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An Effective Well Development Method for Deep Screen Completed Wells

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ABSTRACT

In Lund, Sweden productivity problems were encountered during flow testing of a 1927 m deep gravel packed screen completed well and it became apparent that well development was needed to increase productivity. A hydro-jetting system using coiled tubing in combination with simultaneous pumping was developed and tested and found to be successful. To verify whether the well development improved the well, the results of a pumping test conducted before and after the jetting operation were compared. In addition flowmeter logging during the jetting operation was also used to verify the improvements. Hydro-jetting in combination with simultaneous pumping proved to be an effective cleaning method. After 100 minutes of pumping, there was approximately 110 m less drawdown and 15 l/s higher average flow rate compared to the values before the jetting operation. Influence of wellbore storage was significant during the flow tests carried out before the well development, but was negligible thereafter.

1. INTRODUCTION

The need for well development is always important to consider before conducting the final flow test of a well. This is especially true when conducting a single well test, where near well disturbances can affect and make the interpretation of the aquifer properties more difficult. The cost of well development is often not a big issue for the oil and gas industry, but is more critical for geothermal applications and even more for groundwater applications. Well development methods such as pumping, surging and airlifting can always be applied as a first step in the stimulation of a deep well if a pump or compressor is available on-site. However, there are certain situations where a pump or compressor may not be sufficient, such as if great lifting capacity and/or great air-volumes are required due to a large casing diameter. On the other hand, the application of other well development methods such as swabbing or jetting in deep wells are more complicated. These methods often require a rig and can be quite expensive. One way to decrease the cost of well development is to increase the down- and up-hole transportation of the required equipment and to have a system to verify the improvements of the cleaning.

A cost-effective and successful well development method was used in a deep geothermal well project in Lund. Hydro-jetting using coiled tubing in combination with simultaneous pumping was used and later verified by flowmeter logging. This method can easily be applied for stimulating other deep wells. During flow testing, it became apparent that stimulation was needed to increase the productivity of the well. Several commonly used well development methods were investigated, and hydro-jetting using coiled tubing in combination with simultaneous pumping was found to be the most suitable. It is also time-efficient to use coiled tubing instead of conventional tubing, where a stop is required every 9-27 m (depending on the rig height) to remove or add drill pipe or tubing. Coiled tubing provides a rapid transportation of the jetting tool, which is of great importance in deep wells, where the transport to get into position is time consuming and expensive. To optimize the jetting operation, short term pumping tests and flowmeter loggings were used. The development of the deep well DGE#2 in Lund will be described in detail in this paper.

1.1 Background

In 2000, the Department of Engineering Geology at Lund University began to investigate the feasibility of extracting hot water from deep-seated fractures in the crystalline basement created by tectonic activity in the Tornquist deformation zone close to the city of Lund (Bjelm and Rosberg 2006; Alm and Bjelm 2006). The drilling of the first exploration well started during autumn 2002 and became the second deepest drilling project in Sweden, with a depth of 3701.8 m (Bjelm 2006). After intensive testing, the basement was abandoned as a potential production zone (Rosberg 2007). A fall-back project was then begun to determine the hydraulic properties of a number of sandstones in the sedimentary sequence, about 1950 m deep, resting on the gneiss basement. The focus was set on the sandstones belonging to the Early and Late Cretaceous.

Perforation and flow testing of the potential production zones in the sedimentary sequence were carried out and after evaluation it was decided to drill a second well (Rosberg 2006). The second well, DGE#2, was drilled during the summer of 2004 to a total depth of 1927 m aiming for the same sandstones. Rotary drilling with potassium chloride (KCl) polymer mud was used down to the actual production zones. A dual screen completion was used in DGE#2. The upper screen, installed between 1507 m, and 1539 m is a 9.1" (231 mm) pipe-based, wire-wrapped stainless steel screen. The lower screen, installed between 1569 m and 1673 m, is a 7" (178 mm) wire-wrapped stainless steel screen. The space between the completion liner and the formation is gravel packed.

1.2 Geology

The deep wells in Lund are located within a fault zone running along the Romele horst ridge. The faulting is both normal and reverse. The vertical displacement in this area can be as much as 1500-2000 m. In a regional perspective, the investigated area is a part of the Tornquist zone (also called Tornquist-Teisseyre zone), which is one of the major geological structures in northern Europe. The Tornquist zone is a major tectonic deformation zone which stretches from the North Sea into Poland and continues southeast to the Black Sea (Lindström et al. 1991).

A simplified stratigraphy for the deep well DGE#2 is presented in Figure 1. As can be seen there are three time inversions in the stratigraphic column, confirming the drilling was carried out in a zone with heavy faulting. The potential production zone, at 1507-1539 m where the upper screen is installed, consists of fairly homogenous sandstone (Erlström 2004). The sandstone belongs to the Aelian subdivision within the Early Jurassic. The other production zone, at 1569-1673 m where the lower screen is installed, consists of unconsolidated or poorly consolidated quartz sand (Erlström 2004). The age of the sand is not defined, but it is assumed to belong to the transition zone between Early/Middle Jurassic and Early Cretaceous.

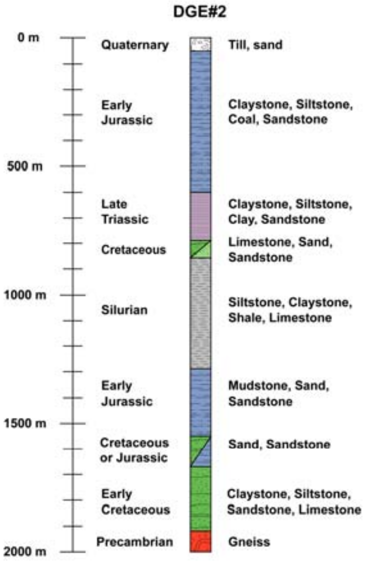

Figure 1: Simplified stratigraphy for the borehole DGE#2. Note that there are three time inversions in the stratigraphic column.

2. METHODS FOR THE WELL DEVELOPMENT

The jetting operation was carried out using coiled tubing equipment (OD 2 ⅜" (60.3 mm)), which consists of a coiled tubing reel of 2000 m, jetting tools, an electrical submersible pump, piston pumps, settling ponds, transfer pumps and cyclones. (See Figure 2.) This system was designed for re-using the produced fluid. The transfer pumps placed in the pond transferred the formation water to the cyclones placed next to the piston pumps, thus allowing for separation of fine particles from the water. The piston pumps forced the water through the coil and the jetting tool. The electrical submersible pump was used to simultaneously lift out the debris and transfer the water to the settling ponds. A parasite string (ID 131.7 mm) was attached to the column riser pipe to guide the jetting equipment and logging tools past the pump. The non-rotational jetting tool consisted of 8 nozzles with opening diameters of 4.5 mm oriented horizontally. The tool was equipped with two extra nozzles pointing downwards for cleaning settled formation material from the sump.

Numerous jetting runs were carried out to improve the inflow to the well. Recommendations from Driscoll (1986) were used to specify the jetting velocity, nozzle pressure and the pulling speed of the jetting tool. The recommended jetting velocity in our case was 30.5-91.5 m/s, maximum nozzle pressure was around 27 bar, and the pulling speed of the jetting tool was 1.2-3.7 m/h. The jetting velocities and jetting tool speeds for the different jetting runs are presented in Table 1. Deviations from the recommended pulling speed can be found in Table 1, which were more of an economical issue than a technical one. However, the entire screen was jetted once with the recommended pulling speed. The nozzle pressure varied between 20 and 27 bar, with an average pressure of around 20 bar. The maximum pressure was only used at the upper screen, where the formation was considered to be more resistant to high pressure jetting compared to the formation at the lower screen. The movement of the jetting tool was always upwards while jetting. To minimize settling of debris in the wellbore, the electrical submersible pump was not shut down until one hour or more after the jetting was terminated. During all jetting runs the outgoing water was visually inspected for formation particles, a way to evaluate of the cleaning of the well. The total volumetric flow rate through the coil and the jetting tool varied between 200 l/min and 700 l/min. But the outflow from the well detected by the ESP was much greater at around 1800-2400 l/min.

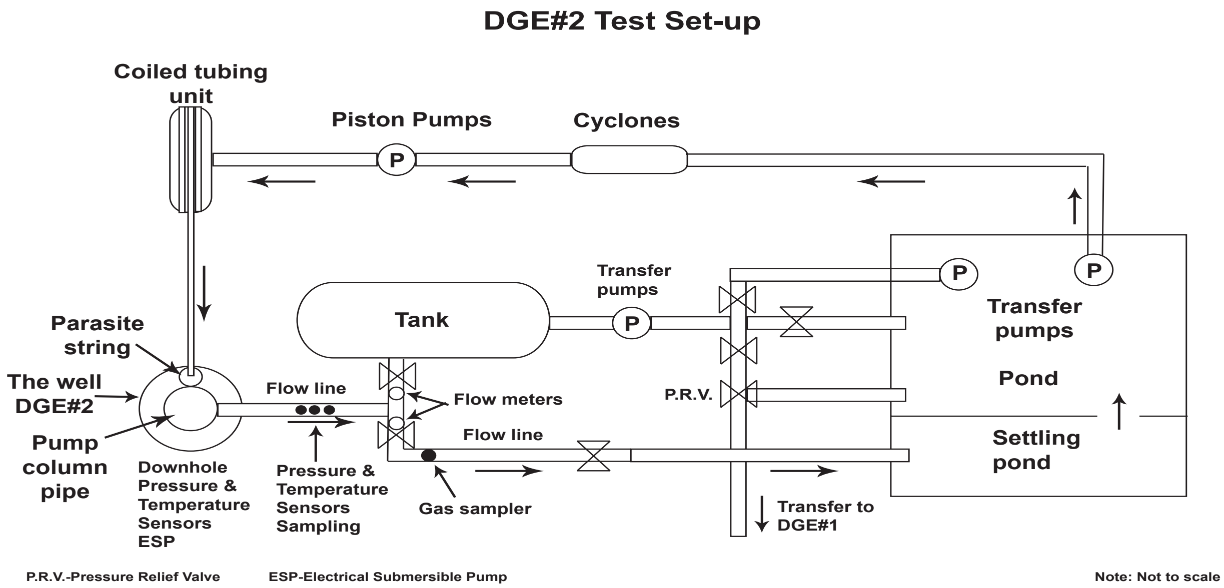

Figure 2: Diagram of the test set-up used for the well development of DGE#2.

Table 1. The different jetting runs in DGE#2.

Date	Jet velocity (m/s)	Pulling speed (m/h)	Cleaned interval	Remarks
2004-12-02			Sump	Cleaning the sump
2004-12-04	31	4	1673-1652 m	Lower screen
2004-12-05	31	3.9	1652-1613 m	Lower screen
2004-12-06	31	4	1613-1569 m	Lower screen
2004-12-07				
Run 1	77	15	1539-1507 m	Upper screen
Run 2	88	20	1539-1507 m	Upper screen
Run 3	88	15	1539-1507 m	Upper screen
Run 4	77	15	1673-1656 m	Lower screen
2004-12-08	77	8	1673-1569 m	Lower screen
2004-12-09	80	20	1673-1569 m 1539-1507 m	Lower screen Upper screen
2004-12-10	85		Sump	Cleaning the sump
2004-12-12	90	4.5	1539-1507 m	Upper screen
2004-12-13		8	1539-1507 m	New jetting tool with larger diameter
2004-12-14	77	10	1673-1640 m	Lower screen
2004-12-15	90		Sump	Cleaning the sump

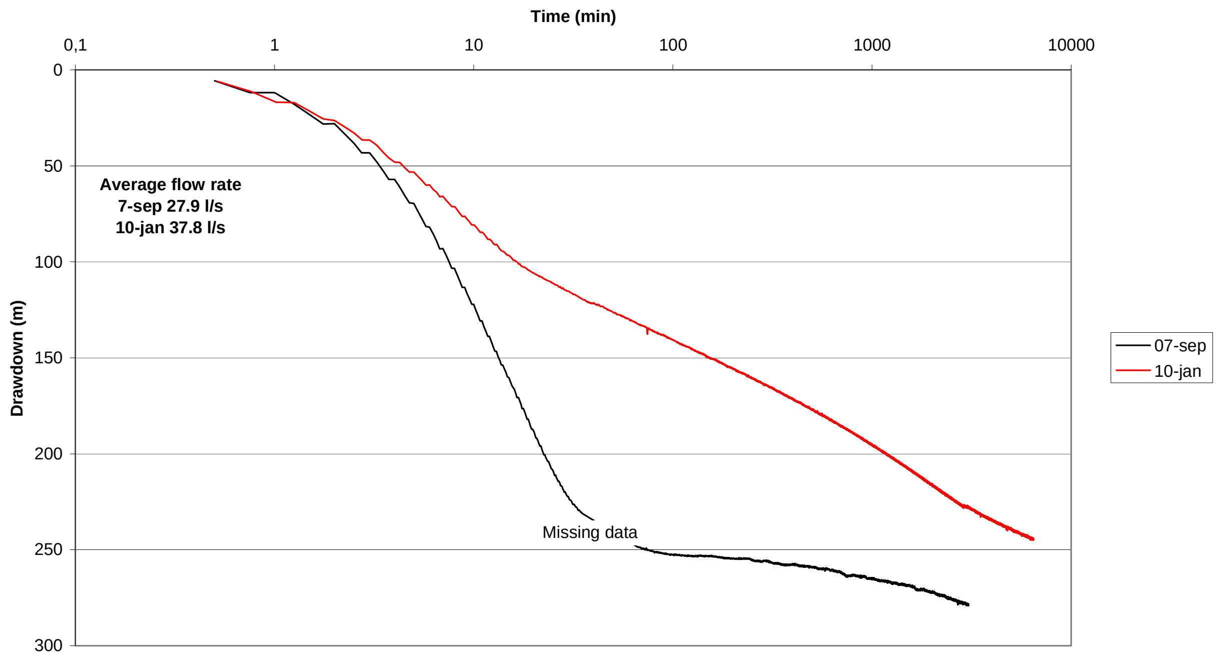

Figure 3: Comparison of drawdown data acquired before and after jetting.

The rest of the volume was disposed of in another deep well: DGE#1. The effect of the jetting operation was also verified by impeller flowmeter measurements. In other words, the flowmeter logging was used as verification of the jetting operation. Data acquired from a flowmeter logging carried out before the stimulation was used as reference data. The flowmeter logging was easy to perform due to the parasite string attached to the pump column pipe, as shown in Figure 2.

Short term pumping tests were conducted 10 hours or more after the jetting was finished to evaluate the cleaning effect of the jetting operation. A speed controlled submersible pump was used, and the same pump speed was used for all tests. A downhole pressure and temperature sensor was installed with the pump, which made it possible to use real time monitoring. In addition, memory gauges were used as a back up. The flow rate was measured by using a Woltmann reverse flow meter, a type of turbine meter. A detailed description can be found in Rosberg (2007).

Other well development methods were also conducted in addition to the hydrojetting. The first method, performed before the jetting operation, included the speed controlled electrical submersible pump. A maximum frequency of 70 Hz and a minimum of 40 Hz were used during the well development. The use of a frequency of 70 Hz created a large pressure drop in the well and increased the inflow to the well. Before the pump ran dry, the frequency was changed to 40 Hz, causing the pressure to increase and the inflow to decrease. A process with a rapid pressure drop followed by a slow recovery of pressure stresses the formation and can thereby clean the well. The pressure drop was around 27-28 bar, and about 250 m of the water column was removed from the wellbore. The produced fluid was visually inspected for formation particles. Another method was to use the jetting tool as a type of surge block, lowering it rapidly (600 m/h) in steps of 20 m. This was possible due to the use of the coiled tubing unit. In this case there was a 13 mm annulus between the screen and the tool, compared to conventional surging where in practice there is contact between the surge block and the screen (e.g. Driscoll 1986; Roscoe Moss Company 1990). When lowering the tool rapidly, water is forced out through the slots in the screen, thereby stimulating the gravel pack. The method was only applied along the lower screen section.

3. RESULTS FROM THE WELL DEVELOPMENT

To verify the efficiency of the well development, a pumping test conducted before and after the jetting operation were compared. (See Figure 3.) Parameters such as wellbore storage and skin factor were also considered to verify possible improvements.

It is shown in Figure 3 that the drawdown has decreased and the flow rate has increased markedly after well development; around 110 m less drawdown and 15 l/s higher flow rate are obtained after 100 minutes of pumping. It can also be seen in Figure 3 that the shape of the drawdown curves have changed. The curve before jetting has a steeper slope compared with the curve after jetting, which indicates longer effects of wellbore storage and larger skin before the jetting than afterward. Influence of wellbore storage was estimated to be 225 minutes for the test conducted before jetting by fitting a unity line to the early drawdown data (log-log scale) and applying the 1 ½ log cycle rule (Horne 1995). The skin factor was estimated as 1.9 from the test conducted before jetting and as -3.6 from the test after jetting, using the Cooper-Jacob method (Cooper and Jacob 1946).

Notable is when applying a straight line to the data between 300 and 1000 minutes during the test conducted before the jetting. (See Figure 3.) By applying the Cooper-Jacob method, the transmissivity is estimated as $3.7 \cdot 10^{-4}$ m^2/s and the skin factor as 12. The transmissivity value is around two times higher than the transmissivity of $1.8 \cdot 10^{-4}$ m^2/s estimated after 1000 minutes. This indicates a barrier boundary (Earlougher 1977) at distance 265 m away from the well, estimated by applying image well theory. However, it hasn't been possible to interpret a barrier boundary, the high transmissivity, or the high skin factor from any other test. So the most probable explanation is that the test was carried out in an undeveloped well, as indicated by the high skin factor, rather than an explanation originating from the reservoir and its limitations.

Impeller flowmeter measurements also confirmed that the well had been improved by the jetting. Data acquired from flowmeter logging carried out before the jetting operation started were used as reference values and compared with logging data collected after the operation. (See Figure 4.) The pump speed was the same for the logging run, resulting in the black and the red curves and higher for the logging run, resulting in the green curve.

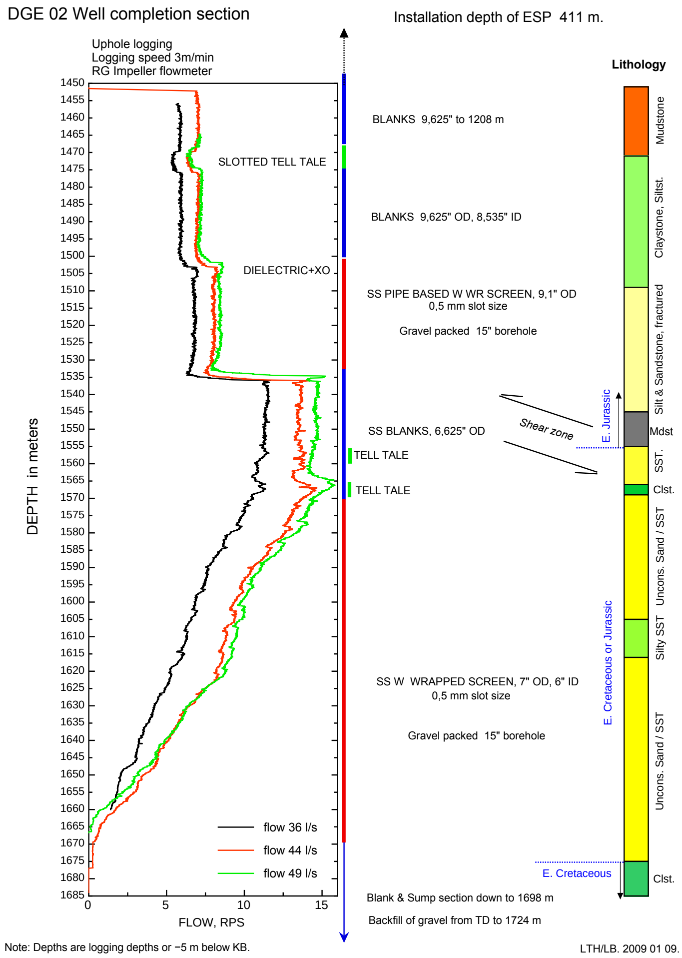

Figure 4: Results from impeller flowmeter logging. The black curve is the reference curve and the red and the green curve are from two different logging runs after the jetting operation (Rosberg and Bjelm 2009).

It can be seen in Figure 4 that the total flow rate increased, which was also confirmed earlier by test pumping. A major part of the contribution to the increased flow rate seems to come from the bottom section of the lower screen up to around 1620 m. It can be seen as an increased slope of the red curve compared with the reference curve. However, the upper screen section did not improve. (See Figure 4.) The curves show a constant value over this section, indicating that there is no further contribution from the upper screen.

The produced fluid was a mix of formation water and deteriorated mud polymer with fine particles from sand and claystone formations. In the beginning of the well development, the dominant part of the debris was residue from the drilling operation. (The mud used was a KCl/Polymer mud, consisting of HEC and Xanthan Gum Polymers, to increase viscosity and gel strengths, and KCl to maintain desired K^+ ion concentration. Hydrogen peroxide and fresh water was later used to degrade the residual polymers after gravel packing). Thereafter, the debris consisted mainly of fragments from the formation. At the end of the well development, the fluid became clear and production of formation particles ceased. The formation water is a brine with a density of 1140 kg/m^3.

DISCUSSION

Hydrojetting in combination with simultaneous pumping proved to be a time-effective cleaning method, in particular when used with coiled tubing and most certainly thereby a cost-effective method as well. The use of jetting led to less drawdown and higher flow rate after the jetting operation as well as an improved skin factor and less influence of wellbore storage. The shape of the drawdown curves also changed. It was steep during the early data for tests conducted before the jetting operation. In contrast, the shape was not as steep during the early data for tests conducted after the termination of the jetting. This less steep shape is probably a result of removal of formation material from the nearby screen space. This interpretation is supported by a change of the skin factor revealed in pumping test data, which was positive before the jetting operation started and became negative thereafter. This change in skin factor shows that the well completion has been hydraulically improved by the jetting, probably due to removal of fine particles clogging the gravel pack and the screen. A positive skin factor is common for a clogged well, as a negative skin factor is common for a well with improved hydraulic conductivity. Evaluation of the influence of wellbore storage before and after jetting also supports that the well has been improved. Before jetting the influence of wellbore storage was evident but was almost non-existing after the jetting.

Impeller flowmeter logging was important for many purposes, e.g. to optimize the jetting operation, to verify the cleaning progress and to locate the productive and non-productive zones. In DGE#2 it was confirmed by flowmeter logging that the one of the potential production zones, located at the upper screen section, was totally inactive. This is of great importance when evaluating the data from the pumping tests, as effects of multi-layered aquifer systems can be neglected. The result from the flowmeter loggings carried out during the jetting operation was invaluable for verifying intervals that needed further stimulation. It was possible to perform logging runs time-efficiently by using the innovative construction of the parasite string attached to the pump column pipe. Time consuming failures such as logging-cable becoming entangled with pump installations were thereby eliminated.

Other well development methods such as varying the frequency of the electrical submersible pump, thereby creating dynamic flow conditions, also worked fine as a cleaning method. As mentioned earlier the maximum and minimum frequencies of the pump were used. The maximum frequency created a large pressure drop of 27-28 bar in the well and increased the inflow to the well. Before the pump ran dry, the frequency was changed to the minimum, causing the pressure above the pump to increase and the inflow to decrease. A lot of debris was initially produced using this method and it can be concluded that varying the frequency under certain conditions works fine as a cleaning method. In general, more debris was produced when using the high frequency. This can be explained by the increase in the lifting capacity acting on the debris due to higher flow rate. The use of the jetting tool as a surge block was tried for well development of the lower screen section, without any noticeable improvement.

CONCLUSIONS

Hydrojetting in combination with simultaneous pumping proved to be a time- and cost-effective cleaning method, particularly when used with coiled tubing. Hydrojetting with pumping contributed to the major part of the cleaning of the well and can be applied to deep screen completed wells in general. Around 110 m less drawdown and 15 l/s higher flow rate were recorded after 100 minutes of pumping. The time-effectiveness of a coiled tubing unit was confirmed by the numerous jetting runs carried out during the stimulation period. The main advantages are the rapid transportation of the jetting tool to get it into position, as well as the possibility of continuous jetting of the full screen completion, thus avoiding particle fall back in the well.

The cost for the entire jetting operation can be compared to lifting the well with nitrogen during one day. In other words one stimulation attempt can be compared to several jetting runs. However the cost for the well development method used was of course reduced due to the availability of the electrical submersible pump, which was already rented and installed for testing purposes. The novelty of using hydrojetting with coiled tubing can of course be discussed, because it is often used in the oil and gas industry (e.g. for removing scaling). On the other hand, the applicability of the well development method used has been described for deep wells with screen and gravel pack completion, which is more common for geothermal and groundwater wells than for oil and gas wells.

It is invaluable to have flow test data from tests conducted before and after well development to validate the cleaning. Interpretation of influence of wellbore storage and skin factor supported the cleaning effect of the well development method used. An evident influence of wellbore storage and a positive skin factor were observed from the test before development, and subsequently the wellbore storage was negligible and the skin factor became negative. In addition, it is also invaluable to have impeller flowmeter loggings before and after stimulation for verifying the downhole improvements. In other words, flowmeter loggings can be used for locating zones that need further stimulation.

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