



Corso di Laurea Magistrale in
RISANAMENTO E PROTEZIONE DELL'AMBIENTE

**"FLOW IN A FRACTURED LIMESTONE AQUIFER: SLUG TEST ASSESSMENT
AND DEVELOPMENT OF A NEW METHOD TO ANALYSE VERTICAL FLOW IN MONITORING WELLS"**

RELATORE

Prof. Ing. Massimiliano Fabbricino

CORRELATORE

Prof. Ing. Armando Carravetta

CANDIDATI

Domenico Perna M67000272

Raffaele Di Nardo M67000298

Anno Accademico 2016–2017

Tesi sperimentale realizzata in collaborazione con l'Università Tecnica della Danimarca (DTU, Kgs. Lyngby, Copenaghen).
Keywords: Limestone; Slug Test; Hydraulic Conductivity; AQTESOLV; Overdamping and Underdamping; Vertical Flow.

Scopes of the work

DTU Environment
Department of Environmental Engineering



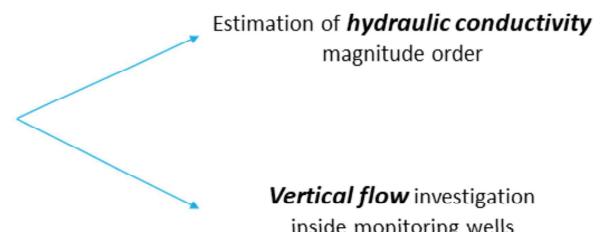
**The Capital Region
of Denmark**

This work is part of Region H **Limestone Project**, a collaboration between **DTU Environment** and **Region H** about the **fate of contaminants in fractured limestone aquifers**

Limestone project

Aims at
improving

Remediation activities in
limestone aquifers

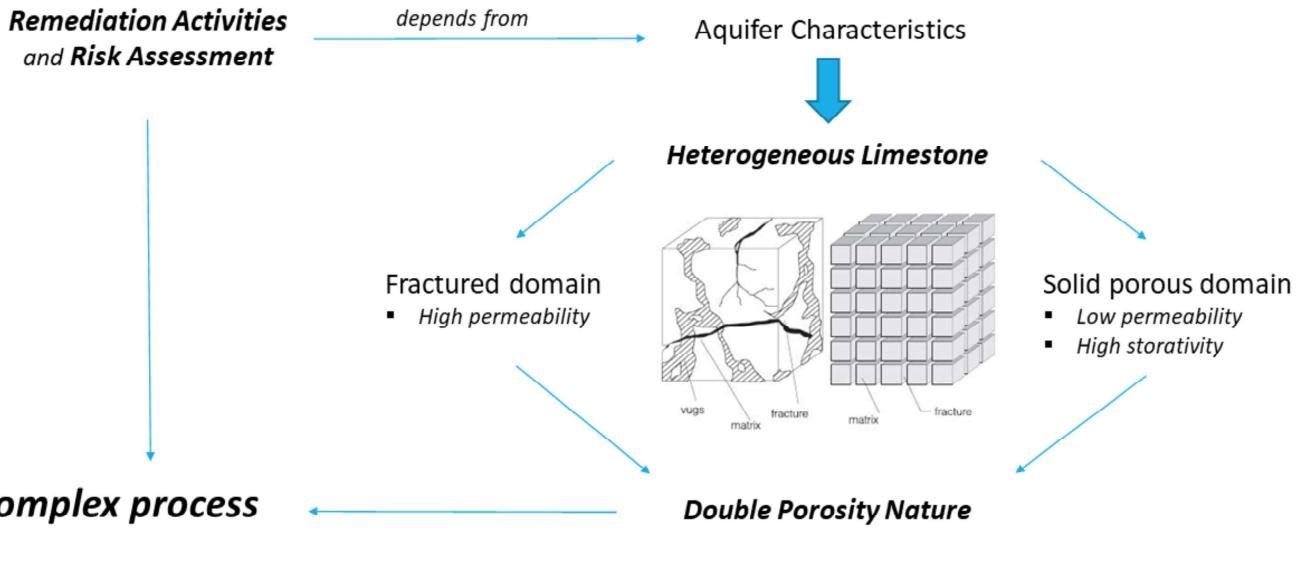


Limestone aquifers are important source for drinking water production, all around the world

- Southern Italy (production of $3,7 \times 10^6 \text{ m}^3$ of water/year) (Celico et al. 2004)
- Copenaghen Region (Hinsby et al. 2003)

Lo studio proposto si prefissa l'obiettivo di migliorare l'efficienza delle attività di bonifica, a mezzo di *pump and treat*, attualmente in esercizio presso un esempio di acquifero calcare (*limestone aquifer*), sito nella regione di Copenaghen.

Fractured Limestone Aquifers



La complessità comportamentale degli acquiferi calcarei fratturati rende complicato il loro studio e la loro modellazione. Tali difficoltà sono solitamente superate, in ambiti pratici, mediante l'adozione di modelli semplificativi a doppia porosità.

Study site

Akacievej site

- **What is it?**
Fracture limestone aquifer
- **What was the contamination source?**
Industrial activities
- **What is the problem?**
PCE-TCE contamination
- **Why remediate it?**
Nearby presence of an extraction well of the Fløng waterworks



- **How remediate it?**
Removal of the most contaminated soil (6-8 m below ground surface) and pump and treat with activated carbon

Il sito di Akacievej costituisce un esempio di laboratorio *a cielo aperto* di cui disporre per lo studio e lo sviluppo di nuove tecniche di analisi e/o bonifica nell'ambito di acquiferi calcarei fratturati. I numerosi pozzi di monitoraggio realizzati nel corso degli anni favoriscono tali attività.

How to reach the scopes?

Estimation of **hydraulic conductivity magnitude order**

How to?

- **Slug Test** with *higher frequency instrumentation* than in the previous studies at site
- Assessment of slug test *interpretative models*

Vertical flow investigation
inside monitoring wells

How to?

- Development of a *qualitative test* the **Camera and Tracer Test**

La possibilità di ottenere stime più precise della conducibilità idraulica, unitamente all'investigazione visivo-qualitativa del flusso verticale in pozzi di monitoraggio, è stata valutata ai fini di incrementare l'efficienza del *pump and treat* attualmente in corso presso il sito di Akacievje.

Vacuum Slug Test

Falling-head slug test, which is able to perturb the water table realizing a **head difference** between the water level in the well and the outside level at starting time test imposing, artificially, a vacuum in the analysed well (Hinsby et al., 1992)

INSTRUMENTATION

- Bladder
- Peristaltic pump
- Vacuum cleaner
- Pressure transducer - data logger
- Field pc
- Generator



ADVANTAGES

- Small amount of water needed
- Single borehole test
- Fast
- Cheap, pumping not needed

DISADVANTAGES

- Limited induced flow
- K-value representative only of the surrounding of the well
- Significant approximation errors (fractured aquifers/ long screen wells)

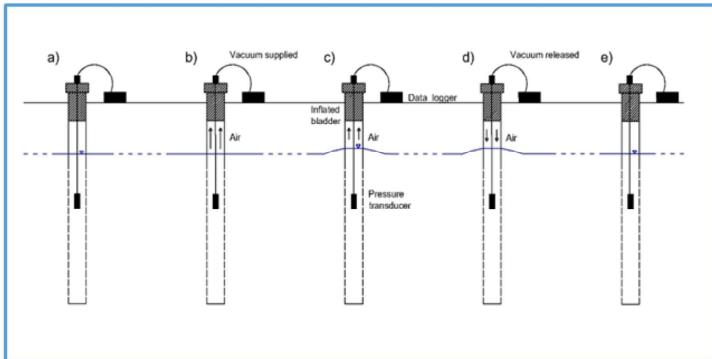
Il *vacuum slug test* rappresenta un'alternativa economica, rapida ed efficace alle usuali prove pneumatiche atte alla stima dei principali parametri idrogeologici di un acquifero. La semplice strumentazione, in particolare, la rende una prova particolarmente adatta a studi preliminari.

Vacuum Slug Test

Test Phases

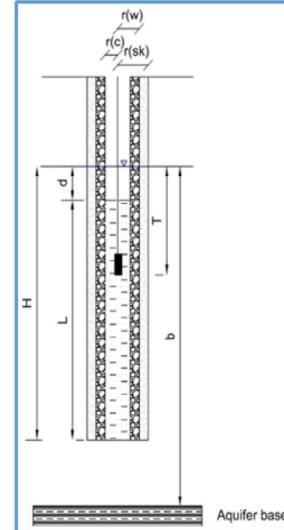
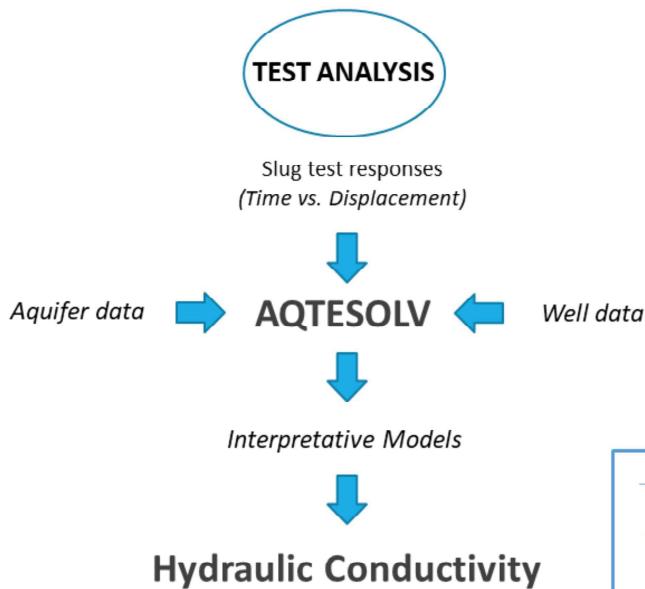
- a) 1-2 Equilibrium condition
- b) 2-3 Vacuum supply
- c) 3-4 Water inflow
- 4-5 Equilibrium condition
- d) 5-6 Vacuum release
- e) 6-7 Water outflow

Water level falling represents the phase (6-7) analysed to estimate **Hydraulic conductivity**



La variazione di pressione all'interno del pozzo, imposta a mezzo di una pompa a vuoto, ed il conseguente trasferimento di acqua tra l'acquifero ed il pozzo, e viceversa, permettono di valutare le caratteristiche di permeabilità dell'acquifero investigato.

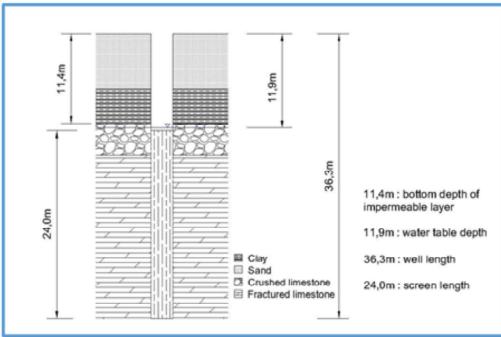
Slug Test Analysis



Geometric Parameters							
WELLS	L [m]	H [m]	b [m]	d [m]	T [m]	r(c) [m]	r(sk) [m]
GEO 4	24,00	24,35	24,35	0,35	3,82	0,0375	0,10
GEO 9	21,00	22,31	22,31	1,31	6,15	0,04	0,10
GEO 19s	3,00	4,42	4,42	1,42	2,51	0,045	0,10
GEO 19d	4,00	12,42	12,42	8,42	10,16	0,045	0,10

L'impiego del software AQTESOLV consente la stima della conducibilità idraulica dell'acquifero sulla base del responso di uno slug test, note che siano alcune caratteristiche dell'acquifero e del pozzo investigato.

Analysed Wells – Geo 4



- Hypothesis of unconfined aquifer

- Tests performed

- 4 Tests at 10 Hz
- 2 Tests at 2 Hz

- Used interpretative methods

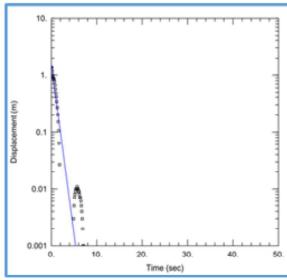
- Bouwer and Rice (comparison with Jørgensen, 2016)
- Springer and Gelhar (*underdamped response*)

Oscillations at the end of the falling curve

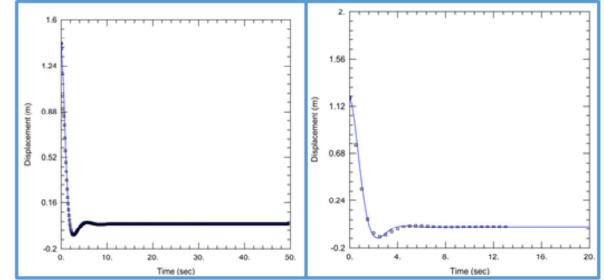
Underdamped response

Springer and Gelhar solution

Bouwer and Rice solution

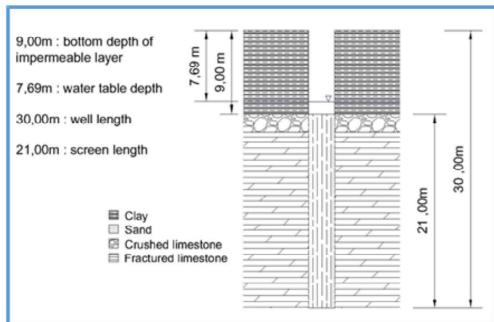


Springer and Gelhar solution



Il responso oscillatorio caratterizzante il pozzo Geo 4 ha implicato l'utilizzo di un apposito modello interpretativo: la soluzione di Springer and Gelhar. Lo studio precedente ad opera di P. Jørgensen (2016) si limitava, invece, all'applicazione della sola soluzione di Bouwer and Rice, con un'interpolazione non ottimale.

Analysed Wells – Geo 9



- Hypothesis of confined aquifer

- Tests performed

- 6 Tests at 10 Hz
- 3 Tests at 5 Hz
- 2 Tests at 2 Hz

- Used interpretative methods

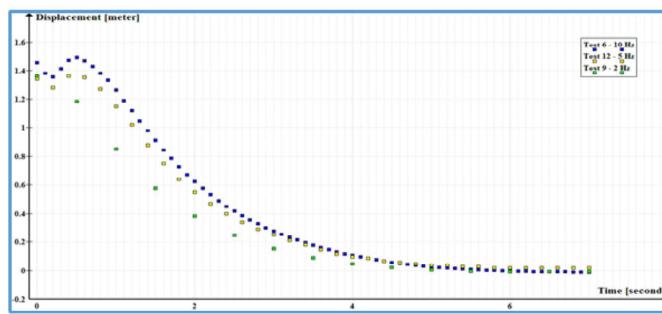
- Bouwer and Rice (comparison with Jørgensen, 2016)
- KGS (comparison with Jørgensen, 2016)
- Springer and Gelhar

Initial oscillations due to:

- Not instantaneous start of tests
 - Initial turbulence

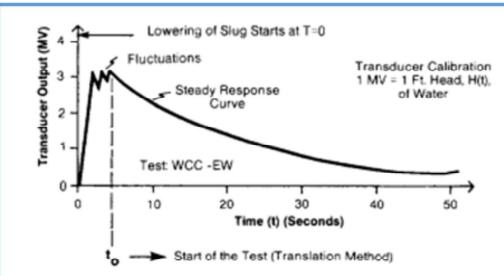
Problems during tests interpretation

Translation Method



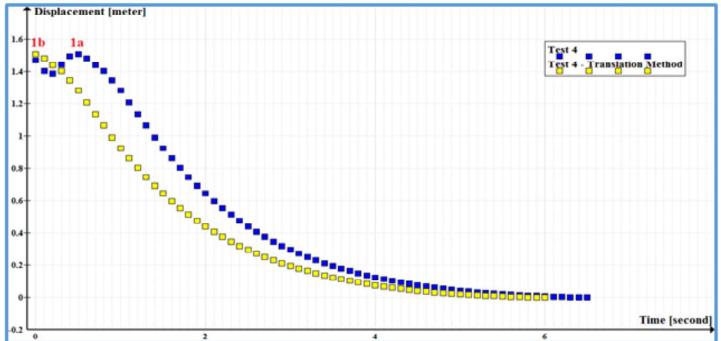
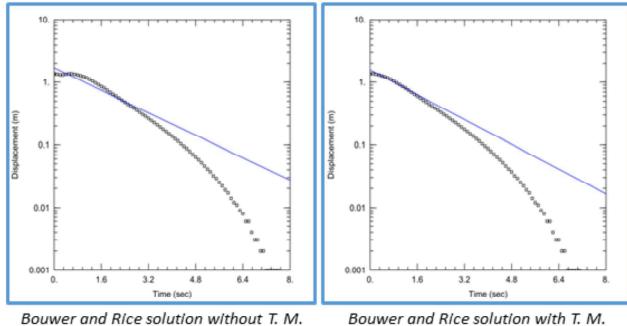
Le oscillazioni iniziali, rappresentando una possibile fonte di errore nella stima delle caratteristiche dell'acquifero, ha richiesto l'impiego di un apposito metodo correttivo: il *Translation Method*.

Translation Method



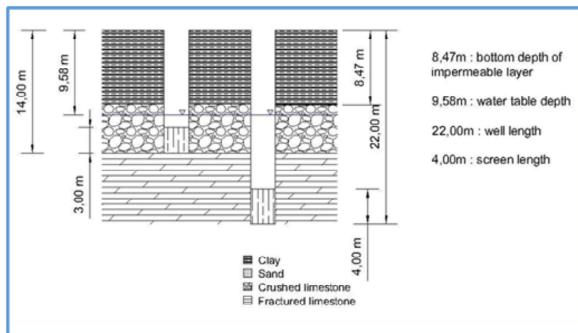
Why use it?

To remove the initial fluctuations to have a more representative test of the aquifer
(Bandit and Miner, 1986)



L'applicazione del *Translation Method* consente di rimuovere dalla risposta di uno slug test i dati non strettamente rappresentativi del comportamento dell'acquifero.

Analysed Wells – Geo 19s (shallow)



▪ Hypothesis of unconfined aquifer

▪ Tests performed

- 5 Tests at 10 Hz

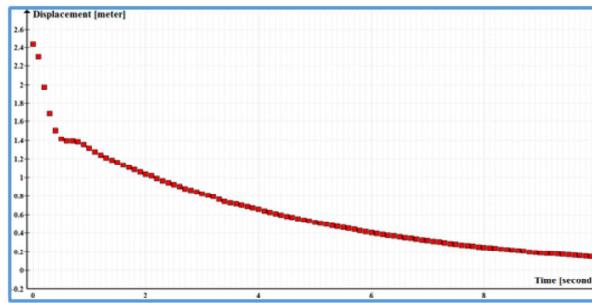
▪ Used interpretative methods

- Bouwer and Rice (comparison with Besora, 2016)
- KGS (comparison with Besora, 2016)
- Springer and Gelhar

Initial double-slope behaviour
due to the effect of the gravel pack

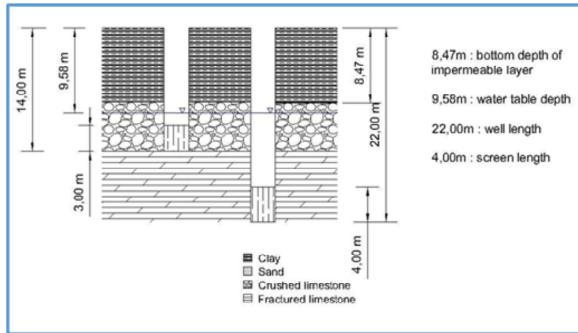
Problems during K-value estimation

Translation Method



Il pozzo Geo 19s rappresenta un esempio dei possibili effetti di disturbo riscontrabili durante l'esecuzione di uno slug test: l'effetto del dreno.

Analysed Wells – Geo 19d (deep)



High hydraulic conductivity (fractured limestone)

The sudden piezometric head change can evolve in terms of oscillations of the water level about equilibrium level

Underdamped response

- Hypothesis of unconfined aquifer

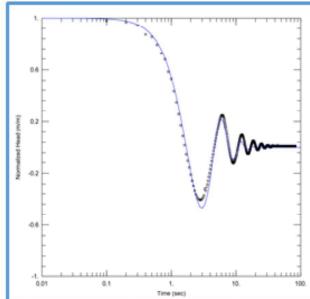
- Tests performed

- 8 Tests at 10 Hz
- 2 Tests at 2 Hz

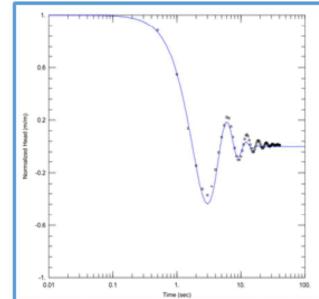
- Used interpretative methods

- Springer and Gelhar (underdamped response / comparison with Besora, 2016)

Springer and Gelhar solution 10 Hz



Springer and Gelhar solution 2 Hz



Il pozzo Geo 19d rappresenta un esempio di come, in zone ad elevata permeabilità, il livello idrico ristabilisca la sua posizione iniziale mostrando un comportamento oscillatorio.

Discussion

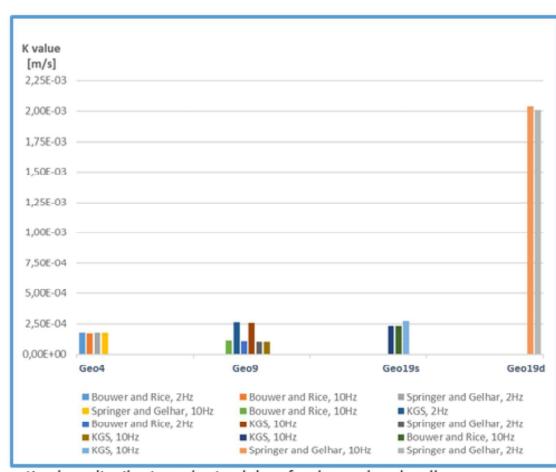
- Influence of the pressure transducer frequency on the hydraulic conductivity estimation

COMPARISON – Average K-values			
WELL GEO 9	Springer and Gelhar	Bouwer and Rice	KGS
	K [m/s]	K [m/s]	K [m/s]
	9,79E-05	1,07E-04	2,60E-04
	9,95E-05	1,03E-04	2,64E-04
PERCENTAGE DIFFERENCE	-2%	4%	-2%

Percentage difference $(K_{10Hz} - K_{2Hz}) / K_{10Hz}$

- Average percentage difference = 3%
- Same order of magnitude

COMPARISON – Average K-values		
WELL GEO 4	Springer and Gelhar	Bouwer and Rice
	K [m/s]	K [m/s]
	1,57E-04	1,74E-04
	1,78E-04	1,77E-04
PERCENTAGE DIFFERENCE	-13%	-2%



K-values distribution: obtained data for the analyzed wells

I test realizzati a differente frequenza di campionamento, 10 Hz e 2 Hz, non mostrano rilevanti differenze.

Discussion

- Influence of the pressure transducer frequency on the hydraulic conductivity estimation*

Comparison with 2 Hz K-values obtained from Jørgensen, 2016

COMPARISON – Average K-values	
WELL GEO 4	Bouwer and Rice
10 Hz	K [m/s] 1,74E-04
2 Hz	1,85E-04
PERCENTAGE DIFFERENCE	-6%

Comparison with 2 Hz K-values obtained from Besora, 2016 (reworked data)

COMPARISON – Average K-values	
WELL GEO 19d	Springer and Gelhar
10 Hz	K [m/s] 2,04E-03
2 Hz	3,17E-03
PERCENTAGE DIFFERENCE	-55%

COMPARISON – Average K-values

WELL GEO 9	Bouwer and Rice
10 Hz	K [m/s] 1,07E-04
2 Hz	1,25E-04
PERCENTAGE DIFFERENCE	-17%

Percentage difference ($K_{10\text{Hz}} - K_{\text{Jørgensen}}\right) / K_{10\text{Hz}}$

COMPARISON – Average K-values

WELL GEO 19s	Springer and Gelhar	Bouwer and Rice	KGS
10 Hz	K [m/s] 2,32E-04	2,36E-04	2,72E-04
2 Hz	2,04E-04	1,63E-04	2,52E-04
PERCENTAGE DIFFERENCE	12%	31%	7%

Percentage difference ($K_{10\text{Hz}} - K_{\text{Besora}}\right) / K_{10\text{Hz}}$

- The use of a higher pressure transducer frequency is not necessary to obtain more precise K - values
- The use of a higher pressure transducer frequency allows to show inertial and gravel pack effects

I test realizzati a differente frequenza di campionamento, 10 Hz e 2 Hz, non mostrano rilevanti differenze.

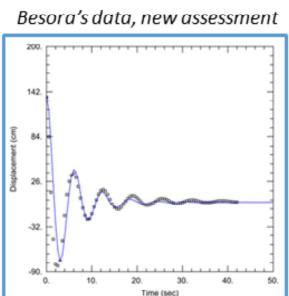
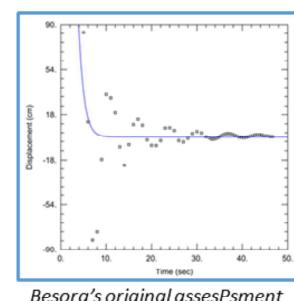
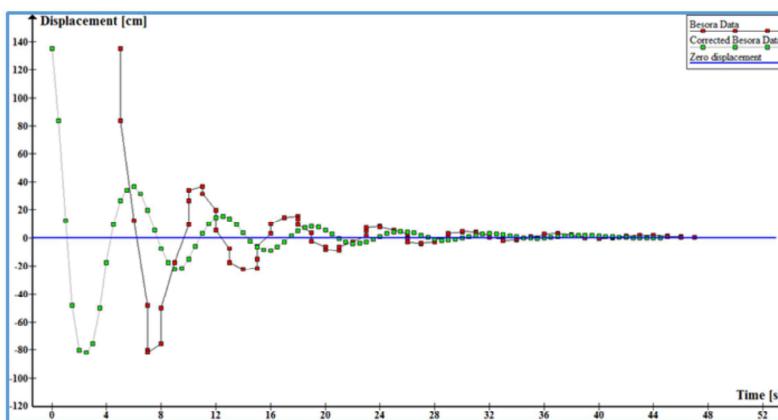
Besora's data correction

Besora in his work performed slug tests using a 2 Hz frequency

In his analysis, Besora did not consider 2 values for second and did not start from $t=0$

Problems reported by Besora was not due to a low instrumentation frequency

A new assessment was necessary before the comparison



La nuova analisi dei dati di P. Besora (2016) è stata necessaria nell'ambito del confronto con il suo lavoro.

Discussion

- Correlation between Slug test and Pumping test

- Slug test gave the same K-value magnitude order of the pumping test
- Slug test gave average percentage differences of 7% (2 Hz) and 8% (10 Hz)

COMPARISON between average K-values obtained from SLUG TEST and K-values from PUMPING TEST					
WELL GEO 19d	Theis Lowering K [m/s]	Theis Increase K [m/s]	Theis Late hours K [m/s]	Moench K [m/s]	Barker K [m/s]
	2,02E-03	2,21E-03	1,66E-03	1,74E-03	1,74E-03
PERCENTAGE DIFFERENCE 2 Hz	0%	-10%	17%	13%	13%
PERCENTAGE DIFFERENCE 10 Hz	1%	-8%	19%	15%	15%

K-values from the pumping test performed by Mostha (2016) for the well Geo 19d

Percentage difference $(K_{10\text{Hz}} - K_{\text{pumping test}})/K_{10\text{Hz}}$

Intense pumping activities at the Akacievje site → Screen Cleaning → Increased efficiency for a slug test

Il confronto con prove di emungimento è stato realizzato con il fine di valutare eventuali discrepanze tra i valori.

Vertical flow in wells

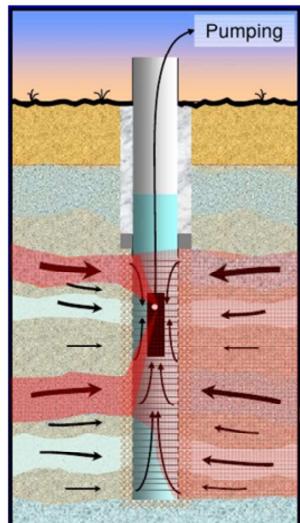
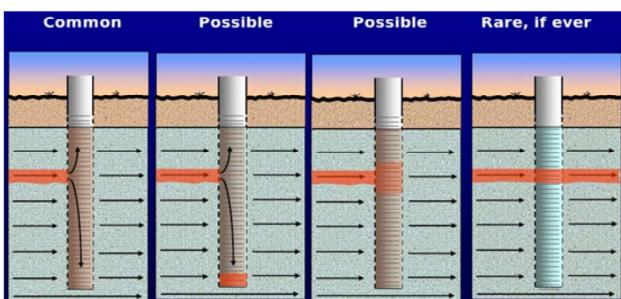
"The vertical flow through a well is a factor to be studied and to be taken into account" (Reilly et al., 1989)

CAUSES

- Pumping (**forced vertical flow**)
- Vertical hydraulic gradient between streamlines intercepted by a well (**ambient vertical flow**)

EFFECTS

- Water (solute) mixing
- Sampling bias



Underwater Camera-Tracer test



Qualitative Assessment of Vertical Flow

L'eventuale rilevanza del flusso verticale in pozzi di monitoraggio ne rende necessaria la valutazione in applicazioni idraulico-ambientali.

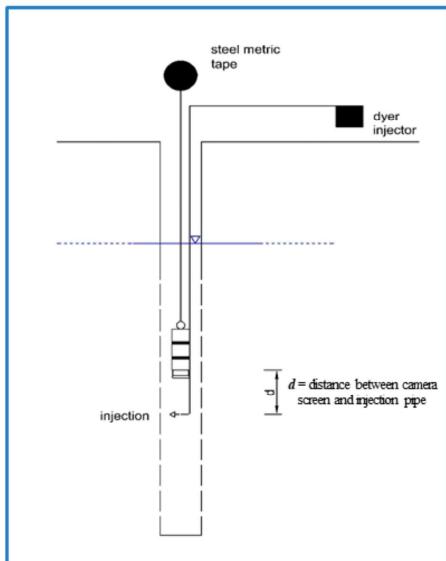
Test design

INSTRUMENTATION

- Camera
- Lighting system
- Plastic casing
- Dye (food colouring)
- Injection pipe
- Injection syringe
- Steel metric tape



The used food colouring



Test mode scheme



Underwater recording system



Lowering system

La semplicità caratterizzante la strumentazione necessaria al test rappresenta un fattore incentivante il suo impiego.

Laboratory tests

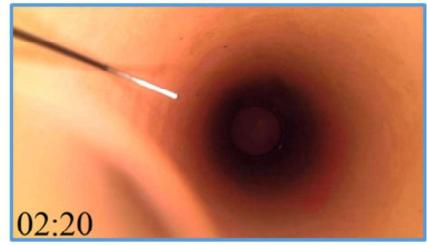
METHODOLOGY

- PVC pipe
 $2\text{ m} \times 0,09\text{ m}$
- Peristaltic pump
 $500\text{ ml/min (max flow rate)}$



SCOPES

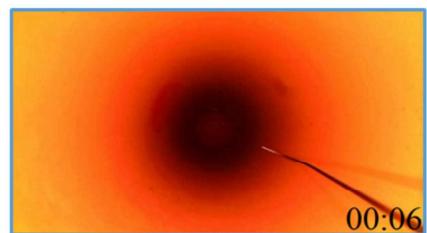
- Solution dye concentration
- Solution amount to be injected
- Best distance-configuration between the injection pipe and the camera screen



Downward flow test $V=4,5\text{ cm/min}$

RESULTS

- 0,025 ml dye / ml water
- 2 ml
- 30 cm or 15 cm
(upward or downward flow)



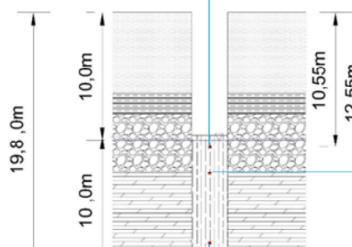
Upward flow test $V=4,5\text{ cm/min}$

La realizzazione di prove di laboratorio si è resa necessaria per lo sviluppo preliminare del test presentato.

Results

Geo5

10,0m : water table depth
19,8m : well length
10,0m : screen length



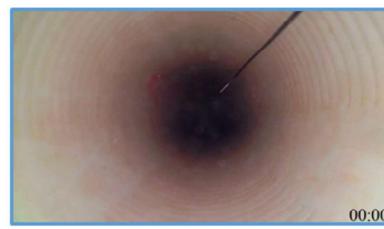
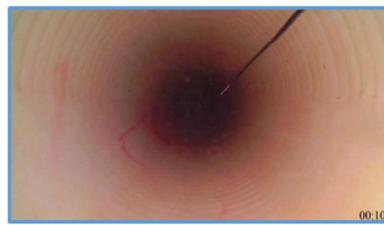
Clay
Gravel
Crushed limestone
Fractured limestone

advection-diffusive transport

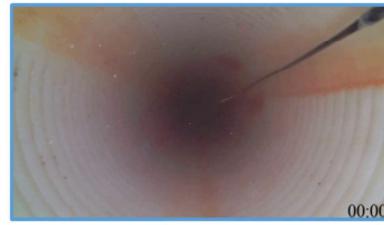
10,55m
12,55m
18,05m
Injection depths

advection transport

Water is drawn prevalently from the lower part of the well



Vertical flow velocity

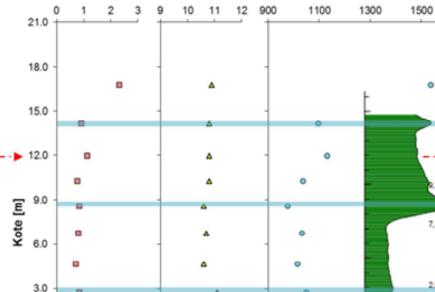
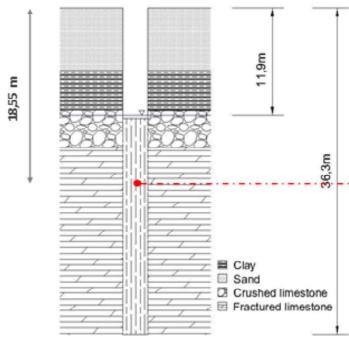


L'investigazione a diverse profondità del pozzo Geo 5 ha consentito di valutare le capacità della prova in esame di relazionare la velocità del flusso verticale alle modalità di trasporto del tracciante.

Results

Geo4

According to **flow log** an outflow fracture is detected in correspondence of a small increase of the flow logged by the flowmeter (**dye go out, across the screen, without spreading**)

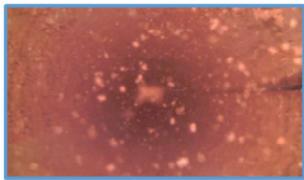


Useful method to investigate location of
Inflow - Outflow fractures

L'investigazione del pozzo Geo 4 ha consentito di valutare la capacità della prova in esame di supportare visivamente dati grafico-numerici.

Field Test - Problems

- High presence of suspended solids



Geo 9



Geo 19s



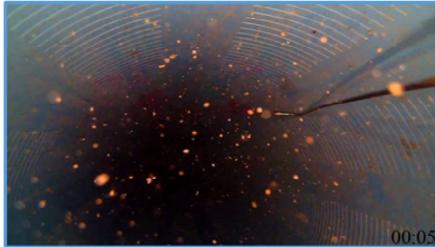
Geo 19d
(screened part)

- Not screened part



Geo 19d
(above screened part)

- Big diameters



Geo 17
22,5 cm of diameter

00:05

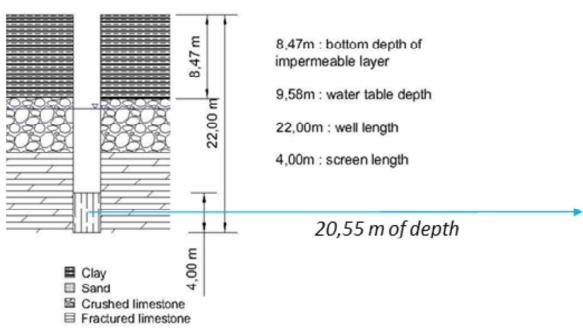
Le caratteristiche e le condizioni del pozzo da investigare costituiscono fattori rilevanti, di cui tener conto all'atto di realizzazione del test.

Results – Geo 19d

- High presence of suspended solids



Distance between the camera screen and the end of the injection pipe was reduced (from 30 cm to 15 cm) in order to improve the view quality



High horizontal velocity component



Swirling motion of the dye

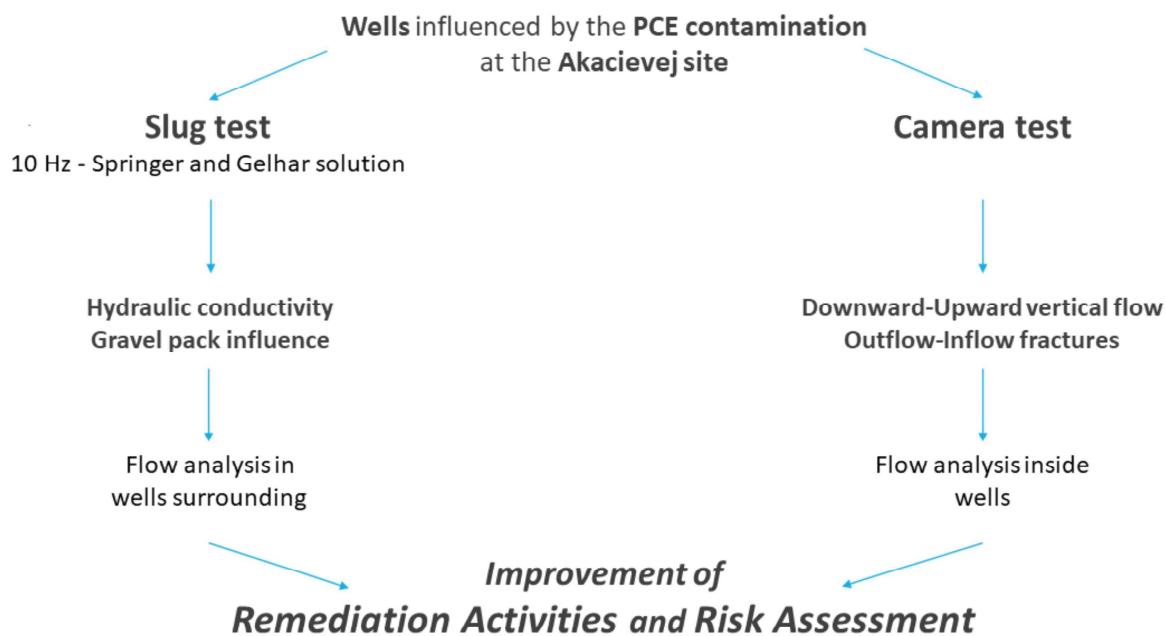
La configurazione della strumentazione può essere modificata a seconda delle condizioni riscontrate nel pozzo da investigare.

Future improvements

- Uncontrollable loss of dye →
 - Pipes with a greater resistance
 - Pipes with a smaller diameter
- Uncontrollable orientation of injection →
 - New lowering method
- Complex test performance →
 - Online-camera
- Influence of wells diameter →
 - Tests at different diameters

La necessità di accorgimenti è indispensabile nel processo di sviluppo di un test di nuova proposizione.

Conclusion



Il continuo sviluppo di modelli ed il reperimento di dati sempre più dettagliati costituiscono processi fondamentali per il miglioramento delle attività di bonifica.

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