The Influence of Geological Models with Different Complexity and Nonlinear Parameters on Land Subsidence Simulation – A Case Study in Yunlin County

Presenter: Yung-Han Yang
Advisor: Prof. Shih-Jung Wang
Date: 2022.10.14

OUTLINE

01 Introduction

Motivation / Purposes

Introduction / Motivation

- Due to groundwater overexploitation since the 1970s, **Yunlin County** is still a serious subsidence area in Taiwan. In addition, the subsidence center of Yunlin County gradually moved from the coastal area to the inland area after 1996.

Yunlin County (2021)

Area: 502.7 km^2

Rate: 7.8 cm/yr

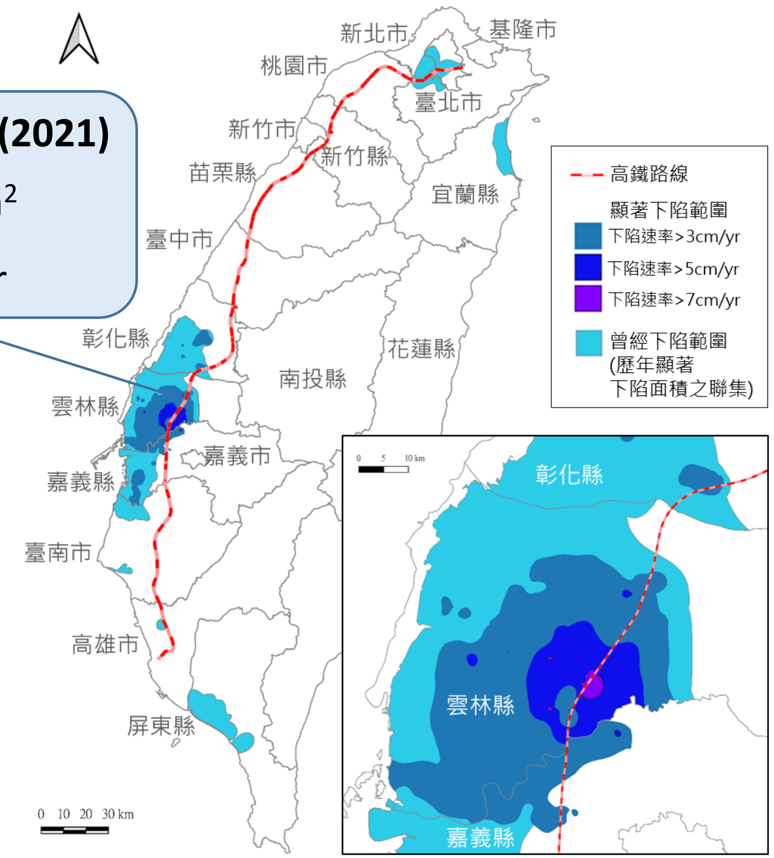


Fig. The general situation of land subsidence in Taiwan in 2021 from WRA.

Mechanism ?

(Lin et al., 2016)

The safety of High Speed Rail !!

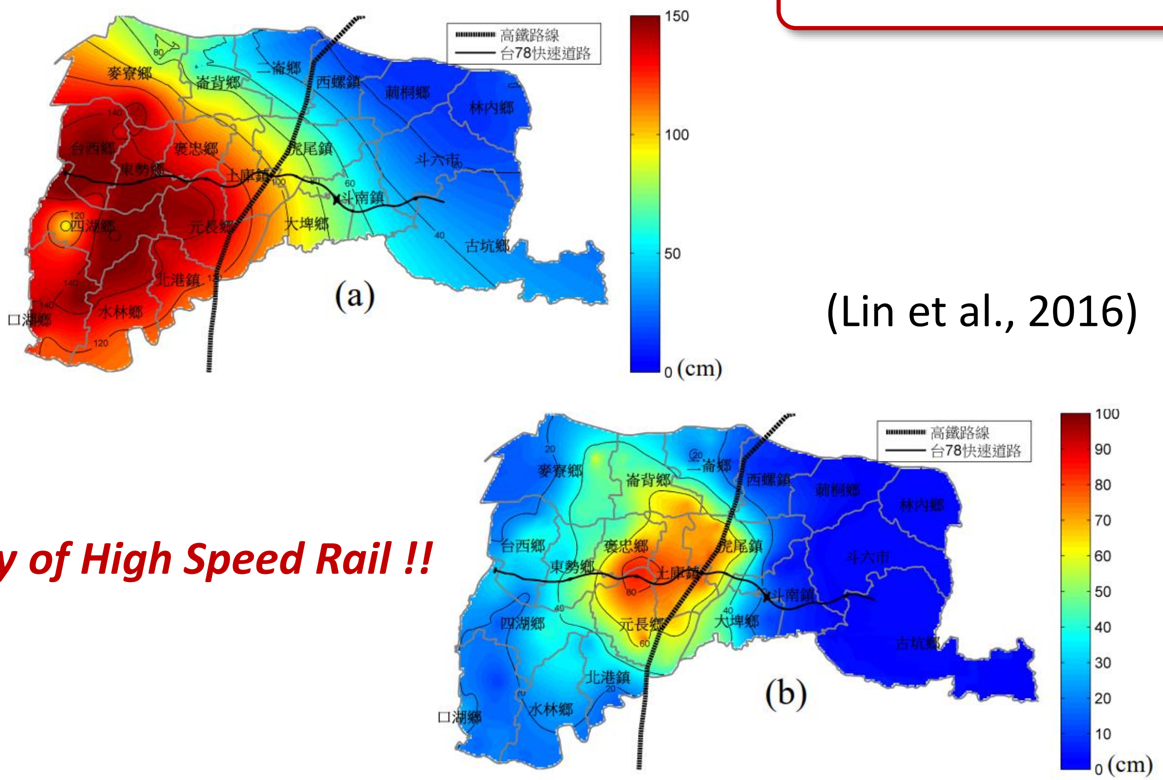


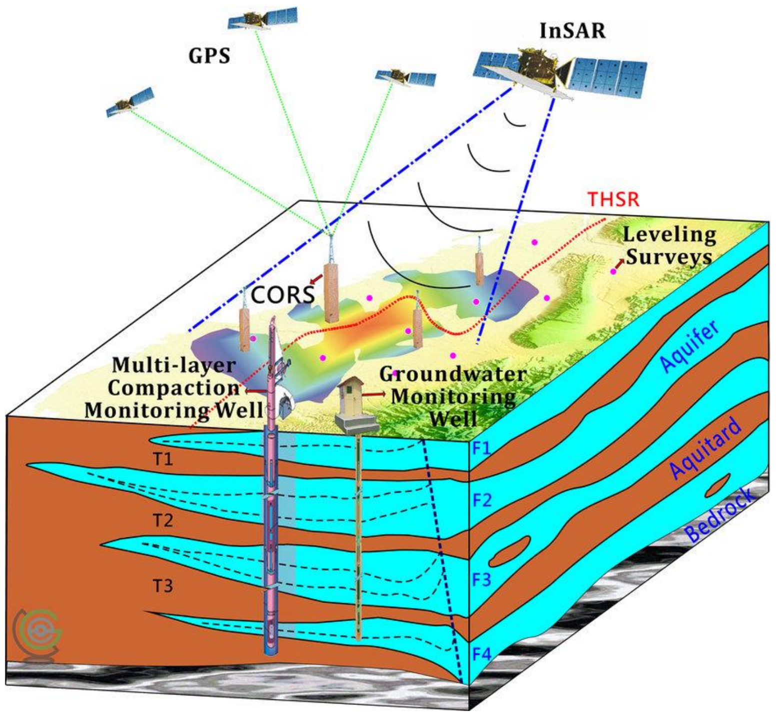
Fig. The distribution of land subsidence in the Yunlin County (a) 1992-2001 (b) 2002-2011.

Introduction / Motivation

- Local geological conditions and structure affect the behavior and characteristics of land subsidence (Bozzano et al., 2015; Liu et al., 2004).
- For land subsidence caused by groundwater overexploitation, reliable hydrogeological models can accurately predict the scale and extent of subsidence and help the planning of mitigation measures (Tzampoglou & Loupasakis, 2018; Li et al., 2021; Musso et al., 2021).

Reliable model !!

Fig. A **conceptual model** with the multi-sensor land subsidence monitoring system in central Taiwan. (Hung et al., 2020) →



- **Land subsidence** caused by a hydraulic condition variation in geological models with different complexity is simulated to explore the influence of **geological materials**, **geological structures** and **deformation effect** on land subsidence simulation.

Different geological models ➕ **Same** hydraulic condition ➡ **Land subsidence**

1. **Geological materials ?**
2. **Geological structure ?**
3. **Deformation effect ?**

02 Methodology

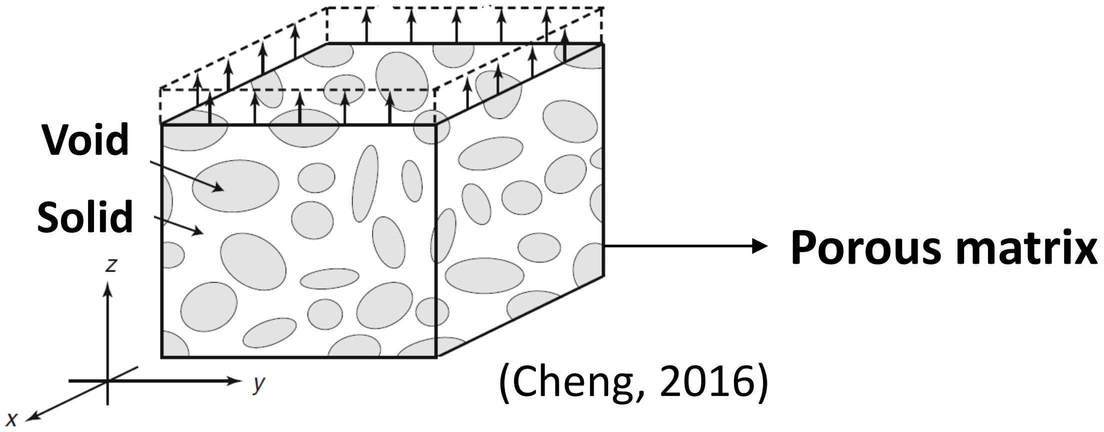
Biot’s theory / Parameter sensitivity analysis / Nonlinear parameters

- **Biot's theory** can simultaneously consider **the vertical and horizontal soil deformation** and the mechanism of the interaction between fluid and solid (Deng et al., 2018).

Hydro-mechanical Coupling

Porous matrix deformation ⟷ **Fluid flow within porous matrix**

Dependent variables: **displacement (u)** and **pore water pressure (p)**



(Cheng, 2016)

- **Parameter sensitivity analysis:**

Changing parameters → Output results

Soil properties — Land subsidence

- **The relative sensitivity, RS** (Chen et al., 2014):

Compare the sensitivity of parameters with different unit

The change of result

$$RS = \frac{\dfrac{g(j_i^* + \Delta j_i) - g(j_i^*)}{g(j_i^*)}}{\dfrac{\Delta j_i}{j_i^*}}$$

Original value of **result**

Dimensionless

The change of **parameter**

Original value of **parameter**

- **The nonlinear parameters** are adopted to describe the variation of soil properties during the deformation process (Wang and Hsu, 2009):

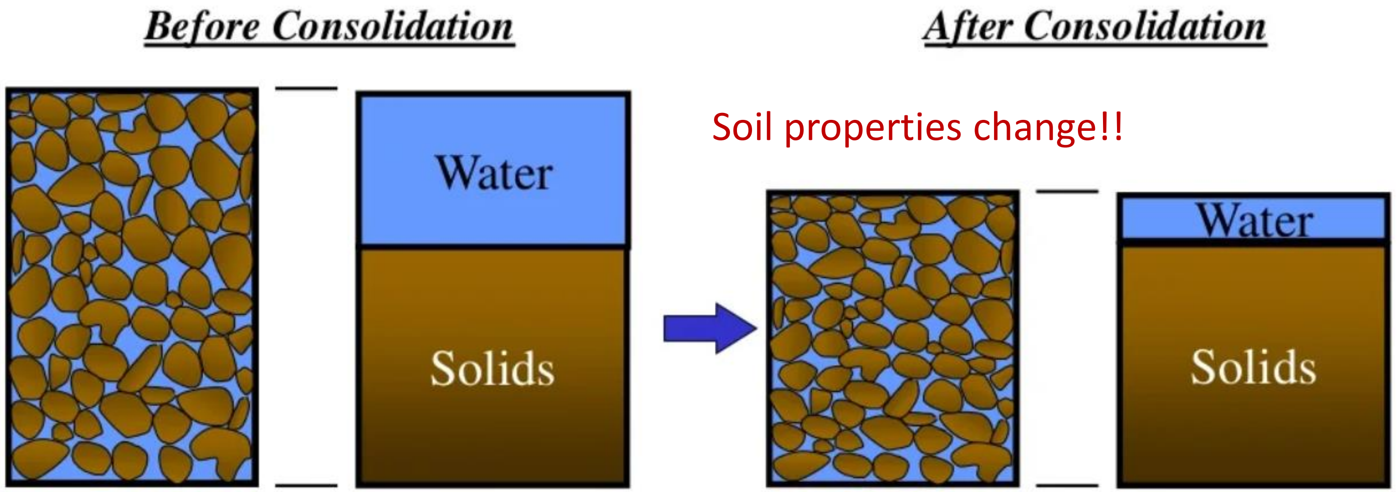
Porosity (n)	Permeability (k)	Young's modulus (E)
$n_1 = \dfrac{n_0 + e}{1 + e}$	$k_1 = k_0 \dfrac{\left(1 + \dfrac{e}{n_0}\right)^3}{1 + e}$	$E_1 = E_0 \left(\dfrac{1}{1 + e}\right)^2$

(Wang and Hsu, 2009)

e: the volumetric strain ($e = \nabla \cdot \mathbf{u}$)

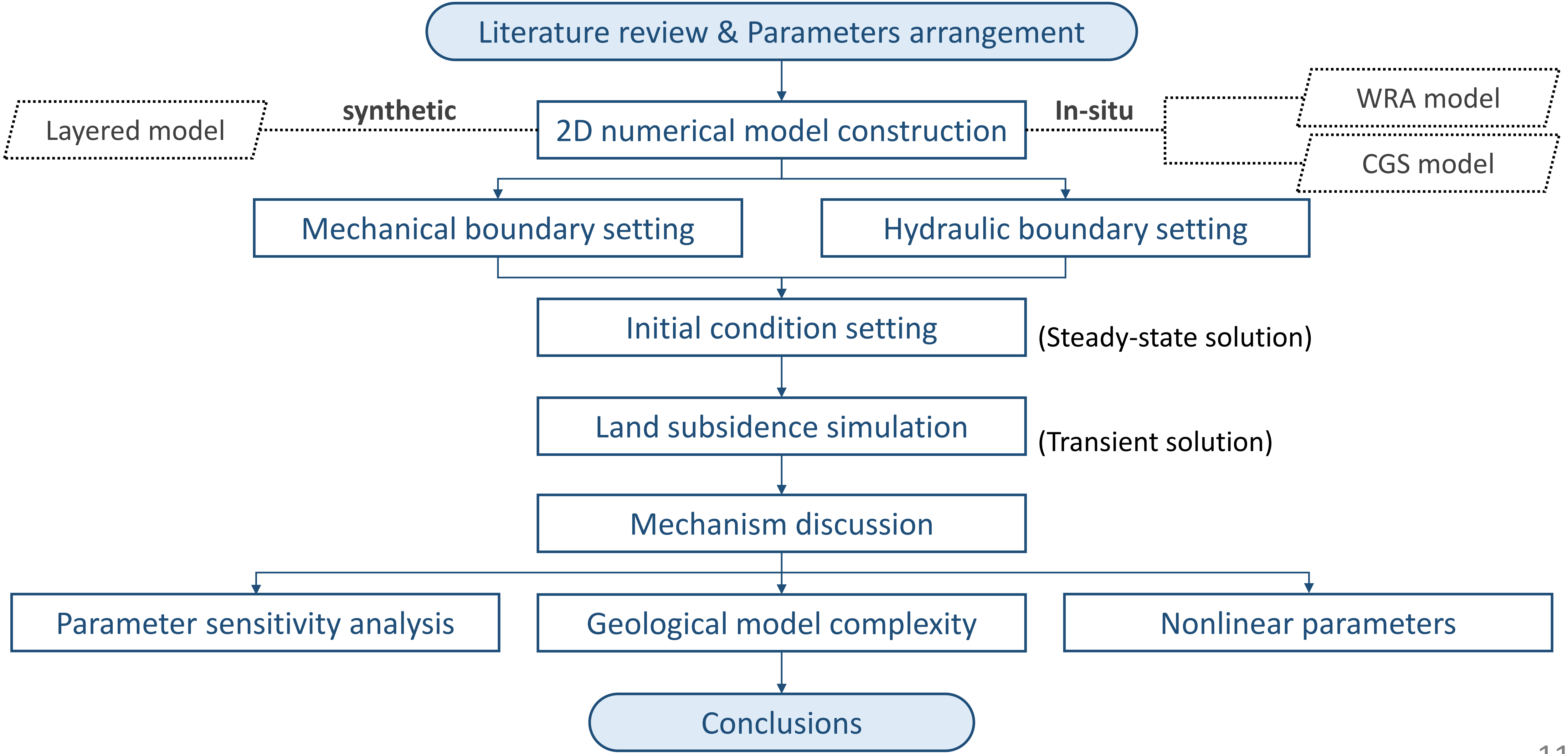
D_0: the parameter **before** the deformation effect

D_1: the parameter **after** the deformation effect



(Irfan M., 2017)

Methodology / Flowchart



03 Model Settings

Model construction / Boundary condition / Initial condition

- **Geological models with different complexity** are constructed using the hydrogeological cross sections from CGS and WRA.

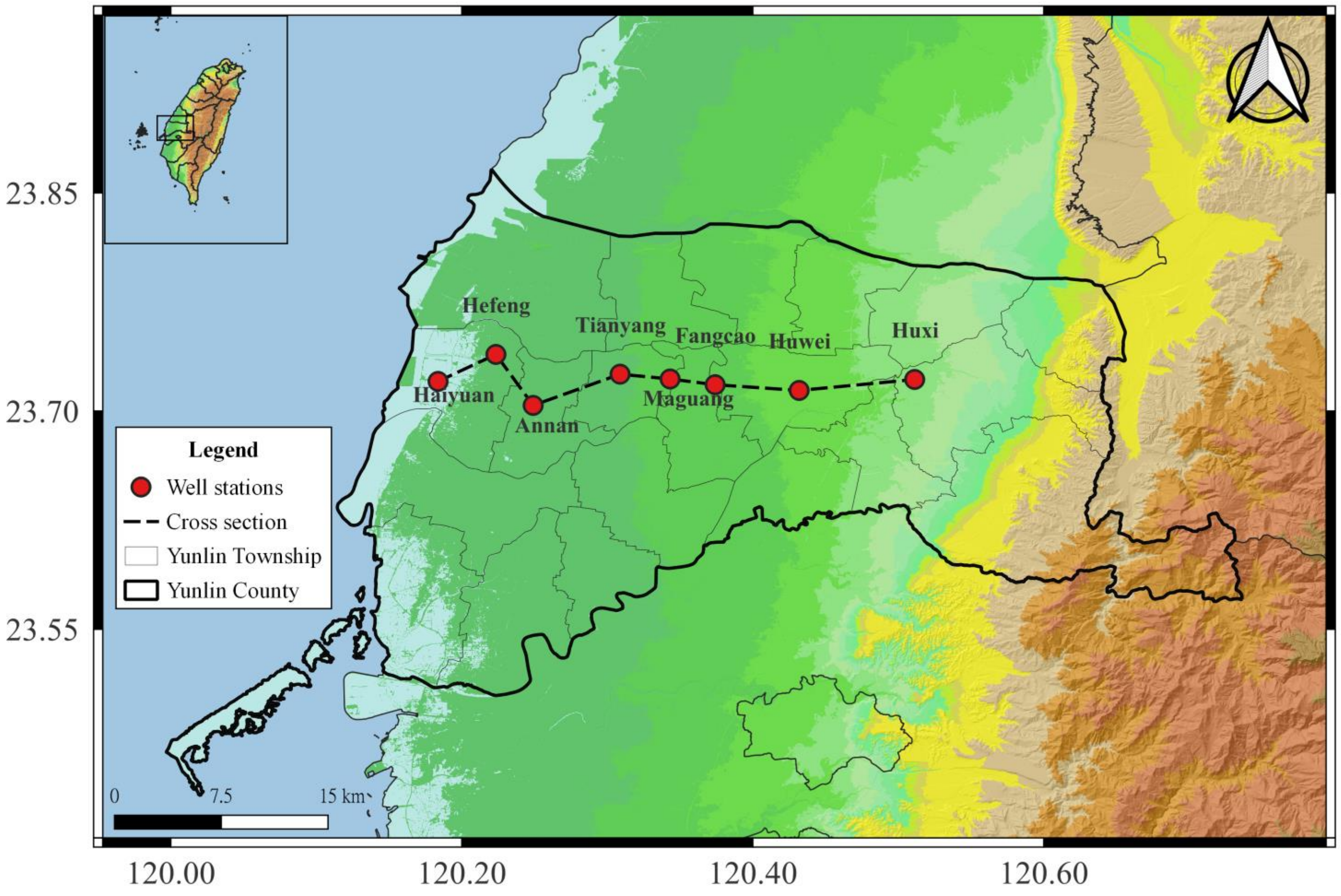


Fig. The geographical location of hydrogeological cross section (Haiyuan – Huxi).

Model Settings / Hydrogeological cross sections

- The hydrogeological cross sections are given coordinates and meshed to construct the **in-situ models**.

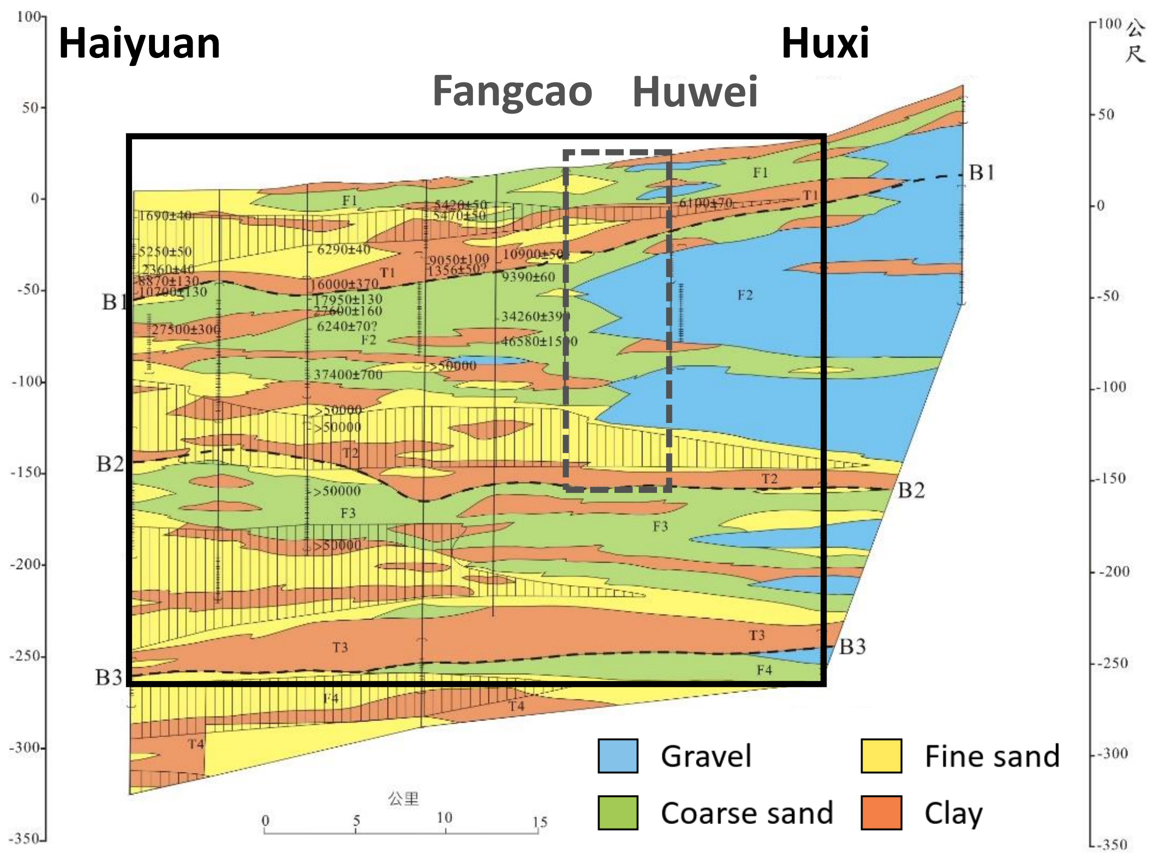


Fig. The construction range of **synthetic model (dashed line)** and **in-situ model (solid line)** in CGS cross section.

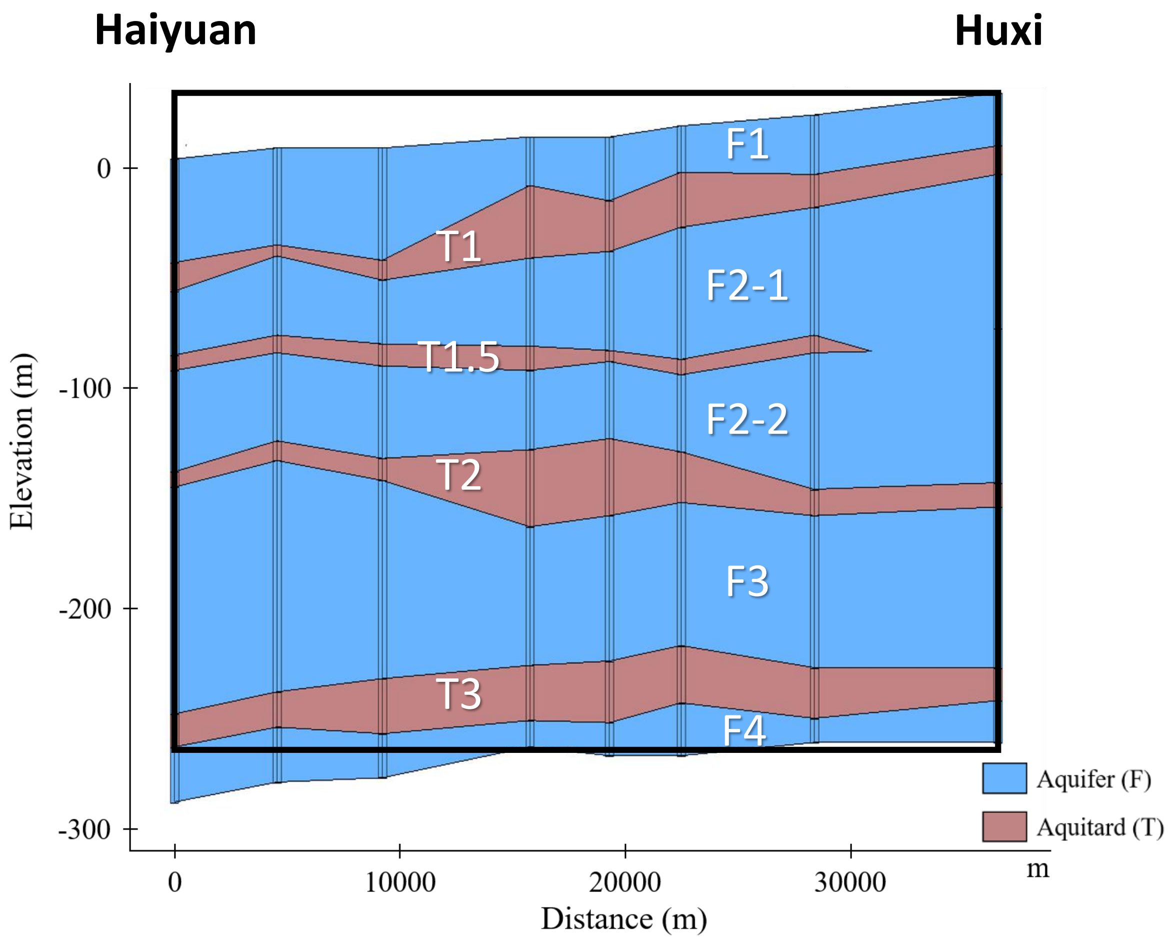
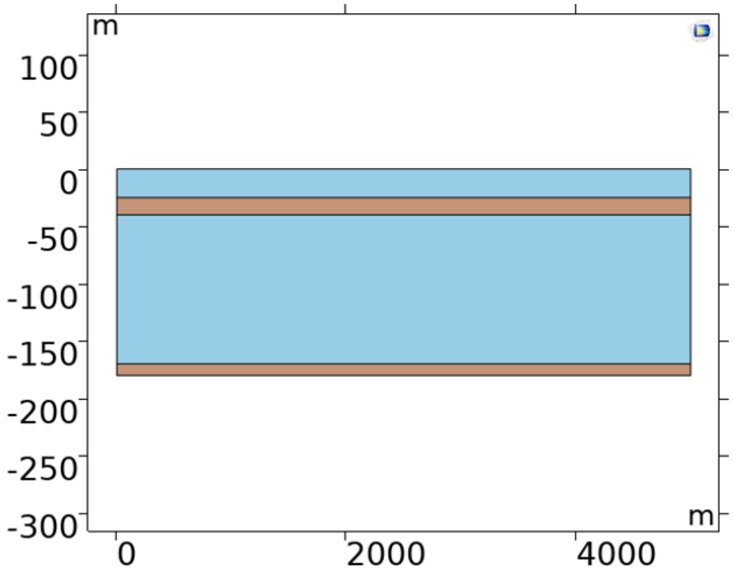


Fig. Hydrogeological cross section created in GMS using **layered borehole data** provided by WRA.

Model Settings / Model description

Synthetic

Layered model



Aquifer Aquitard

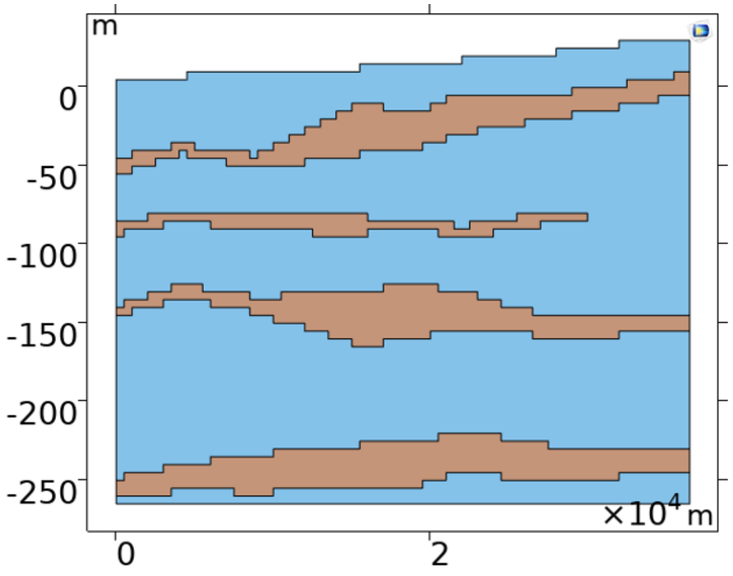
5000 m (distance)

×

180 m (depth)

In-situ

WRA model



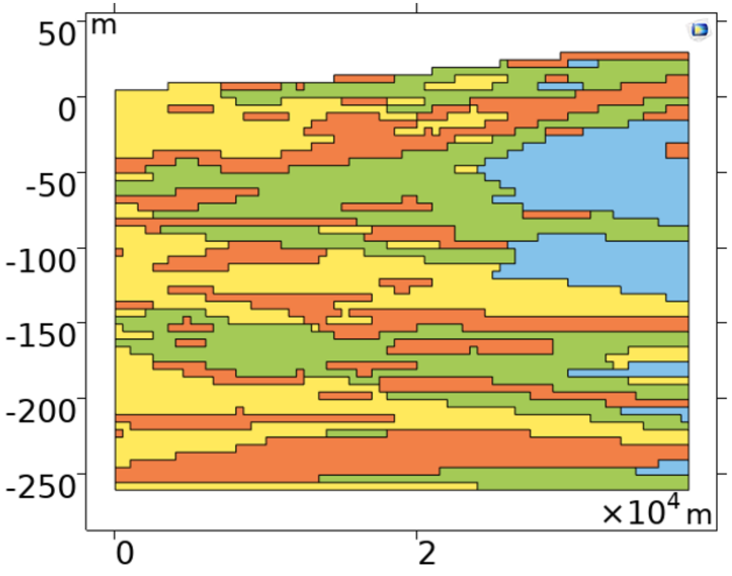
Aquifer Aquitard

36500 m (distance)

×

265~290 m (depth)

CGS model



Gravel Fine sand

Coarse sand Clay

37500 m (distance)

×

265~290 m (depth)

Model Settings / Material parameters

- Soil materials for aquifer and aquitard in the layered aquifer models are respectively set as **Coarse Sand** and **Clay**.

Table The parameters of soil material and fluid material used in this study.

Parameter	Unit	Soil material				Fluid material
		Gravel	Coarse Sand	Fine Sand	Clay	Water
Density	$\mathrm{kg/m^3}$	2141	1988	2090	1886	1000
Porosity	–	0.265	0.345	0.375	0.405	–
Young's modulus	Pa	1.6×10^{8}	5.0×10^{7}	2.0×10^{7}	4.0×10^{6}	–
Poisson's ratio	–	0.250	0.275	0.325	0.350	–
Permeability	$\mathrm{m^2}$	2.7×10^{-10}	1.8×10^{-11}	4.5×10^{-13}	1.0×10^{-17}	–
Fluid compressibility	$1/\mathrm{Pa}$	–	–	–	–	4×10^{-10}
Dynamic viscosity	$\mathrm{Pa \cdot s}$	–	–	–	–	8.9×10^{-4}

(Kezdi & Rethati, 1974; Freeze & Cherry, 1979; Fitts, 2013)

- It is assumed that the sides are affected by the surrounding soil and cannot be deformed horizontally, and there is a ~~bedrock below~~ the model, which cannot be deformed vertically.

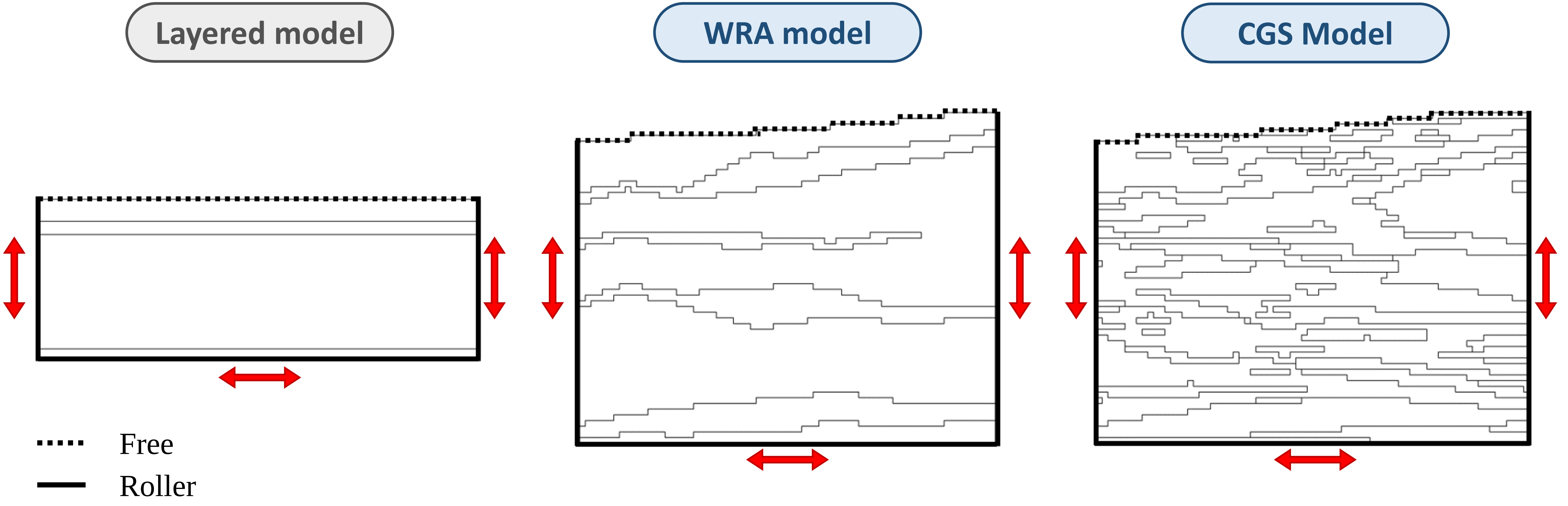


Fig. The **mechanical boundary condition** of geological models.

Model Settings / Hydraulic boundary condition

- In order to discuss the influence of **geological materials** and **structures** on land subsidence, the hydraulic condition will be changed uniformly in the whole aquifer system.

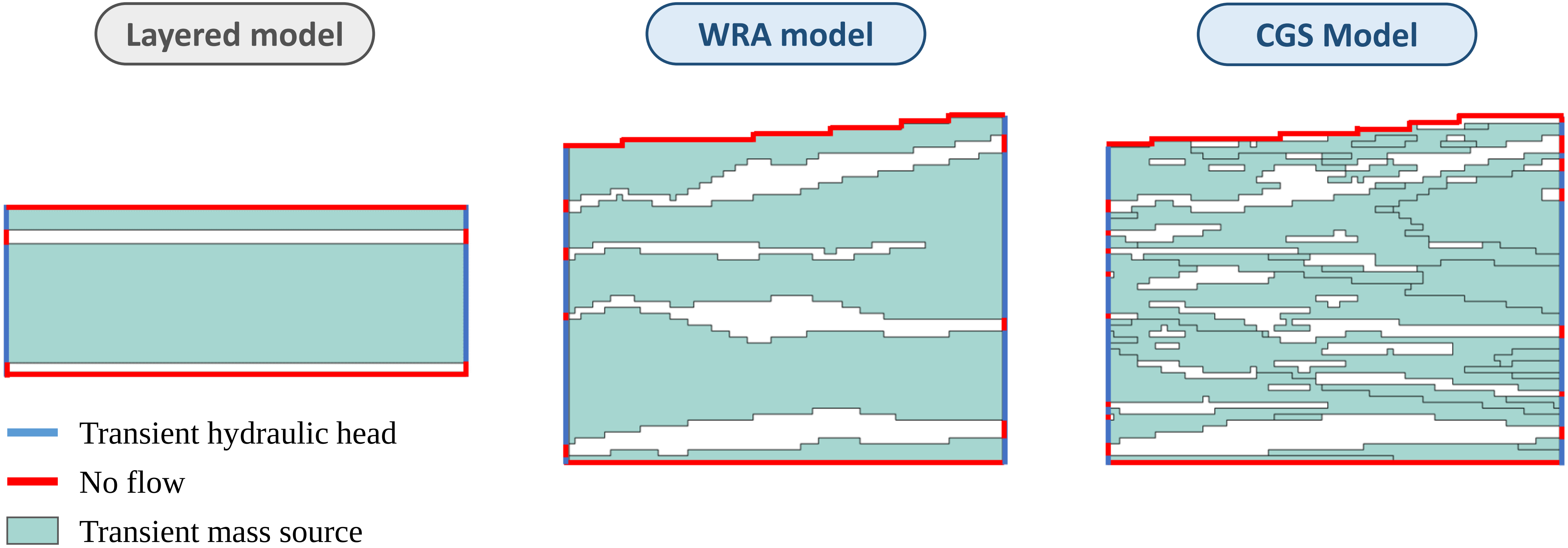


Fig. The **hydraulic boundary condition** of geological models.

Model Settings / Hydraulic condition change

- The **variation of hydraulic condition** is set based on a historical groundwater level observed by the well stations in Yunlin County.

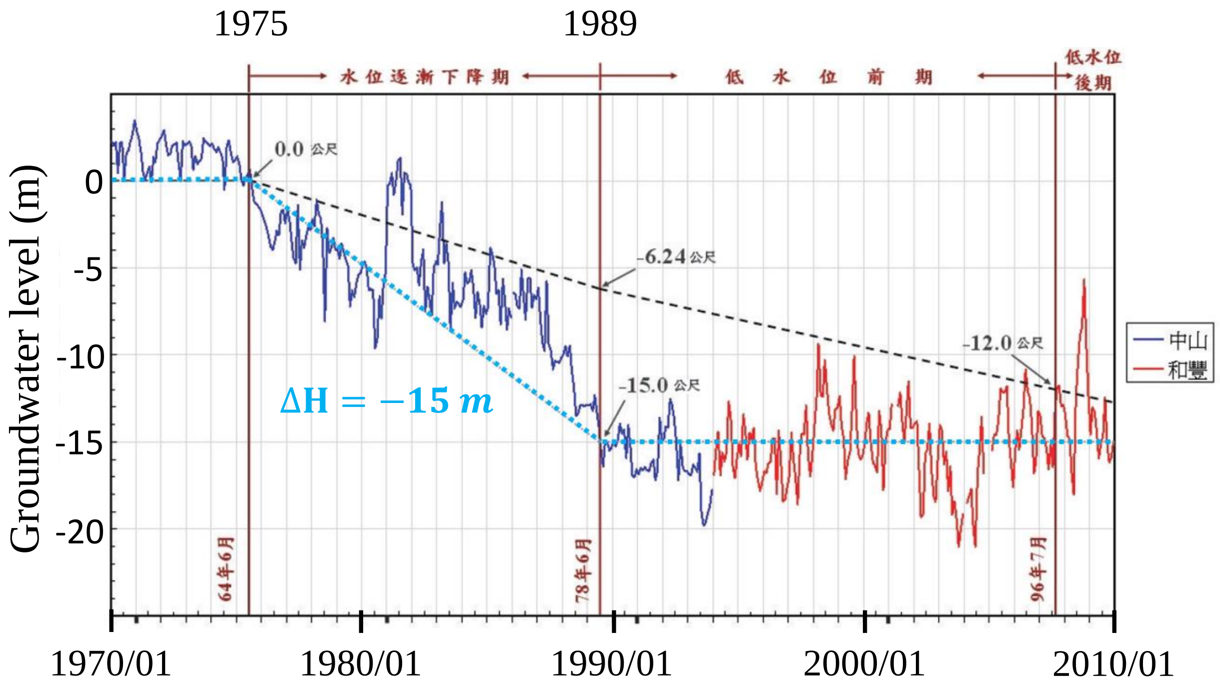


Fig. The historical groundwater level of Zhongshan and Hefeng well stations (Jiang et al., 2011).

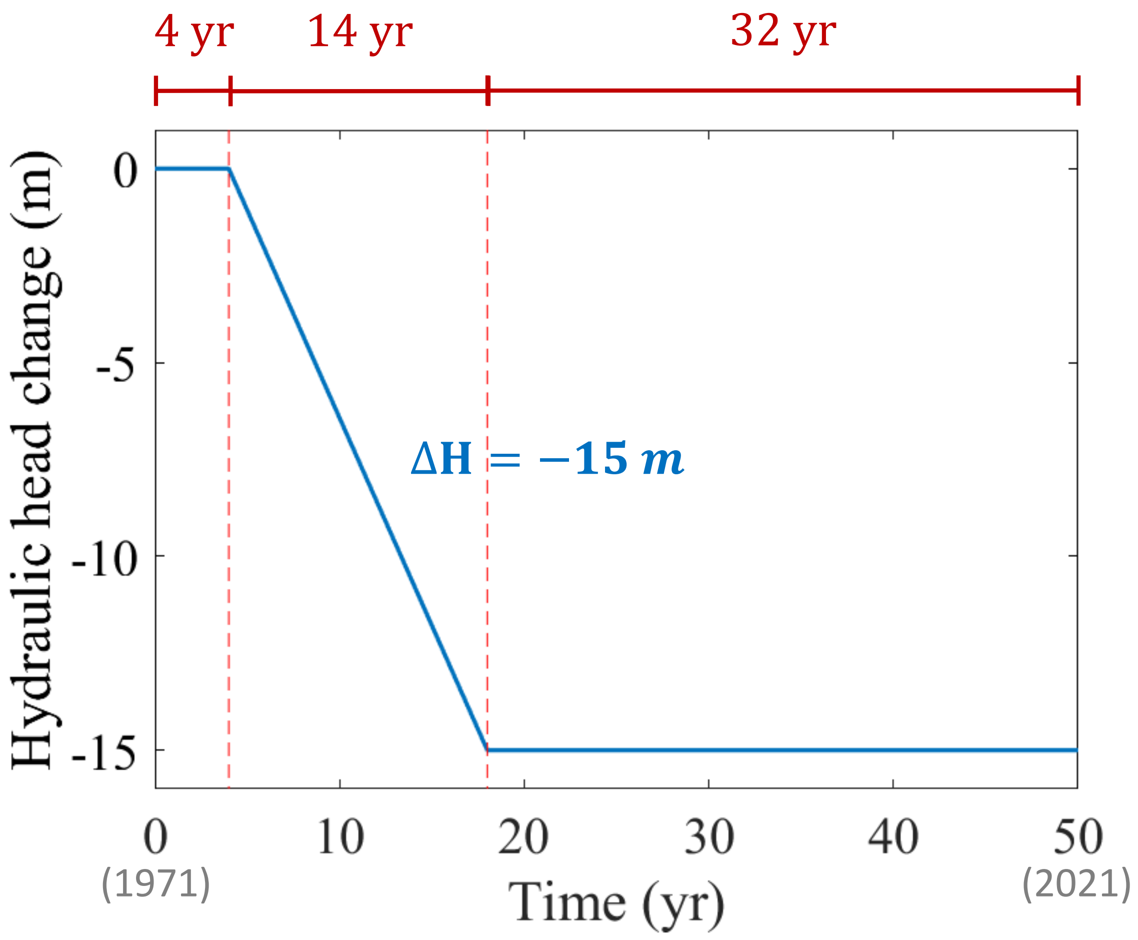


Fig. The hydraulic head change in land subsidence simulation

Model Settings / Initial values for initial condition

- The initial conditions is defined by boundary conditions and initial values of hydraulic head, which are set according to the observation data.

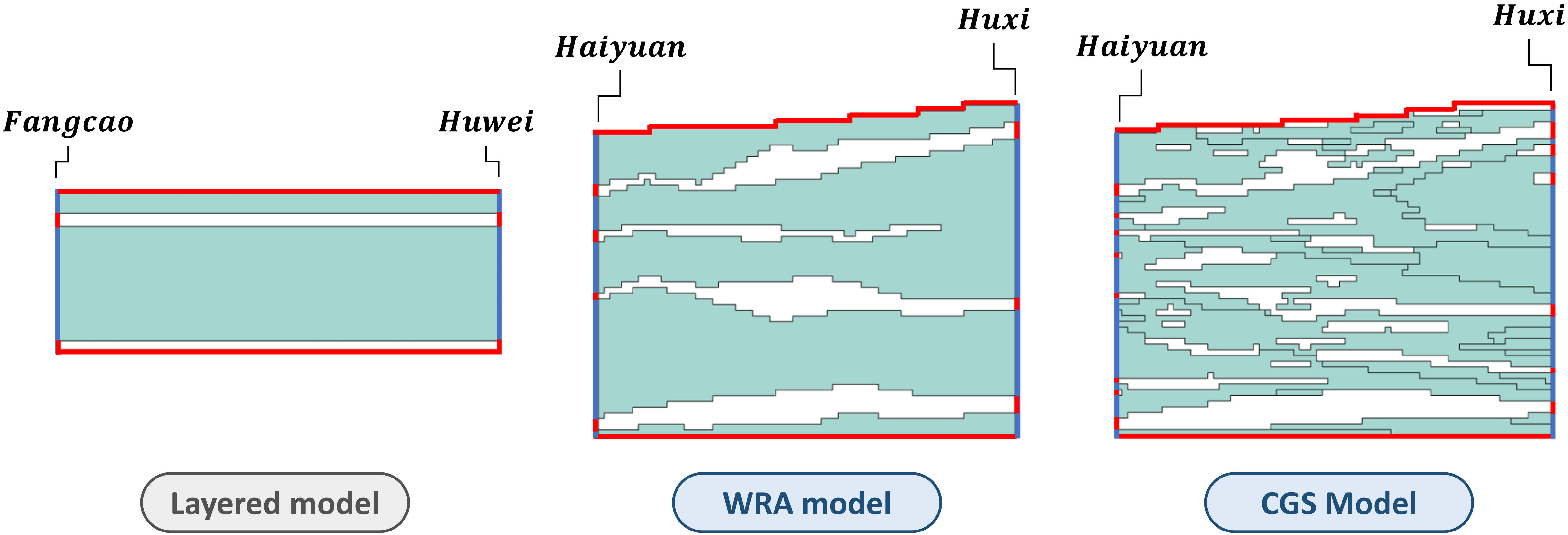
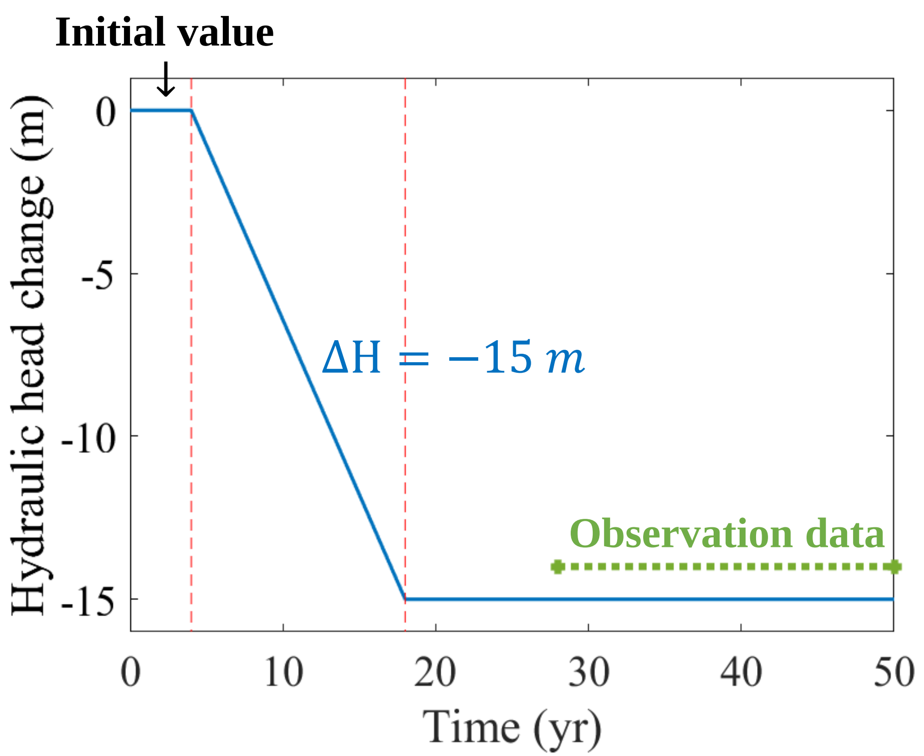
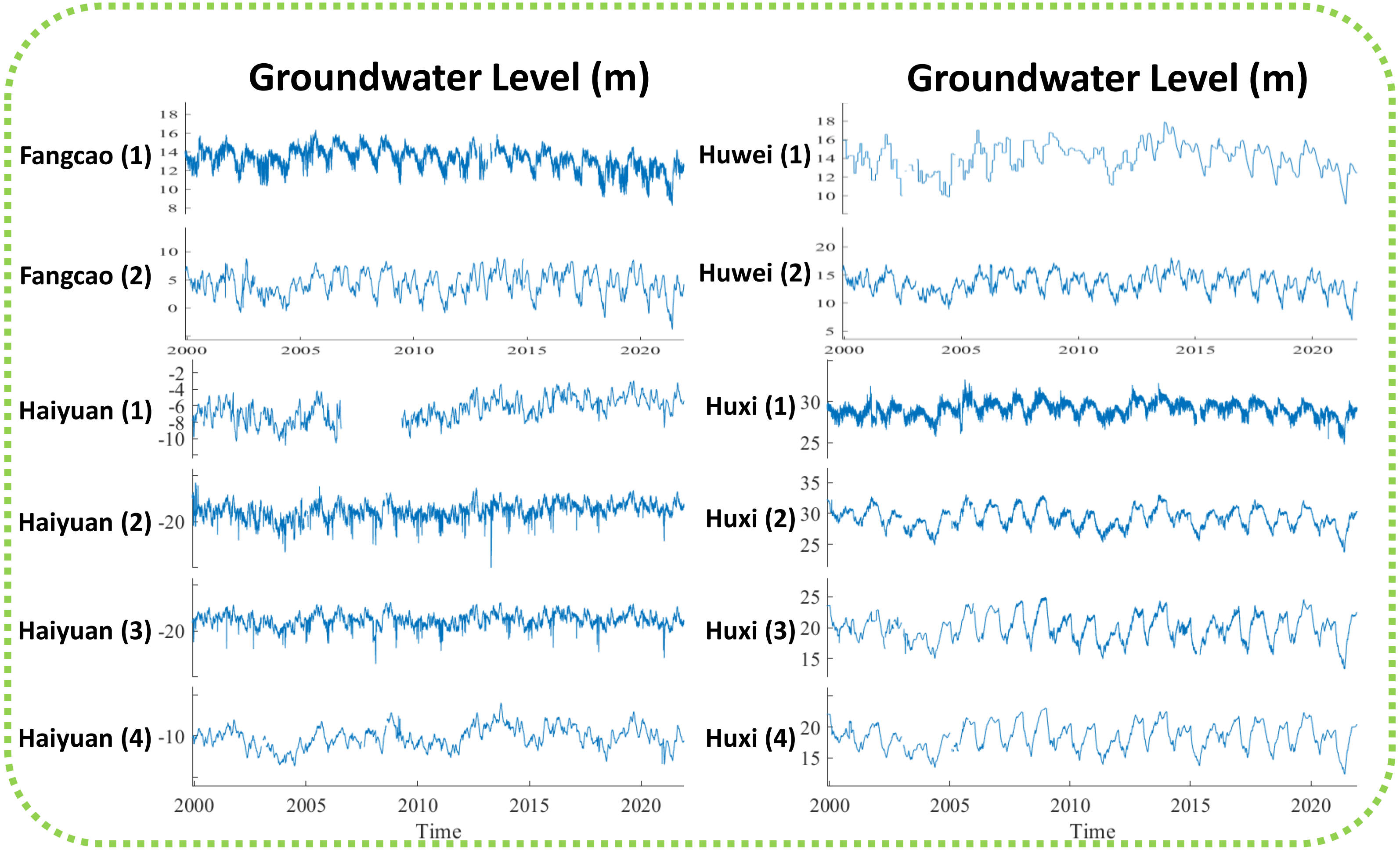


Fig. The **observation well stations** corresponding to the hydraulic head of boundaries.

Model Settings / Initial values for initial condition

- Based on the assumption of hydraulic head change, **the initial value** can be calculated by adding 15 m to the mean value of the observation data.





$$\text{Mean value (obs. data)} + 15\text{ m} = \textbf{Initial value}$$

Model Settings / Initial condition – hydrostatic state

- Use pre-run to solve the steady state, called the hydrostatic state. The solutions are stored and then used as initial conditions for transient simulation runs (Holzbecher, 2017).

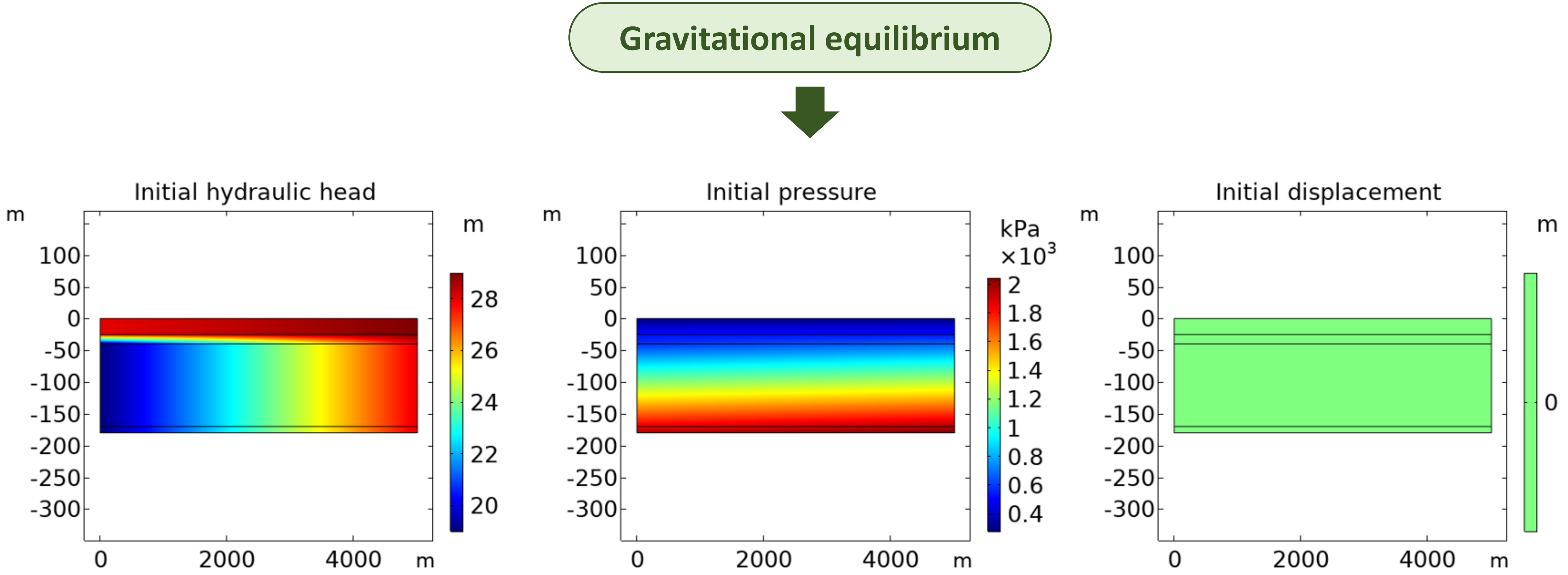


Fig. The **initial conditions** of layered model.

Model Settings / Initial condition – hydrostatic state

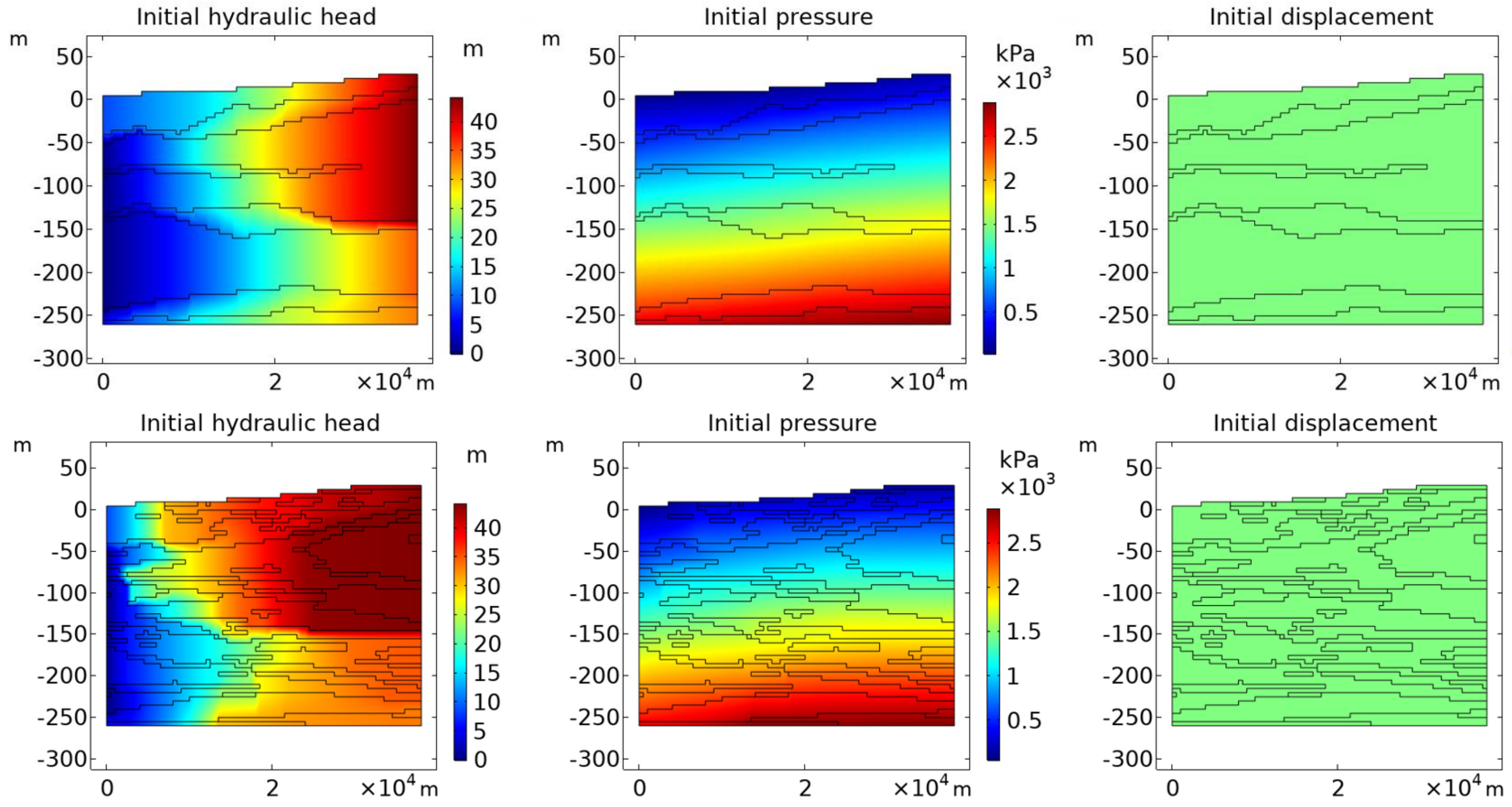
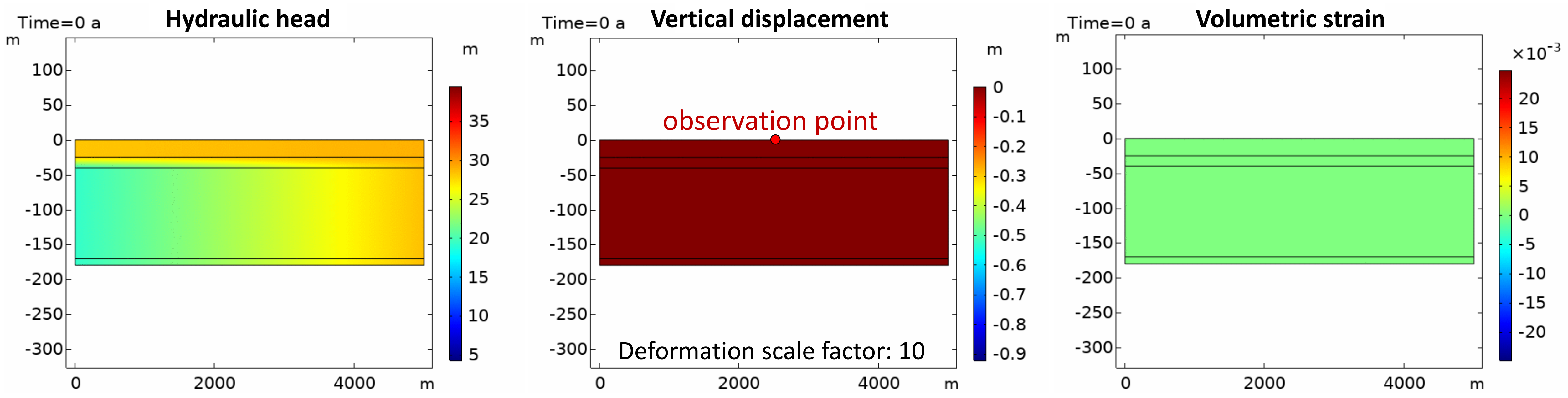


Fig. The **initial conditions** of WRA model and CGS model.

04 Results & Discussion

Parameter sensitivity analysis / Model complexity / Nonlinear parameters

- The **land subsidence** (vertical displacement) is uniform at surface, and continues to subside after the hydraulic head stops decreasing.
- The **deformation** (volumetric strain) of the **aquitard** is much larger than that of the **aquifer**.



Ani. The **hydraulic head change, vertical displacement** and **volumetric strain** in layered model.

Results & Discussion / Layered model – land subsidence

- The accumulated subsidence is mainly caused by **Aquitard 1 (T1)**, **Aquifer 2 (F2)** and **Aquitard 2 (T2).**
- The timely subsidence is caused by **T1** and **F2**, while the delayed subsidence is caused by **T2**.

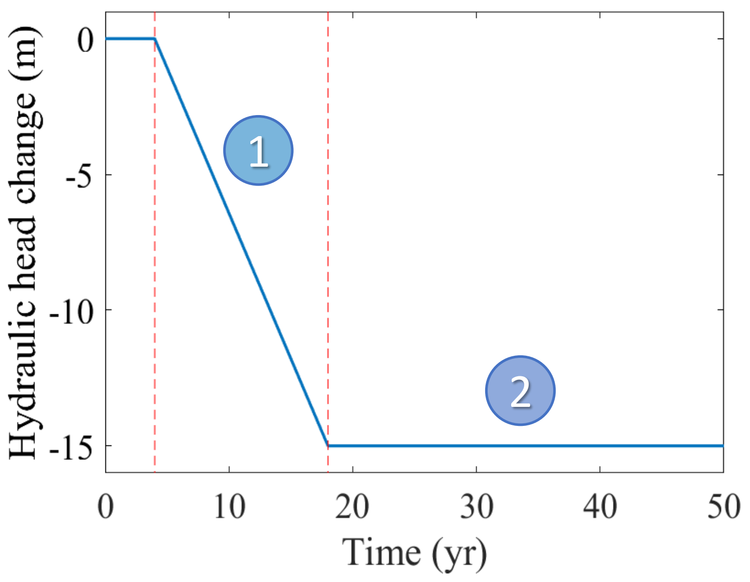
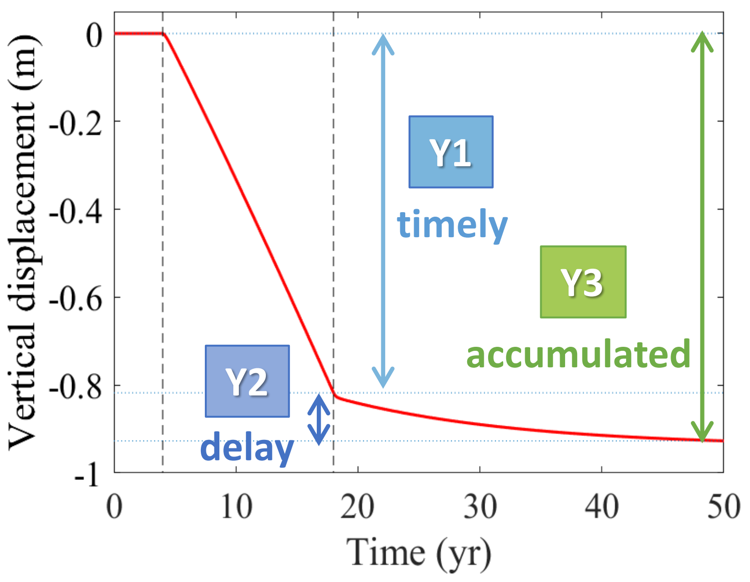


Fig. The **two stages** of hydraulic head change.



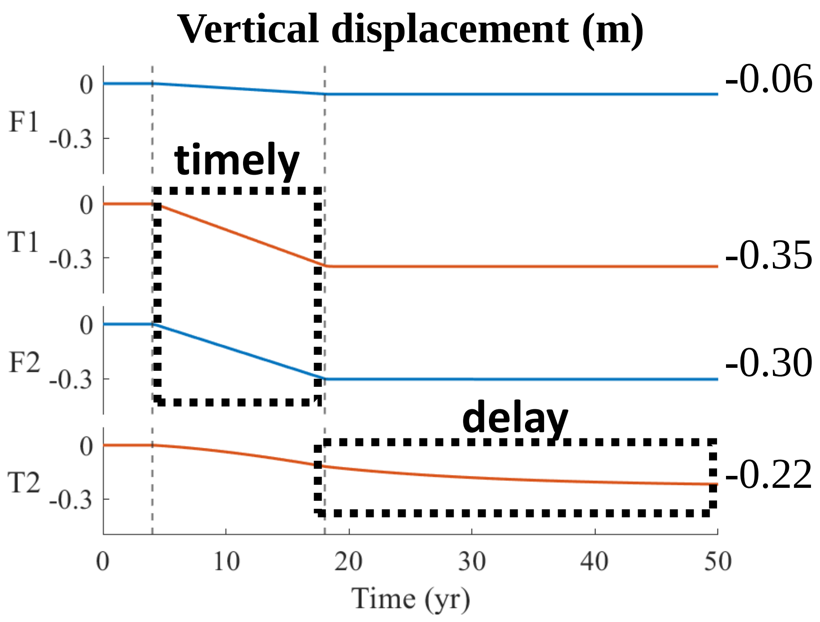


Fig. The **vertical displacement** of observation point in layered model and each layer.

Results & Discussion / Layered model – parameter sensitivity analysis

- The elastic modulus (E and v) of **aquitard** are more sensitive to subsidence than **aquifer**.
- The **aquifer** permeability is sensitive to timely subsidence, and **aquitard** permeability is sensitive to delay subsidence.

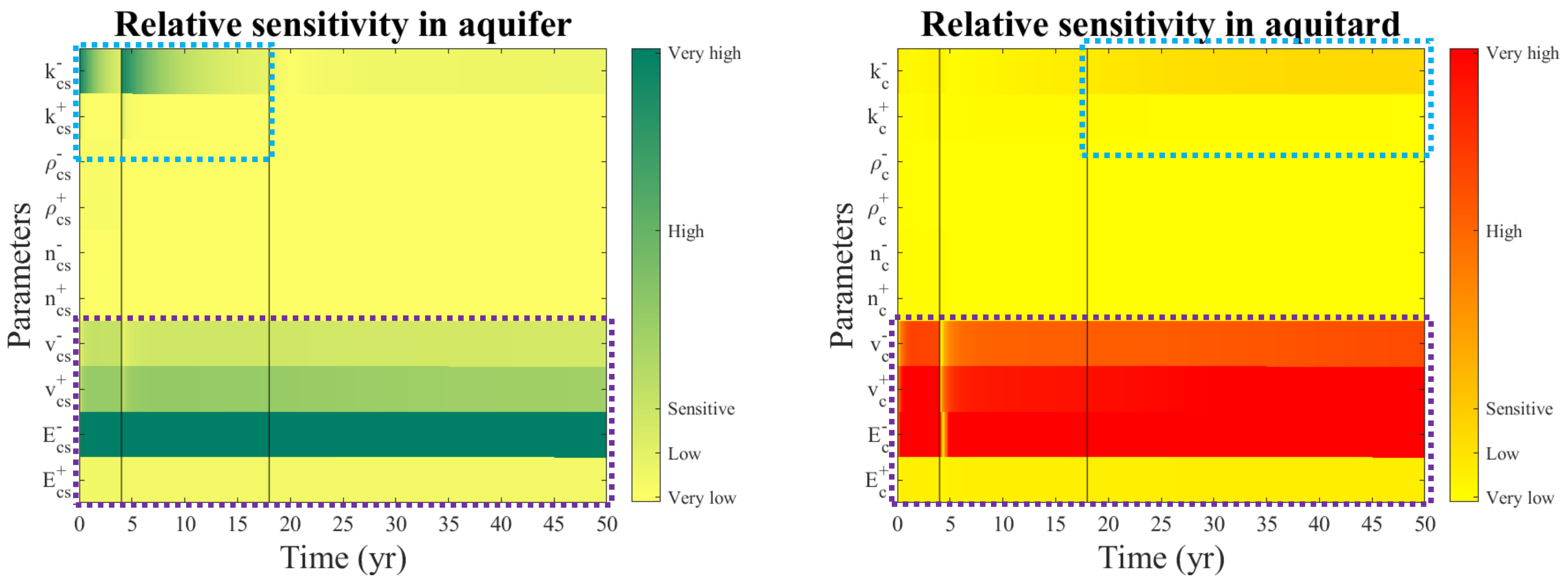
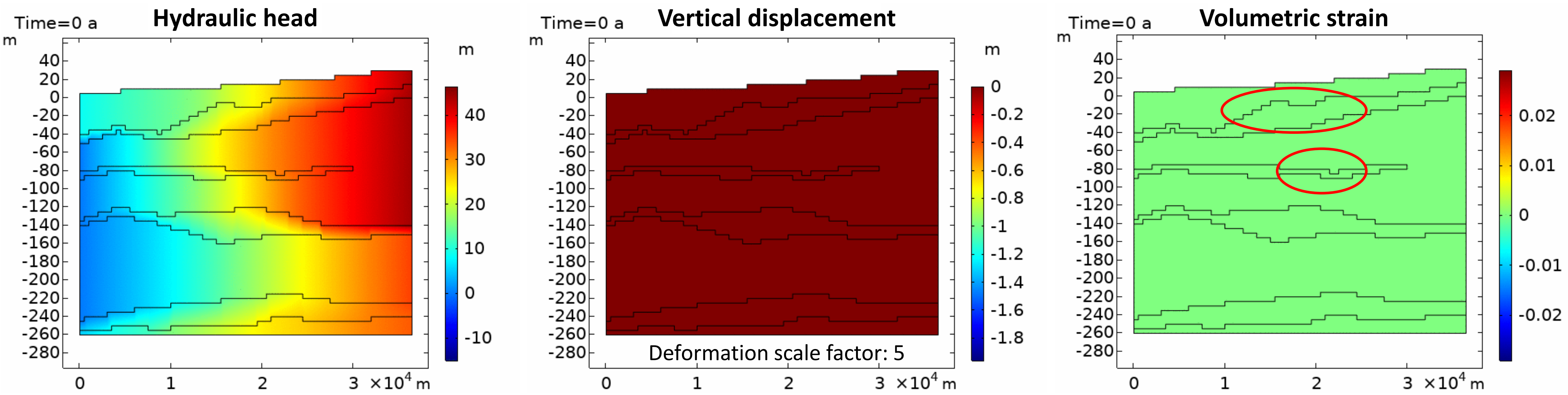


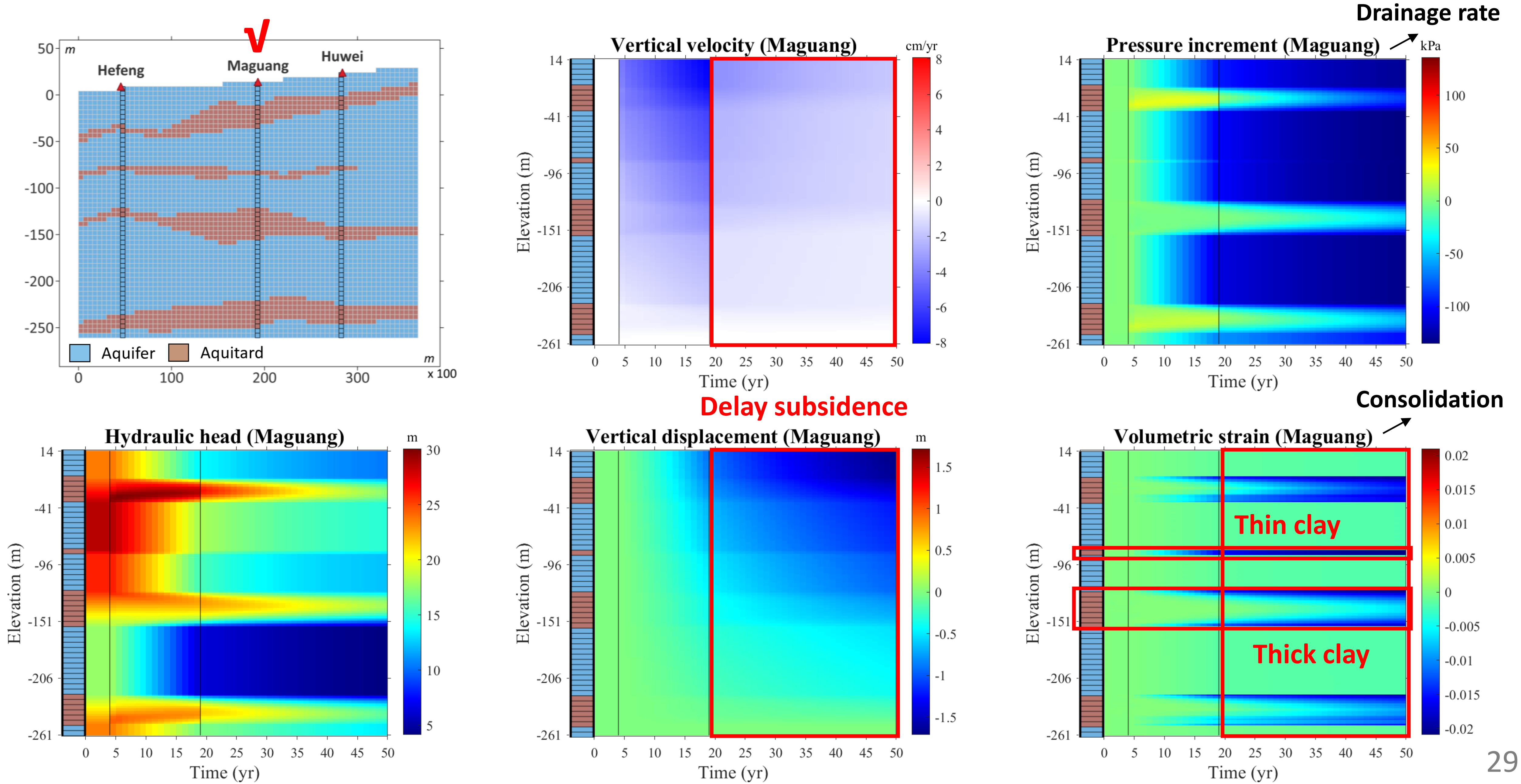
Fig. The **temporal changes** of **relative sensitivity** to subsidence for each parameter in aquifer and aquitard.

- The land subsidence is mainly caused by the compressive strain of **aquitard (clay)**, and its **thickness** affects the drainage rate.
- The timely subsidence occurs in the **entire model**, then the delayed subsidence occurs in the **middle**, where the proportion of thick clay is higher.



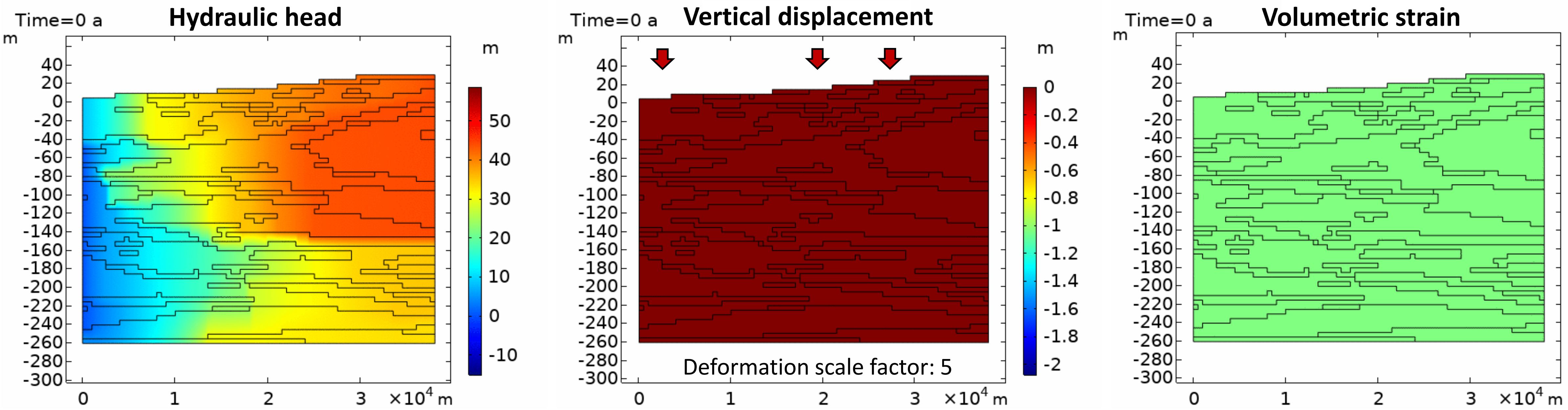
Ani. The **hydraulic head change, vertical displacement** and **volumetric strain** in WRA model.

Results & Discussion / WRA model – Maguang well station



Results & Discussion / CGS model – land subsidence

- In the CGS model, the drainage and consolidation behavior of clay are similar to previous results.
- There are multiple **subsidence centers** in this model, and the subsidence area is more local than the previous model.



Ani. The **hydraulic head change, vertical displacement** and **volumetric strain** in CGS model.

- The porosity and permeability decrease and the Young's modulus increases during the deformation process. Among them, the permeability changes the most.

$$\text{Fractional variation} = \frac{D_1 - D_0}{D_0}$$

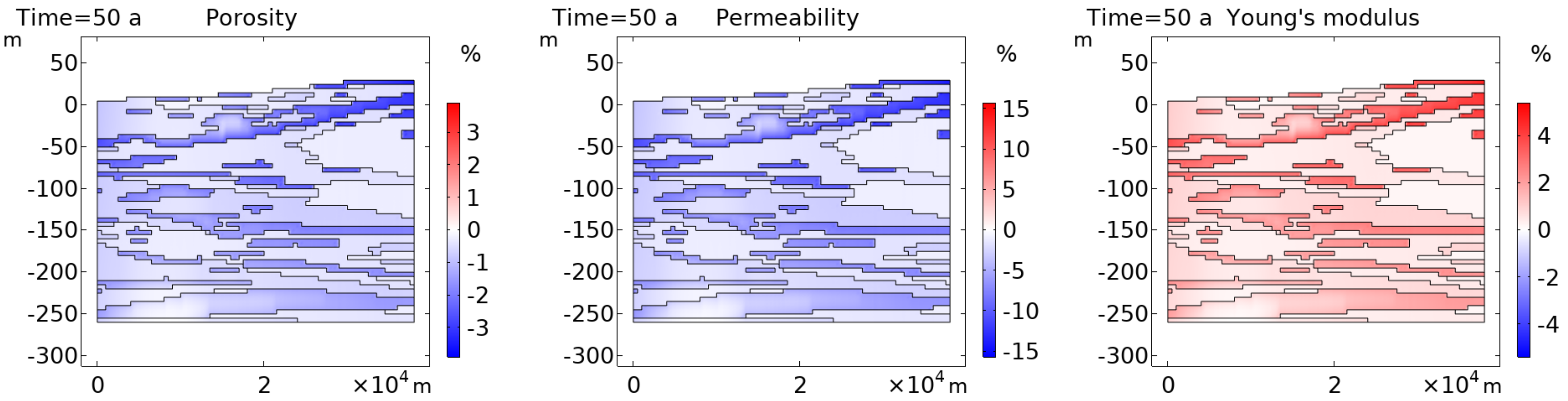


Fig. The **fractional variation (%)** of nonlinear parameters in CGS model.

- The drainage rate and soil compressibility of soil are affected by **nonlinear parameters**, which reduce the subsidence in the entire model.

drainage rate ↑

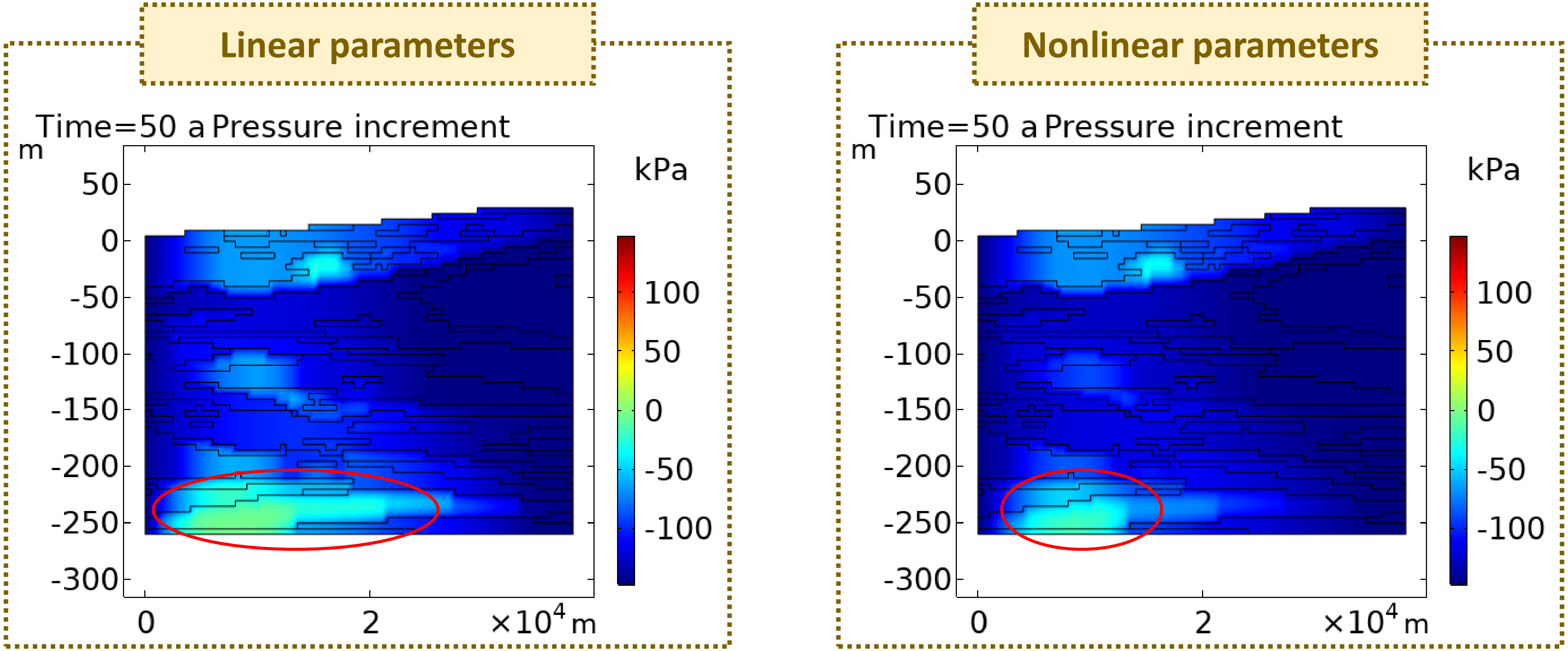


Fig. The comparison in pressure increment of **linear** and **nonlinear parameters** in CGS model.

- The drainage rate and soil compressibility of soil are affected by **nonlinear parameters**, which reduce the subsidence in the entire model.

Soil compressibility↓

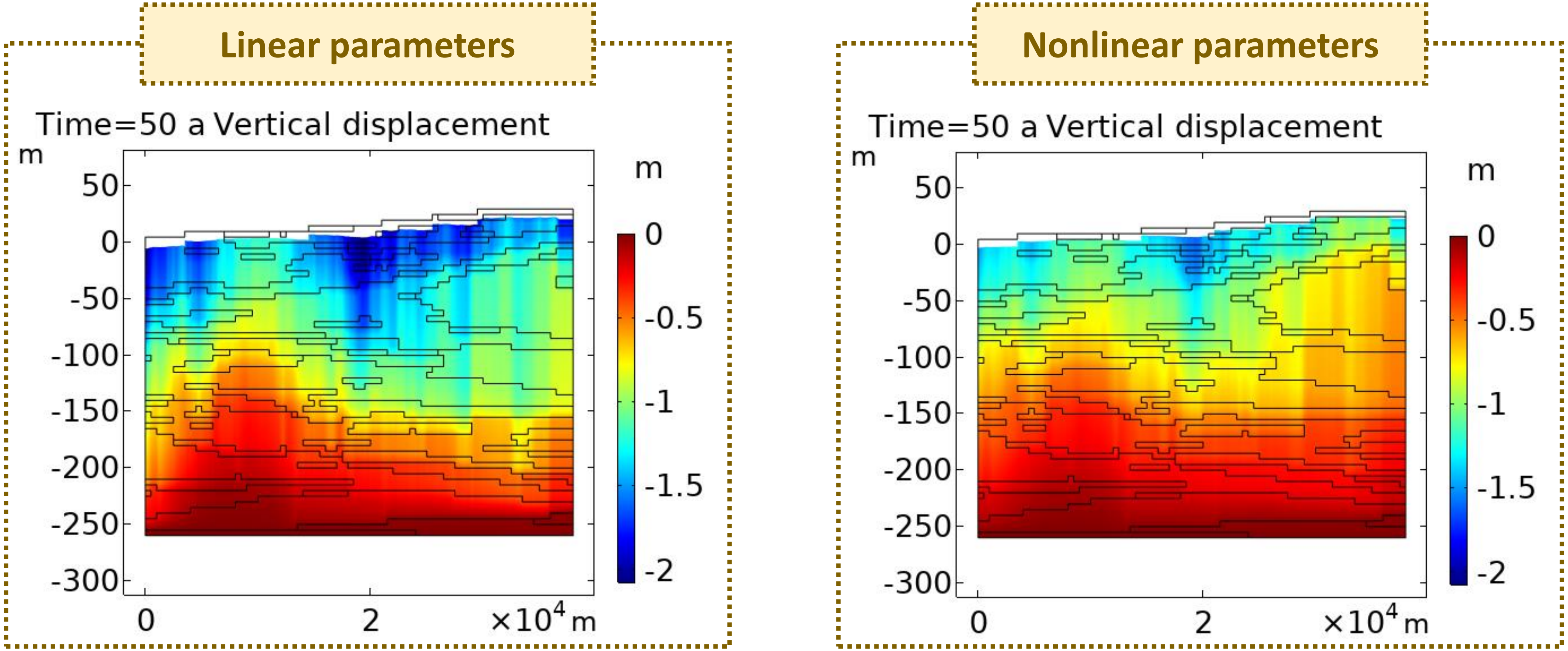


Fig. Fig. The comparison in vertical displacement of **linear** and **nonlinear parameters** in CGS model.

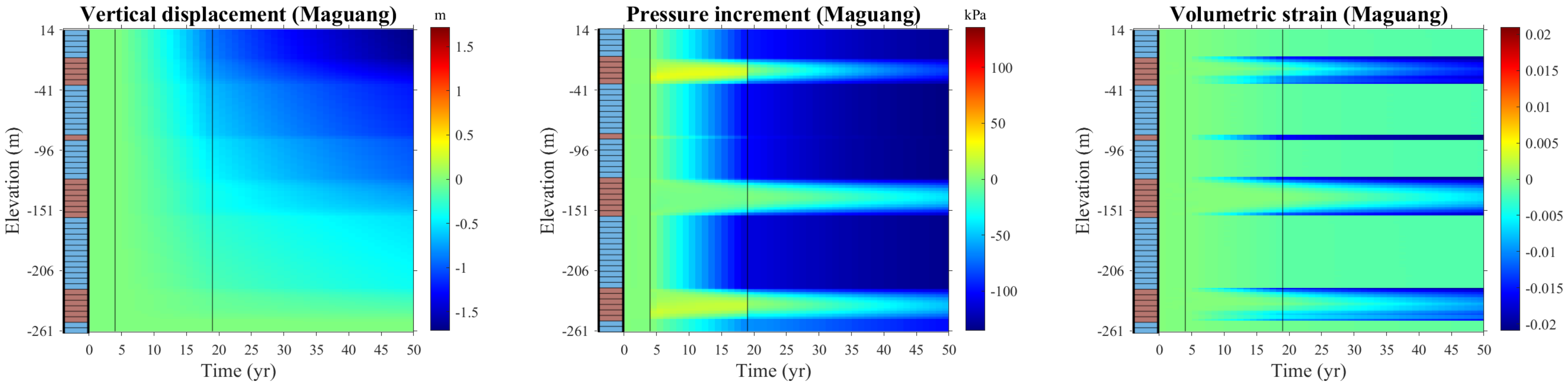
05 Conclusions

Conclusions

- This study simulated **land subsidence** caused by a historical groundwater level event in geological models with different structure:

1

The thickness of clay affects its drainage rate and consolidation.
Moreover, the thick clay dominates **the delay subsidence**.



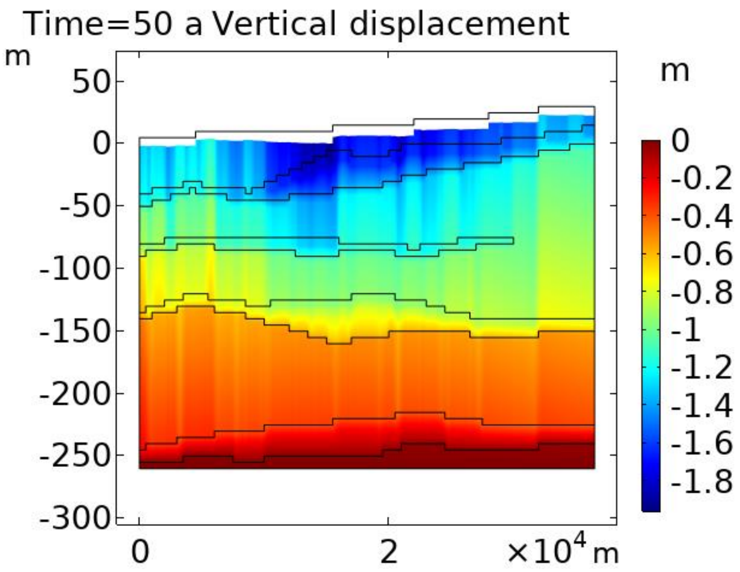
Conclusions

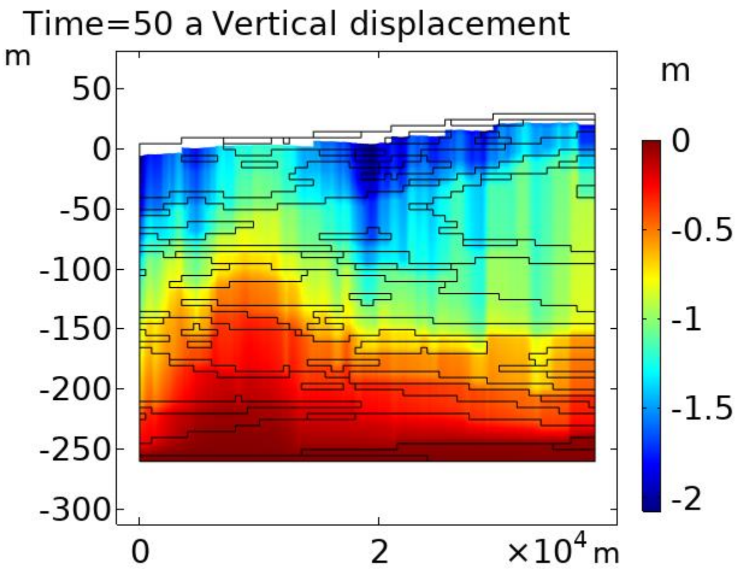
- This study simulated land subsidence caused by a historical groundwater level event in geological models with different structure:

2

The subsidence centers are simulated in the CGS model with higher complexity, reflecting the influence of **geological structure**.

WRA model →





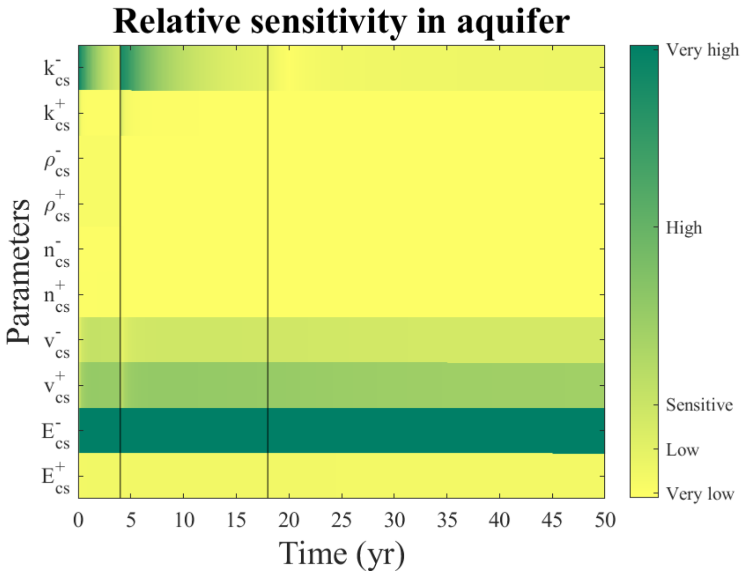
← CGS model

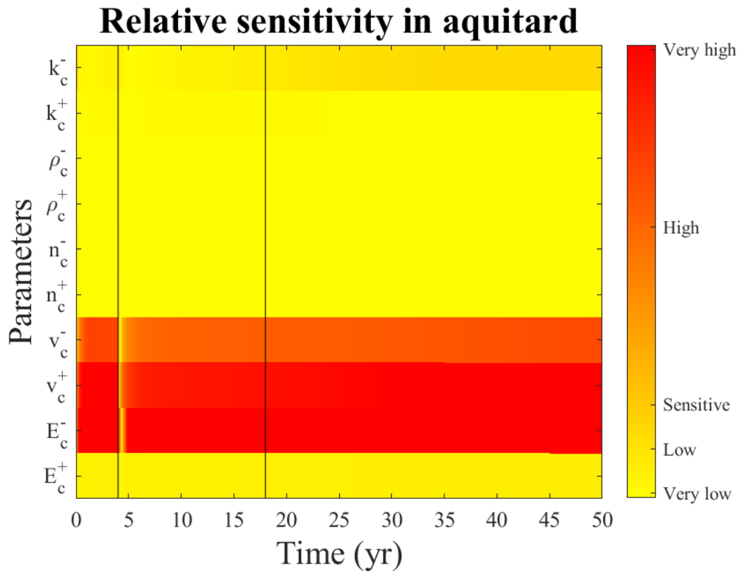
Conclusions

- This study simulated land subsidence caused by a historical groundwater level event in geological models with different structure:

3

The **subsidence** is mainly affected by permeability and elastic modulus, indicating the importance of **geological material properties** for land subsidence.



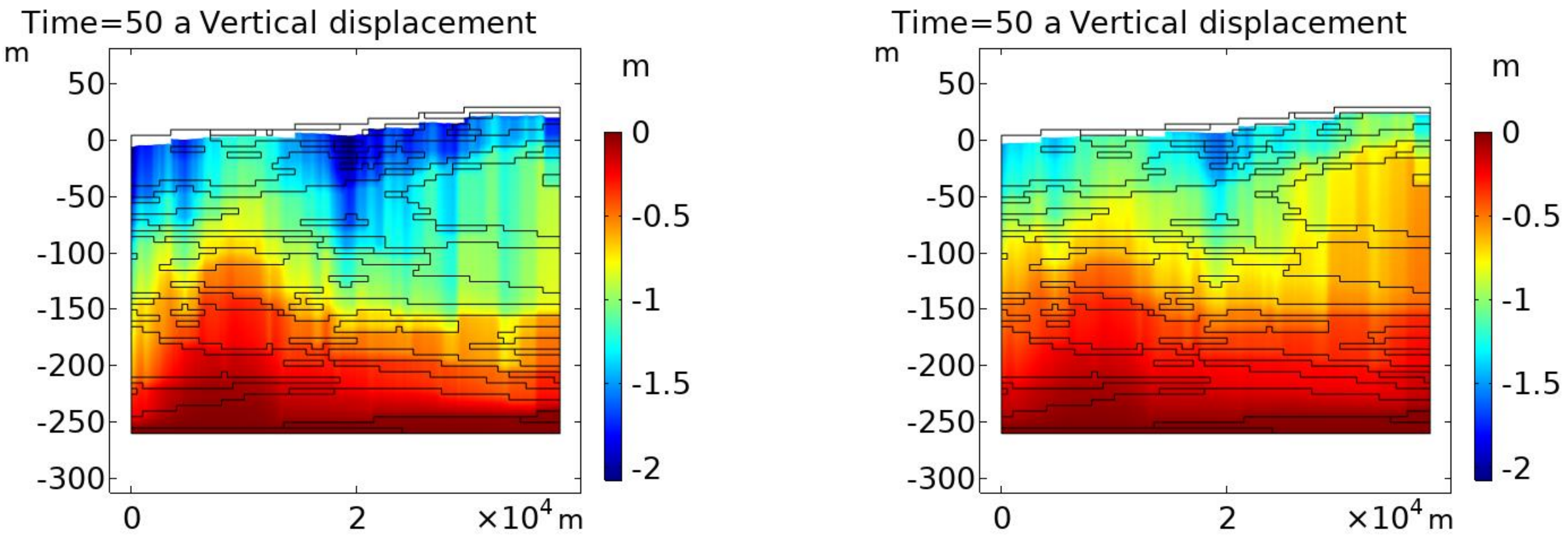


Conclusions

- This study simulated land subsidence caused by a historical groundwater level event in geological models with different structure:

4 It is necessary to consider the influence of **nonlinear parameters**, which leads to the reduction of **land subsidence**.

Linear →



← Nonlinear

THANK YOU

FOR YOUR ATTENTION