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Geostatistical modelling of pore pressure data: An application to Smart Markers (ENSM) in Open-Pit Mining

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Outline

- **Introduction:** Motivation, aims and scopes
- **Smart Open Pit Slope Deformation Management (ENSM)**
- **Methodology:**
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    - Modelling and simulation of pore pressure
    - Validation and post-processing
- **Case study: Sedimentary Basin**
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    - Available data
    - modelling and simulation of pore pressure
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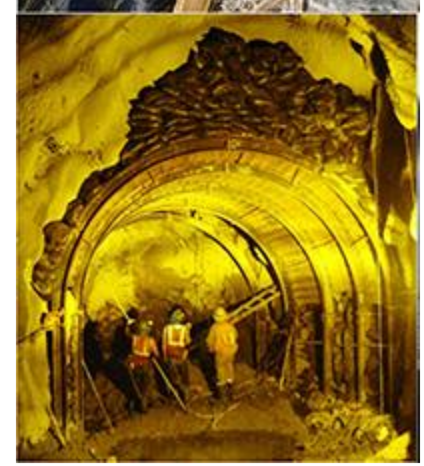
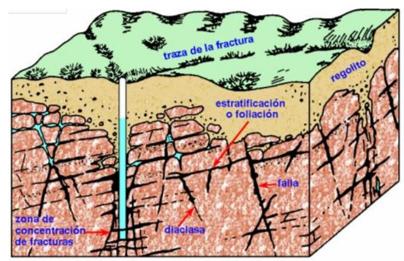
Introduction and motivation

An adequate characterization of the rock mass taking into account the mechanical, hydraulic and engineering properties is a crucial task for the economic development of:

- Underground and **open pit mining**,
- Reservoirs of oil and gas,
- Tailings tanks,
- Management of geothermal reservoirs,
- **Management of groundwater resources,**
- Arrangement of underground nuclear waste.



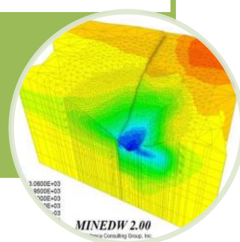
National Research Council (2006)



Smart Open Pit Slope Deformation Management

- In the mining industry it is essential **to know the distribution of the pore pressure exerted by the groundwater in the pit walls**, which depends on the hydrogeological characteristics of the rock and the excavation

Industry Necessity

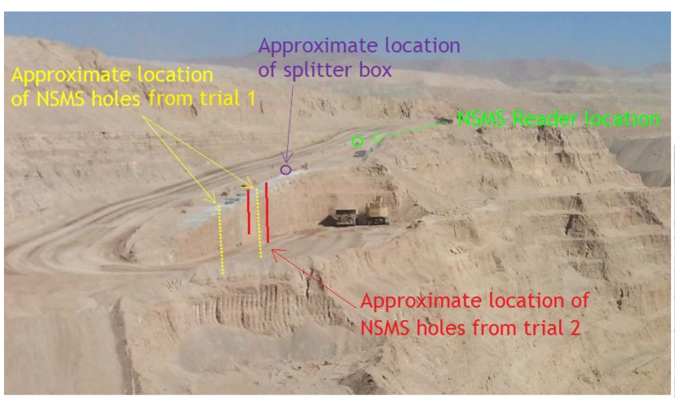


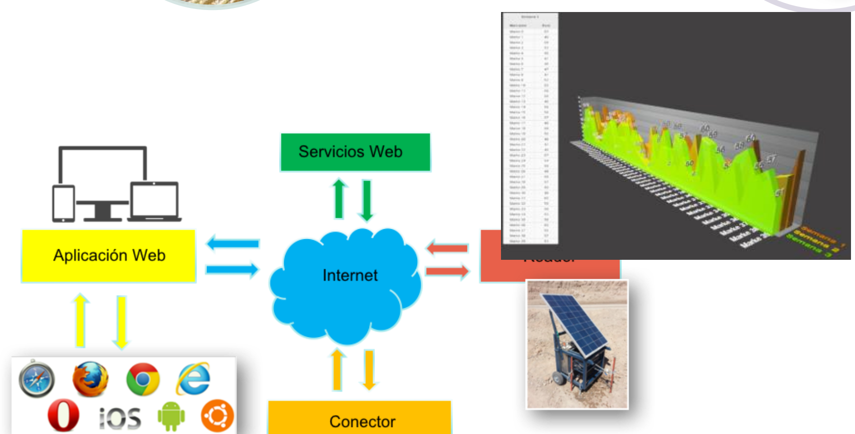
- Obstruct access to operational zones,
- Increase the use of explosives and their failure,
- Generate acid drainage and geotechnical instability in the pit itself.

Effects

- An in-ground monitoring system, **Enhanced Networked Smart Markers (ENSM),** capable of identifying when and where **subsurface deformation** develops, **detecting changes in pore pressure** and transmitting the information wirelessly to the mine site office in real time

Solution





Smart Open Pit Slope Deformation Management

The new ENSM – Evolution of the SM

2009-2012

SM - Smart Marker:

- Monitor the effectiveness of mineral recovery in block-caving mines
- Satisfactorily tested in 17 operations around the world)

(Elexon Electronics)

2013-2015

NSM - Networked Smart Marker

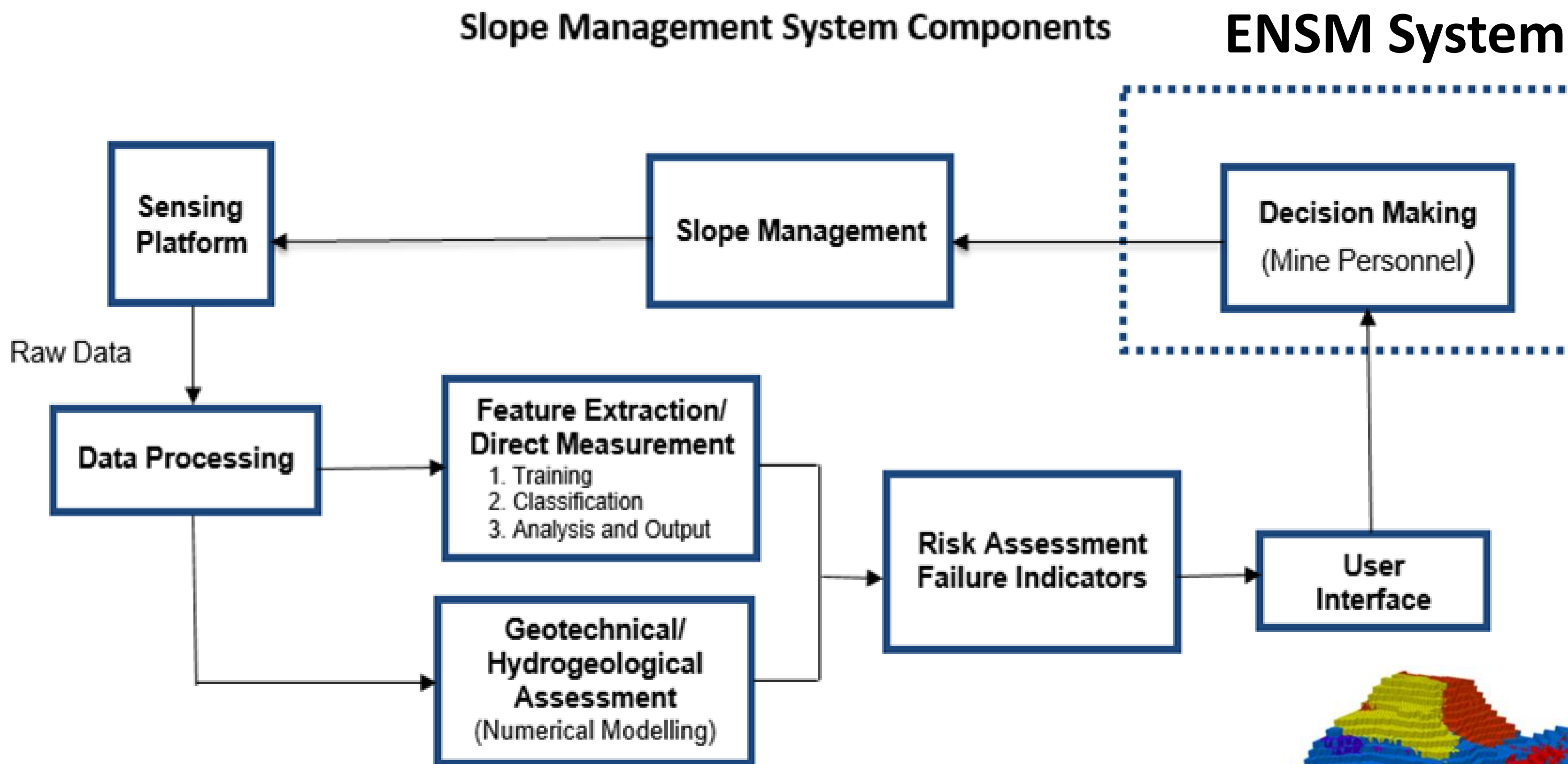
- Wireless transmission between sensors
- Remote acquisition of data
- Tested in an open pit mine (Mina Sur), in holes up to 53 m deep

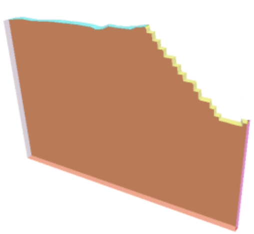
2015
Present

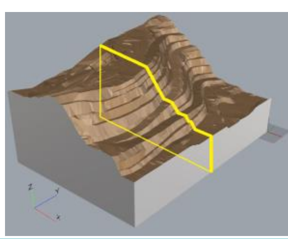
ENSM - Enhanced Networked Smart Marker

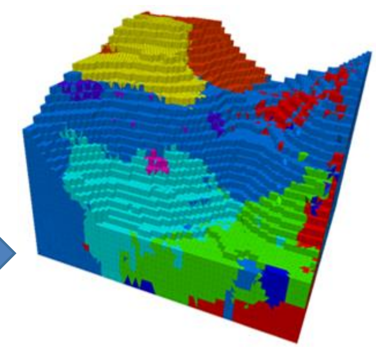
- Incorporation of deformation (inclinometer) and pore pressure measurements
- Currently in the prototype phase

Smart Open Pit Slope Deformation Management





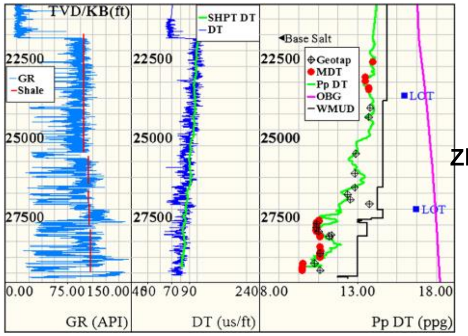




Methodology

Pore pressure prediction

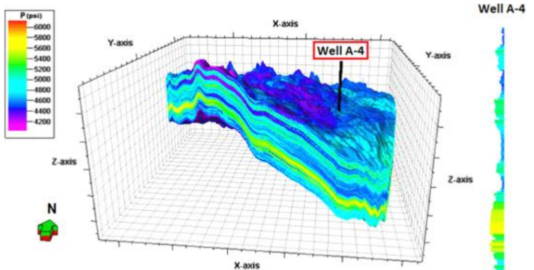
- In mining practice, pore pressure measurements are limited, scarce and scattered by assigning a value per lithological unit theoretically. So, it is required to generate a database of pore pressure from the sonic well logs.



Zhang, 2011

modelling and simulation of pore pressure

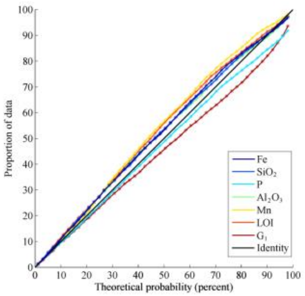
- Exploratory data analysis.
- Cell declustering
- Normal scores transformation
- Variogram analysis
- Simulation by turning bands algorithm
- Back transformation



Azadpour, et al., 2015

Validation and post-processing

- Calculation of probability intervals from realizations at data locations and comparison of theoretical probabilities with the proportions of data that actually belong to the intervals



Mery, et al., 2016

Methodology

Pore pressure prediction using well logs

The fundamental theory for Formation pore pressure (P_{po}) prediction is based on Terzaghi's.

$$\boldsymbol{P_{po} = S - \sigma_e}$$

Eaton's method

$$\boldsymbol{P_{po} = S - \left[(S - P) \left(\frac{\Delta t_n}{\Delta t_o} \right)^{3,0} \right]}$$

$$P = 0{,}0519 * W * D$$

$$\Delta t_n = 10^A 10^{-BD}$$

$$S = 0{,}433 * \rho_b * D$$

$$\rho_b = 2{,}75 - 2{,}11 \left(\frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_{log} + \Delta t_f} \right)$$

Δt_n = Normal trend values of sonic travel time (µs/ft)
Δt_{ma} = travel time of matrix is 47 µs/ft
Δt_f = travel time of fluid is 200 µs/ft
P = hydrostatic pressure (psi)
W = water density (lb/gal)
D = vertical depth (ft)

S=overburden pressure (psi)
A and B are constants which describe the variation in sonic travel time with increasing differential stress

Methodology

Modelling and simulation of pore pressure

Construction of a **model by conditional simulation** of pore pressure:

- Cell declustering
- Normal scores transformation
- Variogram calculation and modelling
- Simulation by turning bands algorithm
- Back transformation

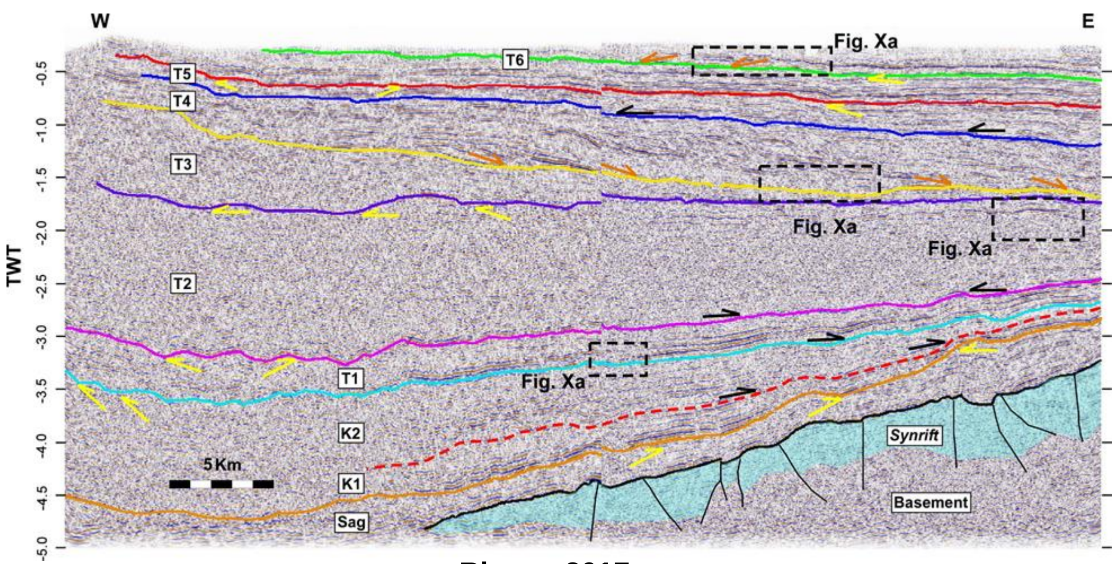
Determination of **post-processing outputs**

- Mapping each realization to assess spatial variability
- Average of multiple realizations as an estimate
- Variance of multiple realizations as a measure of uncertainty
- Calculation of probability maps

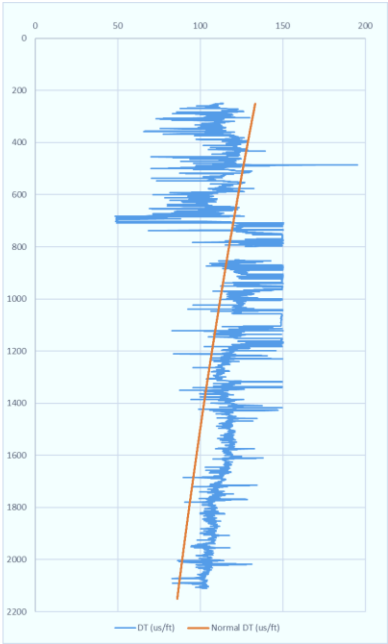
Case study: Sedimentary Basin

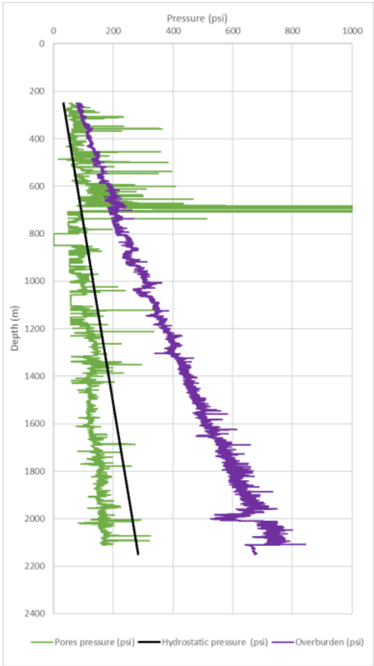
Generalities of the basin

The study area is located in a retro-arc foreland basin that has an extension of 230,000 km and a Cretaceous-Cenozoic succession >7 km thick. Lithologically, the Cretaceous strata is composed of thick shales beds and sandstones of a deep marine environment, whereas the Cenozoic strata is glauconitic sandstones frequently interbedded with shales of shallow water environments.



Rivera, 2017





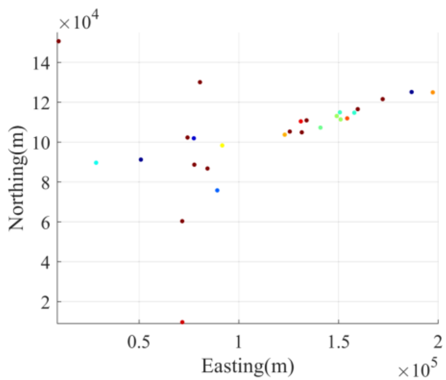
The studied wells reach mostly stratigraphic traps with minor deformation and low structural complexity.

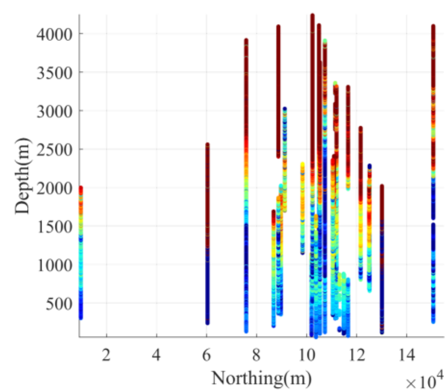
Case study: Sedimentary Basin

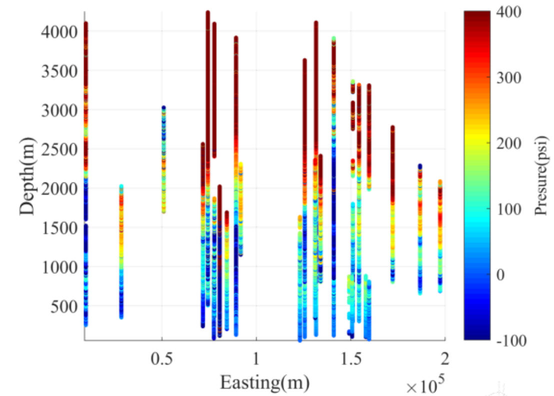
Available data

Original database contains **376.651** row data, with information on density and sonic travel time from surface to total depth.

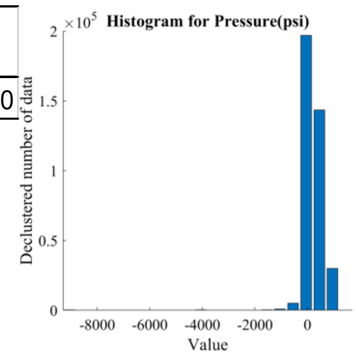
Data located in a volume of 191.000x104.000x4.200 m, about 39 wells

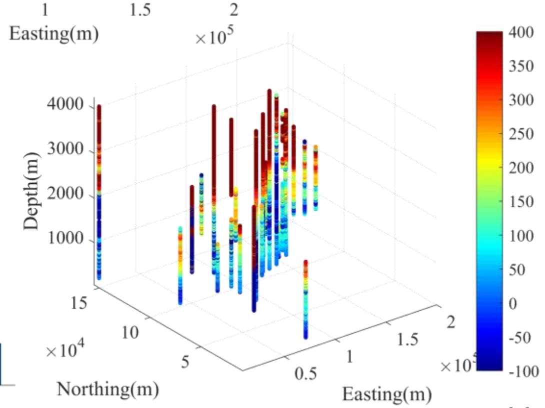






Variable	Number of data	Minimum	Maximum	Mean	Standard deviation
Pores Pressure (psi)	376651	-9290.0999	1198.3232	204.9150	287.4340

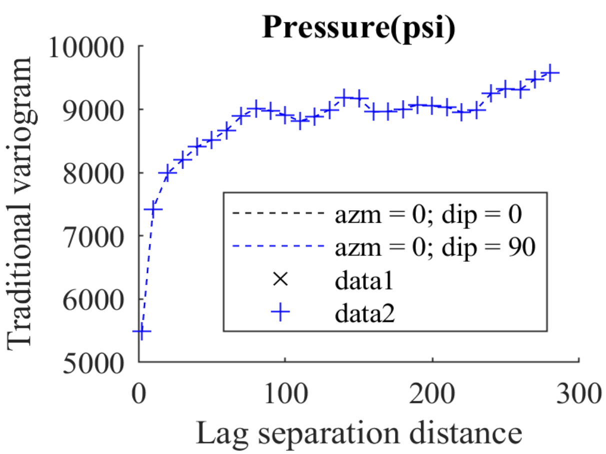


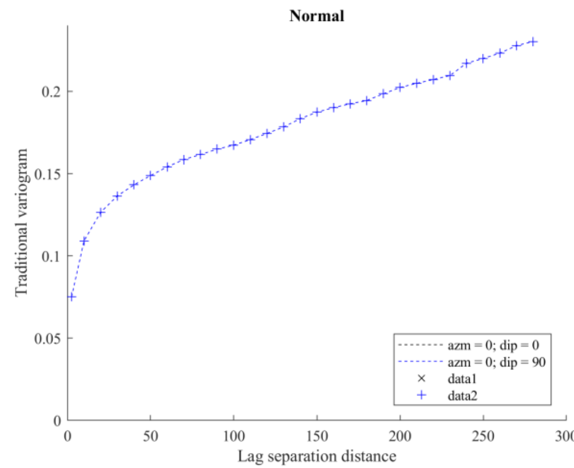


Case study: Sedimentary Basin

Modelling and simulation of pore pressure

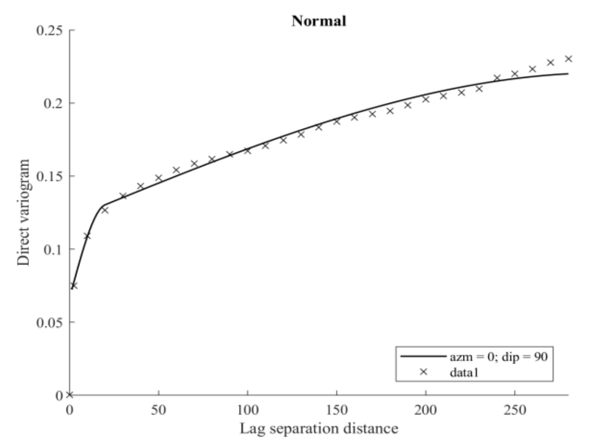
Variogram analysis





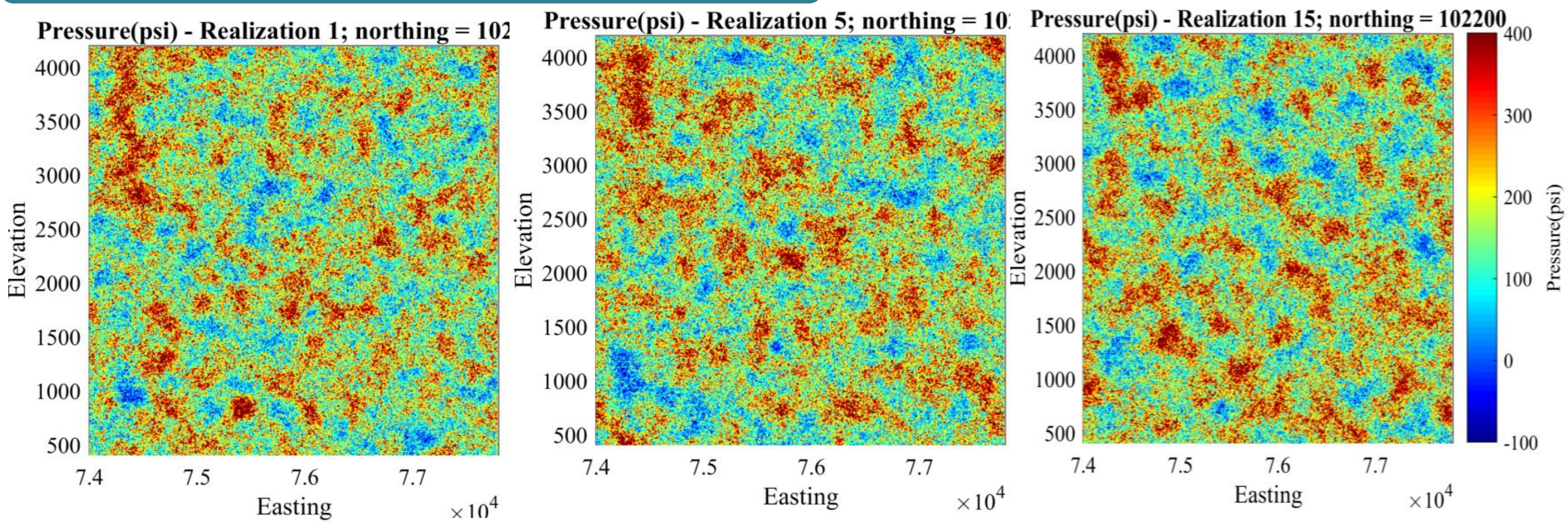
It has a nugget effect and a short-range structure (15-20 meters).

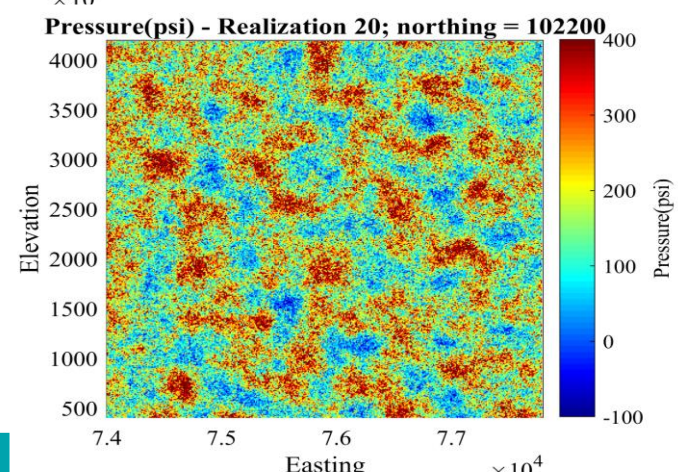
The modeled variogram has three spherical models of reach 20, 100 and 300 meters in all directions



Case study: Sedimentary Basin

Modelling and simulation of pore pressure

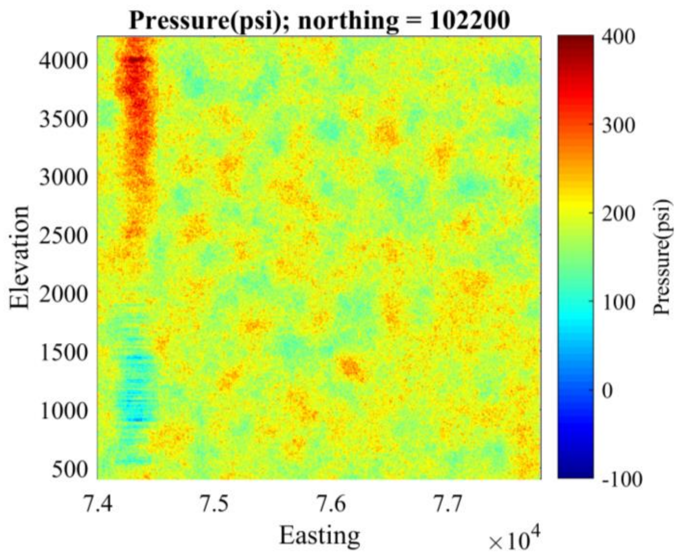


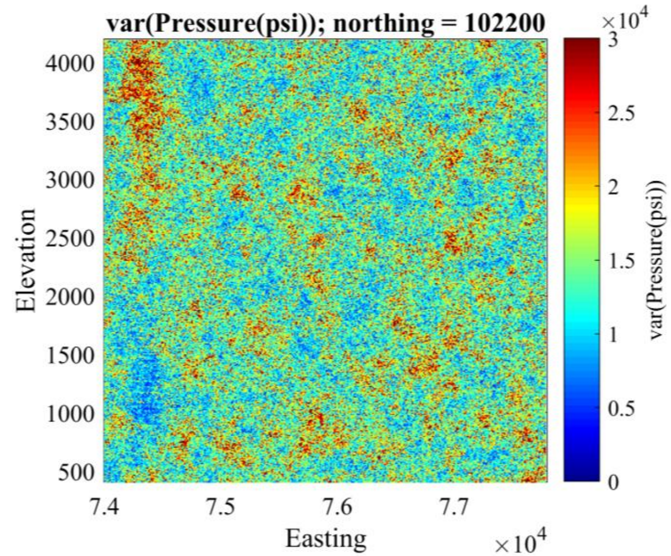


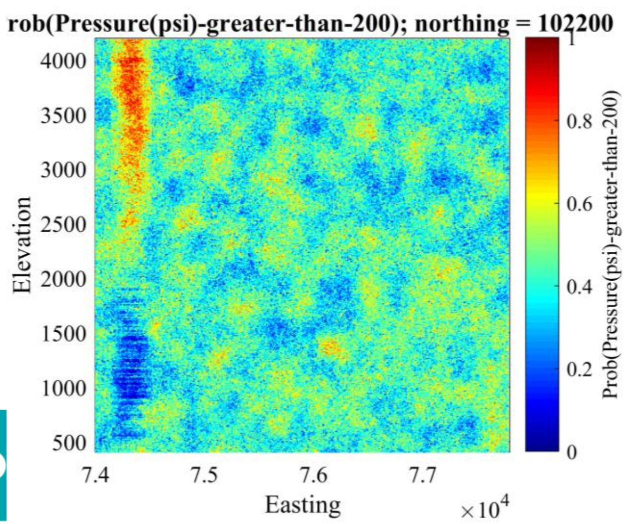
20 simulations were performed on a grid containing 144,400 grid nodes.
Grid mesh: 10 × 10 × 10 m

Case study: Sedimentary Basin

Modelling and simulation of pore pressure







- The average of the realizations is similar to an estimation by kriging.
- The variance of the realizations reflects the uncertainty in the prediction of the Pore Pressure.
- The last map reflects the probability that Pore Pressure is greater than 200 Psi

Conclusions

The increase in the pore pressure (strong hydraulic gradient) affects the geotechnical stability of the slopes due to the fact that the shear strength of the rock mass is reduced, that is, the effective normal tension is reduced.

The results of the sonic log are strongly dependent on the lithology, the degree of compaction, porosity, and fluid content.

The interval transit time depends on the porosity; the porosity and the transit interval time decrease with depth.

Conclusions

Simulation allows mapping the spatial variability of pore pressure and deriving predictions and probability maps.

Using a pore pressure model, we can image the pressure profile throughout the surrounding area with limited data and provide safer well planning.

The results obtained in this study can be considered as a useful tool to replace the formation pressure test for wells in which no measured test data are available.

Acknowledgments

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