A nitrogen slug permeability testing system

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ABSTRACT The collection of accurate hydraulic conductivity data is a key component of most hydrogeological site investigations. Transient, single well “slug” tests are commonly used to collect spatially-distributed permeability data. However, the results can be unreliable, particularly in high permeability formations. Inaccuracies related to difficulties in establishing an “instantaneous” change in water level and collection of accurate early-time response data may occur. Klohn Crippen has developed a nitrogen-based permeability testing system to address such difficulties. Compressed nitrogen takes the place of conventional solid slugs or water injection/removal. A rapid water level change is established through the evacuation of the nitrogen from the testing interval, and a transducer/datalogger is utilized to frequently measure the water level response during testing. The testing setup allows for a rapid testing sequence using a variety of slug sizes. Use of this system in high-permeability formations may result in oscillating water level response data, for which several analytical solutions are available to determine hydraulic conductivity. The use of nitrogen minimizes the potential for affecting local water chemistry, although compressed air may also be used if this is not a consideration. This paper discusses the design, applications and limitations of the nitrogen injection permeability testing system and the interpretation of the data collected.

Introduction

Collection of accurate permeability data is a key component of most hydrogeological or geotechnical investigations. Permeability data may be obtained in-situ, typically through test pumping, slug testing or tracer testing, and through laboratory testing methods. Open, standpipe-type piezometers installed for groundwater monitoring purposes may be slug-tested to provide hydraulic conductivity data of the monitored interval. Slug testing can provide reasonable data provided the practitioner is aware of the correct interpretation required, based on site hydrogeological conditions, and the various limitations of the method. These limitations can include, but are not limited to the following:

- Well “skin effects” associated with annular formation damage due to the drilling technique utilized and/or from insufficient well development;
- Deviations from “ideal” conditions associated with the analytical solution utilized, such as heterogeneity and/or anisotropy, a variably confined/unconfined environment, a sloping piezometric surface or variable density groundwater;
- Significant hydraulic losses due to frictional effects during the slug test as a result of the well construction and/or the testing method used;
- Loss of critical early-time test response data; and
- Failure to impose an initial “instantaneous” change in hydraulic head.

The latter two problems are commonly associated with testing in high permeability formations. There are numerous analytical solutions available for interpretation of slug testing data. All of these solutions assume that an “instantaneous” change in hydraulic head, or “slug”, has been imposed in the well tested. In practical terms, good results may be obtained from a change in hydraulic head imposed over a matter of minutes for a well installed in a low permeability formation, that responds back to a static water level over the course of hours or days. However, in highly permeable media, with effective transmissivities in the range of 1×10^{-4} m^2/s and greater, a slug must be typically removed within a second or less to provide reasonable results.

Slug testing of piezometers installed within highly permeable media can be particularly problematic. Tests are frequently complete within a matter of seconds, and manual collection of data is difficult and typically inaccurate. Use of a downhole pressure transducer/datalogger (transducer) circumvents some of these problems; however removing or adding a slug in a small diameter well is difficult without disturbing the transducer. Furthermore, displacing the water level by inserting or removing a solid slug is difficult to undertake instantaneously. The water level response is often well underway by the time the slug has been fully displaced, and early time test data may not be recorded. Displacement of the water level by adding or removing water is similarly problematic because of cascading of water down the well casing.

The authors have developed a nitrogen-based slug testing system that addresses these difficulties, and provides a means of capturing more accurate hydraulic conductivity data in high permeability strata.

System Description and Installation

Following measurement of the static water level in the piezometer to be tested, the testing system may be installed. A schematic diagram of the test apparatus is provided in Fig. 1. Key components of the system include:

- A transducer capable of frequent data acquisition (at least 2, and preferably 5 to 10 readings per second);
- A nitrogen injection “head” unit for control of downhole injection pressures and rapid release of nitrogen, or compressed air, at commencement of testing; and,
- A regulated supply of compressed nitrogen and air, with a pressure regulator rated to 1380 Kpa (200 psi) maximum, and calibrated for maintaining lower pressures as required.

The injection head unit is the key component to the system design. The head has been constructed to fit within a standard 49 mm ID PVC piezometer casing, although the system could be adapted to smaller or larger diameter wells. The system is sealed inside the piezometer casing near surface with a mechanical packer. The injection head unit includes a port for injection of compressed gas into the piezometer and a pressure relief valve for gas expansion and commencement of testing.

Prior to installation of the injection head unit and sealing with the mechanical packer, the transducer is installed inside the piezometer. The transducer cable, either a stranded steel suspension cable (down hole datalogger), or vented cable for direct-read units (surface datalogger), extends through the center of the injection head unit and is sealed in with a rubber seal. If the transducer does not have direct-read capability, data acquisition must be initiated before transducer and injection head unit installation.

The nitrogen supply is then connected to the injection port with appropriately rated compression fittings and pressure tubing. Nitrogen is the preferred gas for injection use, particularly where groundwater quality is a consideration, as the gas will not oxidize organic or inorganic constituents in the groundwater. A photograph of the testing setup is provided in Fig. 2.

System Operation

Once installed, a starting pressure of less than 200 kPa (30 psi) is applied downhole and maintained using the supply bottle regulator. Analogous to changes in atmospheric pressure, the nitrogen injection will force the water surface in the piezometer downward an amount related to the barometric efficiency of the formation, as shown in Fig. 3a. The barometric efficiency of an aquifer is equivalent to the change of pressure head of the aquifer

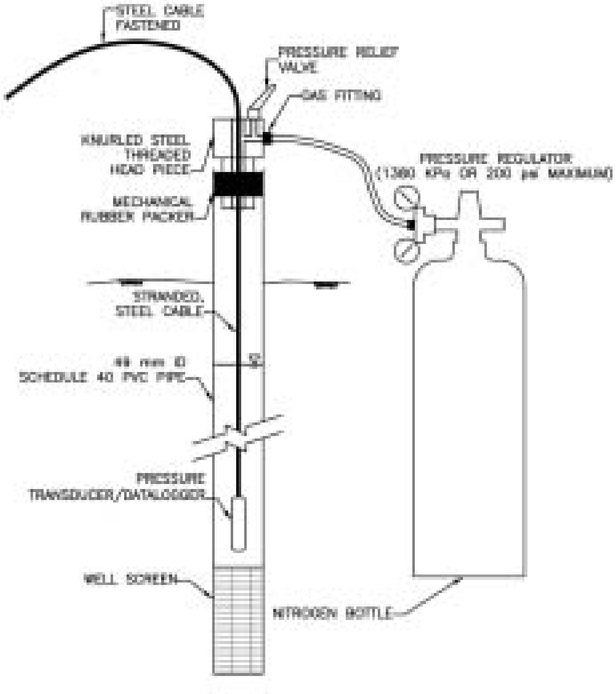

Fig. 1. Schematic layout of the nitrogen- slug permeability test system.

Fig. 2. Use of the testing system in the field.

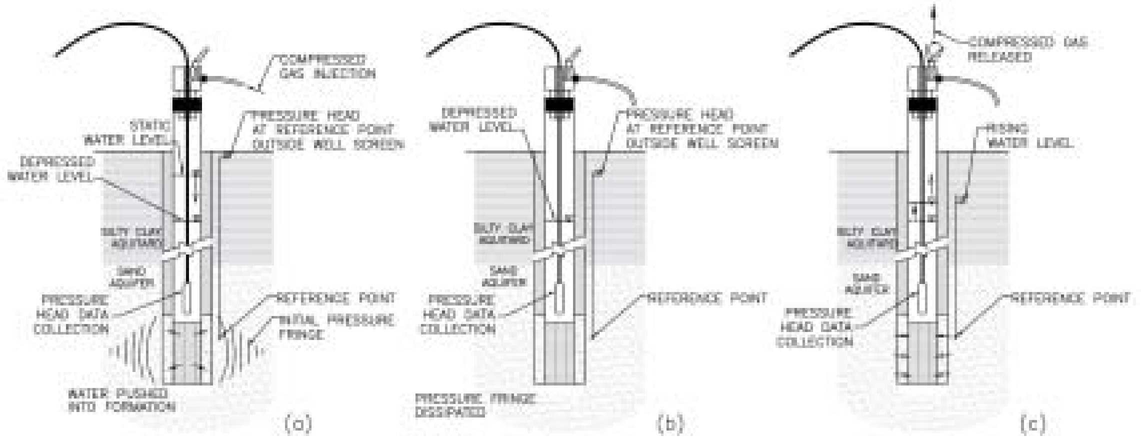

Fig. 3. Operation of the nitrogen slug permeability testing system. (a) Injection of compressed gas causing pressure fringe in formation. (b) Dissipation of the pressure fringe to static piezometric condition. (c) Release of gas pressure to initiate rising head slug test.

divided by the change in atmospheric pressure (Freeze and Cherry, 1979).

Prior to the injection of compressed gas, the total pore pressure at the piezometer intake is the atmospheric pressure plus the weight of the water column. The injection of compressed gas increases the total pressure inside the piezometer, causing a "fringe" of excess pore pressure to develop in the formation surrounding the piezometer intake. The pressure fringe dissipates as the height of the water column inside the piezometer decreases, until the former static piezometric head is reached.

This pressure fringe dissipation will occur at a rate directly proportional to the effective transmissivity of the piezometer intake and surrounding formation. In this context, the "effective" transmissivity is defined as approximately equivalent to the formation hydraulic conductivity multiplied by screen length, depending on the geometry of the installation. If the transducer is installed with a direct readout at surface, the time required for the pressure fringe to dissipate to static conditions will be directly observable. If the transducer is installed without direct readout capability, judgment will be required to assess when the surrounding formation reaches static conditions. In most cases this will range from a few seconds to a few minutes, since the application of this system is designed for high-permeability formations. It should be confirmed that the slug test was initiated at static conditions following retrieval of the data.

During the period of aquifer pressure stabilization, the lock-in gas pressure should be monitored and the system checked to ensure there are no significant leaks. The use of wells constructed with flush-threaded, lock-tight pipe joints, equipped with rubber O-rings, is recommended. Wells completed with substantial bentonite clay and/or cement seals above the testing interval, and at surface, also maintain pressures best. In this regard, the system may also be used to test the integrity of the well construction and annular seals.

If some minor leakage occurs, it may be possible to establish quasi-static pressure conditions by continuously adding compressed gas to the testing interval, to maintain a relatively steady pressure inside the well.

Maximum lock-in pressures in excess of 200 kPa (30 psi) are not recommended for the following reasons:

- The mechanical packer may fail, and the unit will be ejected under pressure from the piezometer;
- Test responses with initial slugs of greater than a few m may be inaccurate due to hydraulic inefficiencies; and
- Pressures greater than this may threaten the integrity of the piezometer construction and/or annular seals.

Once the system is at static pressure conditions, a rising-head slug test may be initiated by venting the compressed gas from the piezometer via the quick-release valve on the top of the injection head unit, as shown in Fig. 3c. The datalogger will record the pressure response observed at the transducer.

The tests should be repeated with different slug sizes by varying the locked-in injection pressures inside the piezometer. With this system, and particularly with a direct readout transducer setup, several tests may be accomplished within a few minutes, depending on the permeability of the test interval.

The system likely will not work well where the monitoring well screen straddles the water table. In this case, gas will vent into the unsaturated formation and erratic data may result.

Test Examples

The system was used for permeability testing in a number of deep monitoring wells at a site in the interior of British Columbia. The wells were installed within an unconfined to semi-confined sand and gravel alluvial terrace aquifer. Depth to water table ranged from approximately 5 m to 60 m. For economic reasons, the substantial depth to groundwater over much of the site generally precluded the use of conventional test pumping methods for the assessment of aquifer hydraulic properties. Some interpretation of hydraulic conductivity using grain size data was undertaken, however the soil samples collected were not considered entirely reliable, due to the air rotary drilling technique utilized, which caused significant mixing of samples and some loss of fines during circulation. The monitoring wells were screened across high permeability sands and gravels at a substantial depth, and were, as a result, difficult to test using conventional slug test methods.

Wells with static water levels up to 60 m below ground were tested successfully using this method. Furthermore, and despite the significant depth to the piezometric level, only limited quantities of compressed gas were required to establish an effective slug.

The first set of test results is presented in Fig. 4. This test was conducted in a 49 mm ID monitoring well with the well intake from 70.6 m to 75.1 m below ground, and a piezometric level of 11.13 m below ground. The well screen was installed in an unconfined to semi-confined fine sand that extends below a depth of 77.7 m.

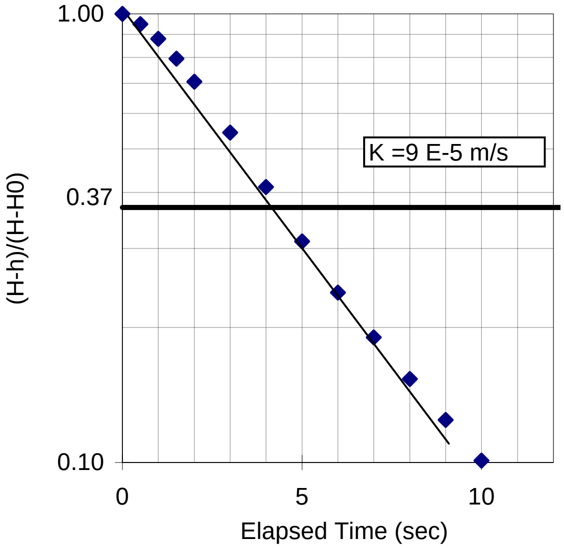

Fig. 4. Rising head slug response for Monitoring Well MW2002-1A, analyzed using a Hvorslev (1951) solution.

Fig. 4 shows a conventional semi-logarithmic slug test plot with the ratio of unrecovered piezometric head (H-h) to initial slug head ($H-H_0$) plotted against elapsed time. For this test, 90% of the test response occurred within 10 seconds.

The last 10% of test response is generally considered to be less reliable than the foregoing 90% of the test, since this late-time response is more strongly affected by observational errors (Hvorslev 1951), and by deviations from the ideal conditions assumed by the analytical solution. For this well, it is therefore critical to collect data from within the first 10 seconds of initiating the test. This would be difficult to accomplish using conventional slug testing methods, especially with the water table at 48.38 m below the ground surface. A hydraulic conductivity of 9×10^{-5} m/s was interpreted for this test, using the analytical solution of Hvorslev (1951). The piezometer intake length was 4.5 m, so an effective transmissivity of approximately 4×10^{-4} m^2/s is interpreted for this testing setup.

The test data is effectively linear when plotted, although there is a slight downward curvature to the response curve during the first two seconds of groundwater level recovery. This dampening of the early-time response data is interpreted to be a result of the finite time required for the gas to escape the well. Design improvements to the injection head unit, including increasing the diameter of the relief valve, would likely serve to reduce this period of response dampening. However, with the rate of data acquisition possible with commercially available transducers, the data does indicate that there is a practical upper limit to the effective transmissivity that may be tested, estimated to be in the range of 1×10^{-2} m^2/s to 5×10^{-2} m^2/s. The well intake length may be limited in order to test to the highest possible hydraulic conductivity. However, testing in the high-permeability realm presents other difficulties, largely related with hydraulic losses at the piezometer slotted intake and in the immediately surrounding formation. Consideration must be given to constructing wells as hydraulically efficient as possible. At the very least, the well screen slot size and filter pack should be matched to the formation grading, such that the intake does not have a lower permeability than the formation.

The second test was conducted in a 49 mm ID monitoring well with well intake from 18.5 m to 23.1 m below ground, and with a piezometric level at 3.72 m below ground. Fig. 5 shows a linear plot with the ratio of unrecovered piezometric head (H-h) to initial slug head ($H-H_0$) plotted against elapsed time. For this test, 90% of the test response to static water level occurred within 2.2 seconds of commencement of testing. The initial amplitude of this oscillating response was 16.8 cm.

Discernible oscillating responses are typically observed when sufficient momentum is generated in the rising water column to overcome hydraulic losses, or frictional effects, within the well. This response is a function of the permeability of the formation and the mass of the water column, is typically observed in high permeability formations, and particularly where a well contains a significant water column depth.

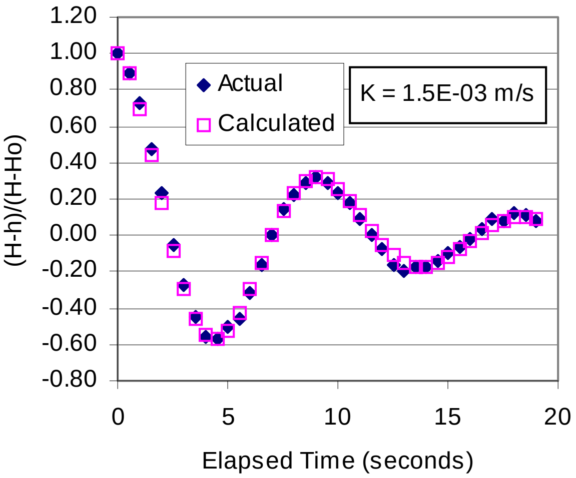

Fig. 5. Response for Monitoring Well MW2001-6B, analyzed using the McIlwee et al. (1992).

A hydraulic conductivity of 1.5 x 10^{-3} m/s was interpreted for this test using the analytical solution of McIlwee et al. (1992). This solution employs a curve-fitting technique based on adjusting the period and dampening factors. The piezometer intake length was 4.6 m, so an effective transmissivity of approximately 6.9 x 10^{-3} m^2/s is interpreted for this testing setup.

Van der Kamp (1976) presents oscillating test examples with initial response amplitudes of a few centimeters or less. Van der Kamp recommends the imposition of relatively small slug displacements in order to reduce the effect of friction losses within the well.

The collection of high-quality oscillating response data provides an additional source of quality control when estimating hydraulic conductivity.

Summary

The design and application of the nitrogen slug permeability testing system are summarized below.

- The nitrogen slug permeability testing system consists of a transducer capable of frequent data acquisition (at least 2 readings per second); a nitrogen injection head unit for control of downhole injection and release of compressed air; and a regulated supply of compressed nitrogen and air, with a maximum 1380 kPa (200 psi) pressure regulator;
- The system captures critical early time data, necessary for obtaining accurate hydraulic conductivity estimates for highly permeable formations, and is more effective than conventional slugs in imposing near-instantaneous changes in hydraulic head;
- The system does not work well for slotted casing straddling the water table due to loss of gas and pressure into the unsaturated zone; and,
- The time required for the gas to vent from the well causes a dampening effect of initial results. This limitation, and the data acquisition rates of commercially available transducers provides a likely upper transmissivity limit for testing in the range of 1 x 10^{-2} m^2/s to 5 x 10^{-2} m^2/s.

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