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Some Solutions to Necessary but Risky Open Borehole Development

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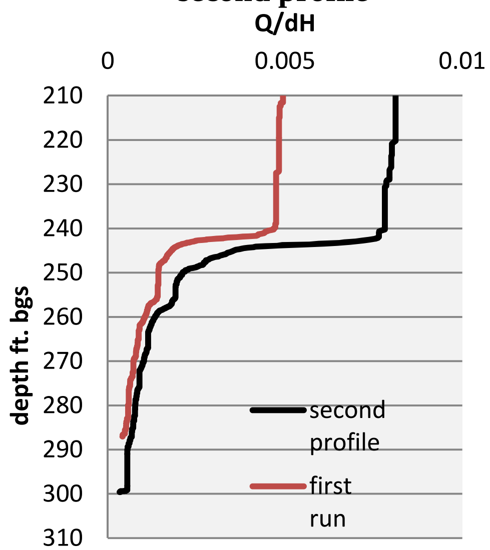
Abstract

Boreholes in fractured rock are often drilled with two objectives, water supply or contamination assessment and remediation. Both uses benefit from development of the well (i.e., the removal of mud and cuttings from the permeable features). Well development of a cased hole with a screen and filter pack is relatively easy. Development of an open uncased hole in fractured rock can be more problematic. In an open hole, the usual development methods might collapse the hole, trap tools in the hole, or lead to other costly consequences such as slough bridging, or backfilling the borehole. However if the transmissivity distribution is an important parameter to the situation, and it usually is, the transmissivity of the formation cannot be measured with the fractures plugged with drill cuttings. Casing the hole is not an option if access to the entire formation is needed. This paper describes some of the relative merits of several development techniques in open holes. Some measurements are provided showing the insufficient well development in a few open holes. The practical limitations of some common methods are calculated. The production of large amounts of contaminated water can be costly. A new technique using a flexible liner is added to the list of development methods. Transmissivity changes during the development process should be measured to help determine when the development procedure is sufficient to the purpose of the borehole. Several such measurement methods are described. Examples are provided of the results of development in sandstone and limestone formations using flexible liners.

Background

Many FLUTe flexible liner methods are used in open stable boreholes in fractured rock. One method is the transmissivity profiling technique. This technique uses an everting borehole liner to map the transmissivity distribution in a borehole. However, in the situation where a borehole in dolomite was measured twice (Fig. 1), it was been found that the second profile showed a higher transmissivity in a major flow zone than the first profile measurement. It is noteworthy that the first profile was measured after the same sealing liner was inverted from the borehole.

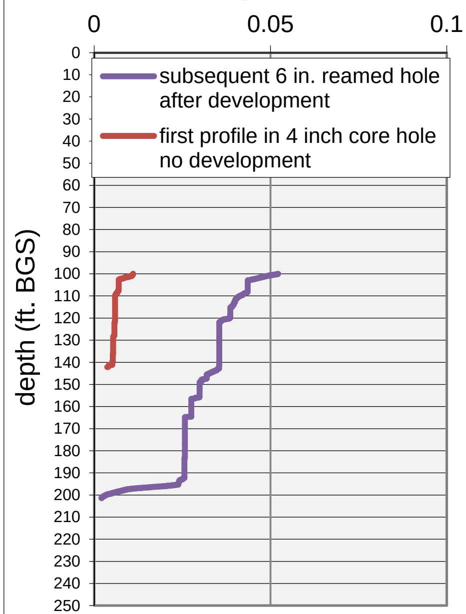
Fig. 1. Comparison of first and second profile



In another situation, the first transmissivity profile of a HQ cored hole in sandstone showed very limited transmissivity in the bottom half of the hole (Fig. 2). The hole had not been developed. The liner was removed, and a thorough development of the borehole was performed and the second profile of the same hole (Fig. 2) showed a fourfold higher total borehole transmissivity and a very large transmissive interval in the bottom end of the borehole which was not measured before the hole was rigorously developed. This new transmissive interval was three times the total transmissivity of the original borehole. This is not surprising, but it does show the measurement of the difference.

In another situation, the transmissivity profile was performed, the liner then inverted from the hole, and packer testing was done. The packer testing showed a higher transmissivity than the liner profile in the bottom portion of the hole. This hole had an exceptionally high transmissivity in the upper portion of the hole. The probable cause was that simply pumping a borehole, as was done, with an interval of very high transmissivity does not remove the cuttings from the rest of the borehole fractures because the drawdown is not sufficient.

Fig. 2. Flow rate/dH
(ft. in^2/s/psi)



In another situation, a cased well in limestone with several screens was developed by pumping the 3" well with a centrifugal pump moved so as to be positioned in each of three screened intervals. When the "development" was completed it was found that the casing had filled with 14 ft of sediment. A flexible liner was installed and then removed. The casing filled with an additional 50 ft of sediment. The sediment was removed with an air-lift pump. When the liner was reinstalled, it propagated to the bottom of the hole fourfold faster than the first installation past the second and third screens. The initial development was drawing largely from the top screen.

The accumulating evidence is that the liner removal by inversion from the borehole extracts cuttings from the fractures and the subsequent measurements show a higher transmissivity. It is well known that the drilling procedures tend to clog the fractures in the formation with drill cuttings and formation fines. Therefore, the well must be "developed," as the process is called, for the removal of those cuttings from the fractures to obtain higher water production or to measure the natural transmissive paths in the formation. This need to develop a well is not new to drillers or hydrologists. So why is there evidence of insufficient development of open holes in fractured rock?

An open borehole in fractured rock has a special problem with the standard development procedures as compared to development of a screened well. The open uncased borehole in fractured rock may collapse or slough if one gets too violent in the development process. Devices such as surge blocks as described in Driscoll ("Groundwater and Wells"), and some of the other devices for forcing water into and out of the formation in order to remove the drill cuttings and mud, may destabilize the wall of an open unsupported borehole causing slough of the wall material which can cause several problems. The slough may trap the surge block or packers, if used. The slough material can also block the hole. Both are expensive situations to remedy. Unfortunately, the more violent the flow into and out of the fractures, the better they are cleared of cuttings. The more the fractures are free of cuttings, the better the transmissivity measured will match the unclogged fracture flow before the hole was drilled. That is the essence of the problem of developing an open hole in fractured rock.

Possible development procedures for uncased holes

Considering how the cuttings are forced into fractures and how they are best removed, it is desirable to develop an inward flow from the formation to the borehole. Since we are not dealing with granular materials like a filter pack or sediment, there may not be much advantage to reversing that flow, but unless it reinserts the cuttings, there is little harm in a radial outward flow followed by a strong inward flow. A problem observed by the author was that a well was being developed using a small pump (~10 gal/min.) which was lowered to different elevations in the hole. Unless the hole was of low transmissivity, such a procedure does not produce much drawdown and therefore little gradient in the fractures to carry the cuttings out of the fractures. Such a pumping procedure is drawing from the largest fractures only. It makes little difference where the pump is positioned. It seems essential to have a large drawdown and the associated steep gradient across the cuttings to remove them from the fractures. The drawdown should be larger than the head which drove the cuttings into place. The cuttings emplacement in the fractures occurs because the pressure in the borehole during the drilling process is greater than the formation pressure. That pressure difference may be highest for the deepest fractures suggesting that the deepest fractures would be the most tightly clogged. This seems to fit our limited experience described above (Fig. 2). Drilling methods which can create flow into the hole while drilling are therefore less likely to clog the fractures (e.g., the air rotary technique). The other extreme situation is when circulation is lost and all the cuttings are carried into the formation. This can occur even with air rotary drilling. All drill holes should be developed.

If a pump is to be used as the development device, the pump should be of a flow rate sufficient to develop a large drawdown of the water level in the borehole producing a strong inward flow to dislodge the cuttings. The obvious question is how does one know that the well is clean and the cuttings have been removed? That will be addressed later. Clearly, one can't see very deeply into the fractures, even with a borehole camera, so some measurement criteria are needed.

The advantage of a mechanical pump (e.g., a centrifugal pump) is that it can be easily lowered down the well. It makes little difference where the pump is located in the well because there is not a significant gradient in the open well. If the pump itself is a major obstruction in the well, it may be important as to where it is located. One is always drawing mainly from the largest unclogged fractures. A larger drawdown tends to force the cuttings from the smaller fractures. The obvious disadvantage of a pump is that it will produce contaminated water if it is a contaminated site. Disposal can be very expensive. Another disadvantage of the pump is that any cuttings produced from the fractures may be going through the pump which is often damaging of many kinds of pumps. Finally, if there are some very high flow zones in the hole, the pump capacity may not be sufficient to produce a useful drawdown.

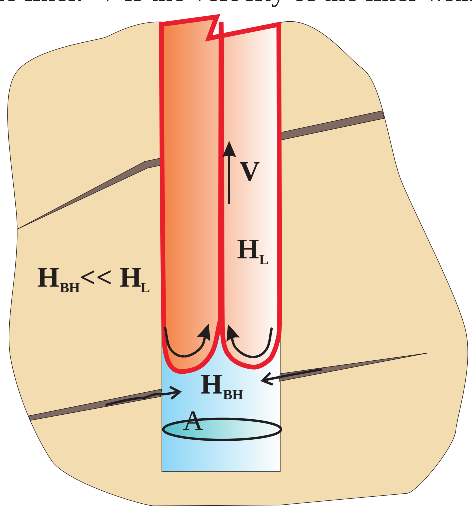
A pumping system that is relatively immune to sand/cuttings ingestion is the air-lift pump. The air-lift pump is a nicely simple pumping system (see Driscoll). It does require a relatively large, high pressure, air flow if the pumping rates must be high. An air-lift pump also is sensitive to the geometry of the water table and well depth. Ideally, the air-lift pump also produces a lot of water. It is not practical to attempt an air-lift pumping of an open hole without the use of a smaller diameter inductor pipe (see Driscoll). It is a major advantage that it is harder to entrap an air-lift inductor pipe than some other pumping devices. It is also very convenient that an air-lift pump can be lowered to the bottom of the hole to remove cuttings that were extracted from the formation and which have settled to the bottom of the hole. But an air-lift pump may require a drill rig to handle the pipe and a large compressor for sufficient air flow.

Simply pumping water from a well at a sufficiently high rate (possible rates will be discussed) is helpful to the development. The pump need not be installed very deep in the well (but below the drawdown level) so it is not so vulnerable to caving of the hole and entrapment. A packer can be used with a pump to isolate a section of the hole to allow a larger drawn down than if the entire transmissive hole is being pumped. This can avoid the problem of a single large flow zone frustrating a large drawdown on the smaller fractures. However, raising and lowering a packer in a borehole can aggravate slough of the borehole. Slough on top of the packer can entrap the packer. That could be expensive. Straddle packers can further reduce the interval of the hole being pumped for development, but with a greater risk of entrapment if the hole sloughs in the straddled interval.

So far, the criteria for the optimal well development method are: *large drawdown, high pumping rates, minimum equipment in the hole that can become entrapped, minimum production of investigation derived waste (IDW) and minimal mechanical contact with the borehole wall to aggravate slough of the wall material.* If significant sediment is being produced, it is very useful to be able remove the sediment from the bottom of the hole. Also, it is desirable that there be some measurement of the improvement in transmissivity to allow some judgment of a sufficient development effort. Pumping until clear water is produced is not a confirmation that all the fractures are clear of cuttings, because only the largest producing fractures may be clear.

A new and different development method

Fig. 3. Inverting liner geometry
H_L is the head in the liner, H_{HB} is the head beneath the liner. V is the velocity of the liner withdrawal



As described earlier, the problem of insufficient well development was brought to the attention of the author because the performance of a FLUTe transmissivity profile in a borehole a second time showed an increase in the borehole transmissivity. The performance of a second transmissivity profile required the removal of the flexible liner installed the first time. That removal procedure can develop a relatively large drawdown of the borehole head, especially at the bottom of the well. Figure 3 shows the geometry of an inverting liner as it is being removed from the borehole. The tension on the liner at the surface produces an upward force on the bottom end of the liner. That force produces a differential pressure across the bottom end of the liner causing a drop in the head beneath the liner. That drop in head beneath the liner is reduced by flow from the formation into the borehole beneath the liner. However, maintaining a constant tension on the liner produces a constant drawdown beneath the liner despite the inflow from the formation. Mathematically, the tension on the liner is: T= ½ A ΔP, where A is the area of the borehole and ΔP is the pressure difference across the bottom end of the liner. The term ΔP is the pressure difference between the water column head inside the liner and the head in the borehole. As the tension on the liner is increased, the head beneath the liner must decrease. The lower head beneath the liner is essentially the drawdown relative to the formation head. For a common tension of 300 lb applied to a liner in a 4"diameter hole, the drawdown would be about 50 psi or 115 ft. That is a very large drawdown compared to most pumped wells. In fact, increasing the tension may lead to cavitation and a vacuum beneath the liner. The practical limit is the differential pressure that the particular liner strength allows.

The development of a large drawdown beneath the liner is common near the bottom of the hole where the open borehole transmissivity does not allow a rapid inflow of water. As the liner inversion uncovers more transmissive intervals in the borehole, the inflow increases and the draw down is reduced for a fixed rate of inversion. The rate of inversion can be increased to the limit of the method for the liner removal. The hand-cranked winch method is operator dependent. For the linear capstan, designed and built by FLUTe, shown in Fig. 4, the rate of liner removal is controlled by a variable speed motor. The linear capstan also measures the tension on the liner and the speed can be controlled to maintain a relatively high and constant tension to allow a desired drawdown beneath the liner.

The obvious effect of the liner inversion is to apply an abrupt and very steep gradient to each fracture as it is uncovered by the liner. The fact that the head difference is applied abruptly is useful since the instantaneous gradient is much more steep than the later steady state gradient. The useful features of the method are the large drawdown and steep gradient which are very well suited to pull the cuttings and mud from each fracture as it is uncovered by the inversion process.

There is another feature of this liner method of borehole development that meets the criteria for a preferred development technique. That is that the process is gentle and supportive of the hole wall with no chance of entrapment. It is important that with hundreds of liner installations and removals, none has been entrapped by slough of the hole wall. As the liner is emplaced, it does not touch the borehole wall until it is supporting the hole wall. As the liner is being removed, when the liner support of the wall is removed, there is no liner below the potential slough to be entrapped. Only rarely have holes sloughed after the liner was removed. Even more rarely have the holes bridged due to slough after the liner removal. However, it has occurred.

Another very attractive feature of the inverting liner method of borehole development is that all the contaminated water produced from the formation beneath the liner remains in the borehole. In fact, the same amount of water is drawn from the same fractures as was injected into the formation during the liner installation. The water removed from the liner is the potable water added during the liner installation and the water may be replaced inside the liner since it is often installed again to reseal the borehole. If the liner water is not to be used to reinstall the liner, the water should be tested for contamination since, over the long term, chlorinated solvents will diffuse into the liner water.

Fig. 4. FLUTe Linear Capstan removing a liner from a borehole by inversion

Finally, the measurement of the success, or failure, of the development procedure is not often considered. For a water well, any higher transmissivity is better. However, for a borehole measurement of the formation transmissivity, it is best if all the permeability is restored, but there is no obvious measurement which will certify that all fractures have been cleared of drill cuttings. It is still true that a higher transmissivity is better. I would suggest a measurement of the total transmissivity of the borehole after each development episode to quantify the improvement. Furthermore, a measurement of the transmissivity after each of several development episodes provides a means of judging when the development has reached a practical limit. Ideally, subsequent measurements would show diminishing improvement with each episode and give an indication of when the increase is no longer of practical importance. I don't know to what extent that is commonly done.

A simple measure of the borehole transmissivity is to pump at a measured rate and to then measure the drawdown of the water level in the borehole. If the transmissivity increased, the drawdown will be less. Another method uses the FLUTe everting liner to perform a measurement of the entire borehole transmissivity by measuring the initial descent rate with a constant driving head. In the examples provided, a 3-4 fold increase is easy to measure. A more complete borehole transmissivity profile will show the location and amount of change in transmissivity throughout the borehole.

In many situations the liner is installed immediately after the hole is drilled, and developed, in order to prevent cross connection. Later the liner is withdrawn and reinstalled for a transmissivity profile. The sealing liner withdrawal can be very useful for enhanced development of the borehole prior to the transmissivity profile.

Rates of pumping practical with the several methods

In order to develop an open well, the water level in the well must be drawn down significantly to develop a good gradient in the fractures in order to move the cuttings out of the fractures. In wells of low transmissivity, that may not require a high rate of flow. However in some wells one must develop a very high flow rate. Driscoll says that flow rates of 30-80 gal/min are reasonable with a 2-3 inch inductor pipe for air-lift pumping. The actual flow rate depends on the depth of submergence of the pipe and the air flow rate that can be developed.

A 3 inch submersible pump can usually exceed 15 gal/min. This is much less than can be done with an air-lift pump. The pump hose diameter and length can be the limiting factors for the flow rate for a submersible pump. The drawdown at any flow rate is entirely dependent upon the total borehole transmissivity. A very large flow path anywhere in the borehole will limit the drawdown possible for clearing of the smaller fractures with a pump.

The inverting liner will develop a drawdown depending upon the tension applied to the liner. Near the bottom of the hole, the transmissivity of the open hole beneath the liner may not be very high allowing a large draw down. However, as more of the hole is uncovered, the inflow rate increases. The limiting factor is how fast the liner can be pulled from the hole to maintain a large drawdown as more flow zones are uncovered. The current linear capstan has a speed limit of ~34 ft/min. In a 6 inch hole, that leads to an inflow rate of 25 gal./min. with a maximum tension limit of 650 lb and an associated drawdown of 100 ft. Generally, the drawdown beneath a flexible liner should not exceed about 50 ft before there is a risk of damage to the liner. The control of the liner removal rate controls the drawdown applied. The tension is monitored electronically with the linear capstan. The time to install, remove and to reinstall a liner is usually less than one day. However, that is seldom done.

It is interesting to note that normal well development for water production wells does not need to emphasize the development procedure. If the well has a low production rate, the drawdown will be large and the development may be relatively complete. If the well has a high flow rate, the development of all the flow paths is not needed. But for a remediation investigation, all flow paths are usually of interest.

Conclusion

It is common knowledge that boreholes need to be well developed for hydrologic studies. However, the FLUTe transmissivity profiling method has shown that some boreholes are not adequately cleared of drill cuttings when common development methods were used. The probable reasons that some boreholes in fractured rock are not well developed is that the process is time consuming, difficult for high flow holes, requires costly disposal of IDW, and is a possible hazard to the borehole stability. A development procedure is usually performed. The degree of success is not easy to measure.

Because the traditional development procedures provide some risk of destabilizing the borehole, some methods, such as a surge plug, may best be avoided. If the hole sloughs during the development procedure, it may entrap the development device or cause the hole to bridge. So the development procedure must be as gentle as possible in order to reduce the risk of slough of the borehole wall.

Some development devices such as high flow mechanical pumps and air-lift pumps are well suited to development of open boreholes in most circumstances. The pumping rate must be high for very transmissive formations in order to develop a sufficient drawdown. Unfortunately, that can then produce very large volumes of investigation derived waste (IDW) which may be expensive to treat. A straight air-lift inductor pipe with no moving parts makes it attractive for pumping large volumes of water with sand and gravel and with less risk of entrapment, but only if the water table and hole depths are compatible with the method. However, there are situations when pumping methods will not adequately remove the cuttings from the fractures.

The inverting liner method of development is not so useful for a borehole with a very transmissive feature at the bottom of the hole. The high flow feature at the bottom of the borehole will limit the drawdown that can be obtained by liner inversion. However, that is not often the situation. A highly transmissive fracture, or solution channel, anywhere in the borehole also reduces the utility of traditional pumping of the open hole. The proper use of packers is helpful in that situation.

Fortunately, the inversion of a FLUTe liner is a development method with characteristics that usually satisfying the criteria listed above: "large drawdown, high pumping rates, minimum equipment in the hole that can become entrapped, minimum production of IDW, and minimal mechanical contact with the hole wall to aggravate slough of the wall material." It is also useful that the installation of the flexible liner provides a direct measure of the borehole transmissivity which can be done each time the liner is installed and removed to determine the development effect on the transmissivity distribution. Sometimes, the liner can be installed and removed several times in one day with a transmissivity profile obtained from each installation.

References: Driscoll, *Groundwater and Wells*, second edition;   plus FLUTe papers on transmissivity profiling at several NGWA fractured rock conferences. Contact FLUTe at info@flut.com for copies.