NASA Jet Propulsion Laboratory
California Institute of Technology

University of Cagliari
Faculty of Engineering and Architecture

Geotechnical numerical model and COSMO-SkyMed/Sentinel-1 Interferometric Analysis applied to the Mosul dam, Iraq

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Master's Degree Thesis in Civil Engineering – Structure

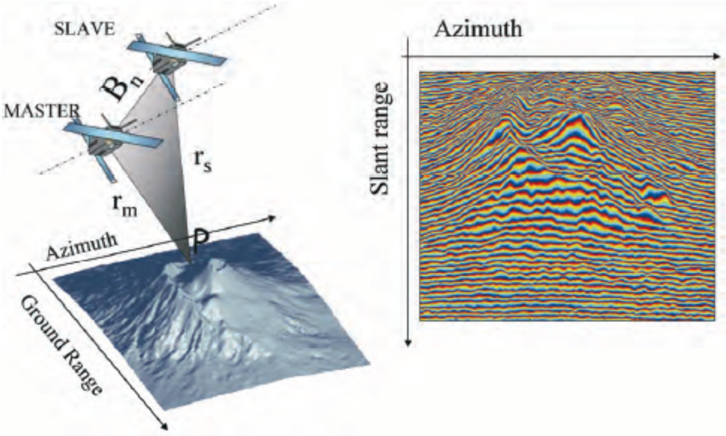
Academic Year 2017-2018

Multi Temporal-InSAR

SLC SAR images acquisition

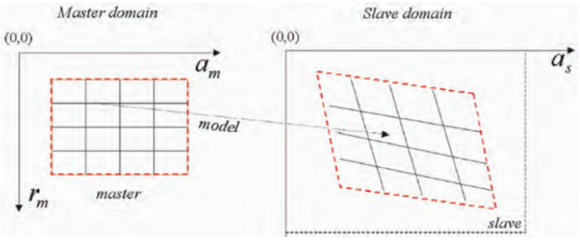
- Same area
- Different times
- Same acquisition geometry

Basics: Persistent scatterers (***PSs***)



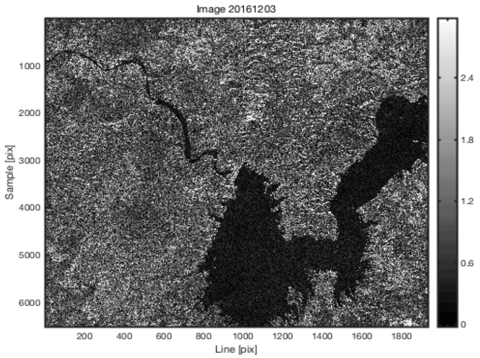
Method

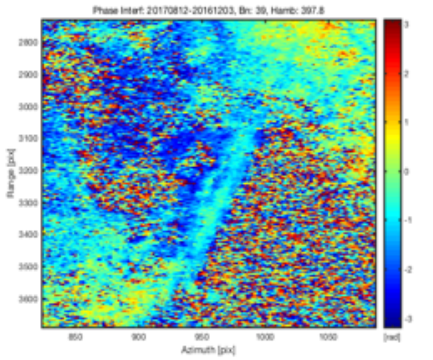
- Co-registration ➔ ***Master***
- *n* acquisitions ➔ *n-1* ***SAR Interferograms***



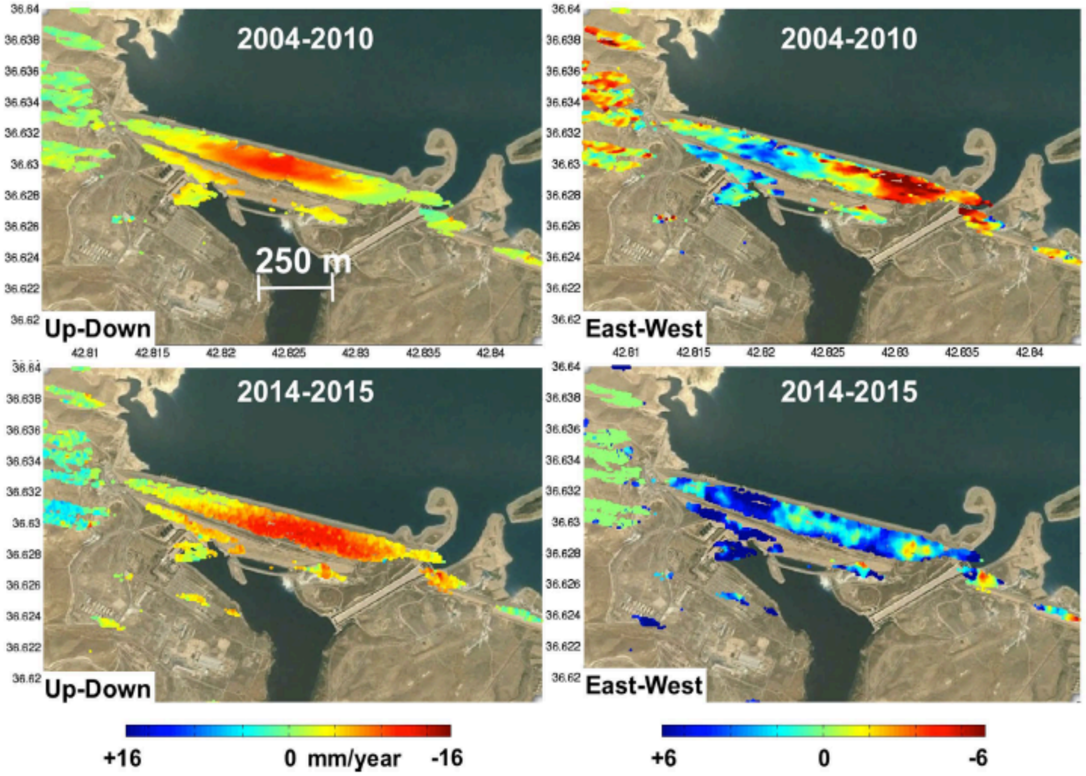
SAR Signal Components:

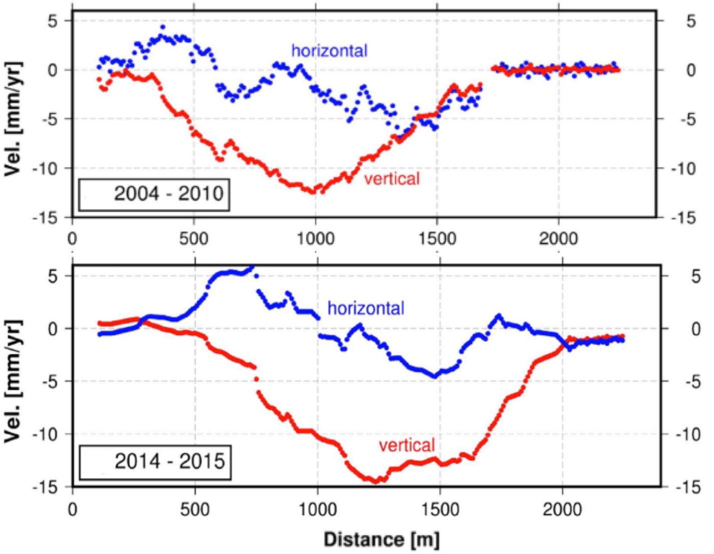
- Atmospheric
- Residual topographic
- Deformation

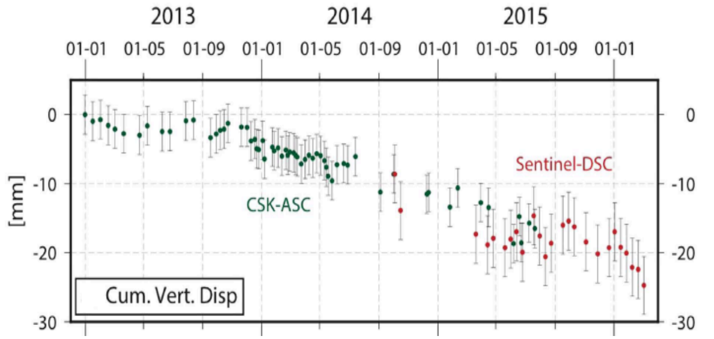




MT-InSAR Analysis on the Mosul Dam (2004-2015)

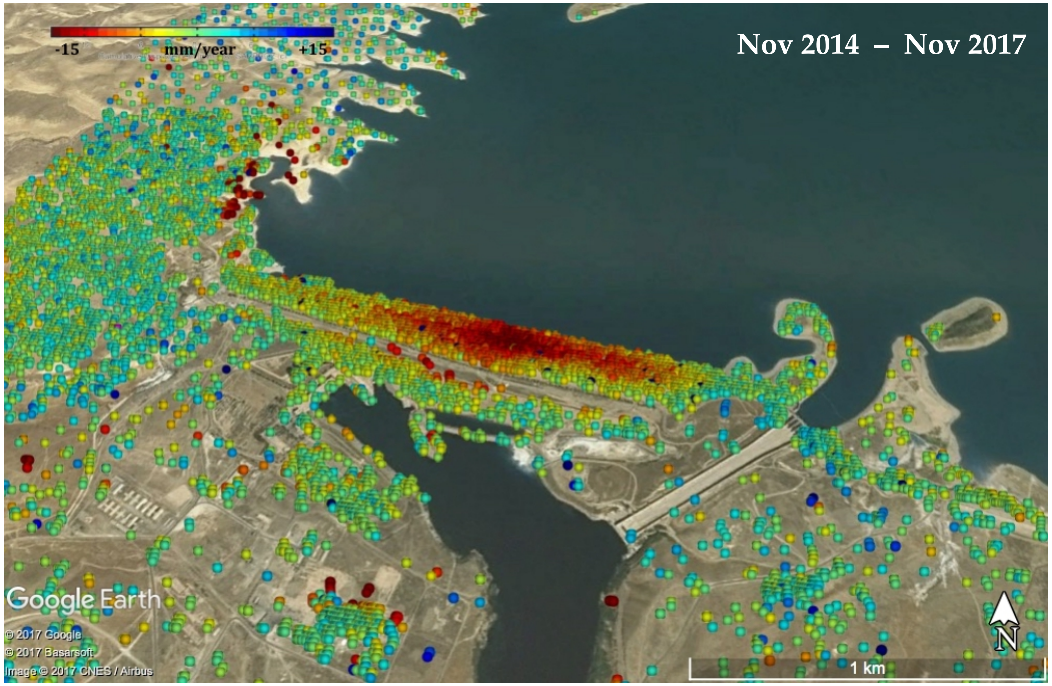


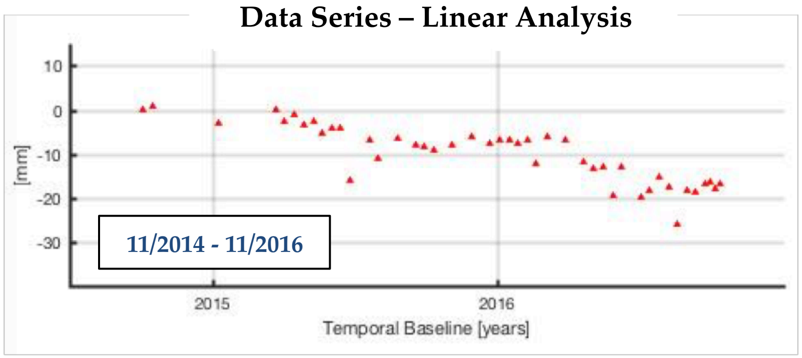




P. Milillo et al. Space geodetic monitoring of engineered structures: The ongoing destabilization of the Mosul dam, Iraq, 2016

MT-InSAR Analysis on the Mosul Dam (2015-2017)




Data Series – Linear Analysis

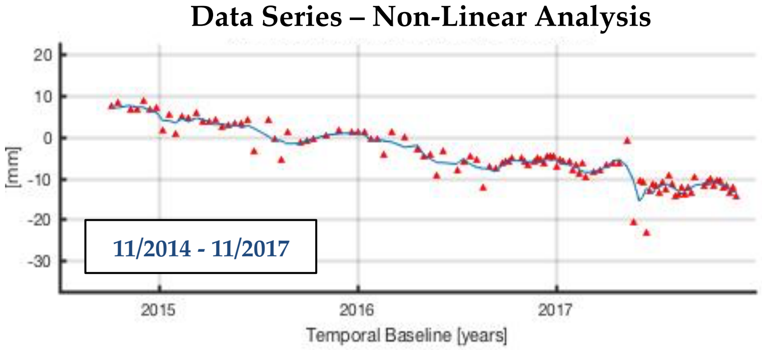

Data Series – Non-Linear Analysis

Table 1. InSAR analysis results

Time Period	Cumulative Displacement
2004-2010	≈ 12.5 mm/year
2014-2015	≈ 15.0 mm/year
2015-2017	≈ 12.3 mm/year
2017-Nov 2017	≈ 9.3 mm/year

Geotechnical Numerical Model: Dam body

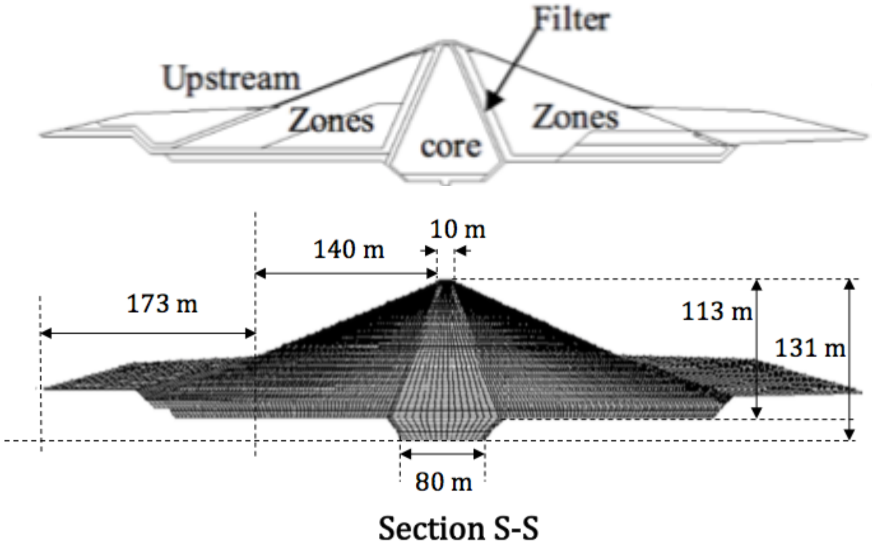
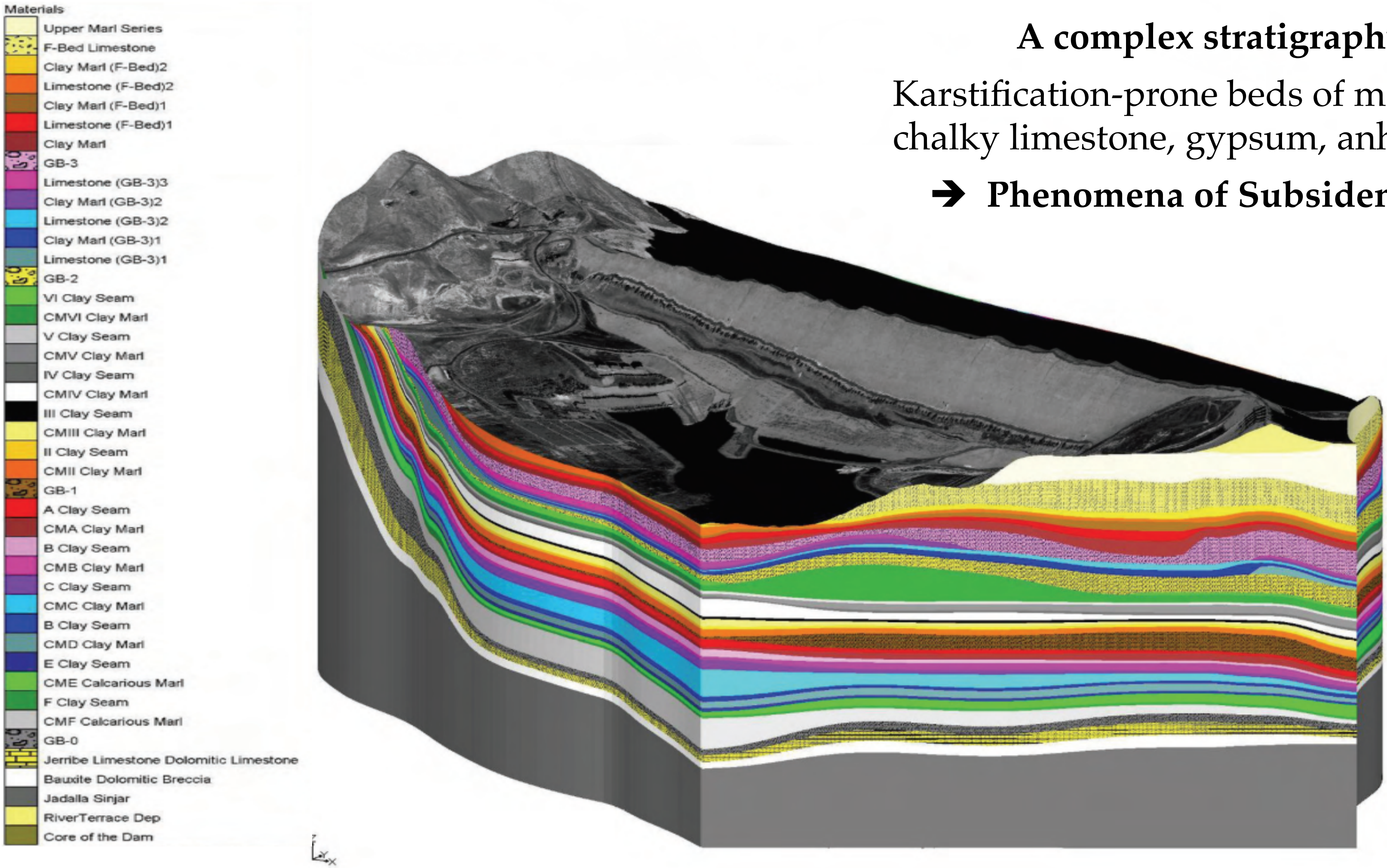


Table 2. Physical characteristics of the Mosul dam body

Material	Υ_d [kN/m^3]	K [kPa]	G [kPa]	c [kPa]	k [m/s]	Φ [°]	n [-]
Clay (Core)	18.0	8.89 E+03	2.96 E+03	25.0	1.0 E-11	39.0	0.3
Sand (Shell)	19.5	4.67 E+04	2.80 E+04	0.0	1.0 E-07	37.0	0.1

Geotechnical Numerical Model: Stratigraphy



A complex stratigraphy

Karstification-prone beds of marls, chalky limestone, gypsum, anhydrite

➔ **Phenomena of Subsidence**

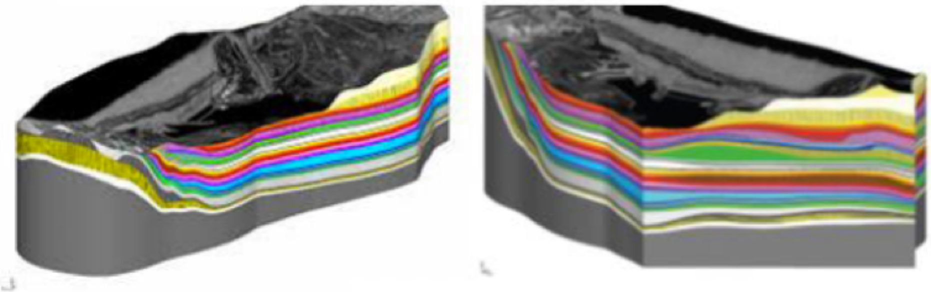
Kelly J, Wakeley et al. Geologic Setting of Mosul Dam and Its Engineering Implications, Final Report, U.S. Army Engineer District, Gulf Region, Baghdad, Iraq, 2007

Geotechnical Numerical Model: Stratigraphy

A first strongly approximation:

A single layer representing the karstified foundation layers

➔ ***Limestone/GB***



Kelly J, Wakeley et al. Geologic Setting of Mosul Dam and Its Engineering Implications, Final Report, U.S. Army Engineer District, Gulf Region, Baghdad, Iraq, 2007

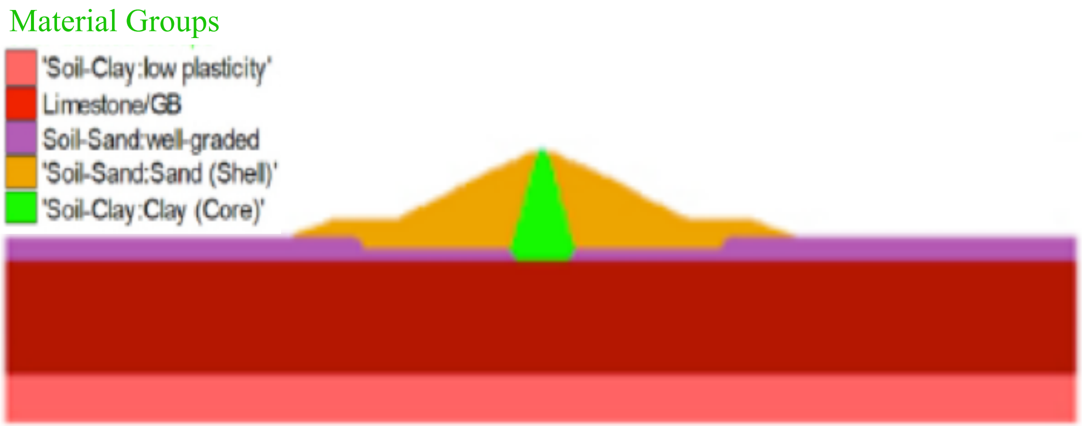
Failure Criterions adopted:

- **Hoek-Brown:**

Limestone/GB foundation layer

- **Mohr-Coulomb:**

Dam body materials, Soil-Clay and Soil Sand foundation layers



Geotechnical Numerical Model: Stratigraphy

Uniaxial compression tests on the cylindrical samples of **gypsum** taken in the Mosul dam area

Average values of E_i and σ_{ci}:

$$E_i = 2316.4\ MPa$$

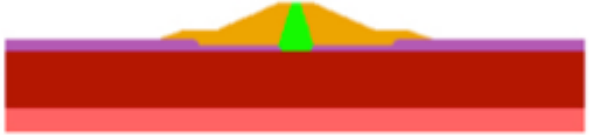
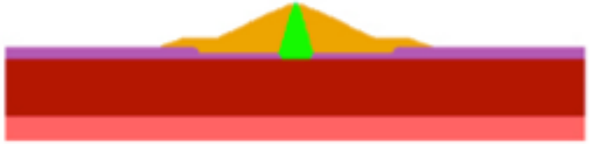
$$\sigma_{ci} = 10.52\ MPa$$

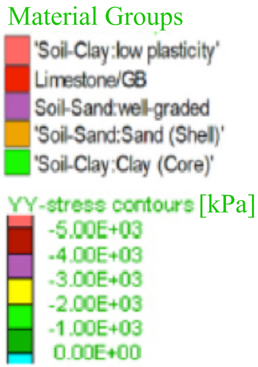
Suhail A.A. Khattab. Stability analysis of Mosul dam under saturated and unsaturated soil conditions, PhD thesis, 2013.

Table 3. Hoek-Brown parameters of the ground layers foundation

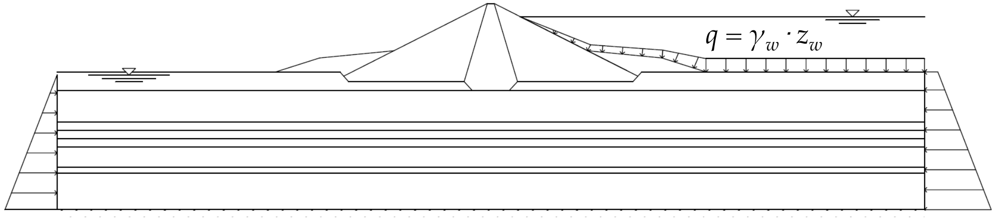
Material	Δz [m]	Υ_d [kN/m^3]	K [kPa]	G [kPa]	c [kPa]	k [m/s]	Φ [°]
Soil-Sand: well graded	28	17.0	2.78 E+04	2.08 E+04	0.0	1.0 E-07	35
Limestone/GB	134	19.7	3.86 E+05	2.32 E+05	-	1.0 E-09	-
Soil-Clay:low plasticity	55	19.7	8.33 E+07	6.25 E+07	1000	1.0 E-09	24

Geotechnical Numerical Model: Construction steps

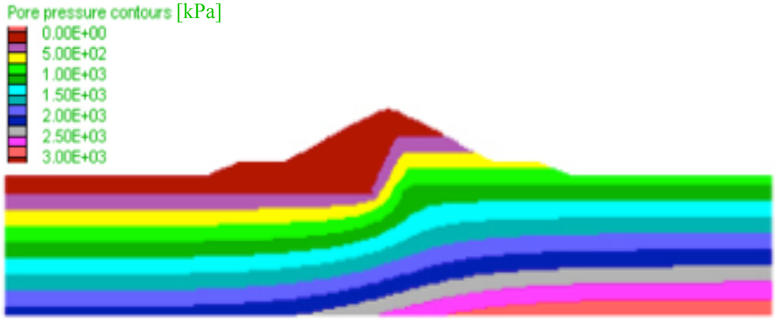
Step	Construction steps	Vertical total stresses
1		
2		
3		
4		
5		
6		

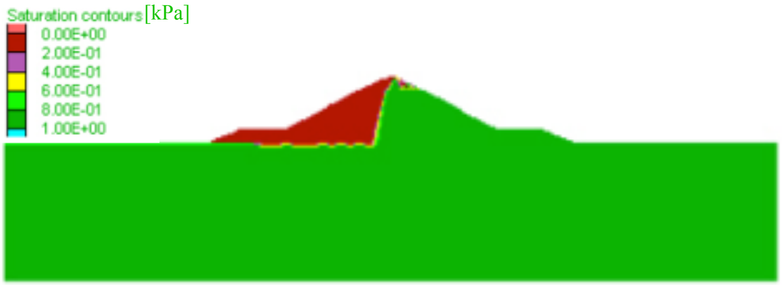


Geotechnical Numerical Model: Reservoir Water Load

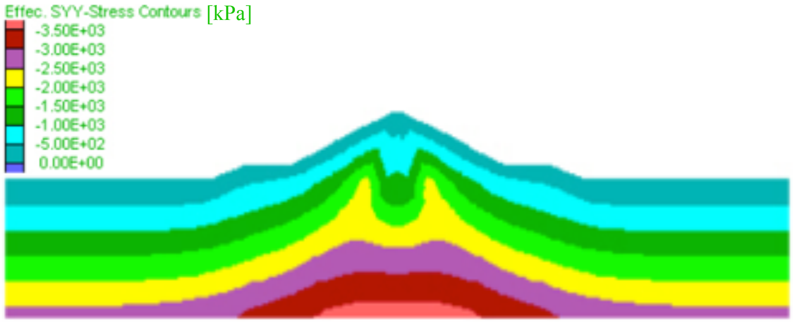


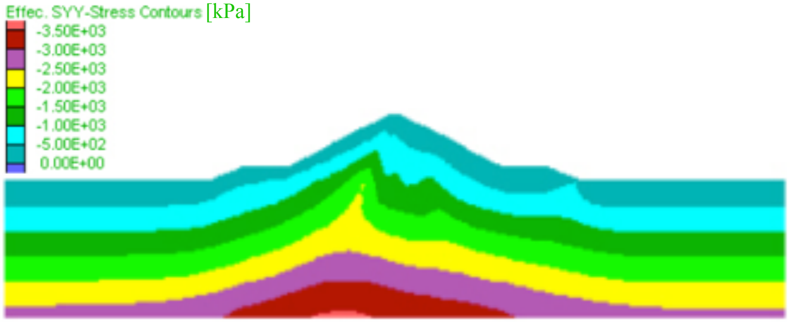
Water pressure distribution and **Saturation**





Comparison between σ'_{yy}





Hoek-Brown failure criterion

- **Compressive strength**

$$\sigma_1^{'} = \sigma_3^{'} + \sigma_{ci}\left(m_b\frac{\sigma_3^{'}}{\sigma_{ci}} + s\right)^a \xrightarrow{\sigma_3^{'}=0} \sigma_1^{'} = \sigma_{ci}s^a = \sigma_c$$

- **Material constants**

$$m_b = m_i\exp\left(\frac{GSI-100}{28-4D}\right)$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right)$$

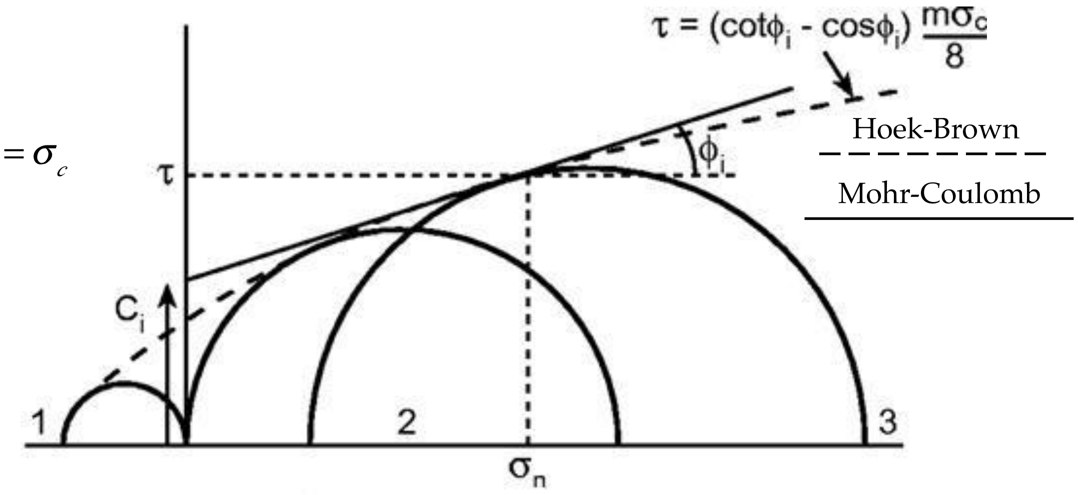
$$a = \frac{1}{2}+\frac{1}{6}\left[\exp\left(-\frac{GSI}{15}\right)-\exp\left(-\frac{20}{3}\right)\right]$$

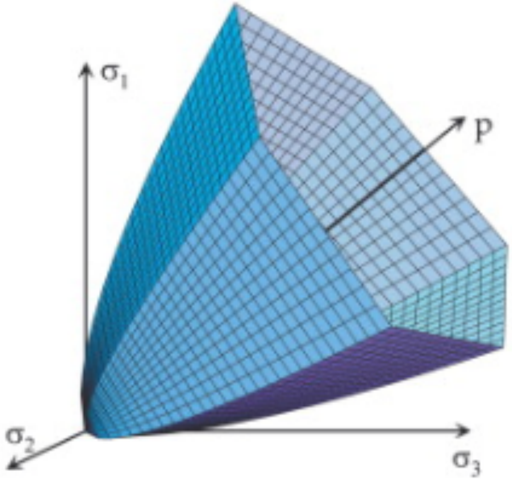
- **Geological Strength Index:** ***GSI***

$$GSI \in [0 \div 100]$$

- **Disturbance factor:** ***D***

$$D \in [0 \div 1]$$

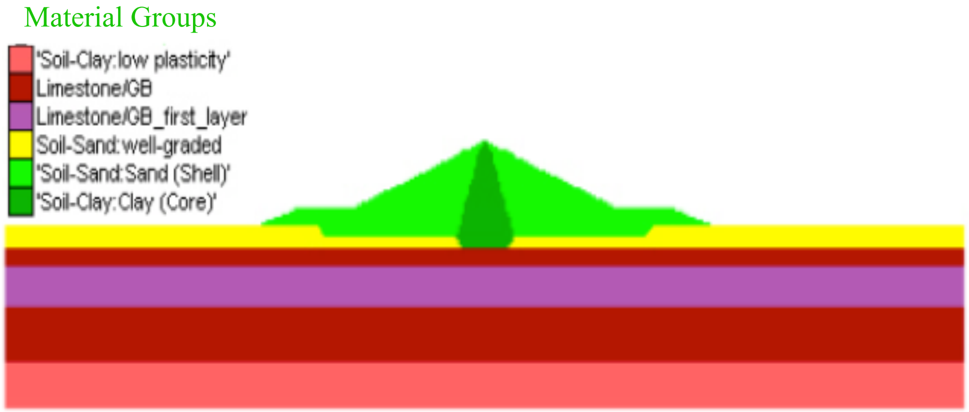




Degradation of the Gypsum foundation layers

Degradation of **two Limestone/GB foundation layers**:

- Different **depth** and **thickness**.
- **Three different** approaches.

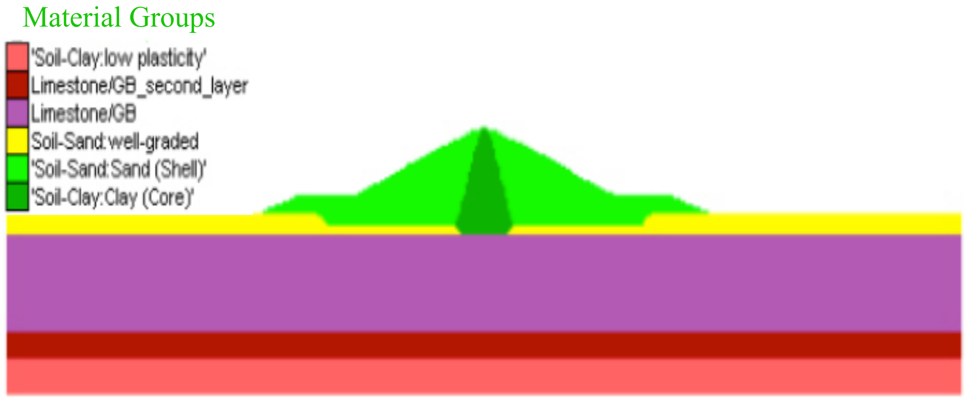


First foundation layer:

$$z = 70\ m$$

$$\Delta h = 40$$

$$y_{disp} \cong 1.25\ cm$$



Second foundation layer:

$$z = 160\ m$$

$$\Delta h = 26\ m$$

$$y_{disp} \cong 1.5\ cm$$

Degradation of the Gypsum foundation layer: Method 1

Generalized Hoek and Diederichs

$$E_{rm} = E_i\left(0.02 + \frac{1-0.5D}{1+\exp\left(\left(60+15D-GSI\right)/11\right)}\right)$$

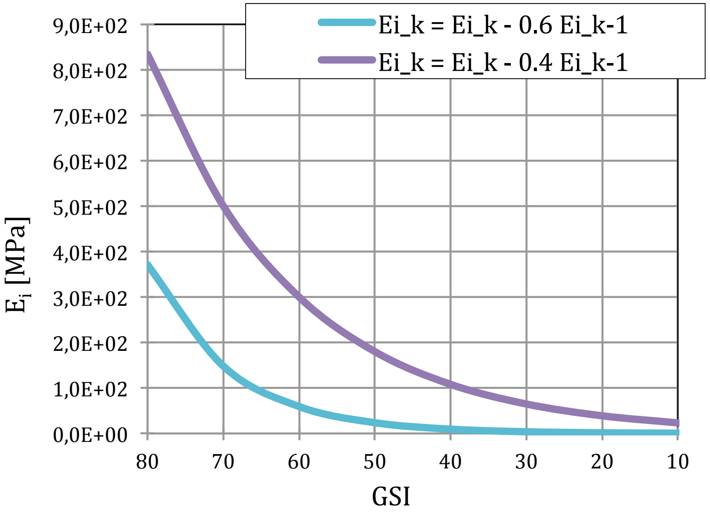
$$\sigma_c = \sigma_{ci}\, s^a$$

$$m = f(GSI, D) \quad s = f(GSI, D) \quad a = f(GSI)$$

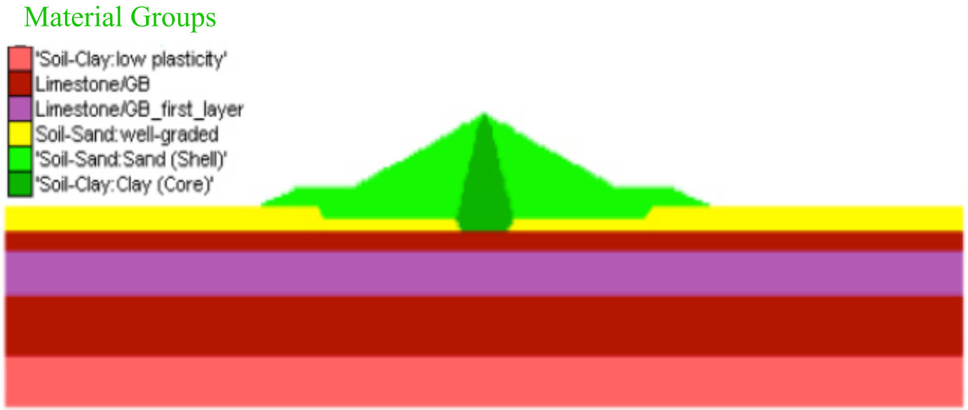
$$GSI \in \left[80 \div 10\right]$$

$$D \in \left[0.2 \div 0.9\right]$$

Degradation laws of E_i



Degradation of the 1st foundation layer

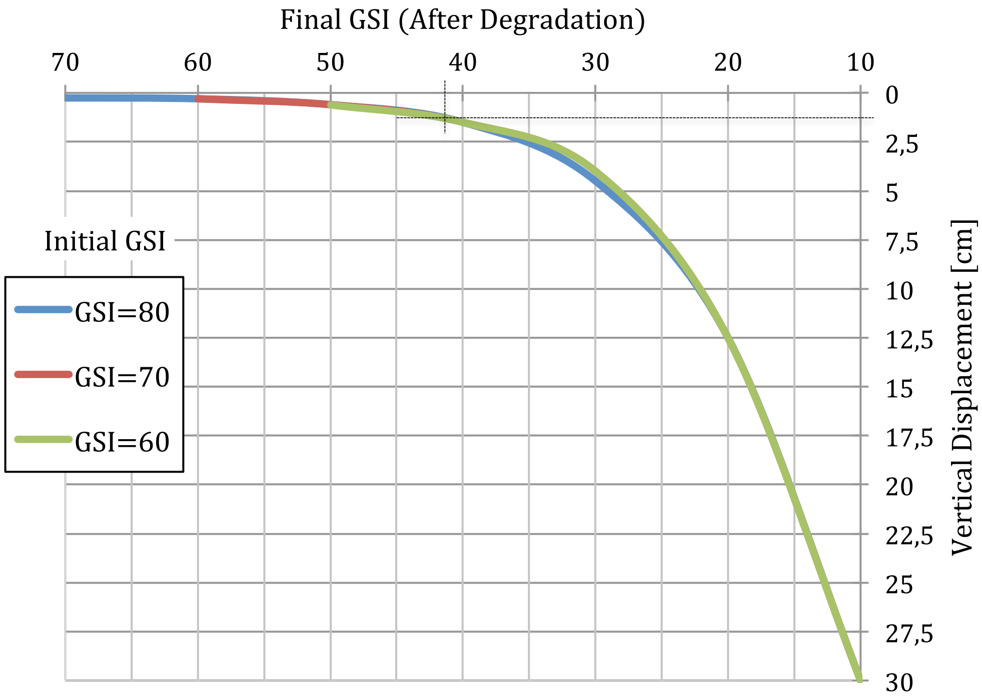


Method 1 (E_i reduction of 60%) - Results

Table 4. Values of the vertical displacements [cm] for the E_i reduction of 60 %

Final GSI (After Degradation)

	Initial GSI (Before Degradation)				
GSI	80	70	60	50	40
80	-				
70	0,25	-			
60	0,3	0,3	-		
50	0,6	0,6	0,6	-	-
40	1,5	1,5	1,5	-	-
30	4,5	4	4	-	-
20	12,5	12,5	12,5	-	-
10	30	30	30	-	-

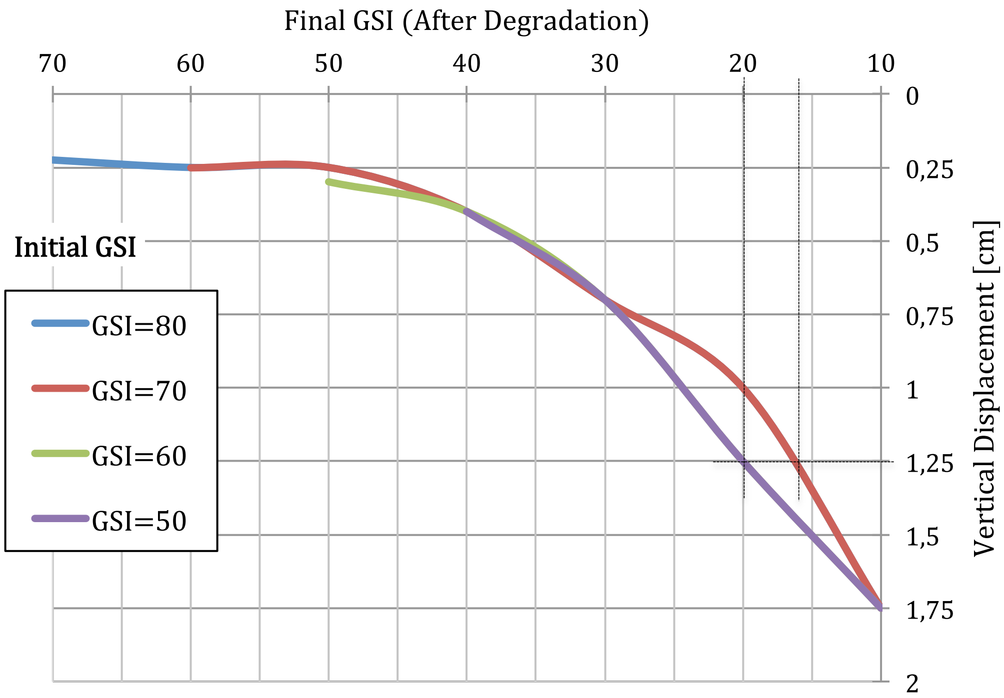


Vertical displacements [m] after the degradation of the first layer from GSI=80 to GSI=40

Method 1 (E_i reduction of 40%) - Results

Table 5. Values of the vertical displacements [cm] for the E_i reduction of 40 %

		Initial GSI (Before Degradation)				
	GSI	80	70	60	50	40
Final GSI (After Degradation)	80	-				
	70	0,25	-			
	60	0,3	0,3	-		
	50	0,6	0,6	0,6	-	-
	40	1,5	1,5	1,5	-	-
	30	4,5	4	4	-	-
	20	12,5	12,5	12,5	-	-
	10	30	30	30	-	-



Vertical displacements [m] after the degradation of the first layer from GSI=50 to GSI=10

Degradation of the Gypsum foundation layer: Method 2

Assumption: keep constant the ratio between the strength and the elastic modulus at any degradation step.

$$E_{rm} = \sigma_c \left(\frac{E_i}{\sigma_{ci}} \right)$$

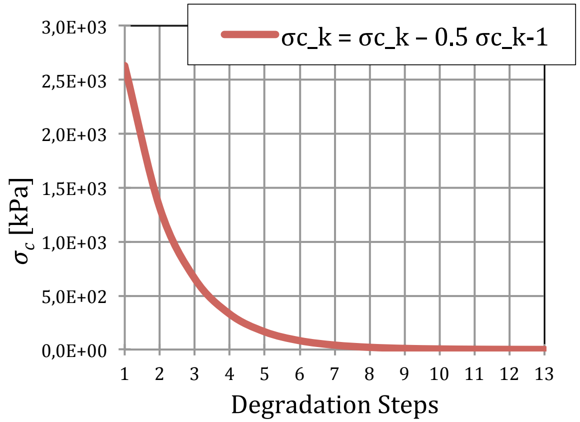
$$E_i = \text{cost} = 2316.4 \ [MPa]$$

$$m_b, s, a = \text{cost}$$

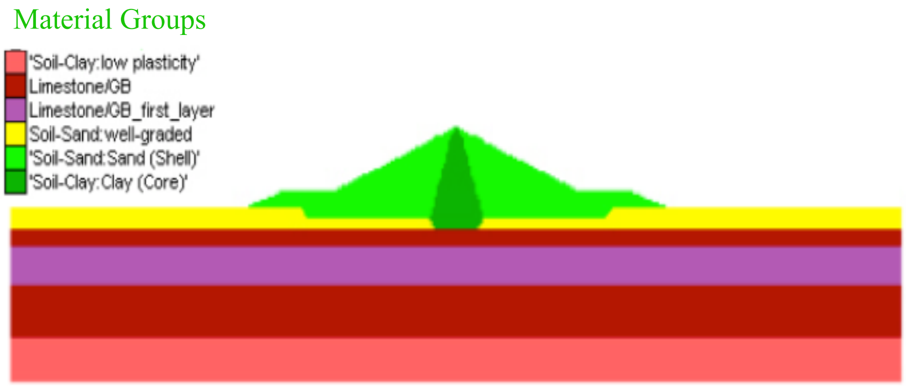
$$GSI = \text{cost} = 80$$

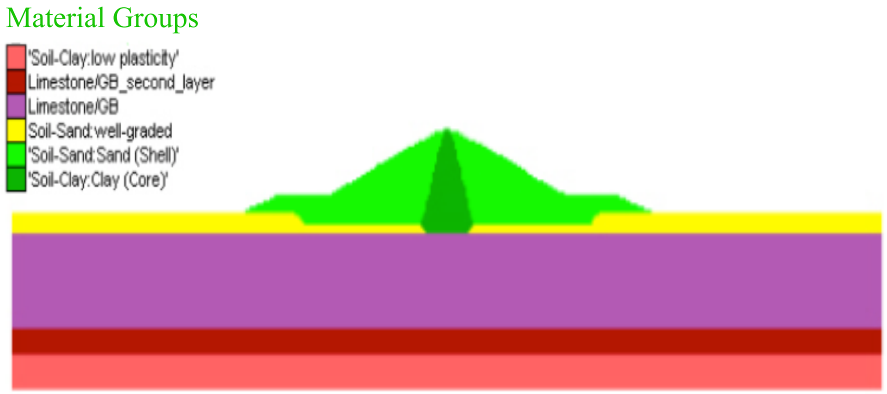
$$D = \text{cost} = 1$$

Degradation control parameter: σ_c



Degradation of the 1st and the 2nd layer





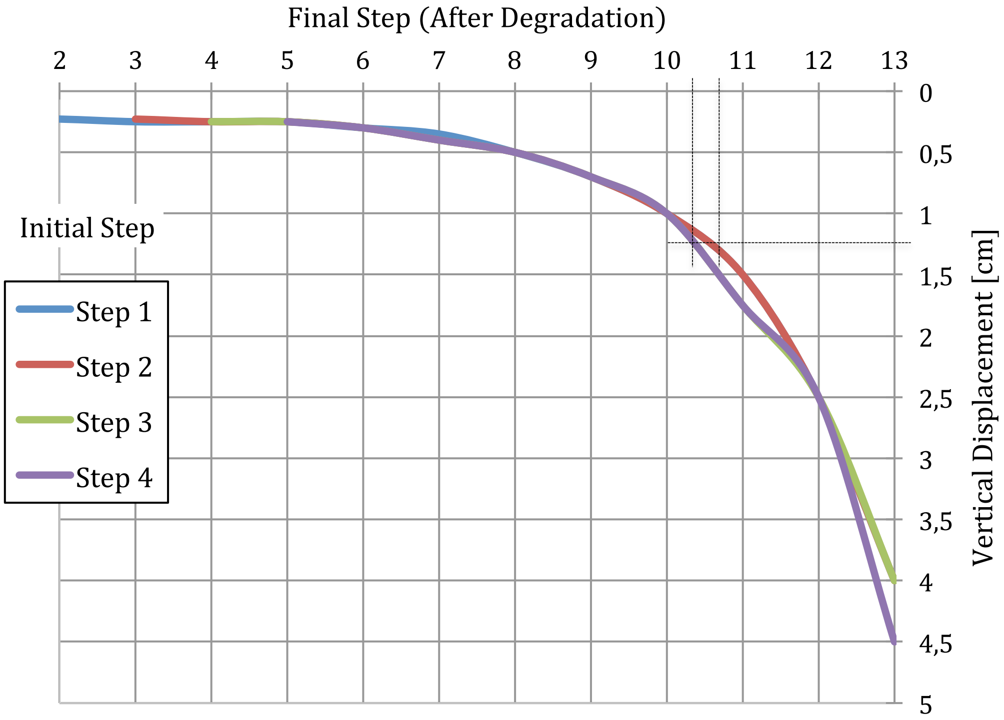
Method 2 (Degradation of the 1st layer) - Results

Table 6. Values of the vertical displacements [cm] obtained by degrading the first layer

Initial Step (Before Degradation)

Final Step (After Degradation)

Step	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Step 1	-					
Step 2	0,225	-				
Step 3	0,25	0,225	-			
Step 4	0,25	0,25	0,25	-		
Step 5	0,25	0,25	0,25	0,25	-	
Step 6	0,3	0,3	0,3	0,3	-	-
Step 7	0,35	0,4	0,4	0,4	-	-
Step 8	0,5	0,5	0,5	0,5	-	-
Step 9	0,7	0,7	0,7	0,7	-	-
Step 10	1	1	1	1	-	-
Step 11	1,5	1,5	1,75	1,75	-	-
Step 12	2,5	2,5	2,5	2,5	-	-
Step 13	4	4	4	4,5	-	-



Vertical displacements [m] after the degradation of the first layer from Step 1 to Step 11

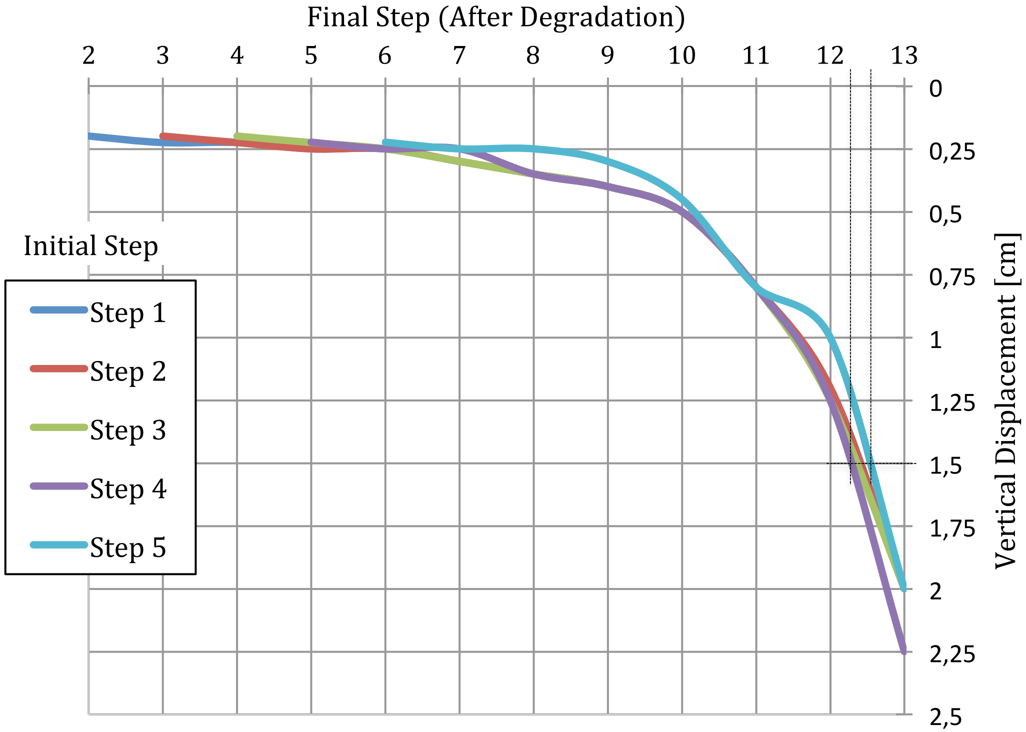
Method 2 (Degradation of the 2nd layer) - Results

Table 7. Values of the vertical displacements [cm] obtained by degrading the second layer

Initial Step (Before Degradation)

Final Step (After Degradation)

Step	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Step 1	-					
Step 2	0,2	-				
Step 3	0,225	0,2	-			
Step 4	0,225	0,225	0,2	-		
Step 5	0,25	0,25	0,225	0,225	-	
Step 6	0,25	0,25	0,25	0,25	0,225	-
Step 7	0,3	0,3	0,3	0,25	0,25	-
Step 8	0,35	0,35	0,35	0,35	0,25	-
Step 9	0,4	0,4	0,4	0,4	0,3	-
Step 10	0,5	0,5	0,5	0,5	0,45	-
Step 11	0,8	0,8	0,8	0,8	0,8	-
Step 12	1,2	1,2	1,25	1,25	1	-
Step 13	2	2	2	2,25	2	-



Vertical displacements [m] after the degradation of the first layer from Step 3 to Step 13

Degradation of the Gypsum foundation layer: Method 3

Assumption: keep constant the ratio between the strength and the elastic modulus at any degradation step, as in Method 2.

Degradation control parameter: ***GSI***

$$E_{rm} = \sigma_c \left(\frac{E_i}{\sigma_{ci}} \right)$$

$$E_i = \text{cost} = 2316.4\ [MPa]$$

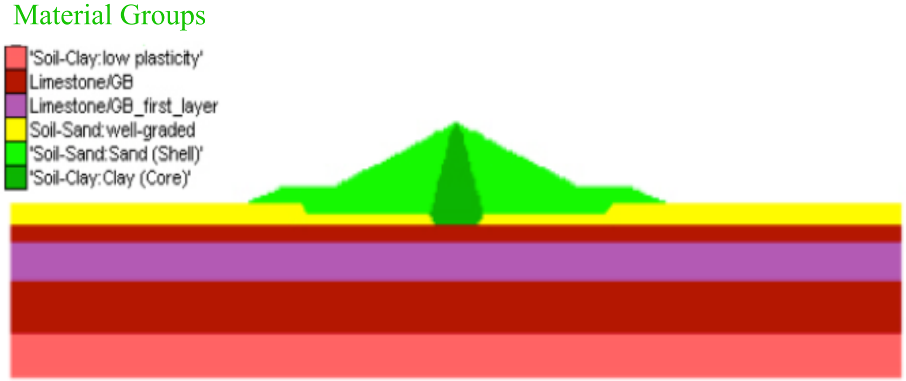
$$\sigma_c = \sigma_{ci}\ s^a$$

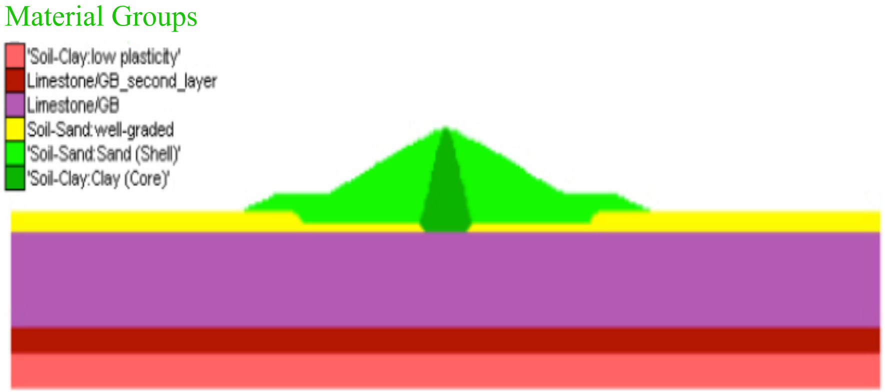
$$m_b = f(GSI, D)\quad s = f(GSI, D)\quad a = f(GSI)$$

$$GSI \in \left[80 \div 5 \right]$$

$$D = \text{cost} = 1$$

Degradation of the 1st and the 2nd layer





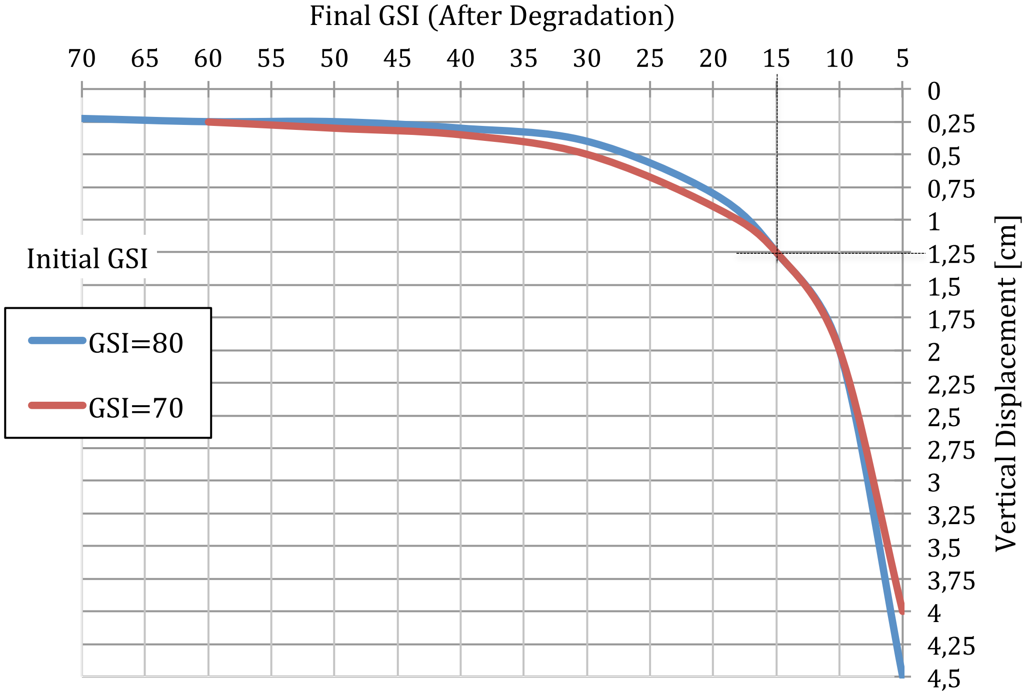
Method 3 (Degradation of the 1st layer) - Results

Table 8. Values of the vertical displacements [cm] obtained by degrading the first layer

Initial GSI (Before Degradation)

Final GSI (After Degradation)

GSI	80	70	60	50
80	-			
70	0,225	-		
60	0,25	0,25	-	
50	0,25	0,3	-	-
40	0,3	0,35	-	-
30	0,4	0,5	-	-
20	0,8	0,9	-	-
15	1,25	1,25	-	-
10	2	2	-	-
5	4,5	4	-	-

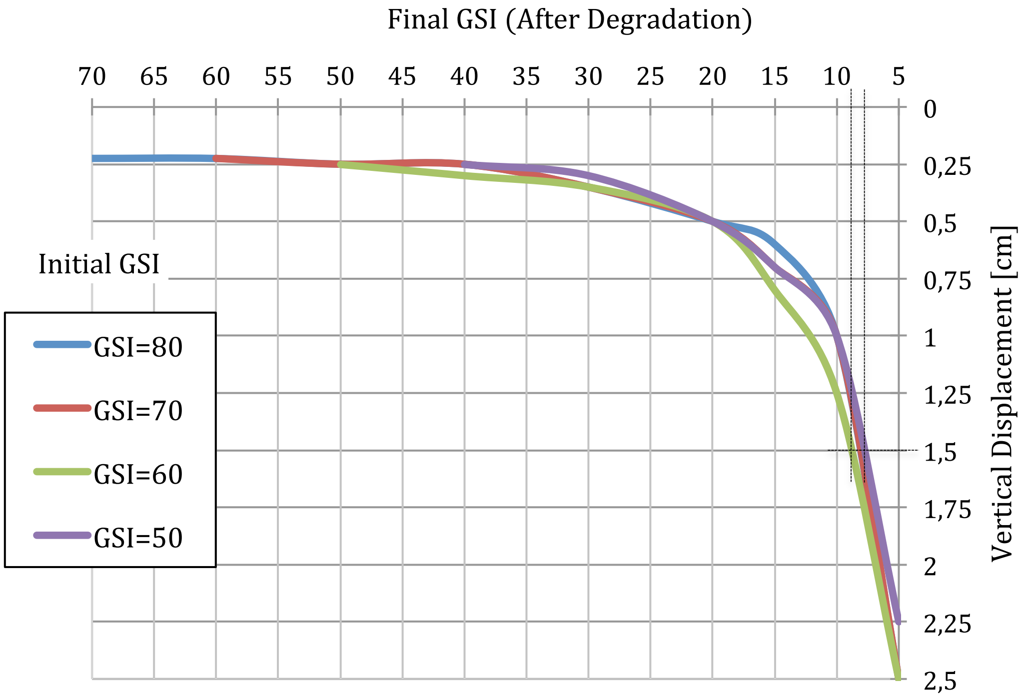


Vertical displacements [m] after the degradation of the first layer from GSI=80 to GSI=15

Method 3 (Degradation of the 2nd layer) - Results

Table 9. Values of the vertical displacements [cm] obtained by degrading the second layer

Final GSI (After Degradation)	Initial GSI (Before Degradation)			
GSI	80	70	60	50
80	-			
70	0,225	-		
60	0,225	0,225	-	
50	0,25	0,25	0,25	-
40	0,25	0,25	0,3	0,25
30	0,35	0,35	0,35	0,3
20	0,5	0,5	0,5	0,5
15	0,6	0,7	0,8	0,7
10	1	1	1,25	1
5	2,5	2,5	2,5	2,25



Vertical displacements [m] after the degradation of the first layer from GSI=80 to GSI=10

Conclusions

- **Structural health monitoring (*SHM*)** through **InSAR techniques:** a useful tool, alone or as a support to the traditional techniques;

- Satellite data allow to monitor **slow-evolution phenomena** such as subsidence and/or settlements of structures;

- Approximations in the **numerical model** of the Mosul dam due to the complexity of phenomenon of gypsum-dissolution and a lack of some data;

- **Modeling the phenomenon of gypsum-degradation**: some **approaches** based on the reduction of the **Hoek-Brown** mechanical parameters allow to reproduce the vertical displacements of some target points on the dam consistent with the satellite time histories;

- **Further developments**: efficiency of the jet grouting curtain and degradation of gypsum as a function of water velocity during seepage.

Thank you for your attention