ALGA
AUSTRALASIAN LAND + GROUNDWATER ASSOCIATION

Building leaders in the sustainable management of **contaminated land and groundwater**

Adelaide Branch Event – 30 July 2024

The highs and lows of sinusoidal hydraulic testing

Developing an alternative method for characterising aquifer hydraulic properties

Chris Turnadge[1], Eddie Banks[2], Margaret Shanafield[2], Todd Rasmussen[3], Ron Kreymborg[4], Kieran Harford[4]
[1] CSIRO, [2] Flinders University, [3] University of Georgia (USA), [4] Kremford Pty Ltd

30 July 2024 | Australian Land and Groundwater Association Technical Event

This research was funded by CSIRO's Deep Earth Imaging Future Science Platform

Tonight:

"Minimum viable product":

This presentation is at least **interesting** to you

Tonight:

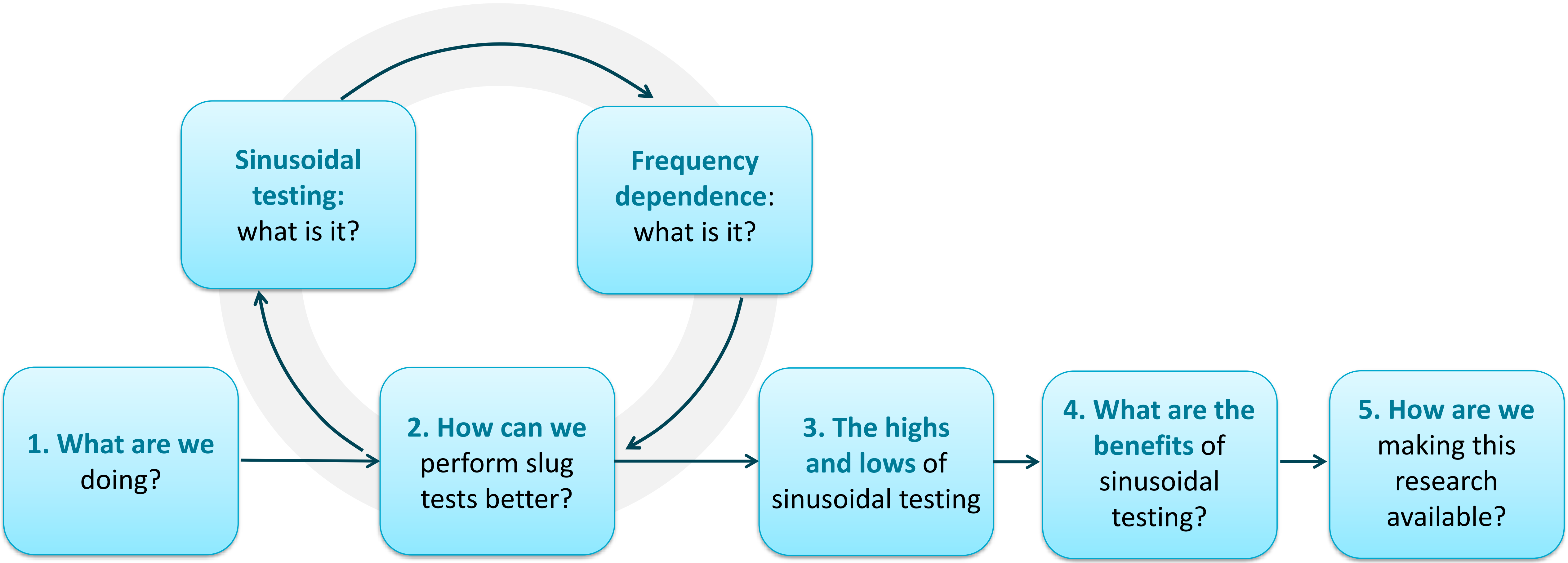
“Minimum viable product”:

This presentation is at least **interesting** to you

Best possible outcome:

This research is of **benefit** to you

Content – A linear, but circular story



1. What are we doing?

In a nutshell...

- **What are we doing?**

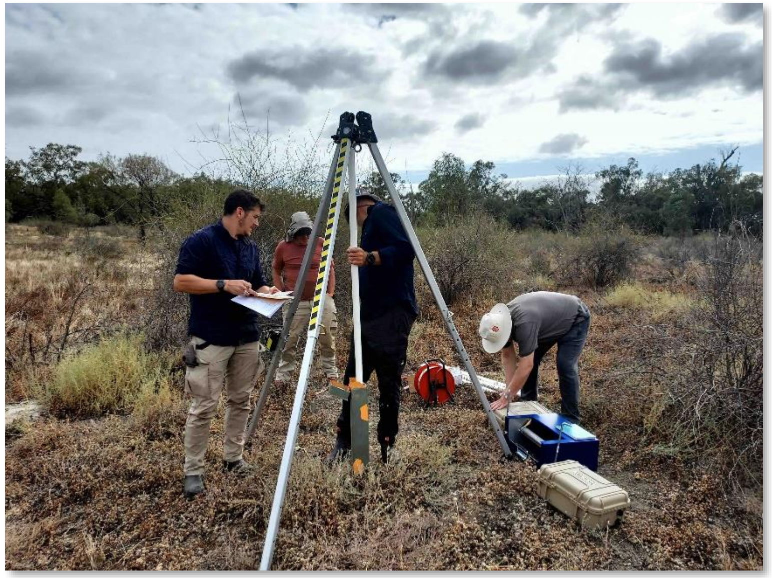
  Developing methods of sinusoidal hydraulic testing

- **Why?**

  To robustly estimate hydraulic properties, particularly in more challenging hydrogeological settings

- **How?**

  Using a transient method of two-well slug testing



2. How can we perform slug tests better?

Pros and cons of traditional slug testing methods

Advantages

- Rapid
- Low cost
- Simple to perform
- Simple to analyse
- Can characterise low permeability units
- Extraction of water not required

(Butler, 2019)

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- Can characterise low permeability units
- Extraction of water not required

(Butler, 2019)

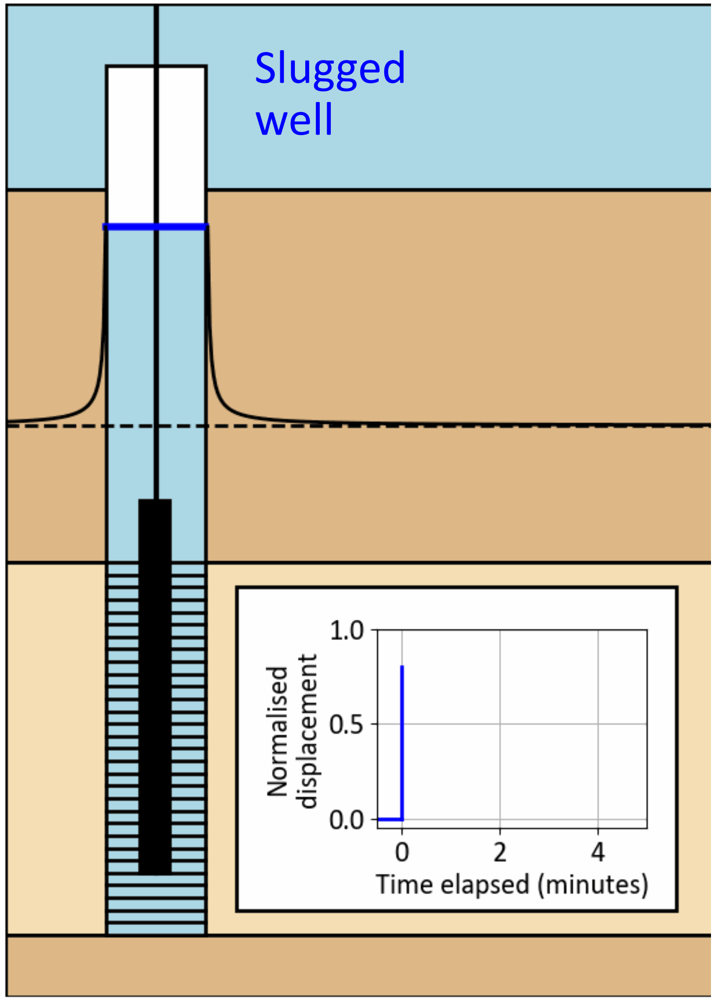
Disadvantages

- Can require **long times** to re-equilibrate
- Can be affected by **borehole storage**
- Can be affected by **skin effects**
- Can't measure response at a **second well**
- Can't estimate **storage** reliably
- Can be affected by systematic measurement **errors**
- Unsuitable for **large diameter** wells or **high permeability** units

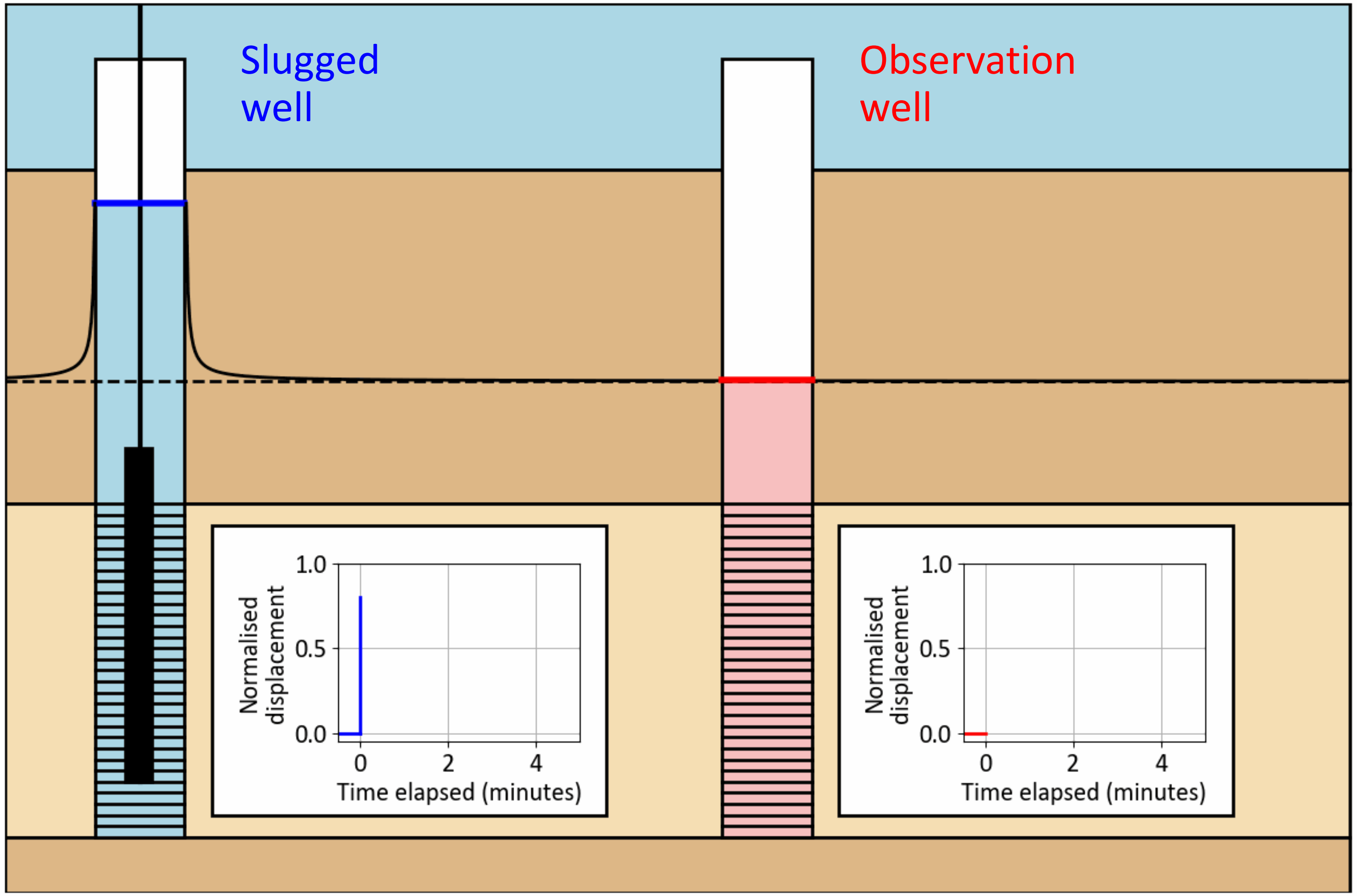
(Butler, 2019; Chapuis, 2015)

Sidebar 1:
What is sinusoidal slug testing?

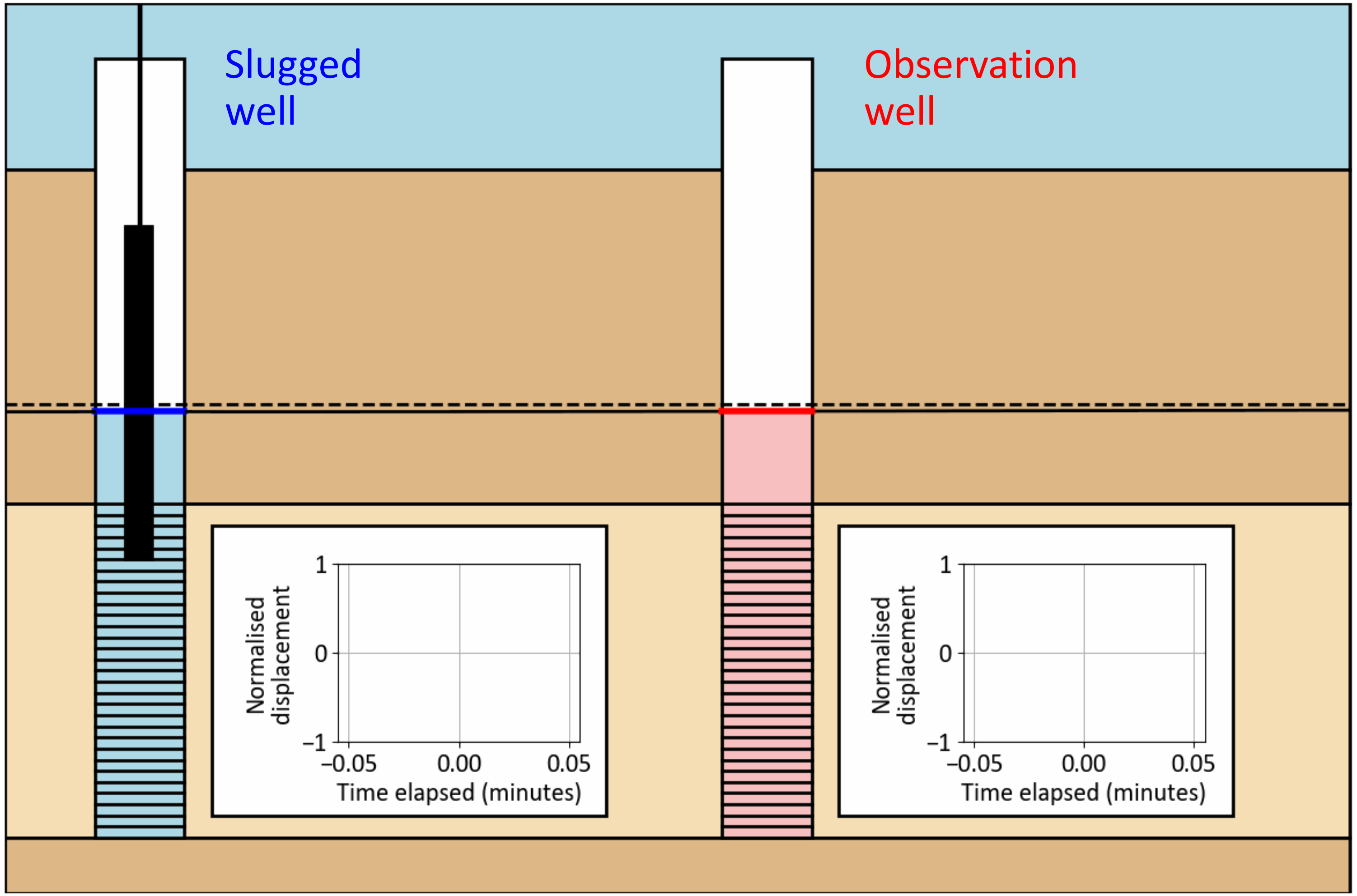
Familiar territory: Traditional **falling head slug** tests (single well)

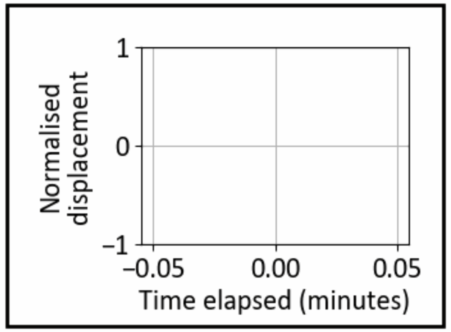


Familiar territory: Traditional **falling head slug** tests (two wells)



Unfamiliar territory: **Sinusoidal slug** tests





Sidebar 2:
What is frequency dependence?

Analogies – Body composition testing

Traditional method

Skin fold testing

(https://www.essendonsportsmedicine.com.au/services/skinfold-assessment)

Analogies – Body composition testing

Traditional method

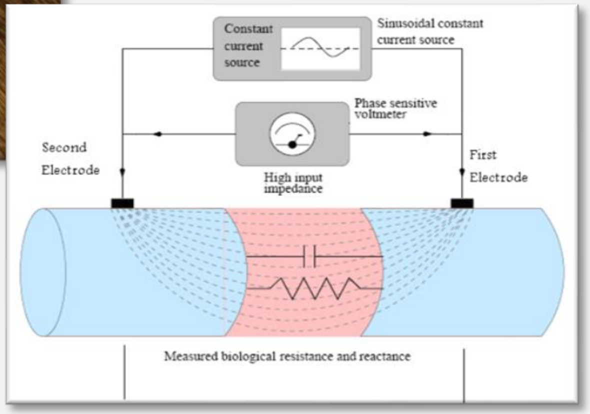
Skin fold testing

(https://www.essendonsportsmedicine.com.au/services/skinfold-assessment)

Modern method

Bioelectrical impedance analysis

(https://ultrarunning.com/featured/garmin-index-s2-smart-scale-review/)



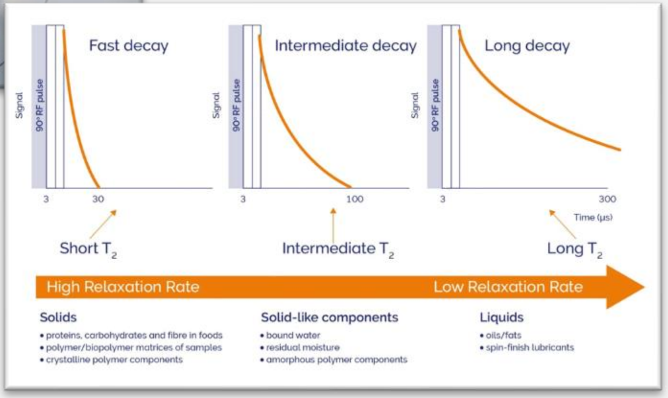
(https://www.researchgate.net/figure/Two-electrode-system_fig3_235337266)

Analogies – Medical imaging

Traditional method

Magnetic resonance imaging

(https://hospitalresearch.org.au/news/latest-news/sa-first-imaging-technology-to-improve-parkinsons-diagnosis-2/)



(https://nmr.oxinst.com/application-detail/what-is-td-nmr)

Analogies – Medical imaging

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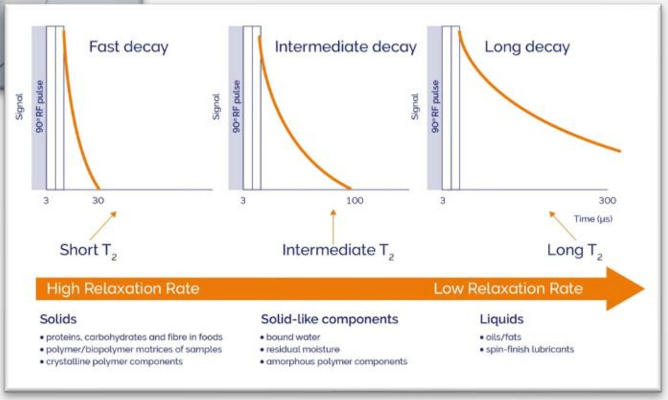
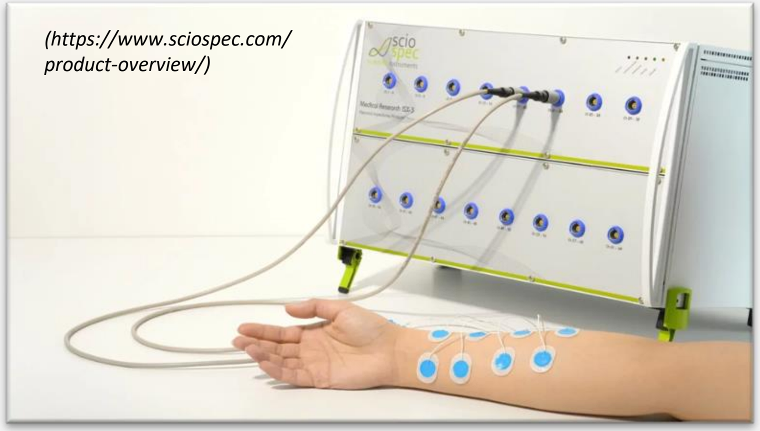


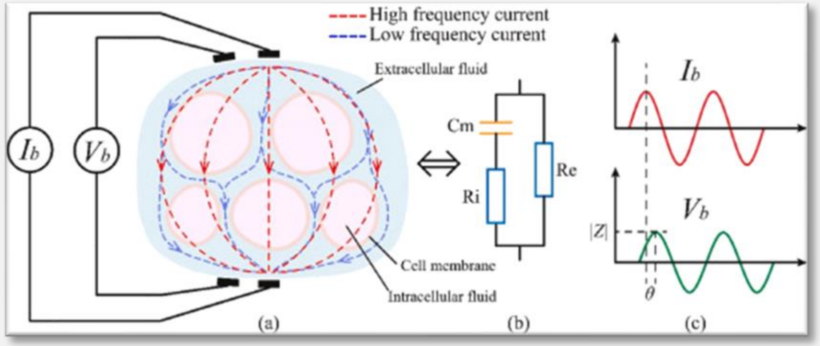
(https://nmr.oxinst.com/application-detail/what-is-td-nmr)

Modern method

Electrochemical impedance tomography

(https://www.sciospec.com/product-overview/)



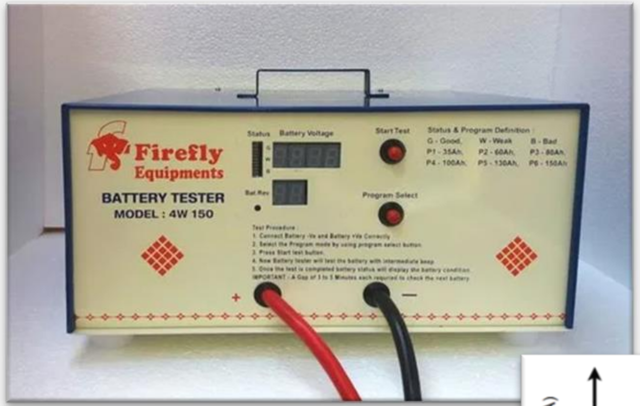


(https://doi.org/10.1016/j.heliyon.2023.e15195)

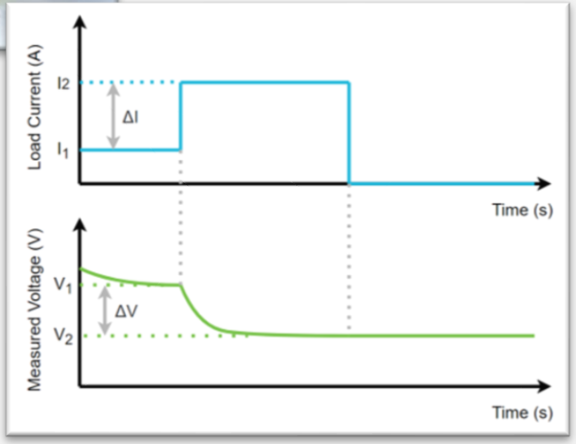
Analogies – Battery testing

Traditional method

Direct current internal resistance



(https://www.indiamart.com/proddetail/car-battery-load-tester-25472020091.html)



(https://www.tek.com/en/blog/testing-battery-resistance)

Analogies – Battery testing

Traditional method

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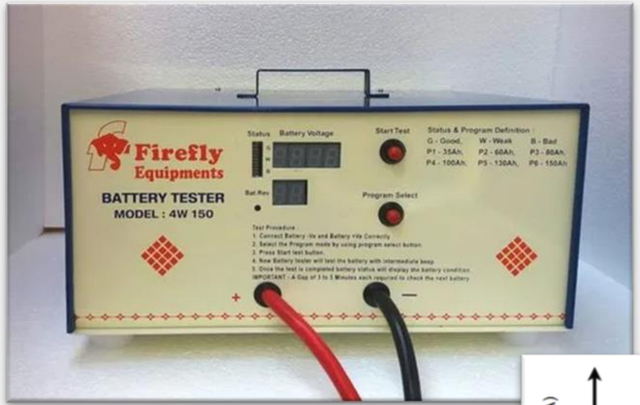

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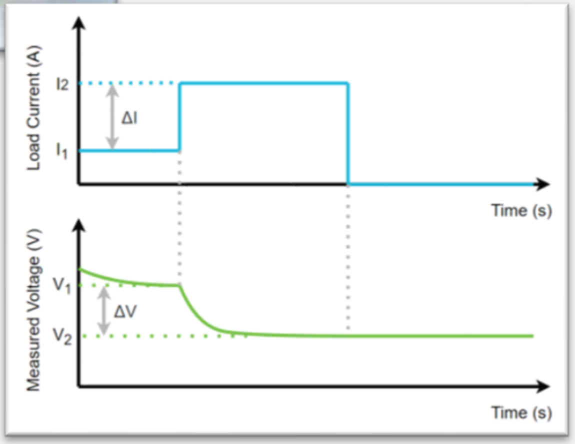
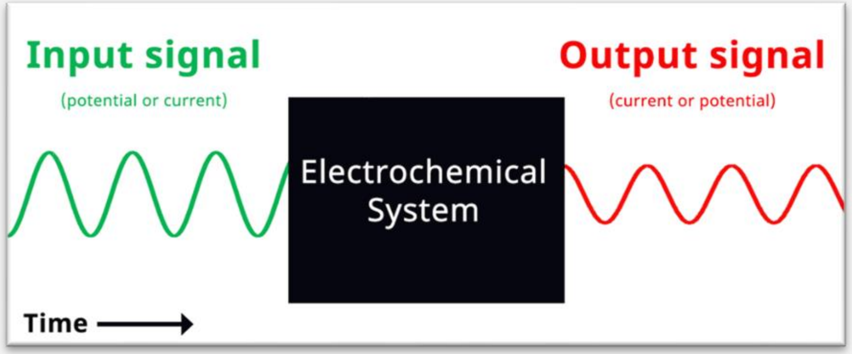


(https://www.tek.com/en/blog/testing-battery-resistance)

Modern method

Electrical impedance spectroscopy

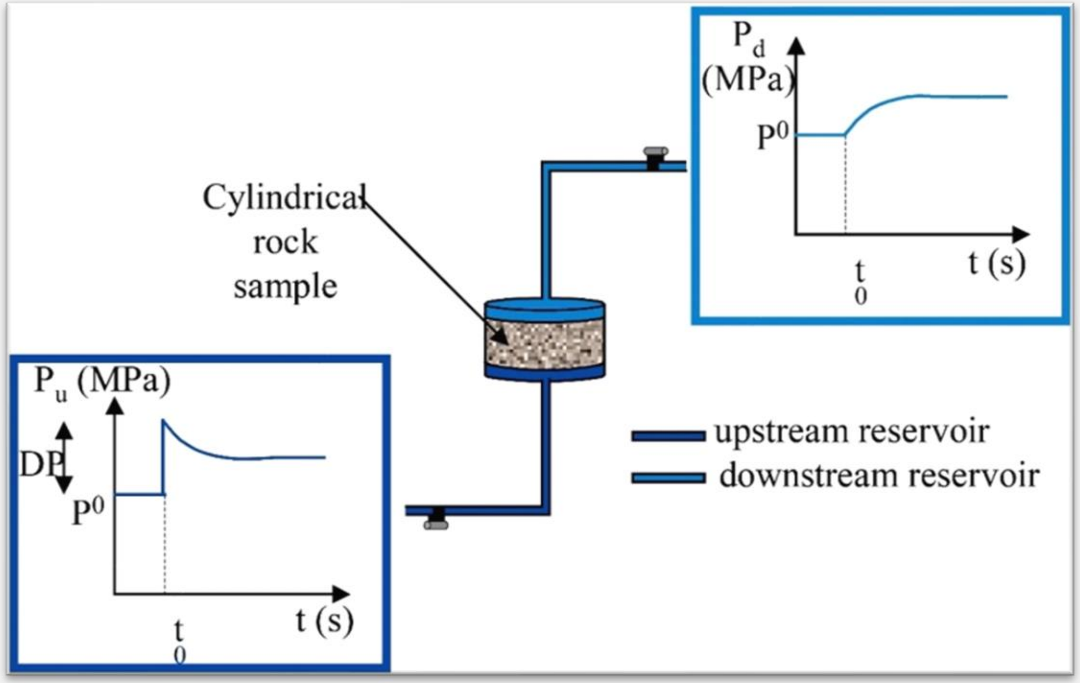


(https://pineresearch.com/shop/kb/theory/eis-theory/eis-basics/)

Analogies – Core permeametry

Traditional method

Transient pulse decay testing



(https://doi.org/10.1016/j.enggeo.2018.10.019)

Analogies – Core permeametry

Traditional method

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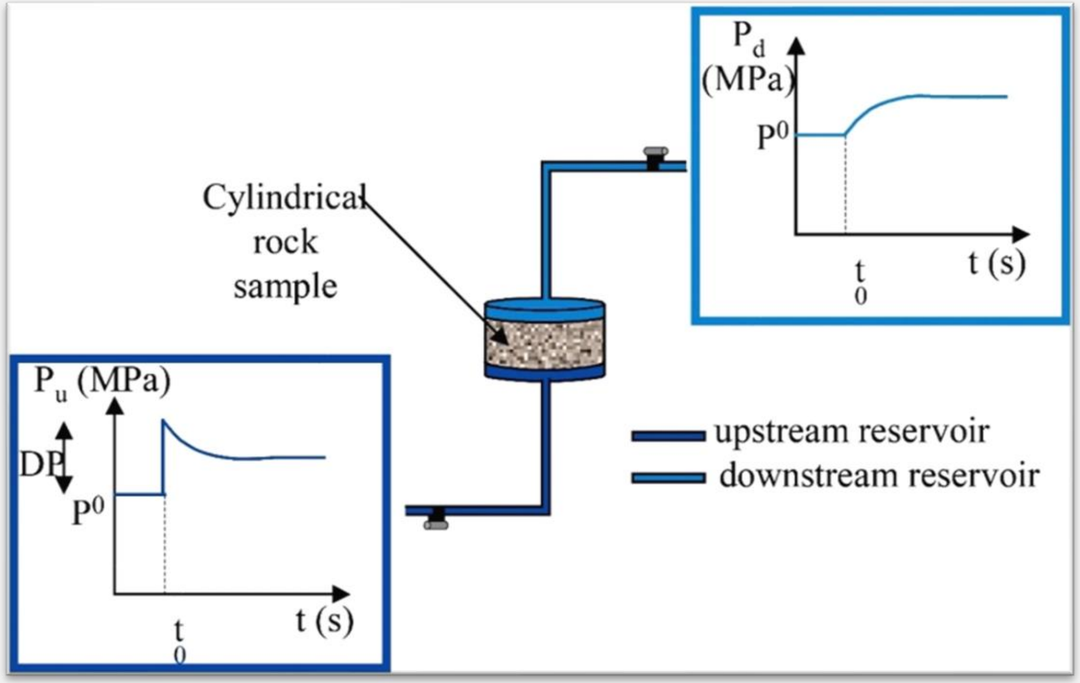
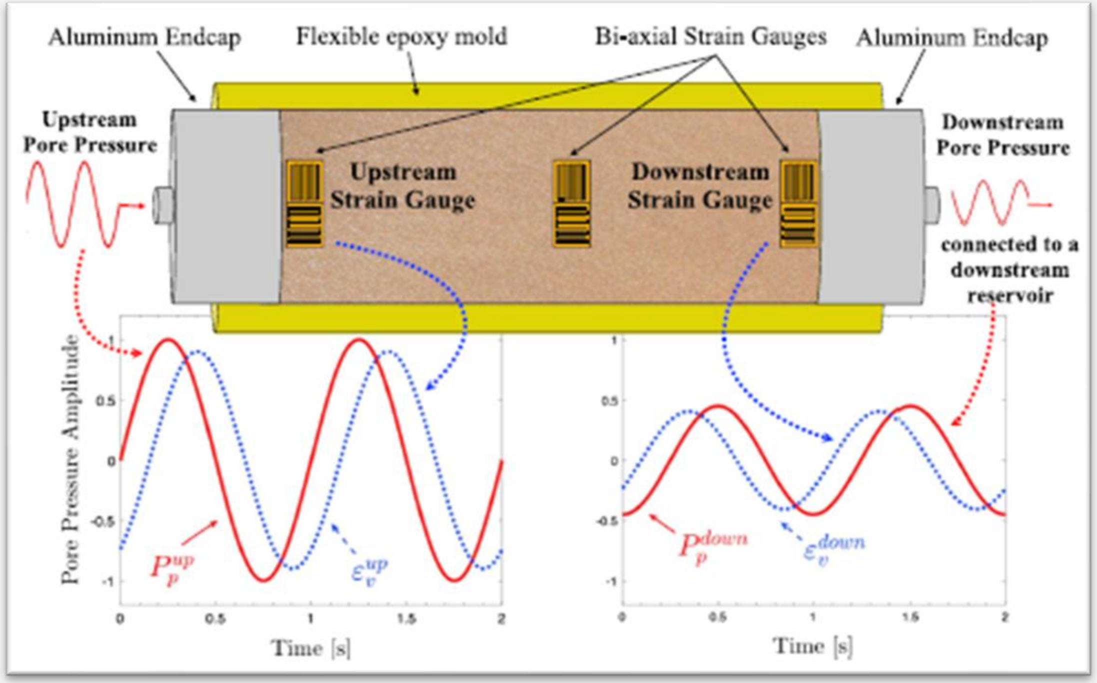


(https://doi.org/10.1016/j.enggeo.2018.10.019)

Modern method

Sinusoidal pressure or flow testing

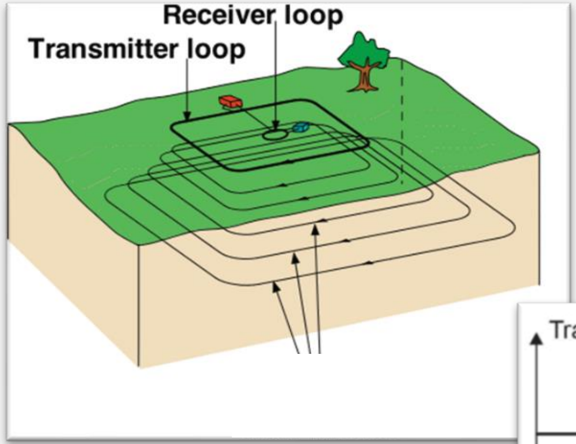


(Hasanov et al., 2019)

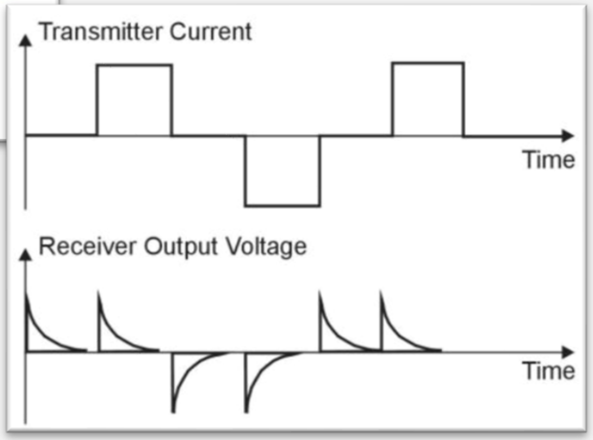
Analogies – Geophysical surveys

Traditional method

Time domain electromagnetic survey



(http://zonge.com/wp-content/uploads/2011/10/tdemIllustrationZongeInternational.gif)

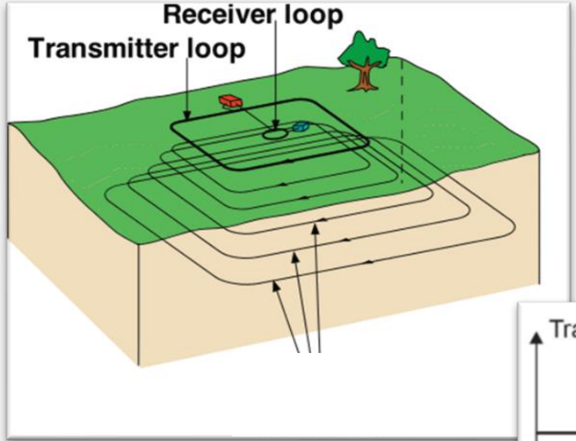


(https://archive.epa.gov/esd/archive-geophysics/web/html/time-domain_electromagnetic_methods.html)

Analogies – Geophysical surveys

Traditional method

Time domain electromagnetic survey



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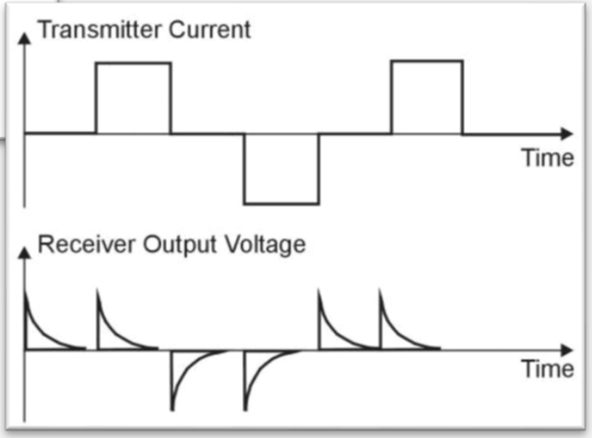
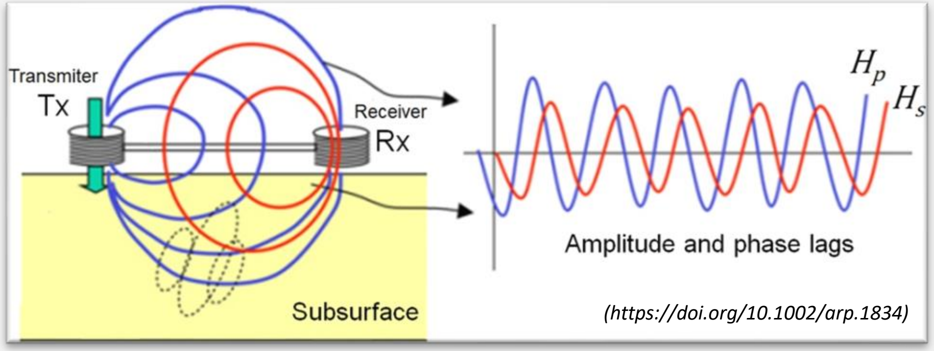


(https://archive.epa.gov/esd/archive-geophysics/web/html/time-domain_electromagnetic_methods.html)

Modern method

Frequency domain electromagnetic survey

(https://www.loupegeophysics.com.au/)

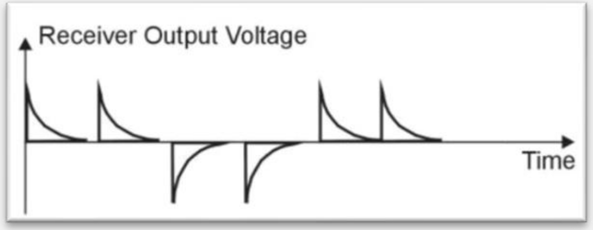


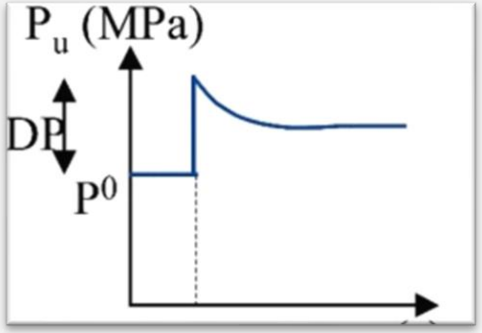
(https://doi.org/10.1002/arp.1834)

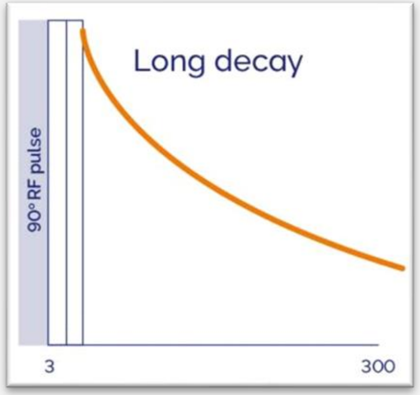
Summary of testing method analogies

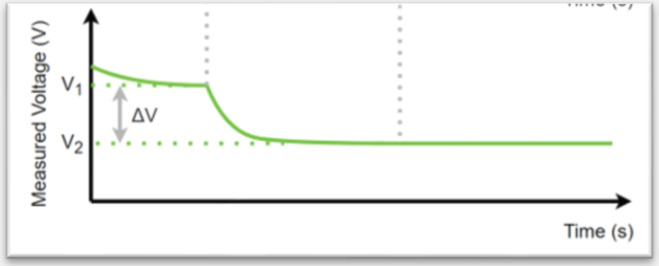
Traditional methods

Often measure responses to **impulse** disturbances





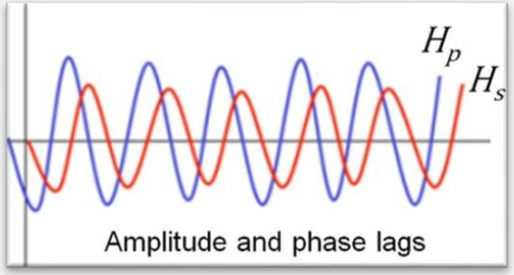


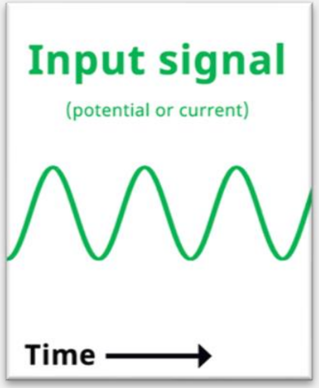


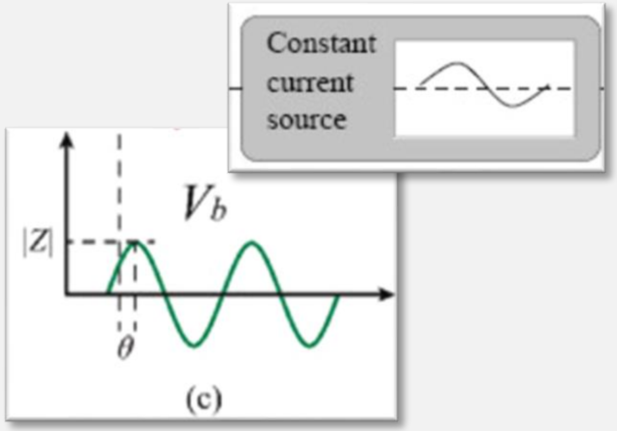
Modern methods

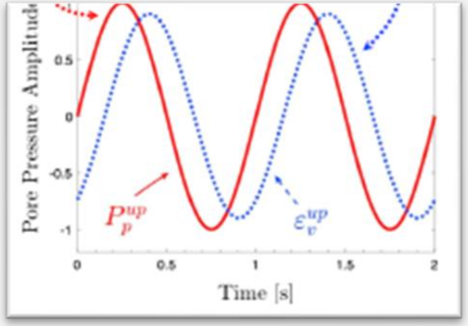
Include measuring responses to **frequency-dependent** disturbances

➢ These can persist **further** and be easier to measure **within noise**



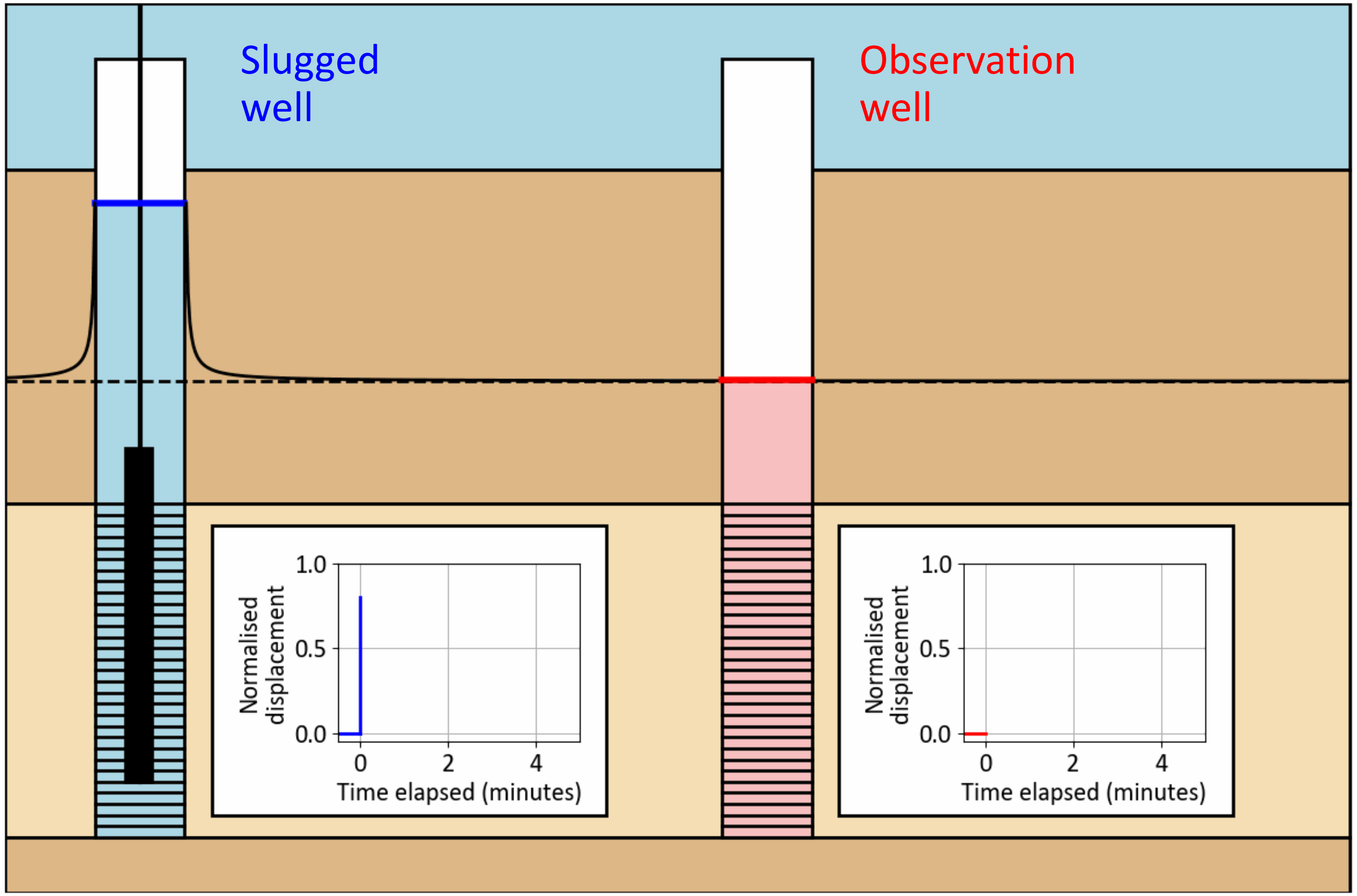




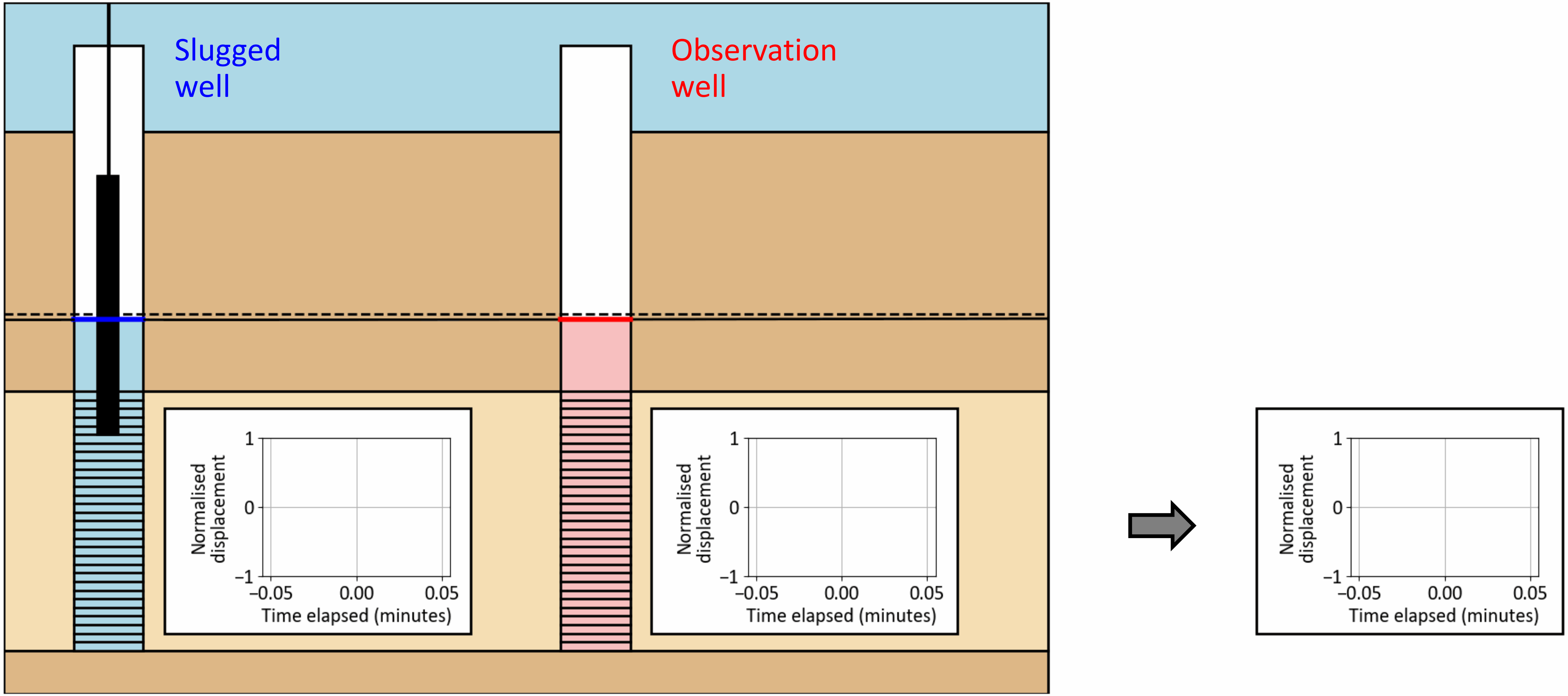


2. How can we perform slug tests better? (revisited)

Recap: Traditional **falling head slug** tests (two wells)



Recap: **Sinusoidal slug** tests



Field methods

Extendable 6-metre-long PVC slug (40 mm OD)

Field methods

Customised electronic winch

Extendable 6-metre-long PVC slug (40 mm OD)

Field methods

Customised electronic winch

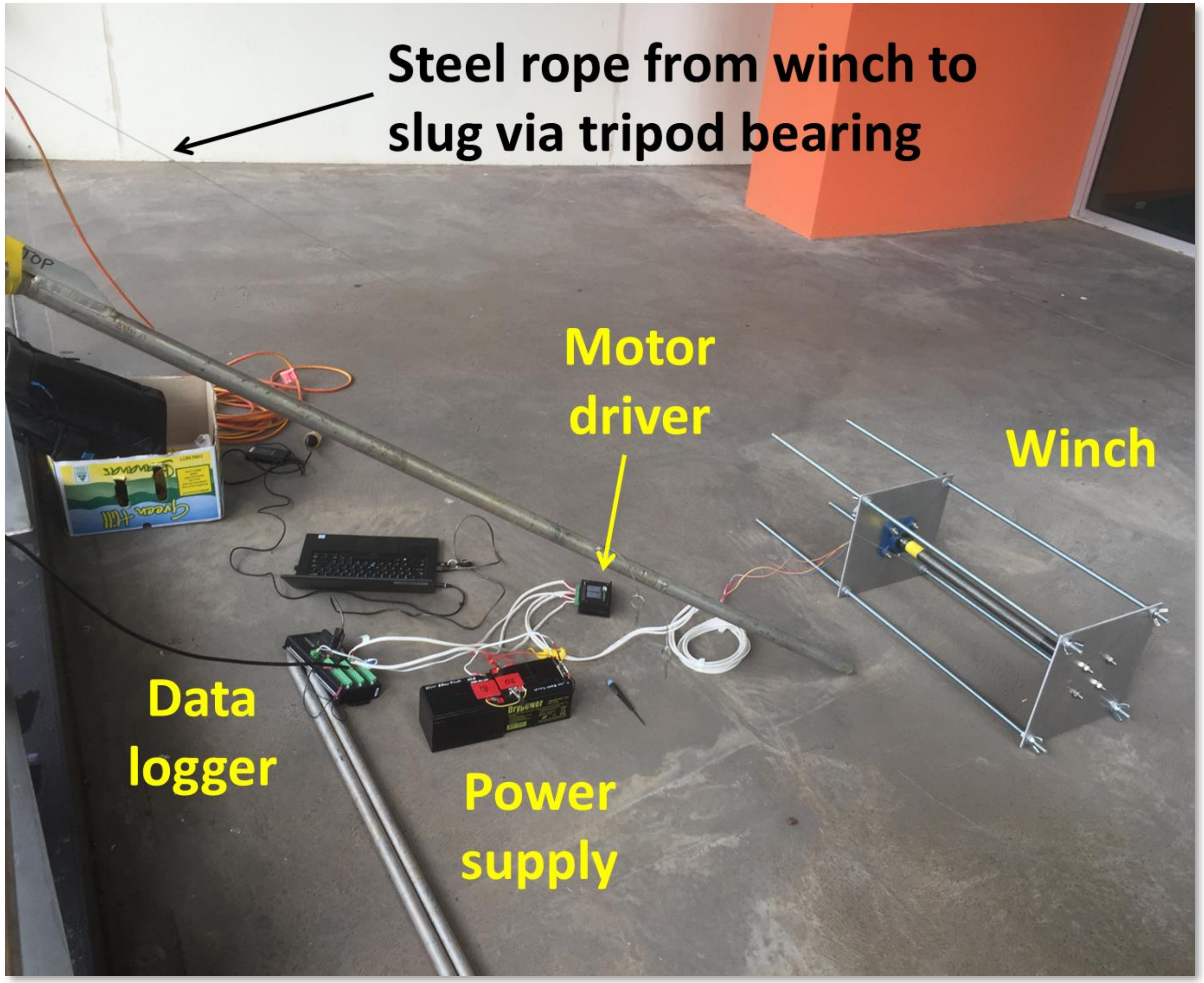
Extendable 6-metre-long PVC slug (40 mm OD)

Real-time wireless measurements

Field methods: Prototype #1 – circa 2020

- Followed precedent set by **Guiltinan and Becker (2015)**
- Self-designed and assembled
- Cheap, off-the-shelf **DC stepper motor** and driver
- Repurposed a **data logger** for automated motor control

➢ **Research quality:** Lots of gaffer tape and zip ties!

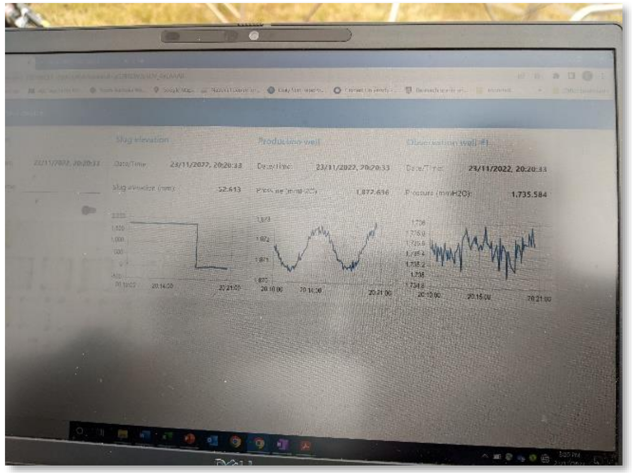


Field methods: Prototype #2 – circa 2022

- **Winch** fabricated by Adelaide firm Simax Engineering
- **Motor control system** designed and manufactured by Melbourne engineering firm **Kremford**
- **Real-time monitoring and visualisation system** designed and manufactured by Adelaide engineering firm Embedtronics

➢ **Tested** at various field sites around Adelaide

➢ **Field demonstration** at Australasian Groundwater Conference in Perth, 2022

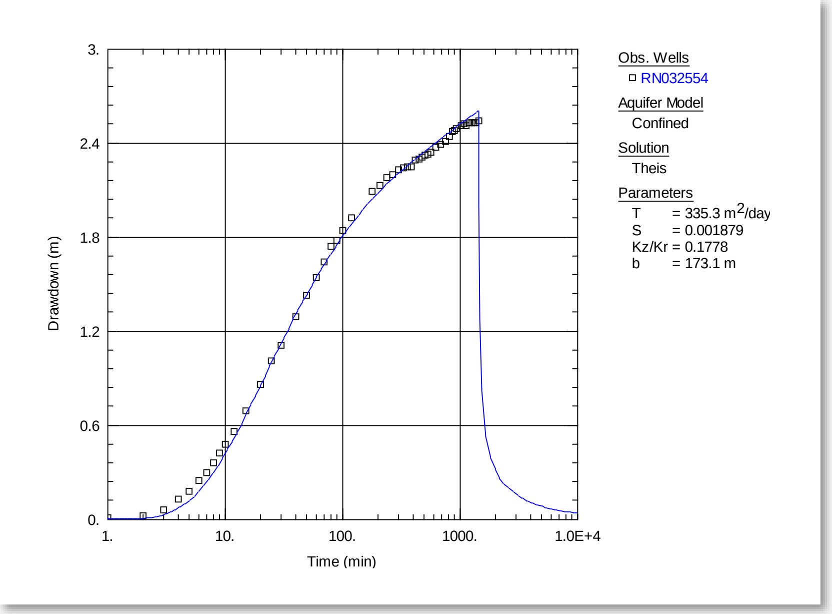


Interpretation methods

Reference point: Interpreting traditional pumping tests

For confined aquifers, we use the Theis (1935) solution:

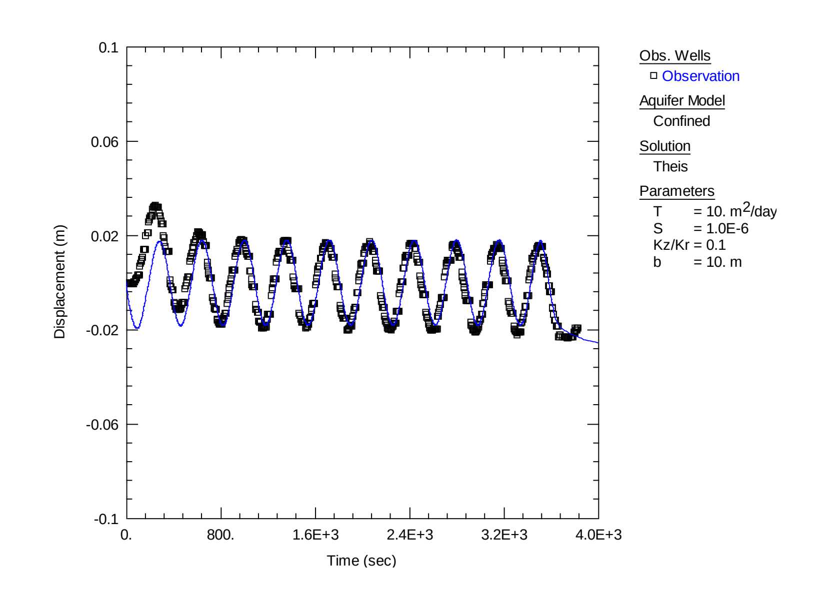
$$s(t) = \frac{Q}{4\pi T} W\left(\frac{r^2 S}{T\, 4\, t}\right)$$



Sinusoidal slug tests

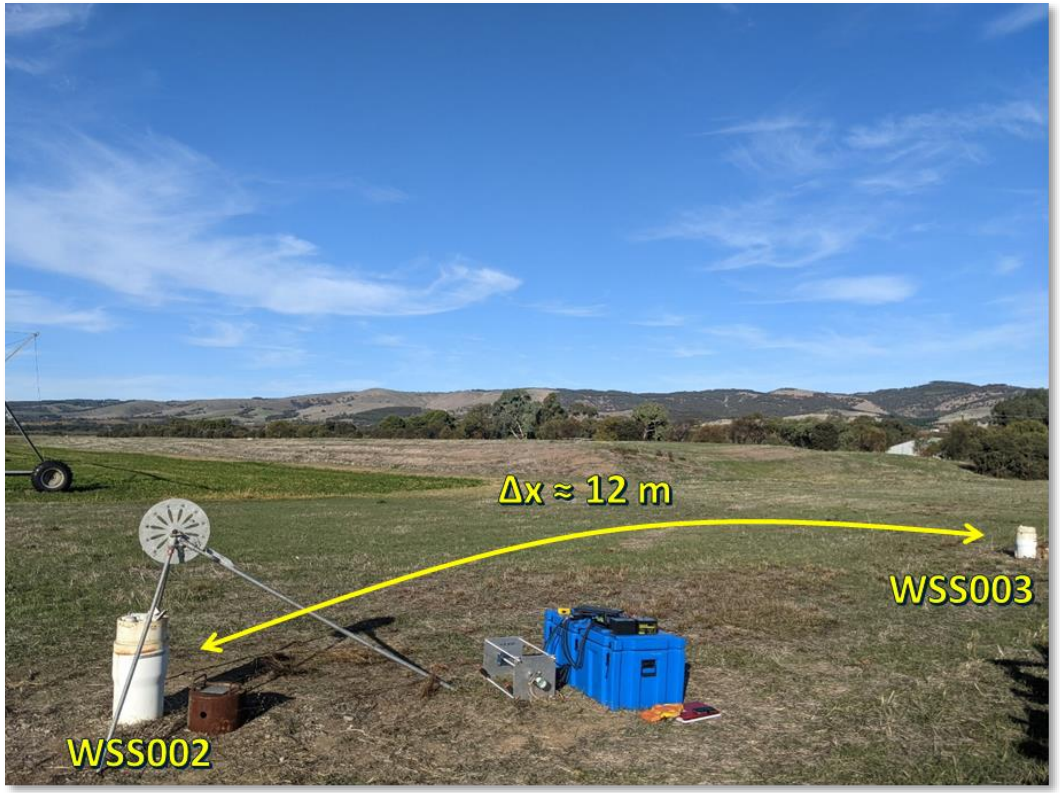
For confined aquifers, we use the Black and Kipp (1981) solution:

$$s(t) = \frac{Q\, e^{i\omega t}}{2\pi T} K_0\left(\sqrt{\frac{r^2 S\, i\, \omega}{T}}\right)$$

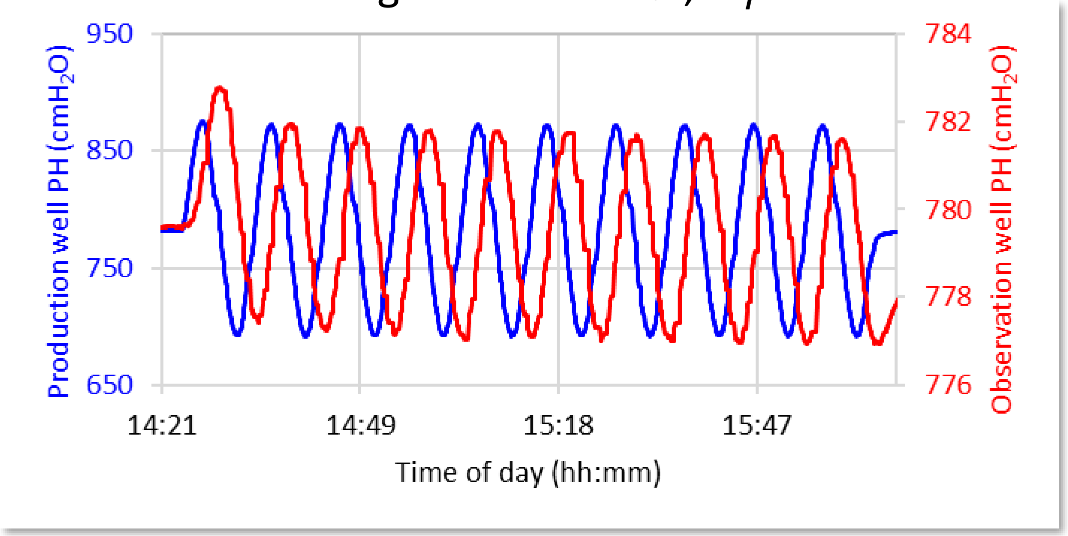


3. The **highs** and **lows** of sinusoidal slug testing

The **highs**: Aldinga field site



Sinusoidal slug test: $\Delta A \approx 2$ %, $\Delta \phi \approx 3$ mins



- Leaky **confined** aquifer (Port Willunga Formation)
- 50 mm diameter wells
  - Propagated sinusoidal signal up to 12 m ✓

The **highs**: Aldinga field site

- Leaky **confined** aquifer (Port Willunga Formation)
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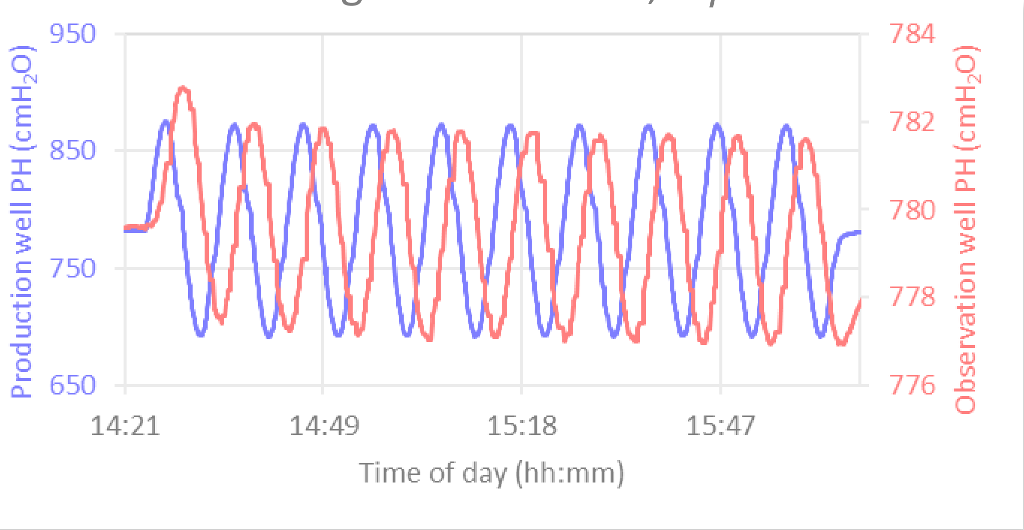
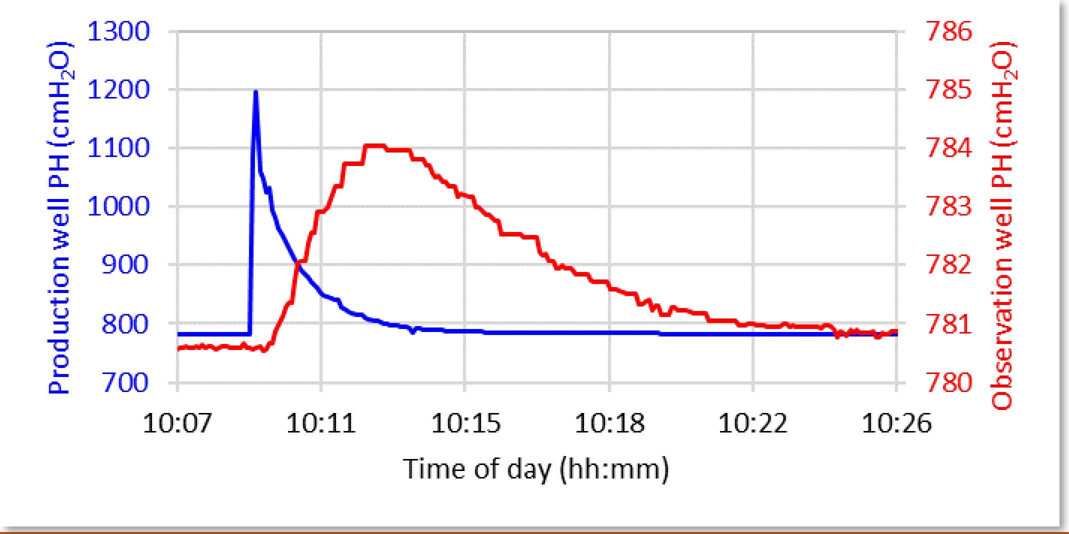
Sinusoidal slug test: $\Delta A \approx 2$ %, $\Delta \phi \approx 3$ mins



Falling head slug test: $\Delta P \approx 0.4$ m, $\Delta t \approx 3$ mins



The **highs**: Aldinga field site

Modelled results

Traditional slug test: (single well)

- $T = 3.7\ m^2/d$
- $S = 4.2 \times 10^{-6}$

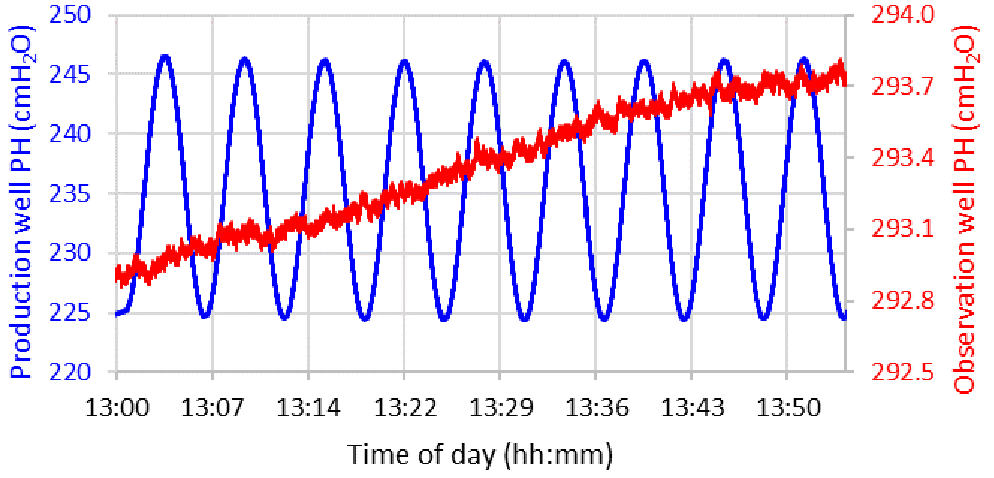
Sinusoidal slug test: (two wells)

- $T = 16\ m^2/d$
- $S = 4.0 \times 10^{-6}$

➢ **BUT!** These estimates are **not** directly comparable, due to differing spatial support

The **lows**: Balhannah field site

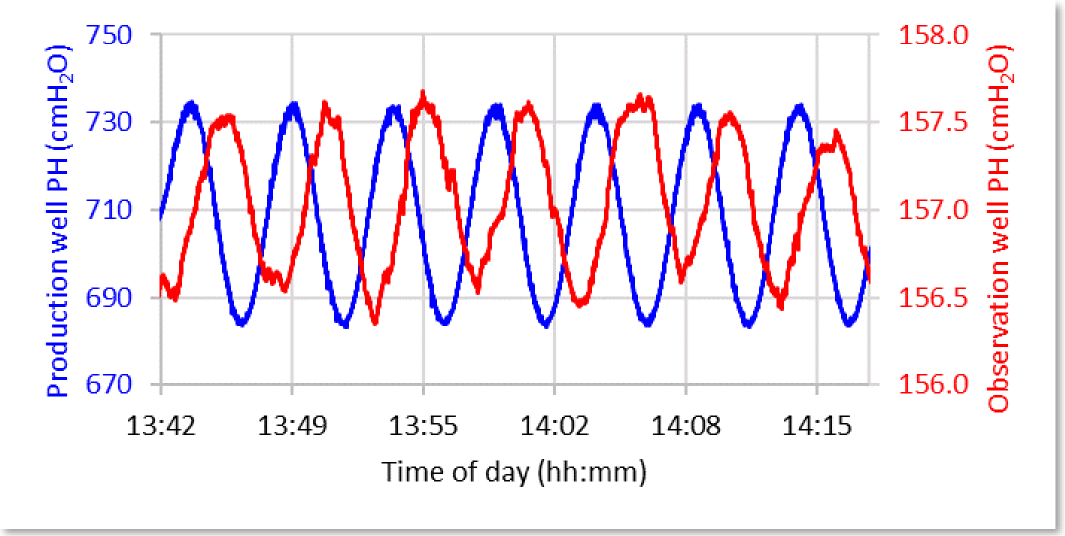
Sinusoidal slug test: no response



- Fractured rock aquifer (Woolshed Flat Shale)
- **200 mm diameter wells**
  - ➢ No measurable propagation of signal
  - ➢ Attributed to large diameter wells

The **highs**: McLaren Vale field site

Sinusoidal slug test: $\Delta A \approx 2$ %, $\Delta\phi \approx 30$ seconds



- Leaky **confined** aquifer (Pirramimma Sand)
- 80 mm diameter wells
  - Propagated sinusoidal signal up to 25 m

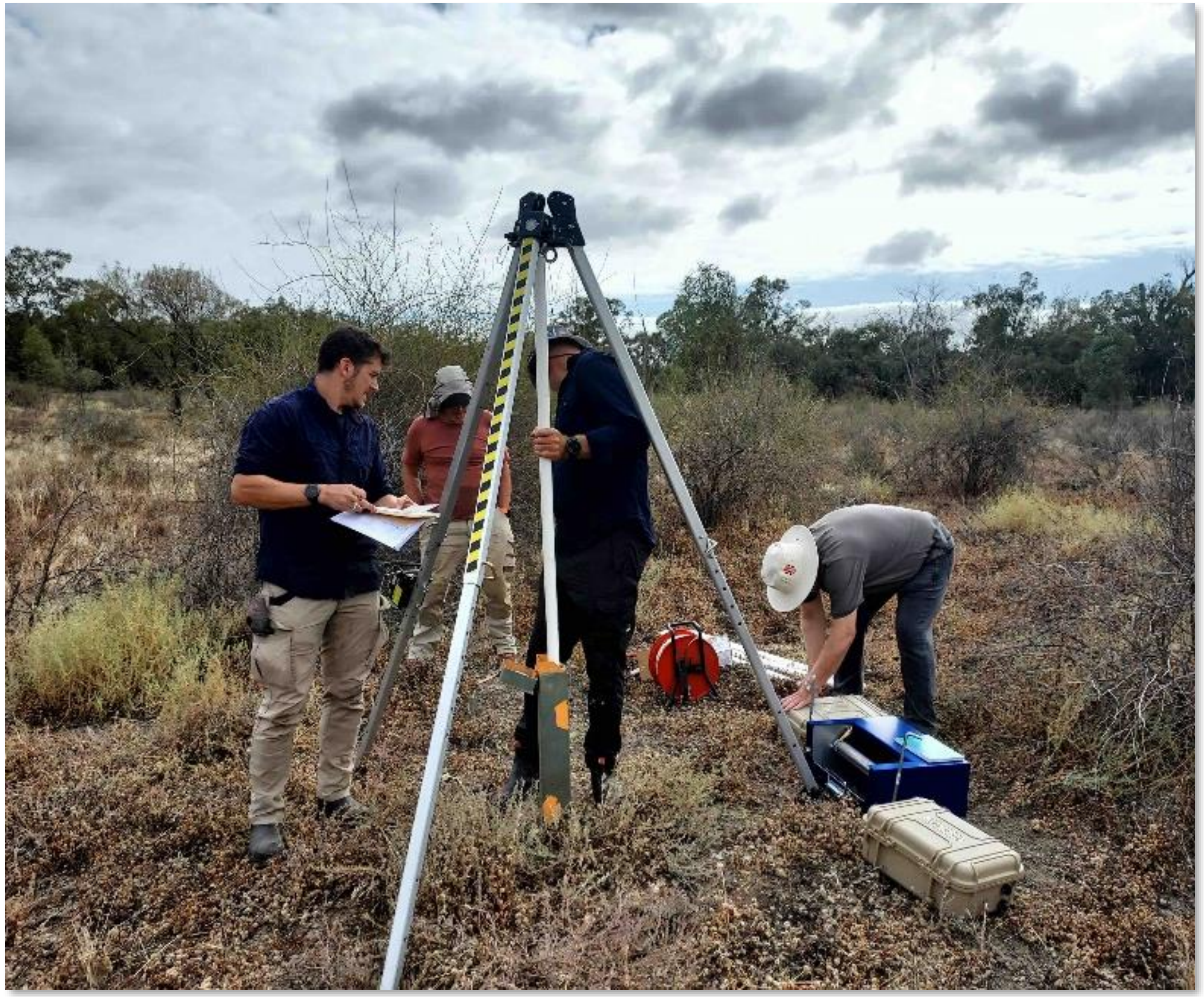
✓

4. What are the **benefits** of sinusoidal slug testing?

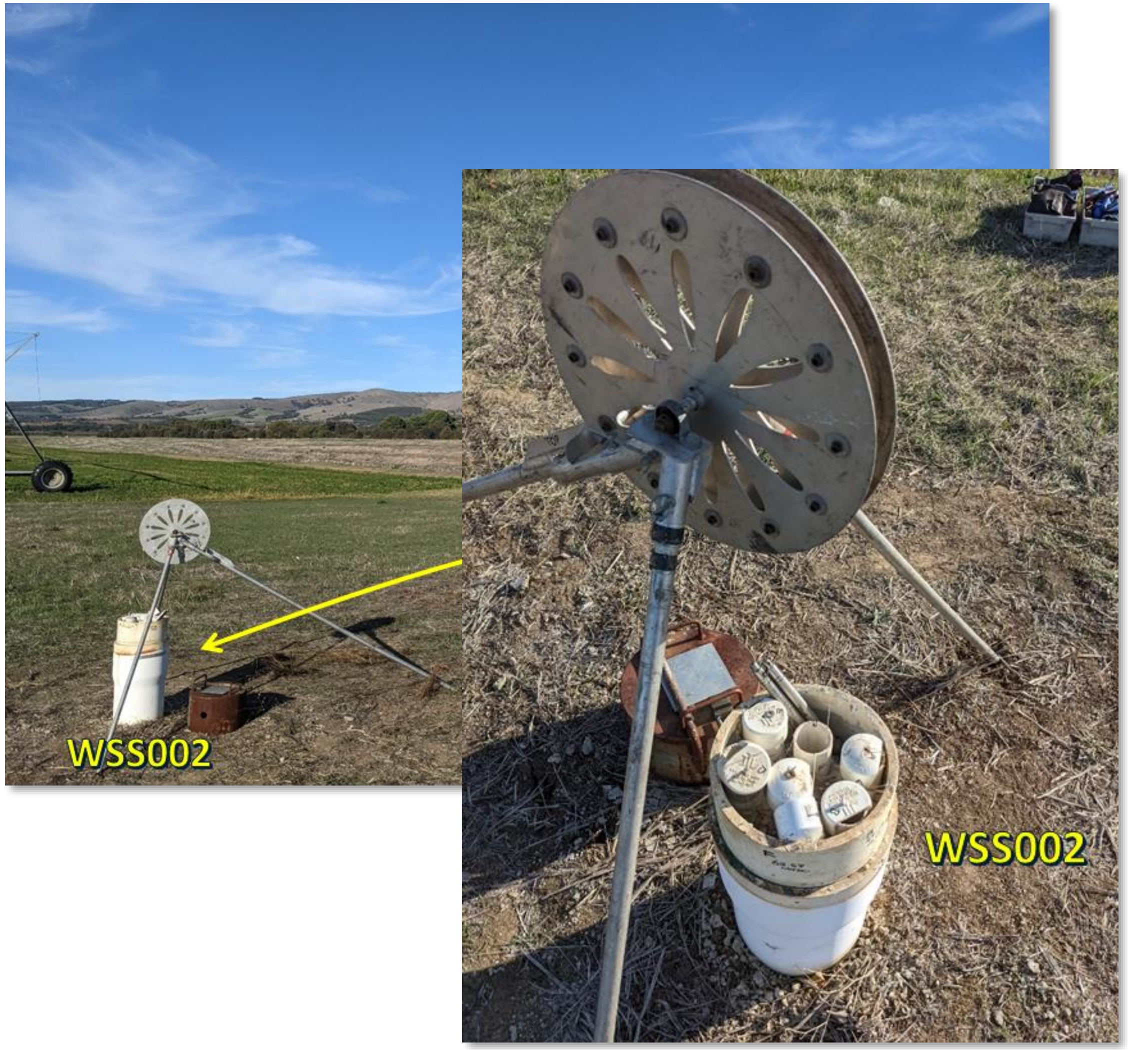
Benefits – Logistical

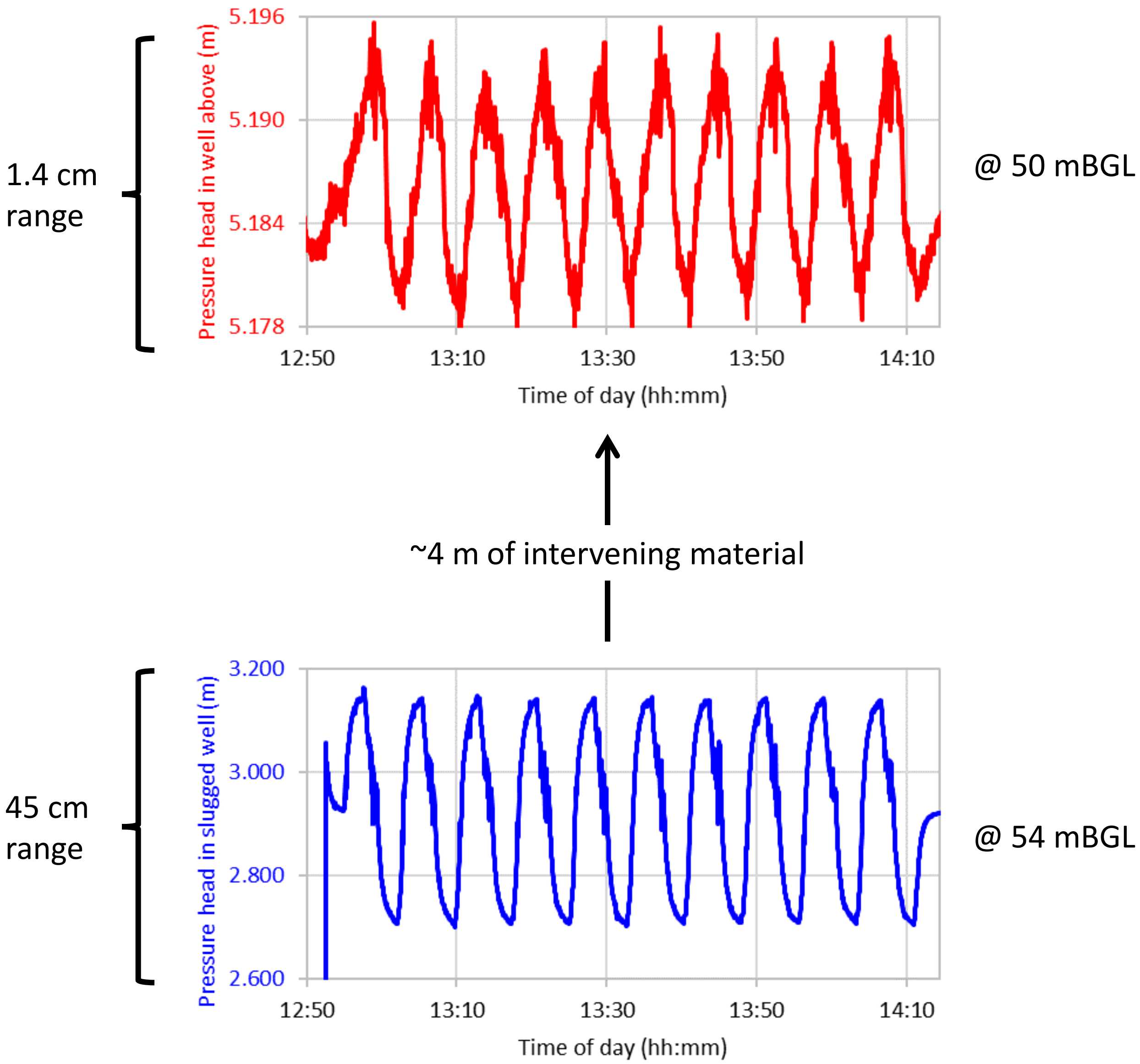
Compared to traditional slug tests:

- **Better propagation** of sinusoidal signals
- **Easier detection** of responses to sinusoidal tests, even in the presence of background noise
- **More rapid** to undertake sinusoidal testing
- **More robust** estimation of storage, in addition to transmissivity
- **Lower uncertainty** of properties estimated, due to multiple replicates (cycles) within a single test



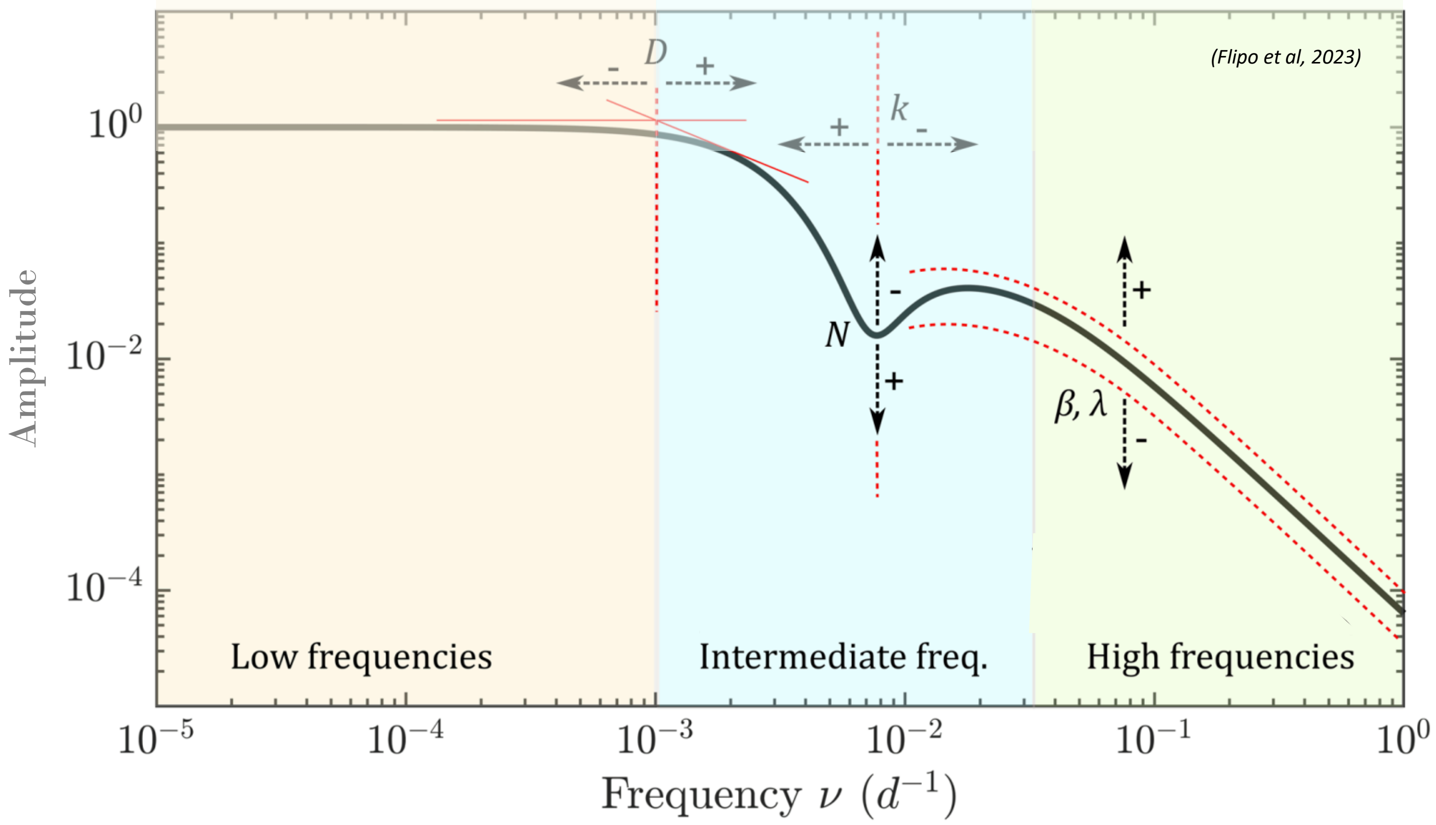
Benefits – Insight 1: Aquitard characterisation





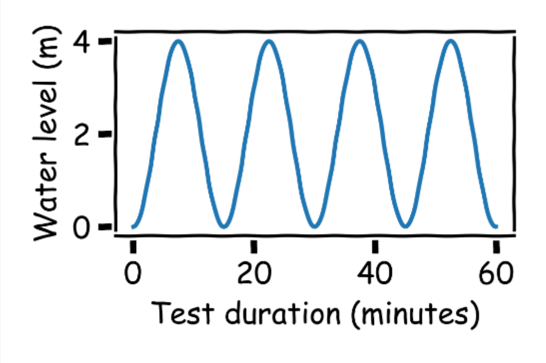
Benefits – Insight 2: Characterising dual domain flow in fractured rock aquifers

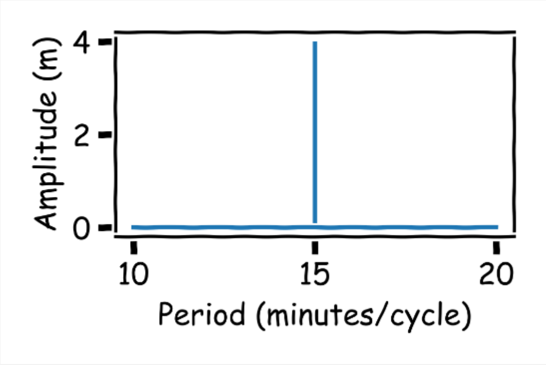
Context 1: Pumping tests	Late time effects; e.g. drainage	Early time effects; e.g. depressurisation
Context 2: Fractured rock aquifers	Slow response, e.g. matrix flow	Fast response; e.g. fracture flow



"Typical" sinusoidal slug test

Uses a single signal frequency

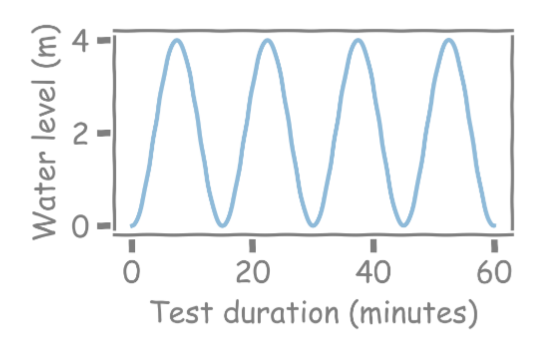


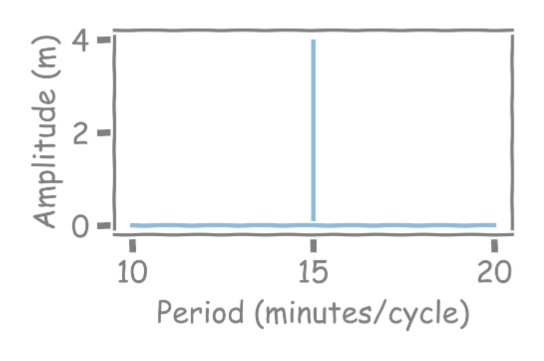


Benefits – Insight 2: Characterising dual domain flow in fractured rock aquifers

"Typical" sinusoidal slug test

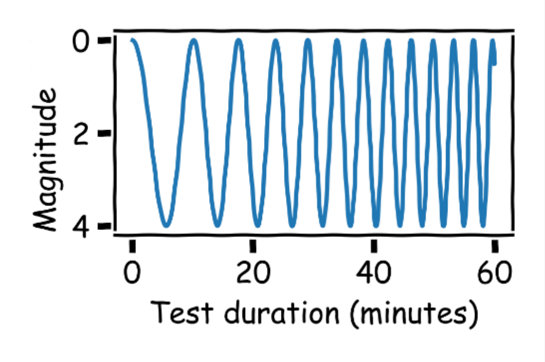
Uses a single signal frequency

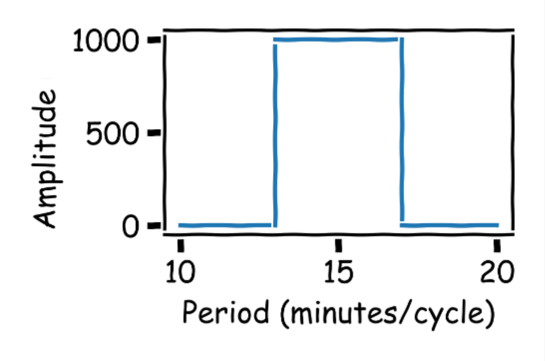




"Sweep" slug test

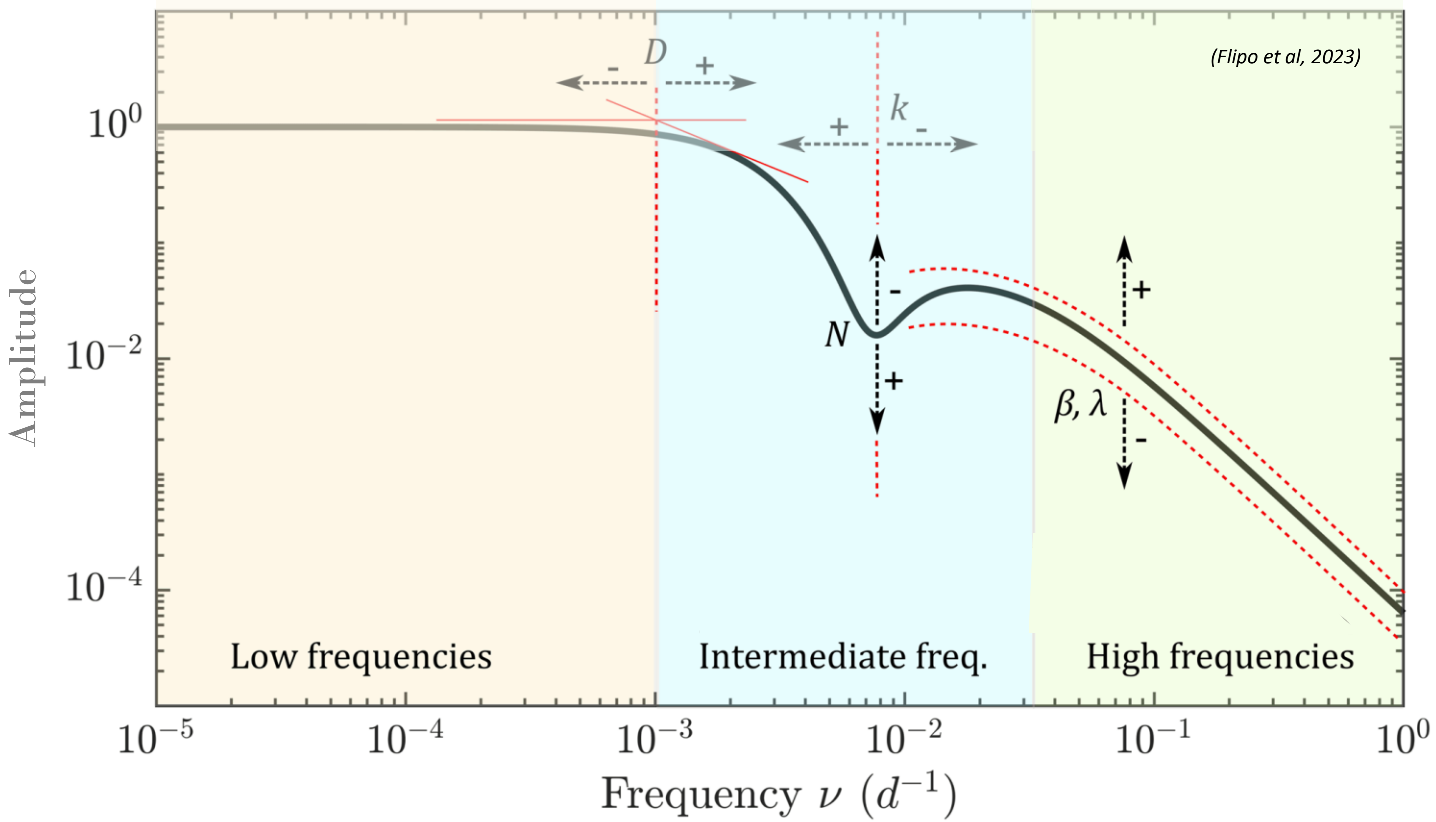
Sweeps continuously from low to high frequency





Benefits – Insight 2: Characterising dual domain flow in fractured rock aquifers

Context 1: Pumping tests	Late time effects; e.g. drainage	Early time effects; e.g. depressurisation
Context 2: Fractured rock aquifers	Slow response, e.g. matrix flow	Fast response; e.g. fracture flow



5. How are we making this research **accessible**?

Partnering with Kremford Pty Ltd to make this research **accessible**

Partnering with Kremford Pty Ltd

- Ron Kreymborg and Kieran Harford
- Over 15 years' experience in providing solutions to industry involving **precise motor control**, including eye testing equipment, labelling and packaging machines and software
- Prior experience in electronic circuit design, microprocessor control, and software **commercialisation**
- Contracted in **2022** to develop precise control of electronically controlled winch
- Since **2023** have collaborated to design and assemble a comprehensive off-the-shelf system to perform for sinusoidal slug testing

KREMFORD

Partnering with Kremford Pty Ltd to make this research **accessible**

Kremford system for sinusoidal slug testing

Simplicity and portability

1. **Power source:** All devices powered using **DC batteries** (either 24V or 5V) to maximise portability

2. **Transportation:** All equipment contained within **6 hard cases**, each with a **maximum mass under 20kg**, to simplify transportation

Base station monitoring node with laptop visualisation

Portable electronically controlled winch

Wireless observation well node, including sensor and cable

ALGA

Partnering with **Kremford Pty Ltd** to make this research **accessible**

Kremford system for sinusoidal slug testing

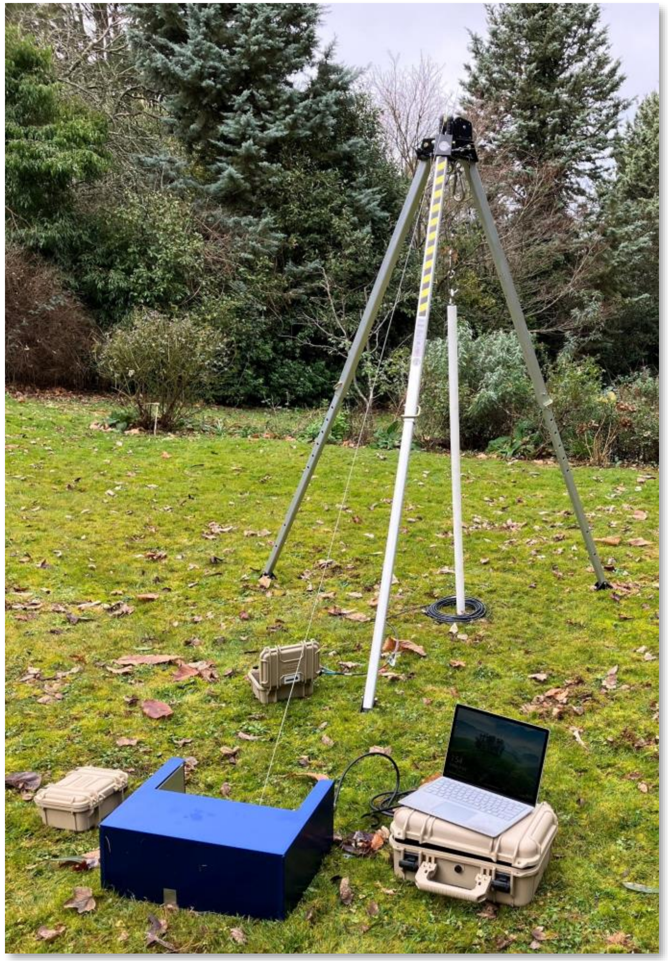
Automated control of slug movement

1. **Extendable slug:**

- Four 1.5-metre-long plastic sections can be connected to assemble up to a 6-metre-long slug
- 40 mm OD is suitable for use in 50 mm ID wells (piezometers) or larger

2. **Electronic winch:** A bespoke portable winch driven by a **specialised** DC stepper motor, allowing **precise control** at **low speeds**

3. **Tripod:** **Collapsible** tripod used to convey steel rope from winch to downhole slug



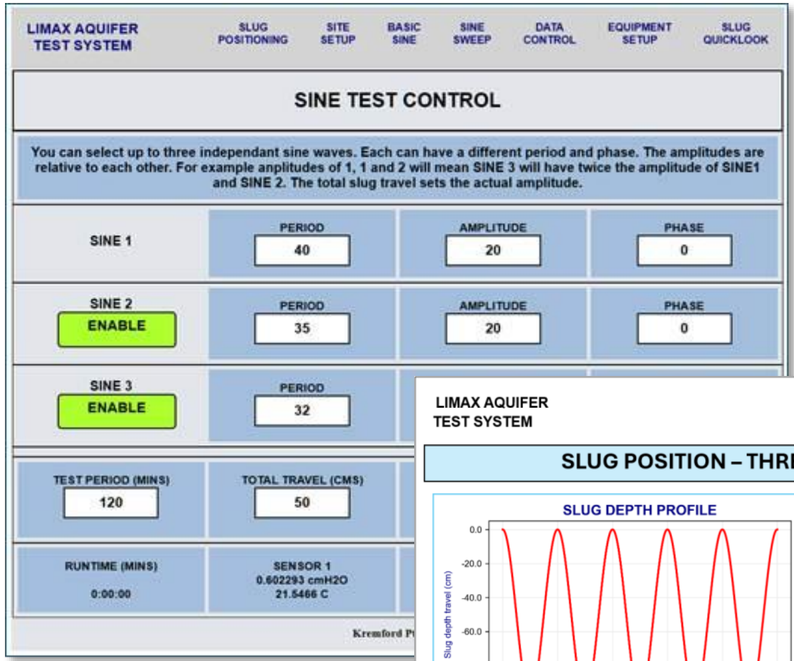
Kremford sinusoidal testing system

Partnering with **Kremford Pty Ltd** to make this research **accessible**

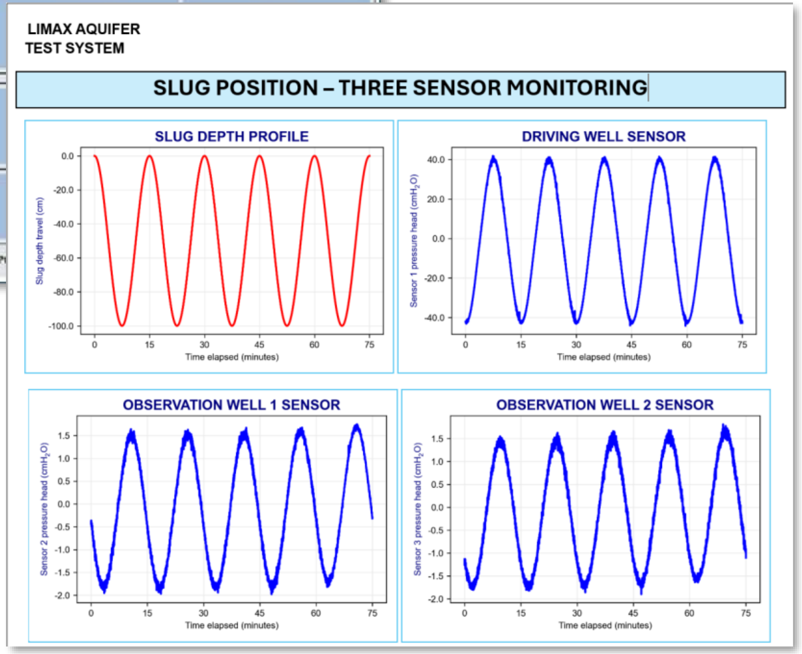
Kremford system for sinusoidal slug testing

Measurements presented in real-time

1. **Monitoring:** Vented, **high resolution** (i.e., 3.5 metre range) pressure transducers for monitoring both production and observation well(s) at **5-second intervals**
2. **Communication:** Observation well pressures sent **wirelessly** back to base station at production well
3. **Visualisation:** All observations presented in **real-time** on a web-based app on a laptop or similar device
4. **Software:** Bespoke software provided to estimate hydraulic properties from measurements **while in the field**



Sine test set-up page



Sine test output page

Wrapping up

The "take home" messages from **us**

1. **Sinusoidal slug testing** can be used to reliably estimate subsurface **hydraulic properties**, including both the **transmissivity** and **storage** of aquifers, and potentially aquitards

2. This method combines the **benefits** of slug testing with the **advantages** of using a **frequency-based** approach

3. The CSIRO, Flinders University, and the University of Georgia have partnered with **Kremford Pty Ltd** to **commercialise** this research for uptake by **industry**

Thank you for listening!

The “take home” messages from **you**!

- From **your** experiences, what **limitations** have you found with slug testing?

- Do **you** see a role for **this method** in assisting contaminated site assessments?

- Would **you** see value in a **pump-based** equivalent of this system?

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