Factors and Mechanisms of Elastic and Inelastic Deformation : A Literature Review and Insights on Land Subsidence in the Choushui River Alluvial Fan

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Date ：2024/12/27

In this talk...

This study aims to understand the influencing factors and mechanisms driving land subsidence, providing insights for groundwater management.

Development of spatially varying groundwater-drawdown functions for land subsidence estimation.

(Chu et al., 2020)

Unraveling elastic and inelastic storage of aquifer systems by integrating fast independent component analysis and a variable preconsolidation head decomposition method

(Li et al., 2022)

What are the features of elastic and inelastic deformation ？

What factors influence elastic and inelastic deformation ？

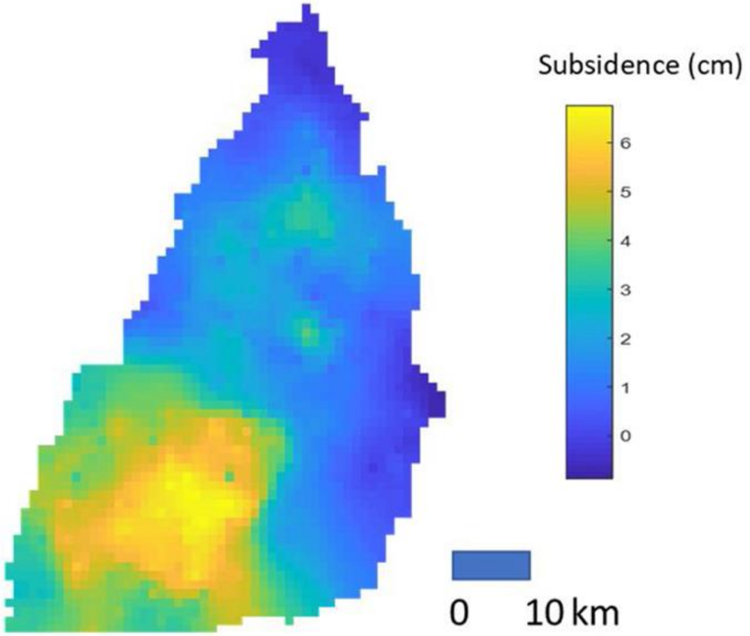
Outline

- Introduction
- Methodology
- Results
- Discussion and Conclusions
- Research Directions

➢ Study area

https://landsubsidence.wra.gov.tw/water_new/Home/Index

- Groundwater is the major source of water for civilian and agricultural use and represents approximately 240,000 m^3/day.
- An area of approximately 300 km^2 experiences significant subsidence (>3cm/year in 2015) due to groundwater overdraft.



Interpolated annual subsidence for 2015 (unit: cm/ year).
This IDW interpolation is based on observed leveling data.
(Chu et al., 2021)

➢ Terzaghi's principle of effective-stress

Groundwater pumping reduces the pore pressure of aquifer

and leads to increases effective stress,

resulting in compaction of the sedimentary layer. (Smith, R. G., & Majumdar, S., 2020)

$$\sigma = \sigma' + u$$

$$\Delta z = S_k \Delta h$$

$$\Delta z_i = \sum_l S_{kl}(ui\,,vi)\Delta h_{il} + \varepsilon_i$$

$\boldsymbol{\sigma}$: the total vertical stress.

$\boldsymbol{\sigma'}$: the effective stress.

$\boldsymbol{u}$: the pore water pressure.

$\boldsymbol{\Delta z}$: the deformation.

$\boldsymbol{S_k}$: the skeletal storage coefficient.

$\boldsymbol{\Delta h}$: the change in hydraulic head.

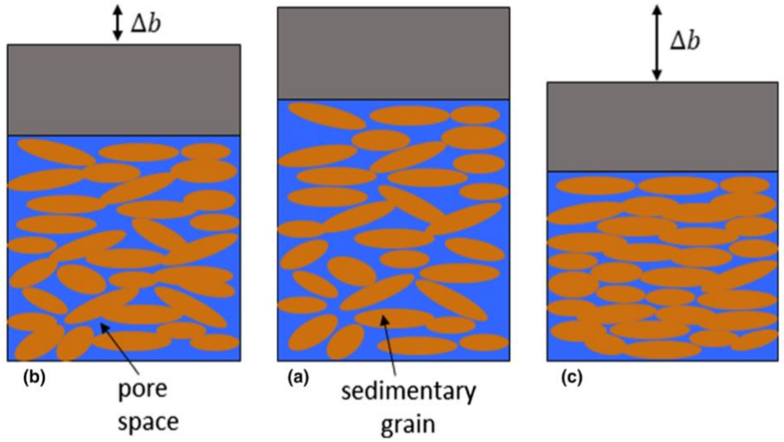
$\boldsymbol{i}$: the observation station number.

$\boldsymbol{l}$: the layer number in the multi-layer aquifer.

$\boldsymbol{\varepsilon_i}$: the residual of the model.

$\boldsymbol{(u_i, v_i)}$: the spatial coordinates at observation i.

Separating Elastic and Inelastic Deformation



(Smith, R. G., & Majumdar, S., 2020)

(a) Initial state

(b) Elastic compaction

The effective stress < The preconsolidation stress

(c) Inelastic compaction

The effective stress > The preconsolidation stress

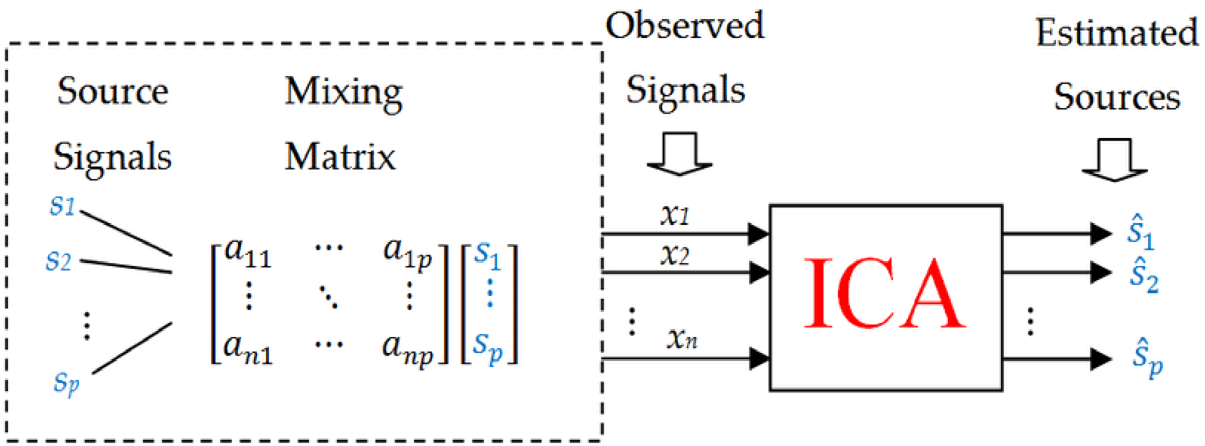
$\boxed{H_{pc} < H}$

$$S_{ke} = \frac{\Delta b_e}{\Delta h_e} \quad S_{ske} = \frac{S_{ke}}{b_0}$$

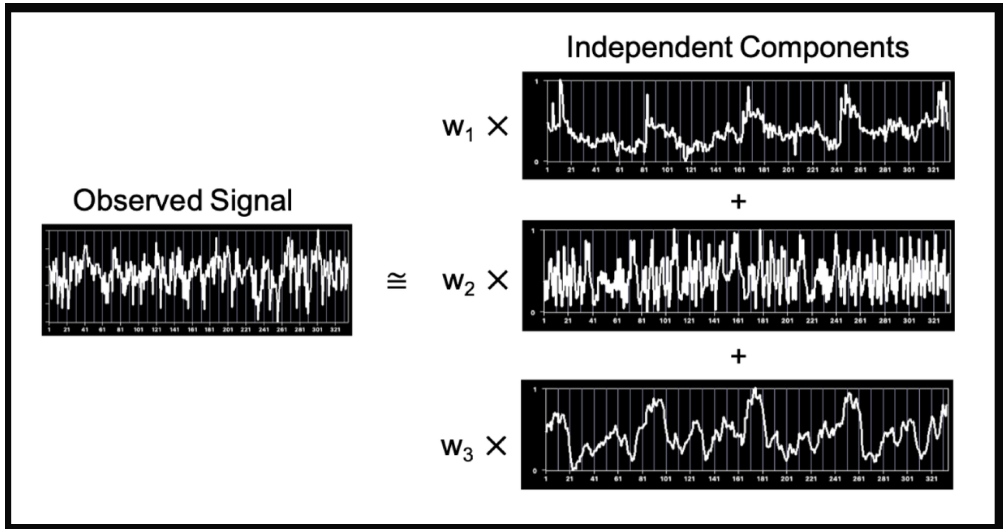
$\boxed{H_{pc} > H}$

$$S_{kv} = \frac{\Delta b_v}{\Delta h_v} \quad S_{skv} = \frac{S_{kv}}{b_0}$$

Fast Independent Component Analysis (Fast-ICA)



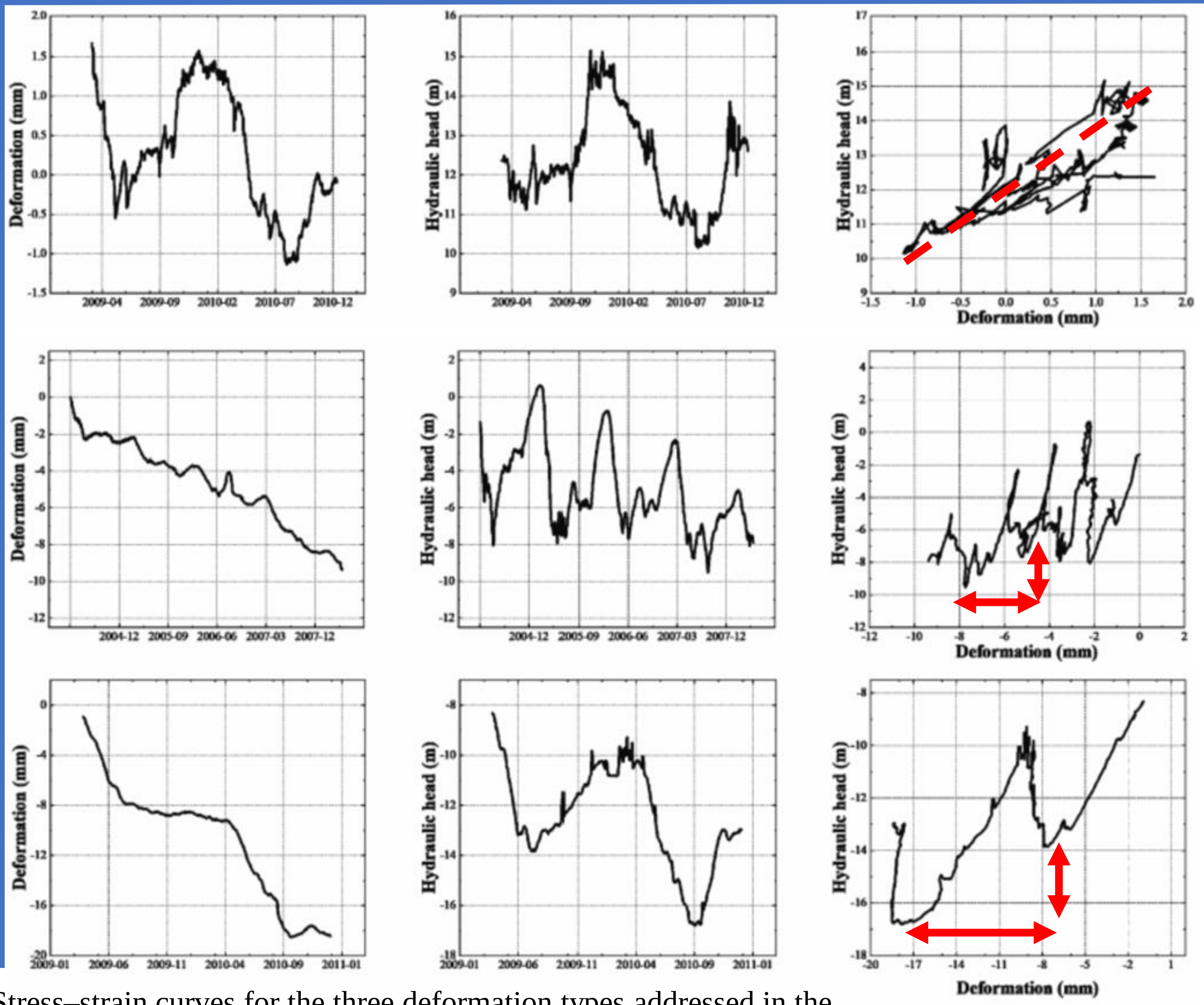
https://www.researchgate.net/figure/Block-diagram-of-standard-independent-component-analysis_fig1_340482282



https://www.newbi4fmri.com/tutorial-10-ica

➢ Deformation types (Extensometer versus Piezometers)

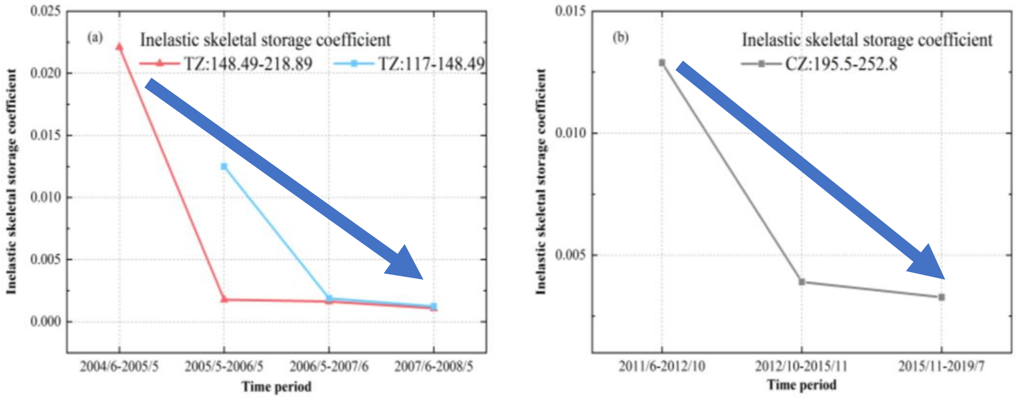
Data / Station	Deformation -Date	Hydraulic head -Date	Hydraulic head-Deformation (Stress-strain curve)
PGZ : 31.9–63.1			
TZ : 82.3–102			
PGZ : 119.64–208.8			



Stress–strain curves for the three deformation types addressed in the study: mainly elastic, mixed elastic-inelastic, and mainly inelastic.

(Li et al., 2022)

Deformation	Hysteresis loop (elastic)	Residual deformation (Inelastic)
Elastic	one	low
Elastic-inelastic	Several	Larger
Inelastic	no	More Larger



S_{kv} versus time for TZ:148.49-218.89 and TZ:117-148.49 (a) and CZ:195.5-252.8 (b). (Li et al., 2022)

➢ Relations between storage parameters and lithology

Storage parameters computed for the various depth layers at the three extensometer stations in the North China Plain. (Li et al., 2022)

Layer ID (name - depth)	Thickness (m) Increase	Lithology	Deformation Type	S_{ke}	S_{kv}	S_{ske} (m^{-1})	S_{skv} (m^{-1}) Decrease	$\frac{S_{ske}}{S_{skv}}$
TZ: 148.49–218.89	70.4	Silt, Fine sand	Elastic-inelastic	2.5×10^{-4}	1.6×10^{-3}	3.5×10^{-6}	2.2×10^{-5}	0.16
TZ:117–148.49	31.89	Silt, Coarse sand	Elastic-inelastic	3.7×10^{-4}	2.6×10^{-3}	1.2×10^{-5}	8.1×10^{-5}	0.14
TZ:82.3–102	19.7	Silty clay, Fine sand	Elastic-inelastic	1.4×10^{-4}	3.0×10^{-3}	7.3×10^{-6}	1.5×10^{-4}	0.05
TZ:48.5–64.5	16	Fine sand, Coarse sand	Elastic	4.6×10^{-4}	–	2.9×10^{-5}	–	–
PGZ:233.5–300	66.5	Sand, Silty clay	Elastic-inelastic	1.7×10^{-4}	7.2×10^{-4}	2.5×10^{-6}	1.1×10^{-5}	0.23
PGZ: 119.64–208.8	89.16	Clay	Inelastic	–	3.0×10^{-3}	–	3.3×10^{-5}	–
PGZ:63.1–119.64	56.54	Sand, Silty clay	Elastic-inelastic	4.5×10^{-4}	3.5×10^{-3}	8.0×10^{-6}	6.2×10^{-5}	0.13
PGZ:31.9–63.1	31.2	Silty clay, Silty fine sand	Elastic	6.8×10^{-4}	–	2.2×10^{-5}	–	–
CZ:195.5–252.8	57.3	Silty sand, Silty fine sand, Silty clay	Elastic-inelastic	1.7×10^{-3}	4.1×10^{-3}	2.9×10^{-5}	7.2×10^{-5}	0.4
CZ:68.3–195.5	127.2	Clay, Silty fine sand	Elastic-inelastic	9.0×10^{-4}	1.5×10^{-2}	7.1×10^{-6}	1.2×10^{-4}	0.06

What are the features of elastic and inelastic deformation ？

Hysteresis loops

Residual deformation

→ What does the stress-strain curve look like？

(Using GNSS, MLCW, and groundwater level data)

What factors influence elastic and inelastic deformation ？

Lithology

Depth

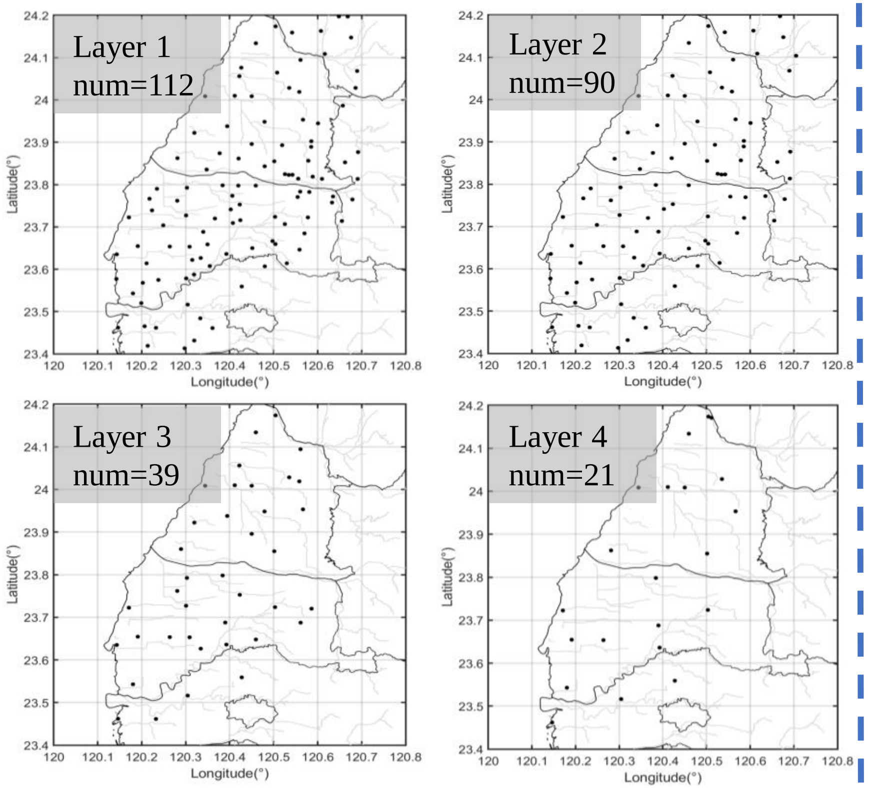
Time

→ Are there any mathematical models that can connect data to explain physical phenomena？

Methodology and data

Groundwater data

Groundwater level Well

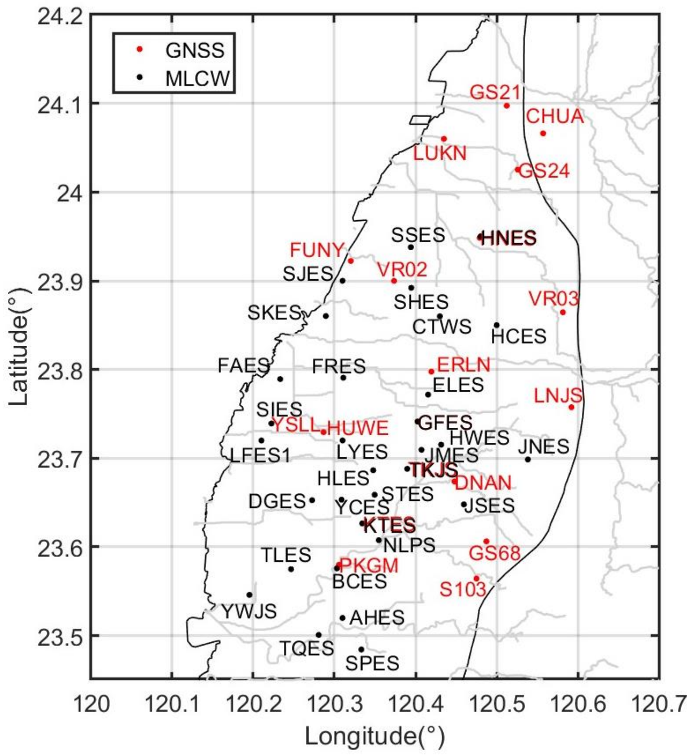


Geodetic data

Global Navigation Satellite System(GNSS)

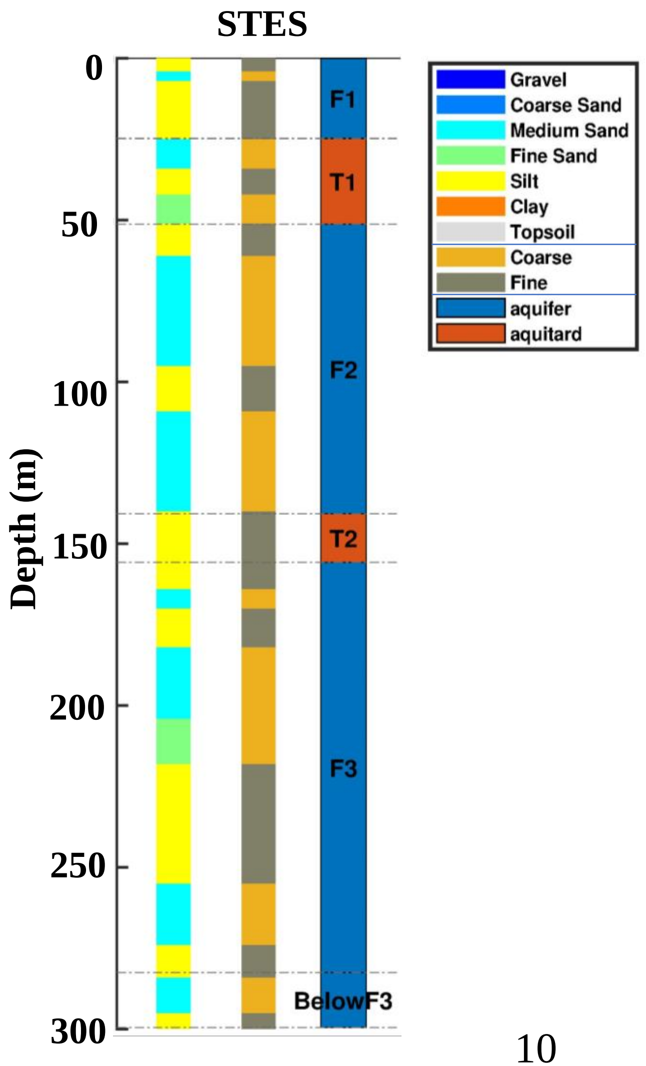
In-situ data

Multi-layer compaction monitoring Well (MLCW)



Lithological data

Drilling data



$$y = a + bt + c\sin 2\pi t + d\cos 2\pi t + eH(t - t_{eq}) + f[-\exp(\frac{-(t - t_{eq})}{\tau})]H(t - t_{eq})$$

Linear **Annual** **EQ offset** **Post**

(Hsu et al., 2020)

➢ Preliminary Results

Deformation types

(MLCW versus Groundwater level)

What does the stress-strain curve look like？

(Using GNSS, MLCW, and groundwater level data)

Deformation	Hysteresis loops (elastic)	Residual deformation (Inelastic)
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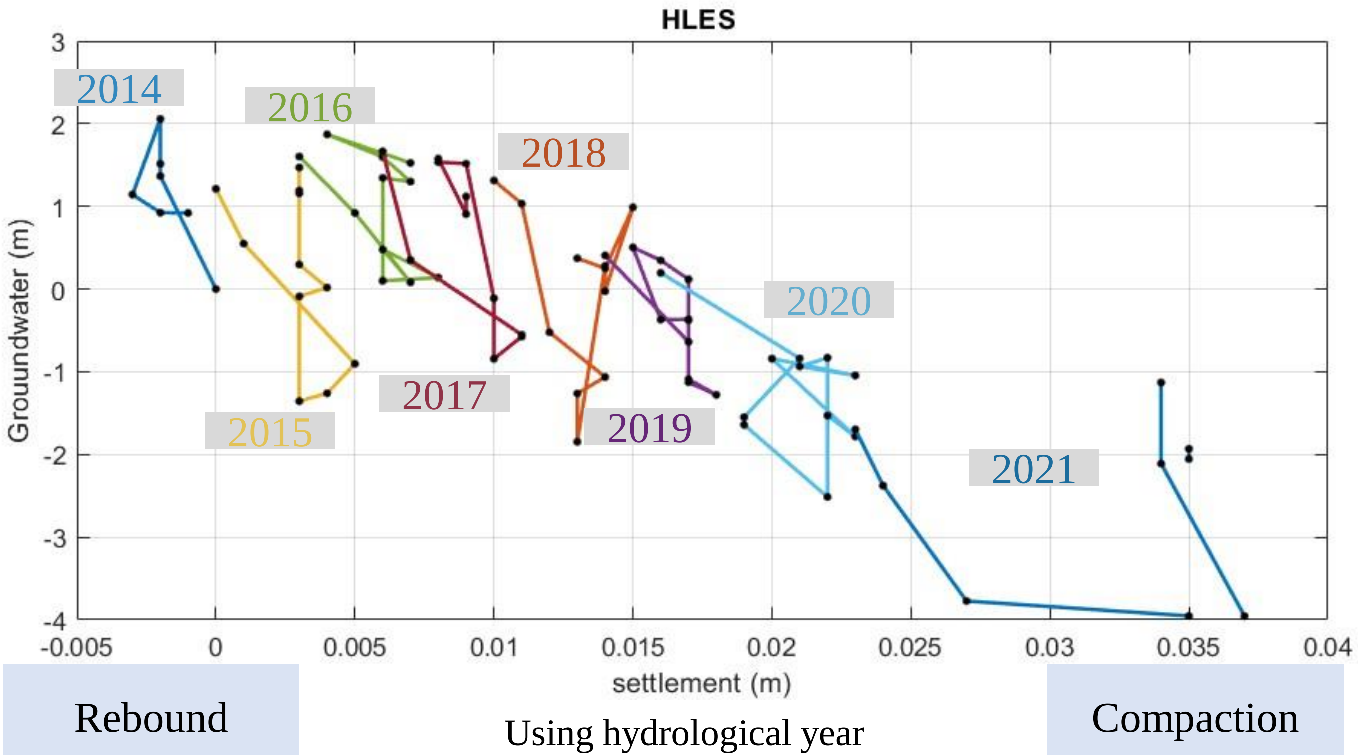
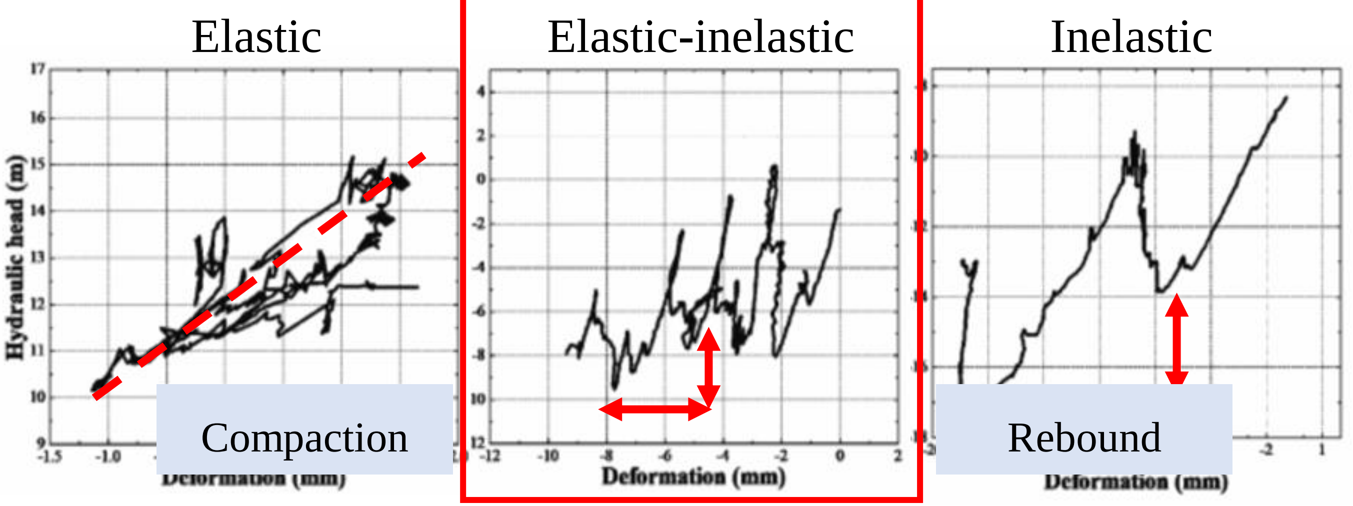


Using hydrological year



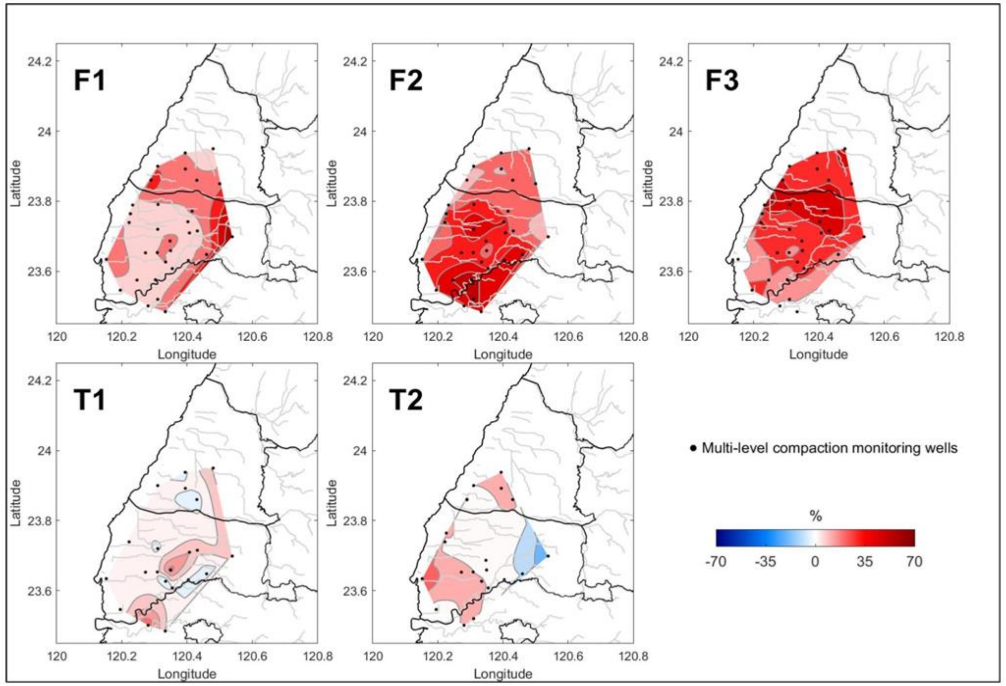
(Li et al., 2022)

Preliminary Results

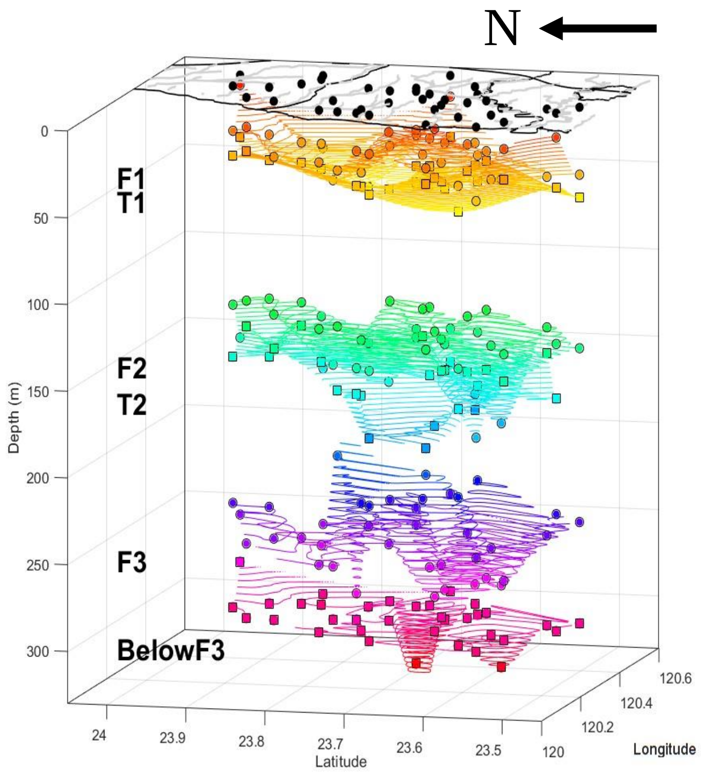
Mathematical Models for Explaining

Physical Phenomena

> Are there any mathematical models that can connect data to explain physical phenomena ?



Percentage Distribution of 5-Year Average Subsidence for Each Layer: Hydrological Years 2016–2020



3D Distribution of Aquifers and Aquitards Based on the Deepest Magnetic Rings in Each MLCW Layer.

Internal Elastic Response | **External Driving Forces**

$$G\nabla^2 u_i + \frac{G}{1-2\nu}\frac{\partial^2 u_k}{\partial x_i \partial x_k} = \alpha\frac{\partial p}{\partial x_i} - (\rho_s + n\rho_f)g$$

- Shear Contribution: Represents resistance to shape distortion from shear forces.
- Volumetric Contribution: Describes changes in material volume due to internal stresses.
- Pore Pressure: Indicates stress caused by fluid pressure within pores.
- Gravitational Force: Accounts for the force from the weight of solid and fluid materials.

Reference

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Thanks for your attention.