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Streaming Potentials Response During Pumping in a Fractured Rock Aquifer

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Abstract

The streaming potential method has emerged as a promising technology for indirect acquisition of spatially dense measurements of hydraulic system state response to pumping. The method relies on measurement of electric potentials that arise from groundwater flow in the presence of the electric double layer at the rock-water interface. Mathematical solutions describing the transient electric potentials associated with pumping tests have been recently developed and demonstrated to yield reasonable estimates of hydraulic parameters (Malama et al., 2009b,a). We report results of laboratory experiments to investigate simulate SP generation in unconfined aquifer under controlled conditions in a lab-scale model instrumented with pressure transducers and non-polarizable electrodes. The measured pressure and streaming potential changes under various pumping rates are presented and discussed. Measurements show unambiguous transient streaming potential responses to groundwater flow in a bounded cylindrical system. Parameters estimated from streaming potential data are comparable to those from drawdown data. Falling-head permeameter tests are used to determine the electrokinetic coupling coefficient (C_ℓ) and hydraulic conductivity (K) of sand from SP data. The field application of the method was conducted in collaborative research work with KAERI in the KAERI Underground Research Tunnel (KURT), which is ongoing. The objective of the field test is to evaluate applicability of the SP methodology to characterizing flow in a fractured rock aquifer.

Lab-scale pumping test simulations

Lab-scale model has a diameter = 173 cm, and comprises: 8 cm layer of bentonite at the base to represent a clay confining layer, and a sand layer thickness = 60 cm. Saturated thickness = 40 cm, and the pumping well is a 1.0 inch PVC tubing with perforations in lower 20 cm. Fine-grained sand from surficial aeolian deposits in SE New Mexico was used in the experiments. When deonized water is added to the sand, it attains an electrical conductivity of $\sim$ 1.0 mS/cm.

SP responses monitored with non-polarizable Petiau ($Pb/PbCl_2$) and biomedical electrodes (Ag/AgCl) at various

- radial distances from the center, and
- depths below the surface.

Two reference electrodes placed in screened PVC tubes filled with sand and placed in fluid filled annulus (see Figure 1). SP measurements are relative to reference electrodes. Column instrumented with biomedical electrodes and moisture sensors to monitor 1D effects of watertable vertical displacement.

Atmospheric, annulus water pressure and fluid pressure in saturated zone measured with pressure transducers. Measurements in saturated sand at

- 3 radial distances (20, 30, 40 cm) from the center, and
- 40 cm below the surface.

Constant head boundary condition maintained around sandtank circumference. Water pumped out from center perforated PVC tubing. Water is recirculated into the tank via a reservior linked to the annulus with an overflow tube.

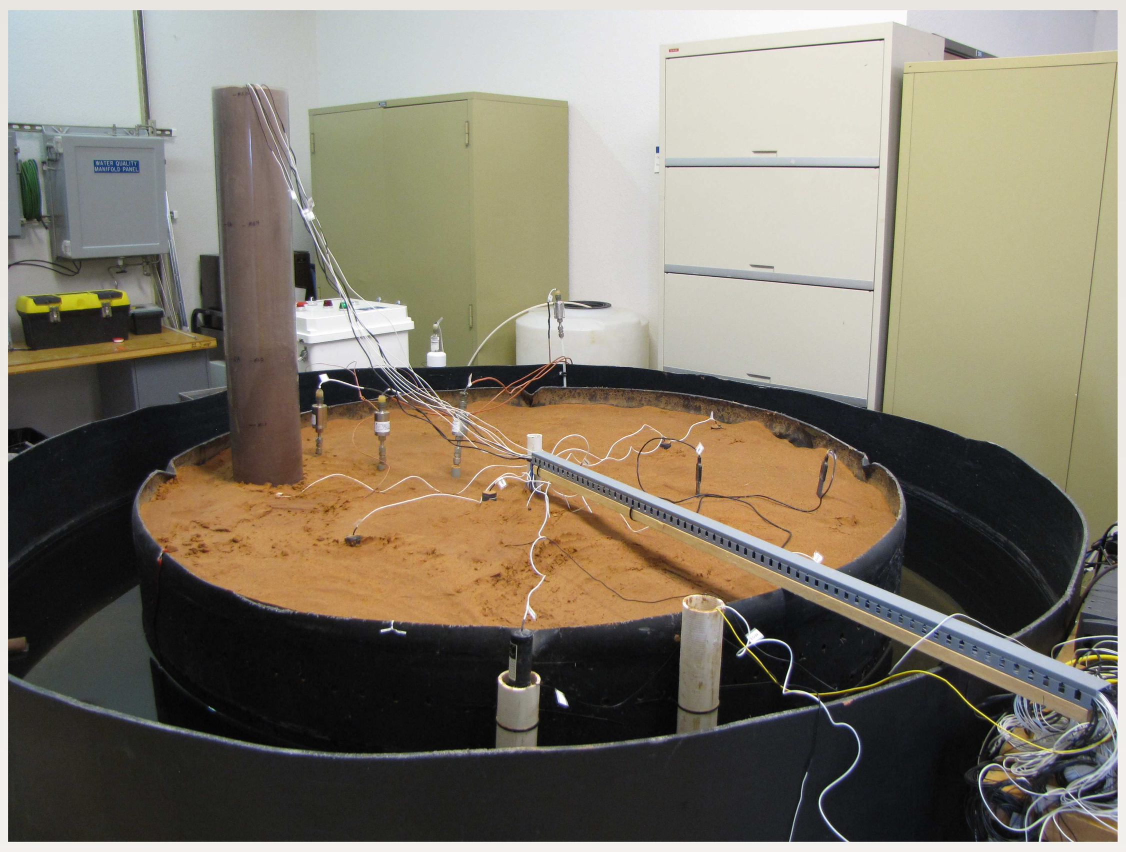

Figure 1: Lab-scale model used in pumping test simulations.

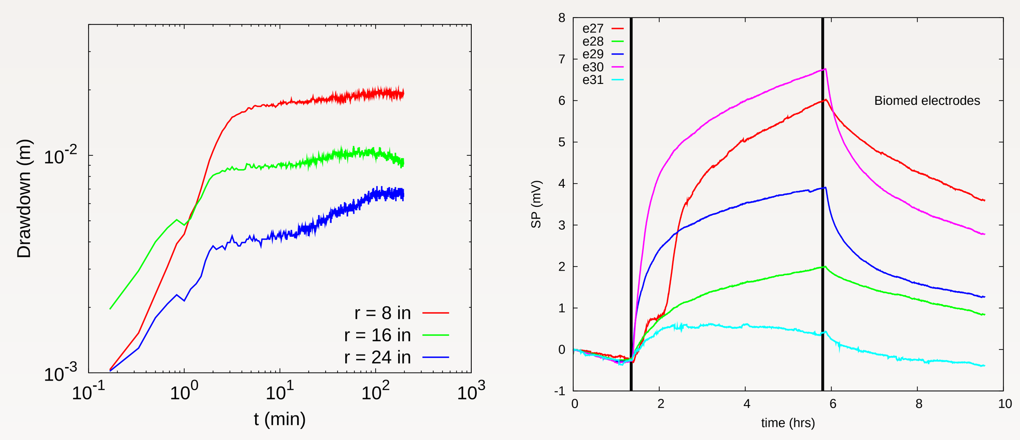

Figure 2: Drawdown and SP data obtained in lab-scale model.

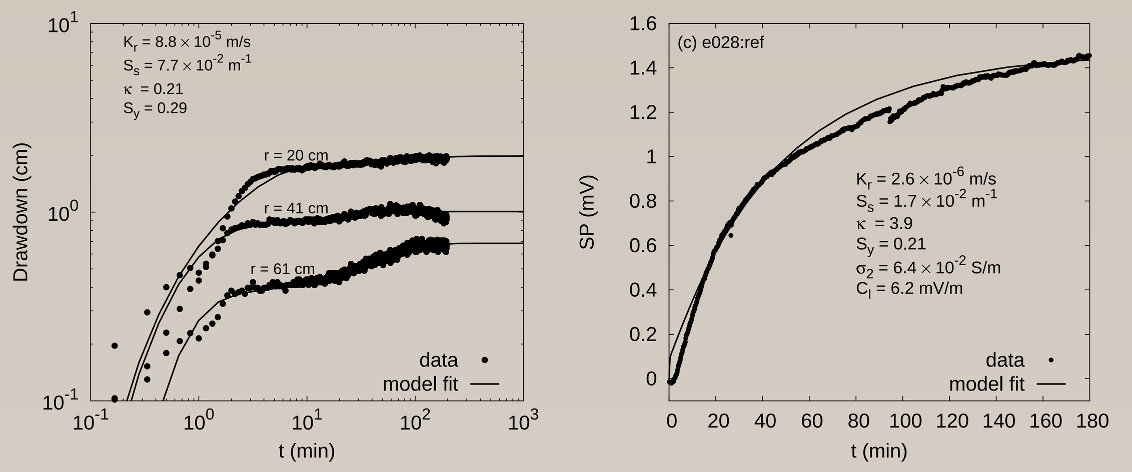

Figure 3: Parameter estimation with analytical model fit to data obtained in lab-scale model.

Parameters were estimated with model of Malama et al. (2009a,b) adapted for a domain of finite radial extent. At lab-scale SP-based hydraulic parameters compare well with those from drawdown data. The model is being extended to include the effect of unsaturated flow using the exponential moisture retention model of Gardner (1958).

Permeameter set-up and Experiments

The electrokinetic coupling coefficient, C_ℓ, is typically measured in the lab using constant-head permeameter tests. We use a falling-head permeameter setup, which is simpler, and demonstrate that SP data from such a setup can be used to estimate both C_ℓ and K. Sample has diameter of 13.9 cm and a length of 25 cm; Falling-head tube has inner diameter of 5.08 cm. Gravel packs are used at sample ends to reduce boundary (end) effects on flow field. Flow is upward through the sample.

Figure 4: Falling-head permeameter and the electrodes used in the experiments. Permeameter SP data obtained with biomedical electrodes.

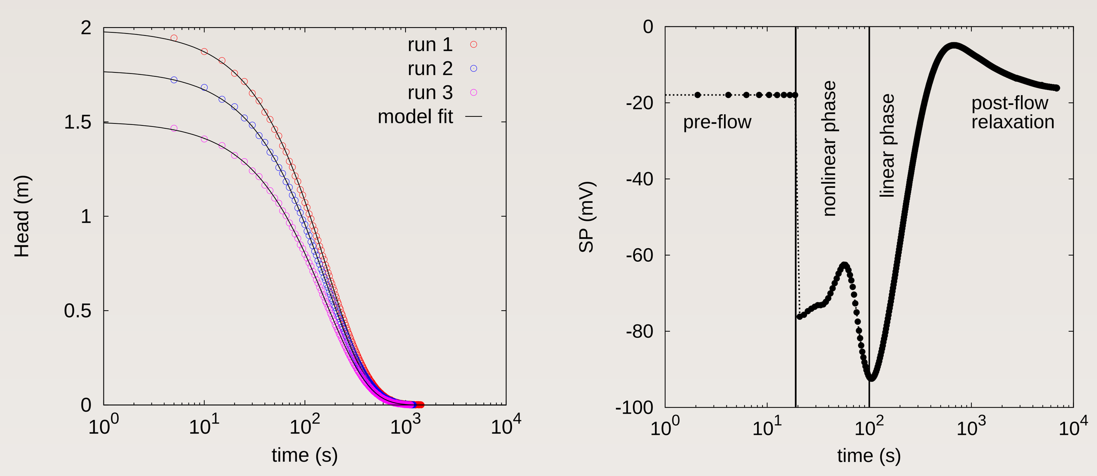

Figure 5: Measured head (with model fit) and SP data showing three observed phases of the response.

Empirical streaming potential model is obtained from

$$\begin{aligned}\phi(t) &= \phi_0 + \phi_1 e^{-\beta t} + \phi_2 e^{-\beta_2 t} \\ &= \phi_0 + C_\ell h(t) + \phi_2 e^{-\beta_2 t}\end{aligned} \qquad (1)$$

where $\phi_1 = h_0 C_\ell$ and $C_\ell = \mathrm{d}\phi/\mathrm{d}h$ is the electrokinetic coupling coefficient, ϕ_2 and β_2 characterize post-flow relaxation. Model does not describe observed early-time behavior, and predicts instantaneous decrease to a much lower SP value than observed upon flow initiation.

Table 1: Parameters estimated from transient h and ϕ data. C_ℓ^* estimated from h vs. ϕ data.

Run	h_0 (m)	β_{flow} ($\times10^{-3}$)	β_{sp} ($\times10^{-3}$)	β_2 ($\times10^{-3}$)	K_{flow} (m/d)	K_{sp} (m/d)	C_ℓ (mV/m)	C_ℓ^* (mV/m)
1	1.99	6.10	6.24	0.98	**17.6**	**18.0**	-93.5	-91.2
2	1.78	6.19	6.14	1.04	**17.9**	**17.7**	-95.6	-91.3
3	1.50	6.27	6.38	1.02	**18.1**	**18.4**	-92.0	-82.1

- If early-time behavior is modeled correctly, the estimated value of C_ℓ may be different.
- $C_\ell^* \lesssim C_\ell$; C_ℓ is from ϕ vs. t (fig 6(a)), and C_ℓ^* is from ϕ vs. h.
- Early-time SP response attributed to spatial effects that are ignored in lumped-parameter conceptualization. Even though lumped-parameter model is adequate for the flow problem even at early-time, this is not be the case for SP.
- Post-flow relaxation is due to diffusion-driven re-establishment of initial equilibrium state. Characteristic time scale of post-flow relaxation is much longer than that of the flow phase.
- Estimates of K from SP data are comparable to those from head data.
- **First time** SP data from falling-head permeameter used to estimate K.

Field-scale SP tests in KAERI's KURT

KURT is a research tunnel for underground waste disposal and site characterization. It is set in a mesozoic granite host rock and has a 6×6 m^2 cross-section and a total length of 252 m. The test site was chosen for collaborative research in streaming potentials associated with pumping tests conducted in fractured rock. It comprises nine open boreholes that were drilled into the tunnel floor to a depth of about 10 m. Fractures in boreholes have been mapped with an acoustic televiewer. The fractured granite gost-rock is saturated with groundwater that has a high in-situ pH ($\sim$ 8.4). Traditional pumping tests and slug tests have been performed to hydraulically characterize the fractured rock. The objective of current collaborative research work is to determine whether measurable SP signals can be generated during pumping tests in fractured rock, and if so, whether these can be used to estimate hydraulic parameters. SP-based hydraulic parameters can then be compared to those obtained by traditional hydraulic test analyses.

Figure 6: Entrance to KURT and streaming potential experimental area.

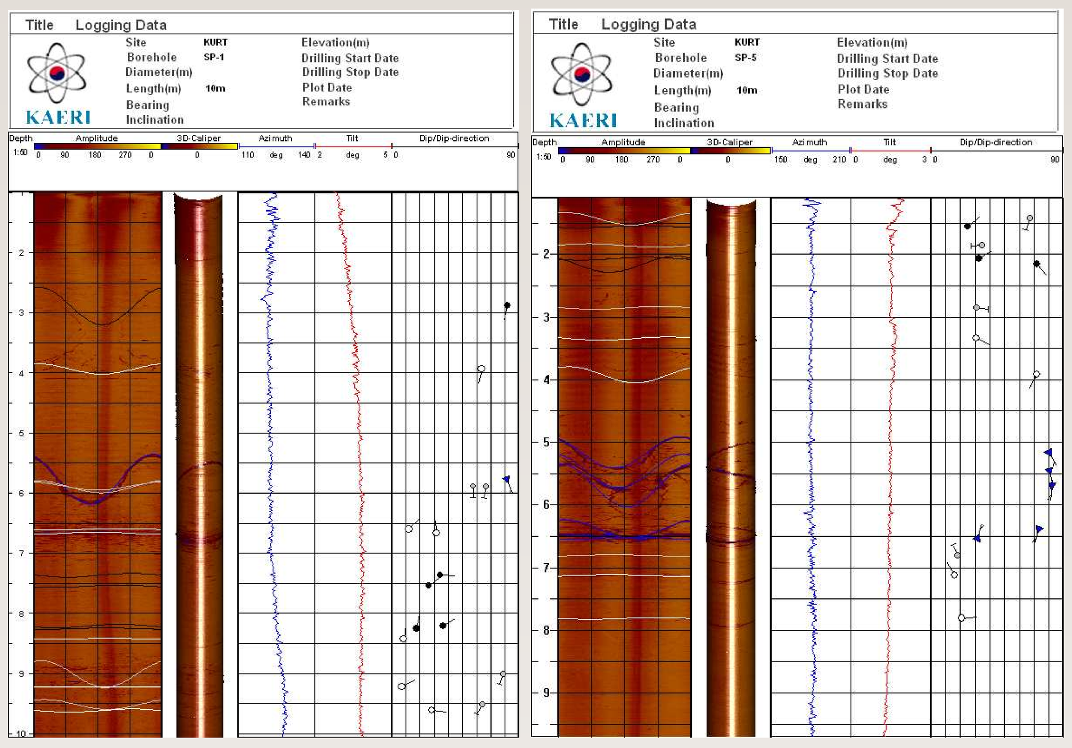

Figure 7: Acoustic televiewer images of two bore-holes in the KURT showing fracture orientations. SP-5 served as pumping well.

Flow occurs predominantly in fractures, which have very low storage. Drawdown data show inflections that are reminiscent of multiple storage mechanisms (multiple porosities associated with major and local fractures, dead-end pores and rock matrix porosity), fracture terminations and intersections with other fractures.

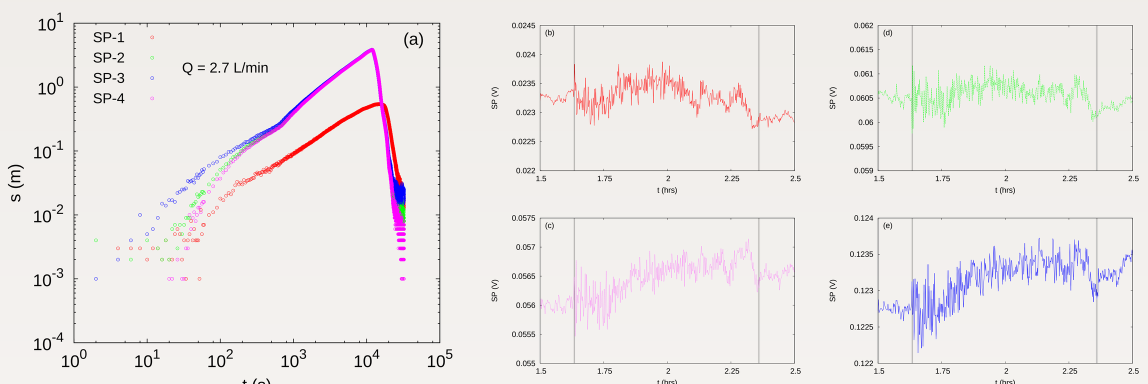

Figure 8: Drawdown and SP response to pumping in central borehole SP-5 of the SP test area in the KURT.

Streaming potential measurements have yielded data that are corrupted with high frequency ($\sim$ 50 Hz) noise associated with the pump electrical supply. This noise needs to be filtered out for the data to be amenable to further analysis. The high resistivity of the granite host rock, high electrode-to-rock contact resistance, and high pH of the groundwater also appear to compromise the SP signal. Work is underway to improve signal-to-noise ratio by (1) use of a dipole electrode arrangement where the reference electrode is installed in one of the boreholes, and (2) minimizing electrical contact between pump and groundwater.

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