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INJECTION WELL OPERATION AND MAINTENANCE

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Abstract

Injection wells are one means of accomplishing artificial recharge of ground-water reservoirs. Because of the high cost of recharge by this method, injection wells are usually used where some other benefit is derived as well. Injection wells are sometimes used for waste water disposal, including storm water, cooling water, and reclaimed waste water. They are also used to control land subsidence. The Los Angeles County Flood Control District has operated injection wells for the past 20 years to create a freshwater pressure barrier to protect the coastal ground-water basins of Los Angeles County from sea-water intrusion. The nature of the sea-water intrusion barrier requires that injection be maintained continually. The District currently has 180 operational injection wells located at 150 sites.

Over the 20 years of operating experience, the District has never had to permanently cease operation of an injection well because of loss of operating efficiency. The District's experience indicates that with a reasonable level of maintenance and for the operating conditions existing at the barrier projects, an injection well should continue to operate efficiently for at least 20 years and probably longer.

Information is presented describing injection well characteristics, typical designs of injection wells, operational considerations, clogging, redevelopment, and well construction costs.

WELL CHARACTERISTICS

In the following discussion consideration is given only to those wells reaching ground water. Thus, the injection wells discussed herein are differentiated from pit-type wells where injection occurs by infiltration into an unsaturated formation. It should be stressed that a thorough geologic understanding of the underground formations is a prerequisite to obtaining the best results. In addition to an analysis of available data to assist in selection of the drilling site, it is desirable to drill a test hold in the vicinity of one or more proposed injection wells. In any event, a detailed log should be taken during drilling to assist in the most effective completion of the well.

Type of Well

The type of well chosen for a given location would likely be similar to that which would be chosen for a pumping well. Depending on the nature of the formation, the injection well would be of the gravel pack or the non-gravel pack type. The gradation of the gravel pack would be chosen to control the migration of fines from the formation, just as in a pumping well.

Drilling Methods

Injection wells can be drilled with any of the three common drilling methods, cable tool, rotary, or reverse-rotary. The cable tool method has been used considerably because of the relatively clean nature of the resulting drill hole. Drilling by the cable tool method encounters expensive difficulties as the holes deepen. Also, drilling by the cable tool method limits the choice of well casing to those materials which have high compressive strength, notably the common steel casing.

The rotary drilling method has not been used extensively for injection wells because of the possibility that the mud cake, which is an essential feature of this drilling method, may not be completely removed from the walls of the drilled hole in the well development process. Should the mud cake not be removed, it is likely that the remaining fine particles will eventually be eroded by the injected water and forced into the formation, thus adding to the clogging problems of the well. It is likely that by careful and thorough development techniques, the fine materials associated with the drilling fluid and the mud cake could be completely removed and the injection well be quite satisfactory. However, the risk and the factor of not being able to see or test the completeness of the development generally has led to the choice of other drilling methods.

The reverse-rotary method has been tried as a compromise with the regular rotary method. In the reverse-rotary method clay is usually not added to the drilling fluid, because the cuttings from the bottom of the hole are forced upward through the drill stem at high enough velocities such that the carrying ability of dense drilling mud is not required. Sometimes when highly-permeable strata are encountered, clay is added to reduce the loss of drilling water. This method, together with the careful placement of the gravel packing and a careful development procedure, results in a satisfactory injection well. Drilling by this method provides the opportunity to use other types of well casing besides steel; which may be particularly significant if corrosion problems exist.

Well Diameter

The considerations for choosing a well diameter for an injection well are quite similar to those used for pumping wells. The larger the diameter of the well, the better are the hydraulic characteristics in the adjacent formation. Consideration must be given to the velocity of outward flow in the immediate vicinity of the injection well casing, in the same way that consideration of the velocity is made for a pumping well. The injection well casing must be large enough to accept the conductor pipe and other facilities which might be placed in the well and to provide ample room for the redevelopment procedures. Of course, the larger the well casing, the greater the cost. For the Los Angeles County barrier projects, injection wells have been standardized at a nominal 30 cm in diameter.

Depth Limitations

Similar limitations to depth arise with injection wells as control pumping wells; that is, generally the cost of the well per metre of depth rises as the well deepens. Certain drilling methods are limited in depth or become considerably more costly as the depth limitations are reached.

There is no apparent reason to indicate that the injection technique should be limited on account of greater depths of injection wells. On the other hand, the deeper the injection well, the more closely it resembles injection wells used in the oil industry where the nature of the formation and the thick overburden allow high injection pressures. High allowable injection pressures would result in reduced frequency of well redevelopment and lower maintenance costs. Redevelopment is discussed in more detail further on.

Well Casing

Well casing can be the usual types of steel used in regular pumping well construction. However, it has been found that the barrier injection wells have a highly corrosive environment caused by intruded sea water. At the barrier projects the corrosivity is enhanced by high dissolved oxygen in the injection water. To minimize corrosion problems, wells have been cased with such non-corrosive materials as asbestos-cement pipe and stainless steel.

Well Perforations

Perforations are adjusted to the formation in a similar way as pumping wells. The size of perforations is related to the size of the gravel pack or the natural formation. Minimum spacing must be related to the strength of the casing. Total area of perforations should be large enough to reduce flow velocity to reasonable levels at the expected injection rate. If the thickness of the formation allows, considerable additional perforation area should be provided to minimize well clogging effects.

Conductor Pipe

An essential feature of an injection well is the conductor pipe required to carry the injection water into the well to a point beneath the water surface inside the well casing. This pipe is required so that the injected water will not plunge into the well casing and cause turbulence which may entrain air bubbles and carry them into the gravel packing of the well and the aquifer formation beyond.

A full flow in the conductor pipe can be assured by designing the size of the pipe so that friction loss is comparable to the distance the water must drop. However, this procedure limits the range of flows which may be used.

Another method is to place a back-pressure valve at the bottom of the conductor pipe. A number of different designs for such a valve can be used. One that was found to be the most successful in the barrier projects involved a round plate which was placed in a horizontal plane and moved vertically within a cylinder which had triangular-shaped holes in the wall with the point of the triangle at the top. The plate was actuated by a stem reaching to the top of the well so that the size of the triangular opening could be varied. The cylinder was seated at the base of the conductor pipe in such a way that the injected water was forced into the cylinder and through the variable-sized triangular holes in the cylinder wall. Because of the corrosion factor, it was found necessary to construct these valves from stainless steel, but even so, considerable operating difficulties were encountered.

Another method is to use a conductor pipe which does not provide for a flowing full condition but which does provide for the exclusion of a continuous supply of air by being constructed airtight. Thus, when the initial body of air is evacuated from the conductor pipe by the flow of the injected water, no additional air is available to become entrained within the flow. Although there are theoretical considerations of dissolved fractions being released from the water under the influence of the reduced pressures, the experience in operating the barrier projects show that this type of conductor pipe is satisfactory, and is the system now used on all operating wells.

Clay Cap

In those formations which are under pressure, the injection well will have penetrated one or more confining layers of fine materials often called the clay cap. In the vicinity of the well penetration of this layer of materials, a structural weakness exists. This weakness is a matter of concern for two reasons. One is that it may provide a channel for considerable leakage of native water or of injected water from the pressure aquifer to overlaying materials, where it may be of little or no value or where it might cause problems such as high ground water. Another concern is that, under the high pressures which exist during injection in the vicinity of the injection wells, movement of water through the area of weakness may cause erosion of the fine materials and eventually a structural failure at this point.

It appears from the experience of the barrier projects that, by a minimum amount of care during construction in the area of the confining member, the potential problems can be minimized.

TYPICAL DESIGN OF BARRIER INJECTION WELL

Following is an example of the typical design of an injection well patterned after those now used for the barrier projects. Basically the well can be described as a gravel packed, asbestos-cement casing well.

This type of well must be drilled by the rotary method, preferably the reverse-rotary method. A 90 cm protective casing is placed which reaches a number of metres into fairly stable soils. The reverse-rotary hole is then drilled approximately 80 cm in diameter to the depth desired. Then perforated, asbestos-cement pipe casing is lowered into the hole with the string of pipe supported upon a steel plate which is attached to the drilling stem with a reverse threaded drill collar. Suitable spacers are connected to the casing at 4 metre intervals (each section of pipe) so that the casing will remain centered in the drilled hole. When the complete string of casing has been placed, the drill stem is disengaged from the left-hand threaded drill collar and plate which remain in the hole.

Next, a tremie pipe is lowered through the drilling fluid remaining in the hole between the casing and the drilled hole so that gravel can be introduced directly at the bottom of the hole. The tremie pipe is slowly withdrawn as the gravel fills the annular space, never being more than 3 metre above the gravel. Just below the confining member (clay cap), the gravel packing is topped with a 30 cm layer of sand,and a 2:1 cement-grout mixture is then placed in the annular space through the zone of the confining member and up to the ground surface. Prior to the placing of the sand layer and the grout mixture, two 10 cm plastic tremie pipes are set permanently extending from the surface to the gravel envelope, so that gravel can be introduced as needed into the annular space below the confining member.

After the grout mixture is placed, development of the well begins by surging within the well casing with the drill stem in such a manner as to remove the fines from the gravel layer and the formation in the vicinity of the well casing. Sometimes a more violent surging is obtained by using a swab, which consists of a leather ring, supported between steel plates and connected to the drill stem, and which has a minimum clearance within the well casing. During swabbing water may be circulated down through the gravel-pack and up through the drill stem to remove the drilling fluid and the fines from the well casing. As fines are withdrawn from the gravel packing, additional gravel is added as needed through the permanent tremie pipes. After surging is completed, the well is developed by pumping. During pumping, gravel is added to the annulus, as needed.

In these wells, conductor pipes are made of 7.5 cm plastic pipes. With this design, no corrosive materials exist in the drilled well to come in contact with the injected water.

OPERATIONAL CONSIDERATIONS

Operation of injection wells requires a normal configuration of connector pipes, fittings, and regulating valves. For maintenance purposes, it has been found necessary to install two valves on the pipeline servicing each recharge well: (1) a valve for on and off operation and (2) a valve for regulation. Experience at the barrier projects indicates that a butterfly valve is probably the preferable valve for on and off operation. All regulating valves on the barrier projects' injection wells were originally globe-type valves, and their operation has proven satisfactory. Possible use of butterfly valves for regulation purposes is being investigated, and preliminary results indicate that they may also be satisfactory. A meter or flow rate measuring device should be included for each well. For operational control of the barrier projects, it is not necessary to record the total quantity of water entering a well, therefore, only a flow rate measuring device has been installed at each well. Both orifice plates and venturi-type measuring devices have been used at the barrier projects. Experience indicates that orifice plates provide sufficient accuracy and offer fewer maintenance problems. Provision should be made for measuring the water level (or pressure or vacuum) in the conductor pipe, within the injection well casing, and within the gravel-pack tremie pipes. These various points of data are valuable in interpreting operational characteristics and problems. A small tap for collecting samples of the injection water has been found useful.

Control of operations for the barrier projects can be accomplished with data from the injection wells once a week. The amount of personnel required depends upon the number of injection wells in the project, the amount and complexity of equipment to be maintained, the degree that the facilities are automated, the relative hazard to adjacent property if failures occur, and the relative economy of close control on the rate of injection versus need for the injection water. Depending on specific conditions, the cost of operating and maintaining an injection well can vary from as low as $1,000 to as high as $6,000 per year.

Injection Rate

The rate at which water may be recharged through a well is dependent on several factors such as injection head, quality of injected water, ground water levels, temperature of water, geologic conditions, well construction, and area of perforations. Clogging, which will be discussed later, also affects the injection rate; generally, all other factors affecting the injection rate remaining constant, the ability to inject water will decrease with time due to clogging.

At the barrier projects, operational injection heads vary from 9 metres to 61 metres, and the transmissibility of the aquifers varies from 0.0002 m^2/s to 0.0018 m^2/s. For wells where a low transmissibility exists and a low operational injection head has been established, the injection rate over a yearly period averages about 0.0085 m^3/s for a year.

The primary consideration controlling the injection rate for the barrier project injection wells is the water requirements for maintaining the required pressure mound to prevent sea-water intrusion. Injection rates for the 180 barrier injection wells vary from 0.0057 m^3/s to 0.028 m^3/s. For the majority of the wells, it is not necessary to operate them at their maximum injection capability.

The operating procedure for the barrier injection wells calls for changes in injection rate to be at a rate no greater than 0.0071 m^3/s every 4 hours. This is necessary to give an opportunity for pressure equalization within the immediate vicinity of the recharge wells. The gradual change is especially important when decreasing the injection rate. One barrier injection well had to be destroyed due to damage caused by a rapid shutoff of the injection rate.

Injection Head

The term "injection head" is used to describe the condition of an injection well with respect to its ability to distribute water into the underground formations. The term is somewhat analogous to a pumping well's drawdown. The injection head may be defined as the height of the column of water within the injection well casing, above that level representing the injection mound, required to overcome friction losses encountered as the water moves into the aquifer. Obviously, the limitation on injection head will vary greatly depending upon the structural integrity of the overlying clay cap, the absence or presence of the clay cap, the amount of hazard to surface installations, and other special considerations at each location. For wells at the barrier projects, the limitations on injection head vary from a low of 9 metres for some wells to a high of 61 metres for other wells.

Injection Water

Because of the filter bed nature of injection wells, water to be used for injection must be highly treated for the removal of suspended matter. The dissolved constituents must be reasonably compatible with the native underground water and the soils of the water-bearing formation. At the barrier projects, injection water is taken from an imported source prepared for municipal and industrial purposes. The suspended solids of this water are generally less than 1 mg/l and the TDS is approximately 290 mg/l. Prior to October of 1974, the TDS was approximately 780 mg/l.

It has been found that water prepared for municipal and industrial purposes having a relatively-balanced calcium carbonate content may create problems when it moves through the gravel packing and aquifer immediately adjacent to the well casing. Apparently, this is because of the nature of calcium carbonate deposition where the tendency to deposit is increased in the presence of greater surface area for such deposition. Thus, by the nature of the travel of water in underground formations, a maximum opportunity is presented for the deposition of calcium carbonate. It is suspected that as the deposition continues the interstices of the formation become clogged, and the injection head required for a given injection rate becomes larger and larger.

CLOGGING

Clogging of injection wells is one of the most serious maintenance problems encountered. Well clogging is believed to occur in the perforations, in the gravel pack, at the interface where the gravel pack contacts the aquifer, and possibly within the aquifer itself.

Clogging may occur in recharge wells because of one or more of the following reasons: (1) biological, (2) mechanical, or (3) chemical. Due to the inaccessibility of the areas of clogging, it is difficult to determine the exact causes; but for the barrier project injection wells, it is suspected that a combination of a build-up of materials brought in by the injection water and chemical changes brought about by the injection water are the primary causes of clogging.

The cause of clogging is further obscured by the fact that some injection wells clog faster than others under "apparently" identical operating conditions. Where one well may clog within several months after redevelopment, an adjacent well may take several years. Some wells have never required redevelopment.

Construction methods and the initial well development appear to be primary factors in determining how a well will react to clogging.

Another factor which obscures the clogging process is the characteristic of an injection well to require less injection head for a given injection rate without any "apparent" outside measures being taken. In other words, a well may exhibit a tendency to "unclog" as well as to clog. This tendency is usually observed following a period of injection rate reduction or shutdown but also has been observed for a well during a period of prolonged continuous injection.

Biological

Dissolved materials, both organic and inorganic, may promote biological growth. These growths may occur inside or outside the casing and perforations, at the aquifer face or in pores of aquifers some distance from the well. The most troublesome is the slime-forming type. The growth may be from new organisms introduced by injection or may be due to stimulation of previously dormant micro-organisms within the formation. Clogging may be due to the slime growths themselves or from chemical products resulting from bacterial activity.

Mechanical

There are clogging mechanisms which are related to the different kinds of well drilling equipment utilized. If the rotary process is used, a hazard of clogging exists if clearing of drilling mud is not complete. There are factors inherent in the type of well construction. Improper design or installation of perforations are examples, as well as the possibility of careless gravel packing. The development method is important. Development must be sufficient, but not excessive as the possibility often exists of exposing layers of fine-grained materials to erosion.

Minute particles carried in the injected water may cause clogging either in the gravel pack, at the interface between the gravel pack (or the well casing) and the natural formation materials, or within the interstices of the formation itself. Depending upon the size of the particles, the gradation of the formation, and the flow velocity, particles may filter out within a fraction of an inch of the face of the well or may be carried on into the formation. The fine-grained, clogging material may have been introduced by the injected water or may be eroded particles from residual layers of drilling fluid on the sides of the drilled hole or may be eroded particles from within the formation itself. There may be re-orientation of the formation particles into a denser, less permeable pattern. In some types of soils, expansion of clay minerals may occur upon contact with a water with new chemical characteristics.

Chemical

Admission of free air as bubbles in the injected water may cause binding in the formation. Gas binding in the aquifer may result from gas coming out of solution when the temperature of the injected water is lower than the temperature of the underground formation.

Chemical clogging may occur at the casing perforations, at the formation face, or in the aquifer itself. Chemical clogging may be caused by: (a) precipitated metabolic products of autotrophic bacteria, including hydroxide of iron, ferrous bicarbonate, metal sulphides, or calcium carbonate, particularly in the presence of high concentrations of dissolved oxygen or chlorine; (b) chemical interaction of the dissolved chemicals in the injected water and in the soil itself; (c) contact of injected water and native underground water or different chemical characteristics yielding precipitates; (d) solution and redeposition of gypsum; and (e) reaction of high sodium water with soil particles causing deflocculation of the soil.

Such factors of the formation itself as its permeability and its porosity may have a significant affect on the clogging. With respect to clogging, the local characteristics of these factors are more important than the more general characteristics.

REDEVELOPMENT OF INJECTION WELLS

When the injection head in an injection well is at the maximum desirable level or the limit of available injection water pressure, it is necessary to do some type of redevelopment so that the well may remain in service at the desired injection rate.

The procedure used for the first well redevelopments at the barrier projects was to disassemble the well and redevelop it by a combination of mechanical bailing, swabbing, surging, and turbine pumping. Over the years of field experience, improvements have been made in the redevelopment method. Today the injection wells are redeveloped by airlift pumping with a dual packer assembly, and occasionally mechanical bailing is used for the removal of fill materials.

The dual packer airlift redevelopment allows for high velocity, low flow rate pumping, and surging. It also enables each section of the perforated interval to be developed to its maximum. This method has proven to be very successful in maintaining the operating efficiency of the injection wells.

The cost of injection well redevelopment varies depending on the length of perforations and individual well characteristics. The average length of perforated interval for the barrier project injection wells is 43 metres. Redevelopment of one of the wells takes an average of 5 days and costs an average of about $1,700 per redevelopment.

TABLE I

Comparative Construction Costs of Injection Wells

Type of Well (1)	Cost per Metre (2)	Average Depth, Metre (3)	Number of Wells (4)	Date Drilled (5)
Cable tool, 30 cm, steel cased, non-gravel packed	$ 57.25	81	8	1952-53
Cable tool, 30 cm, steel cased, gravel packed	106.75	75	2	1953-54
	106.52	94	4	1957-58
Reverse-rotary, 30 cm, asbestos-cement, gravel packed	121.44	82	1	1960
	167.17	124	12	1963
	139.35	122	19	1964
	142.03	173	17	1964
	117.24	113	9	1966
	121.24	185	5	1966
	118.66	99	11	1967
	120.58	127	8	1968
	113.42	68	17	1970
	112.95	117	12	1971
	232.02	218	11	1975
Reverse-rotary, 30 cm, stainless steel, gravel packed	123.88	86	14	1965
	197.47	134	3	1967

CONSTRUCTION COSTS

Costs of contructing injection wells are presented in Table I giving comparative cost information on several types of wells constructed for the barrier projects. Some of the early wells were built by force account and some by contract. Since 1963 all wells have been constructed by contract. The dates of construction have been indicated, but no attempt has been made to equalize the cost data on the basis of construction cost indices. The cost figures shown include the cost of drilling, casing, gravel packing, and installation of necessary piping and valves at each well. The costs of the water supply system, surface enclosure for a well, and contract administration are not included.