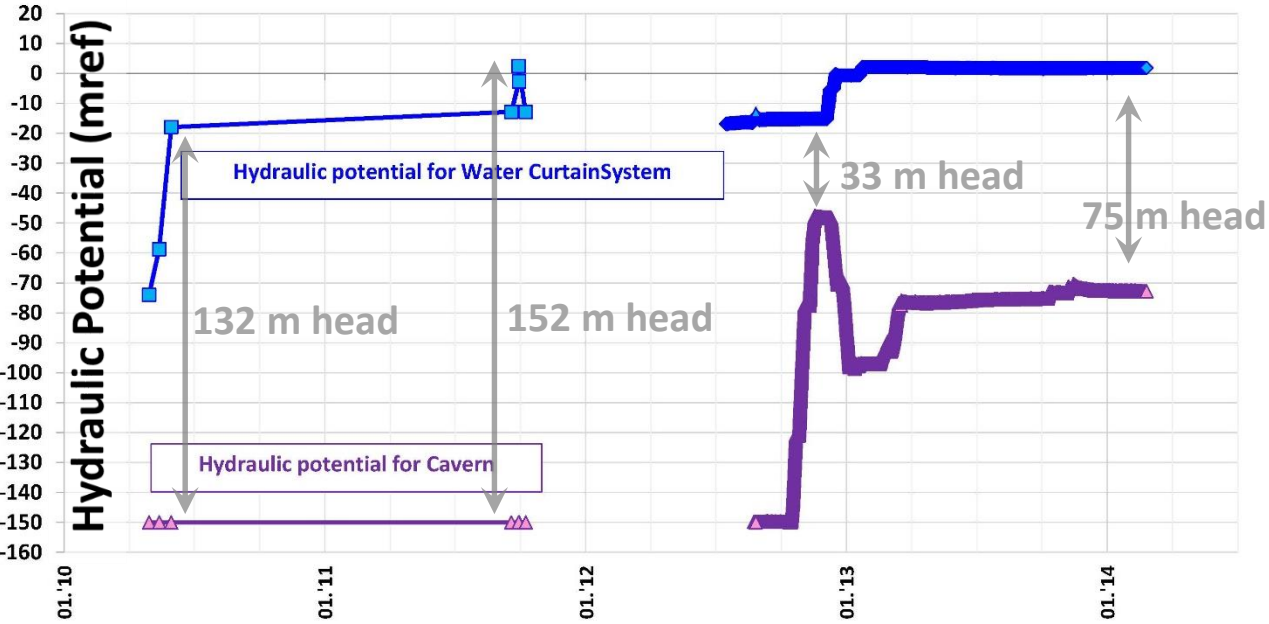
  - Full Size Hydraulic Test of the Water curtain system: FSHT
  - Access Tunnel flooding
  - Cavern acceptance Test : CAT
- Analysis
- **Conclusions**

CONCLUSIONS

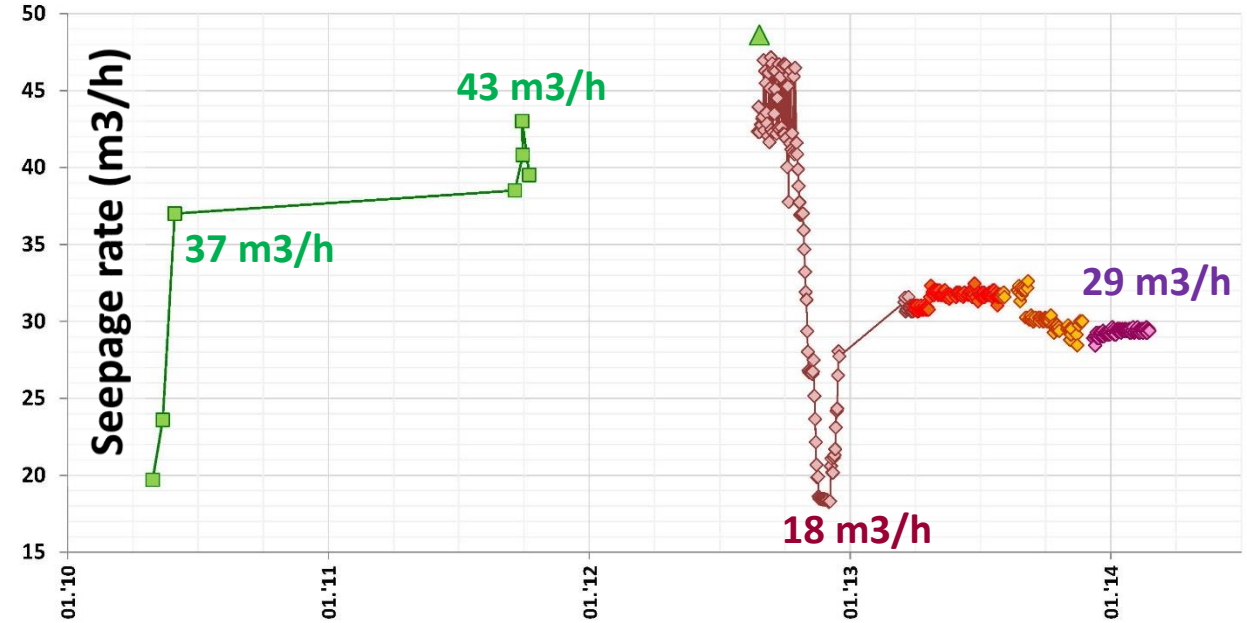


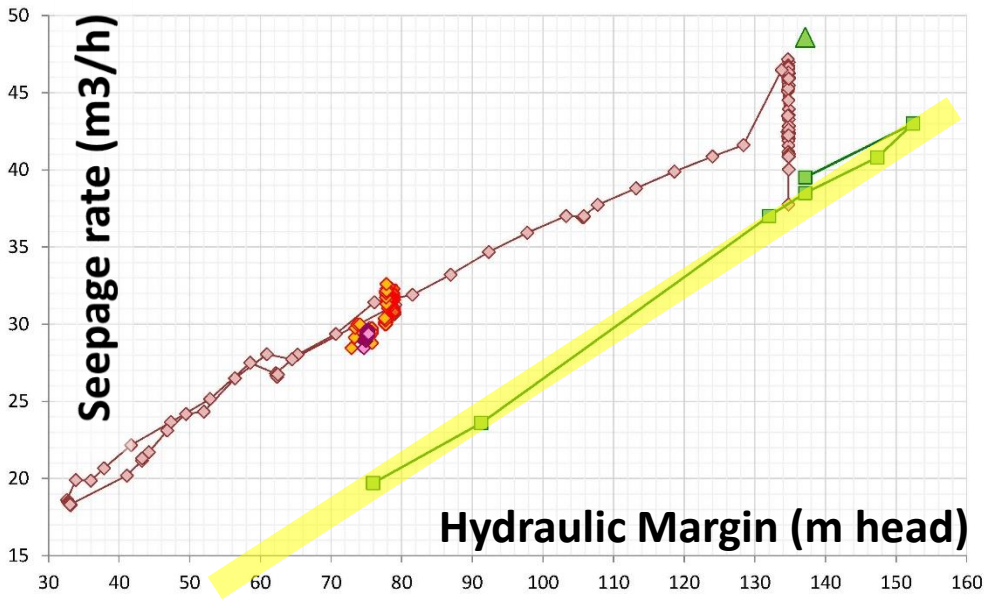
Based on time curves only, it is not easy to identify for possible problematic situation during construction.

While **low seepage during construction** may be due to:

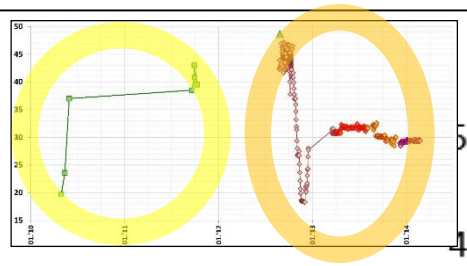
- **efficient grouting**, or to
- **desaturated joints**

Cross plot analysis allows for easier identification of possible critical situation

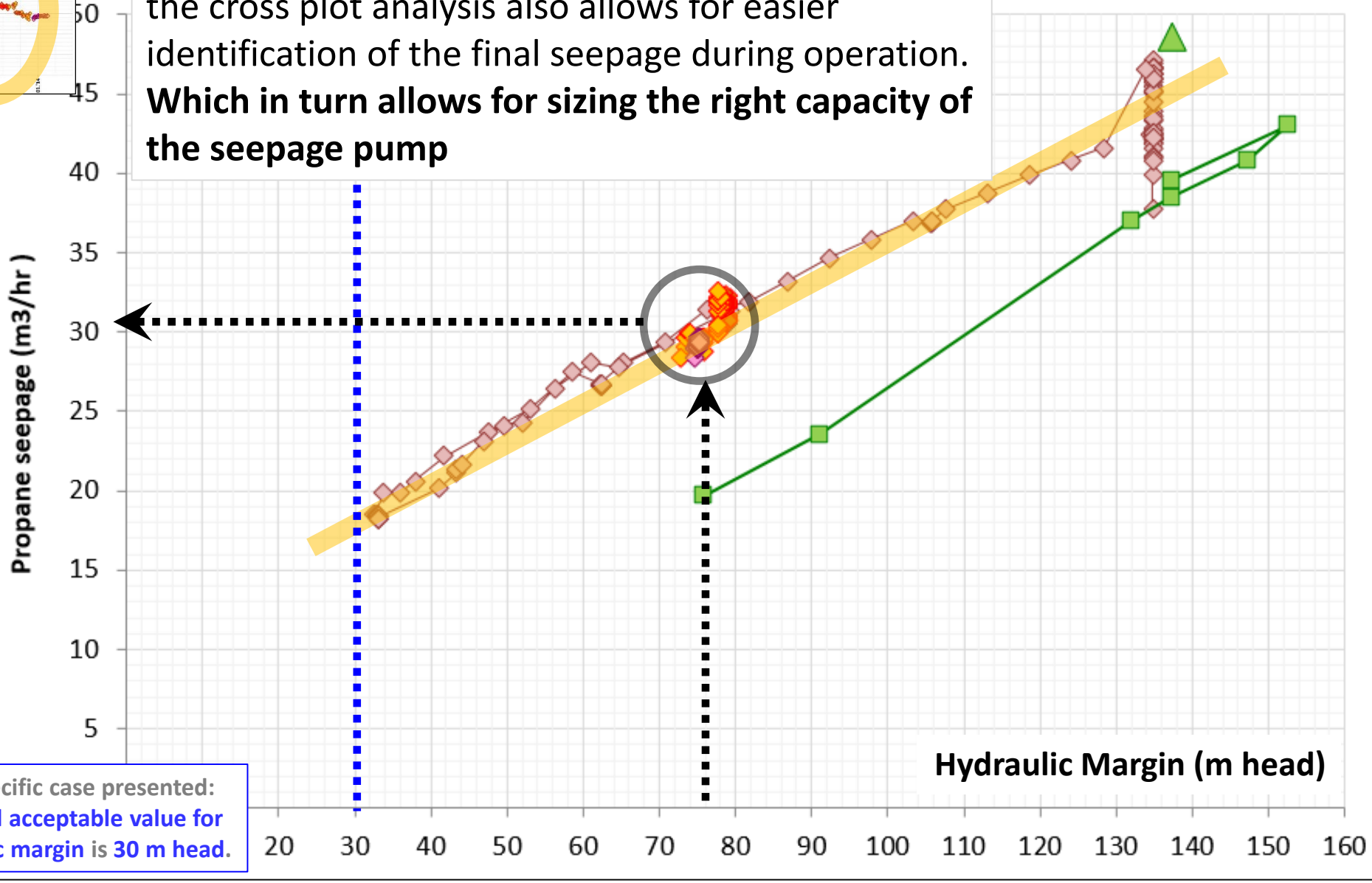




CONCLUSIONS



A second advantage of this type of analysis is that the cross plot analysis also allows for easier identification of the final seepage during operation. **Which in turn allows for sizing the right capacity of the seepage pump**



For the specific case presented: the **minimal acceptable value for the hydraulic margin** is **30 m head**.

CONCLUSIONS

The cross plot analysis for seepage compared to hydraulic margin allows for :

- Early evaluation of the **final seepage for operation**: and therefore for seepage pump sizing

- Allows for distinguishing between:
  - **Favourable low seepage** due to **efficient grouting** works, and
  - **Unfavourable low seepage** due to **local desaturation** resulting in **insufficient hydrodynamic containment**

  And therefore allows for timely implementation of compensation works.