Plumbness and Alignment Standards – Analysis and Recommendations for Operational Applicability

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Introduction

The Salt River Project (SRP) conducted an evaluation of water supply wells installed in the Phoenix, Arizona area between 2005 and 2013 to assess the post-construction deviation of the completed wells. An increased frequency of plumbness and alignment problems were noted by SRP and other entities during recent years, which prompted this investigation of possible causes. Marvin Glotfelty (Hydrogeologist for Clear Creek Associates) and Jersy DePonty (Geohydrologist for SRP Groundwater Resources and Geohydrology Department) serve as Technical Directors of the Arizona Water Well Association, and this issue was also raised at a meeting of that organization, so a study was initiated to seek resolution of the issue. A primary objective of this assessment is to augment current well drilling technical specifications utilized by well designers (such as SRP and Clear Creek Associates) with a revision of the plumbness and alignment requirements that is achievable, measureable and provides for consideration of practical operating conditions.

The plumbness and alignment assessment involved communication with pump companies and pump suppliers with a long history of knowledge and expertise on the impact of a crooked well on the ultimate performance and longevity of pump equipment. The plumbness and alignment data used in this study are derived from recent SRP wells installed between 2005 and 2013. SRP was established in 1903 as the nation's first multipurpose reclamation project authorized under the National Reclamation Act. Today, SRP is the nation's third-largest public power utility and one of Arizona's largest water suppliers delivering nearly 1 million acre-feet of water annually through an extensive water delivery system including reservoirs, water wells, canals and irrigation laterals. SRP owns and operates 263 large diameter (18-inch to 24-inch) water wells in the Phoenix metropolitan area. SRP's service area is comprised of approximately 250,000 acres (about 390 square miles). Due to the advanced age of many of these wells, SRP replaces several wells each year, as needed. The technical specifications for well installation are prepared by SRP geohydrologists, but the actual well drilling and construction work is conducted by well drilling contractors.

Plumbness and Alignment Well Standards

This study considered two common water well standards to evaluate plumbness and alignment criteria; the American Water Works Association (AWWA) Standard for Water Wells (A100-06) and the standard detailed in the Handbook of Ground Water Development (Roscoe Moss Company, 1990). The Environmental Protection Agency (EPA) plumbness standard of 1 degree of deviation per 50 feet is also common, but was not included in this study since it is much less stringent than the AWWA or Roscoe Moss standards, and was not applicable to the wells being evaluated. The AWWA standard is common in the water well industry and is widely used by municipalities, private utilities, industry and consultants. The Roscoe Moss standard provides the primary basis for the plumbness and alignment requirements used in the current SRP well drilling specification. Both of these standards are appropriate for large-diameter water production wells, and are applicable to the use of line-shaft vertical turbine pumps. The typical SRP well is 20 inches in diameter, although 24-inch diameter wells are also installed in highly

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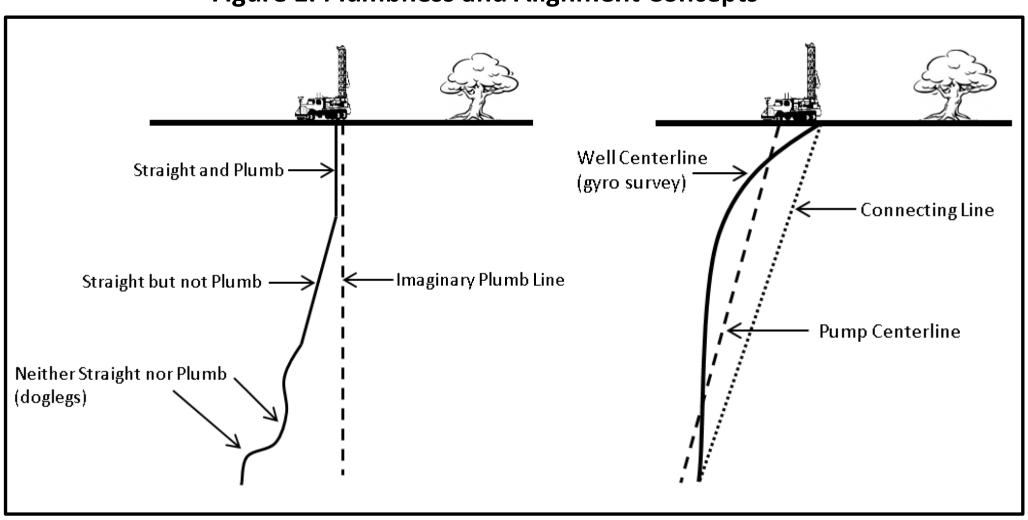
productive areas. Plumbness and alignment standards are separated into two distinct sections; one for plumbness and the other for alignment.

"*Plumbness*" is defined as the quality of being plumb and vertical, with an orientation toward the gravitational center of the earth. The plumbness of a well is determined by the horizontal deviation (drift) from the center point at the top of the well, to the center point at the bottom of the well. A well is considered plumb if the center does not deviate from an imaginary vertical line (plumb line) running from the land surface to the center of the earth (Groundwater and Wells, 2007). Plumbness concepts are illustrated on Figure 1. The plumbness tolerance in previous versions of the AWWA standard (e.g. A100-97) allowed a maximum horizontal drift of ⅔ the inside diameter of the well casing per 100 feet of well depth, and the current version (A100-06) of that standard was restated to a maximum allowable horizontal drift of 0.0067 times the inside well diameter per foot of depth. It should be understood that the maximum allowable drift is the same in both the previous and current versions of the AWWA standard, and that the maximum drift limit standard is not intended to be applicable on an individual foot-by-foot basis. The current AWWA standard is equivalent to approximately ½ degree of drift from a vertical plumb line for most production well casing diameters. For a 20-inch diameter well, this amounts to about 13.4 inches of drift allowance per 100 feet of well depth. In comparison, the Roscoe Moss standard has a maximum plumbness allowance of 6 inches per 100 feet of well depth, regardless of the inside diameter of the well casing. For a 20-inch diameter well, this corresponds to approximately ¼ degree of drift allowance from a vertical plumb line, only about half of the maximum allowable drift of the AWWA standard for that casing diameter. The current SRP well drilling specification incorporates the Roscoe Moss plumbness standard of 6 inches of drift per 100 feet of well depth.

Figure 1. Plumbness and Alignment Concepts



"*Alignment*" is defined as the state of being arranged in a straight line, or in correct relative position. Alignment of a water well refers to the path a well's casing and screen takes from the top of the well to the bottom of the well. The primary goal for alignment is to have a straight well in which each casing section is connected to adjacent casing sections to maintain perfect axial alignment (Groundwater and Wells, 2007). Generally speaking, a well may be aligned (straight) and plumb, straight but not plumb (consistent drift), or neither straight nor plumb (non-vertical with inconsistent drift and doglegs) as illustrated on Figure 1.

The alignment tolerance in the AWWA standard requires the free passage of a 40-foot long section of pipe (called a "*dummy*") with a width no more than ½-inch less than the inside diameter of the well. This "dummy test" requires the dummy to be freely passed throughout the portion of the well where the pump may be set, with no binding or obstructions. This test is intended to determine the maximum degree of misalignment, or doglegs, allowable in the well to accommodate the installation and operation of a line-shaft pump. The Roscoe Moss alignment standard calls for the proper axial alignment (straight line installation with no bends) of a line-shaft pump installed from the center of the well at the land surface to the center of the well at a specified depth. This is referred to as a connecting line (Figure 1). For a 20-inch diameter well, this involves the straight installation of a 14-inch diameter pump. It should be noted that the AWWA standard has an alternate alignment tolerance in lieu of the "dummy test" that also involves an axial alignment evaluation. The alternate AWWA standard uses a pump centerline which isn't centered at the top or bottom of a well but instead minimizes the distance between the centerline of the line-shaft pump and the well centerline (similar to a "best fit" regression line on a graph, as shown on Figure 1). For a 20-inch diameter well this involves the straight and unobstructed installation of a pump with a maximum diameter of 16 inches. The AWWA alternate alignment tolerance is slightly stricter regarding the maximum pump diameter necessary for axial alignment. However, the pump centerline method is more lenient than the connecting line method so the net requirements of the two standards are similar, depending on the magnitude and location of doglegs in the well. The current SRP well drilling specification incorporates the dummy test from the AWWA standard and the axial alignment requirement from the Roscoe Moss standard. The relationship between the well centerline (usually measured with a gyroscopic survey), the connecting line, and the pump centerline is illustrated on Figure 1. Table 1 compares the two plumbness and alignment standards and the current SRP well specification for a 20-inch diameter well.

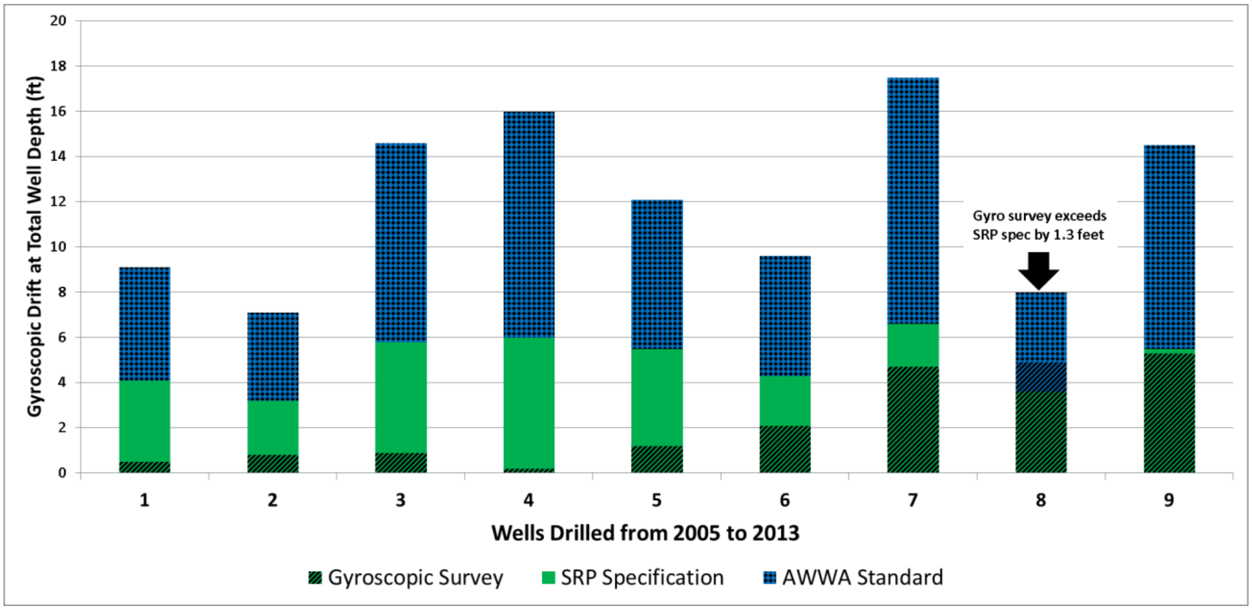
Table 1. Plumbness and Alignment Well Standard Comparison for a 20-inch Diameter Well

Well Standard	Plumbness Tolerance	Alignment Tolerance
AWWA	13.4 inches per 100 feet	Dummy test or proper axial alignment of a 16-inch (maximum) diameter pump using pump centerline method
Roscoe Moss	6.0 inches per 100 feet	Proper axial alignment of a 14-inch diameter pump using connecting line method
SRP Well Specification	6.0 inches per 100 feet	Dummy test or proper axial alignment of a 14-inch diameter pump using connecting line method

Well Plumbness

Plumbness (also termed "*drift*") was the initial focus of this research due to a recent trend of greater drift in recently-installed wells. The increased drift trend is displayed on Figure 2, which provides a comparison between the AWWA standard, the SRP specification, and the measured drift (based on gyroscopic surveys) in nine SRP wells drilled between 2005 and 2013. The wells are labeled "1" through "9" in the chronological order in which they were drilled. As shown on Figure 2, the drift for wells 1 through 5, which were drilled between 2005 and 2010, is approximately 1 foot or less. However, wells 6 through 9, which were installed between 2011 and 2013, have significantly greater drift in the range of 2 feet to about 5 feet. The drift in well 9 was just within the SRP specification and well 8 exceeded the SRP specification by 1.3 feet. To assess the drift exceedance in well 8, three separate gyroscopic surveys were conducted by two separate companies. The gyroscopic survey results were 4.9 feet, 5.5 feet, and 7.7 feet at total well depth. This demonstrates significant variability between the drift results, and the survey variability of 2.8 feet was almost equal to the allowable drift limit of 3.6 feet from the SRP specification. The degree of variability between drift measurements was unexpected and warrants further study. The variability in surveyed drifts may result from technology differences between logging tools of various ages, and may also be due to inherent limitations of gyroscopic survey technology. The accelerometer/inclinometer instrument in these logging tools that measures plumbness of the well is very accurate, with a precision typically within about 0.1°. However, the gyroscopic instrument in these logging tools that measures the azimuthal direction and magnitude is much less accurate in the near-vertical conditions (steeper than about 5°) that occur in water wells.

Figure 2. Gyroscopic Drift Compared to AWWA Standard and SRP Specification



Penetration Rate

The drilling rates for the nine SRP wells were analyzed to investigate possible relationships between penetration rate and increased drift. Each of the wells was drilled using the flooded reverse rotary drilling method in an alluvial basin fill aquifer. There are numerous factors that can cause drift, such as character of the geologic material being drilled, too little or too much weight on the drill bit, trueness of casing or drill pipe, inadequate collar weight near the base of the drill string, or excessive pull-down force on top of the drill pipe. To assess whether the penetration rate is correlative to well plumbness, the wells were categorized by similar geology to provide a more representative comparison of drilling rates. The wells were installed by three different drillers (X, Y, and Z), as shown in Table 2. The average penetration rates for each well were measured using a Geolograph (penetration rate device) from the base of the surface casing (approximately 40 feet) to total well depth. Average penetration rates were considered in the depth intervals from 40 to 400 feet, and also from 400 feet to the total depth (about 1,000 feet), in order to account for variability in geologic conditions. No apparent correlation between drilling rate and magnitude of well drift was identified for these wells. For example, driller X installed wells 4 and 7 and driller Y installed wells 3 and 9 with similar penetration rates, although the drift of the wells are substantially different despite their similar geology. Also, wells 1, 6, and 8 were completed by three separate drillers in similar geology, yet showed decreased drilling rates with increased drift which is contrary to the conventional expectation that increased drilling rates result in increased drift.

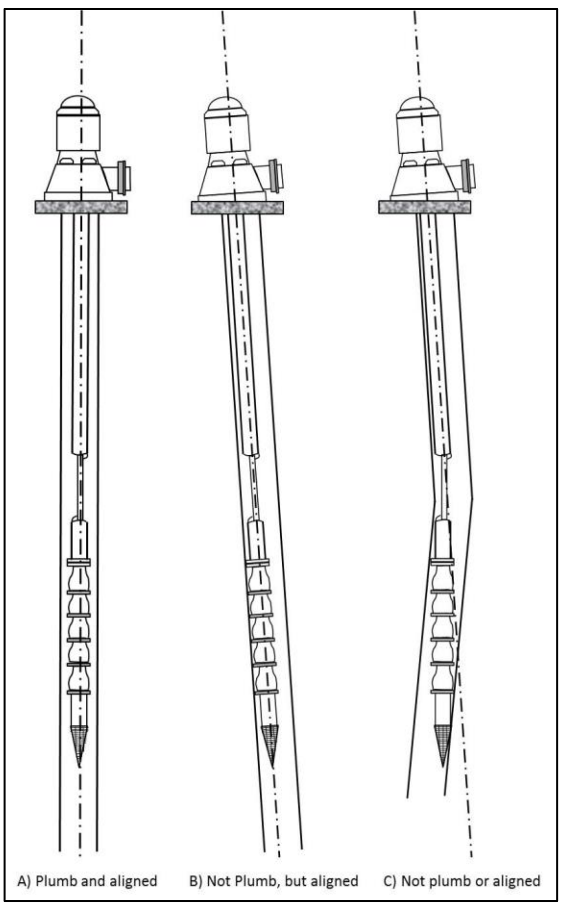
Table 2. Average Drilling Rates for Wells with Similar Geology

Similar Geology:	40 ft - TD (ft/hr)	40 ft – 400 ft (ft/hr)	400 ft - TD (ft/hr)	Total Drift at TD (ft)
Well 4: Driller X	6.1	7.0	5.8	0.2
Well 7: Driller X	5.7	5.1	6.1	4.7
Similar Geology:				
Well 3: Driller Y	10.3	8.5	11.0	0.9
Well 9: Driller Y	7.7	3.7	12.3	5.3
Similar Geology:				
Well 1: Driller Y	21.7	18.0	24.2	0.5
Well 6: Driller Z	14.1	7.3	19.7	2.1
Well 8: Driller X	No data	No data	8.9	4.9

Well Alignment

While drilling rates were not an obvious cause of increased drift in recently-installed wells, it became apparent that shallow doglegs and axial alignment issues were the primary practical operating concerns as the study advanced. Based on discussions with pump companies and suppliers, the impact of a well's axial alignment on the operation and longevity of line-shaft vertical turbine pump equipment is much greater than the impact of a well's plumbness (drift). For example, one pump supplier indicated that a line-shaft vertical turbine pump could operate properly in an aligned well, even if it has a drift angle of up to 30°. Gyroscopic data from the nine SRP wells showed that relatively shallow doglegs around 200 feet in depth were problematic for proper axial alignment of line-shaft pumps. Doglegs in the borehole will generally result in associated doglegs in the cased well, which will ultimately limit the available free clearance for the pump to be installed. For example, if a 14-inch outside diameter pump is installed into a 20-inch inside diameter well casing, there will be 3 inches of clearance on each side of the pump in a "perfectly" plumb and aligned scenario, as shown on Figure 3A. A vertical turbine pump can still operate properly in a non-plumb well, as long as there are no doglegs, provided the motor base at the land surface is shimmed (wedged at an angle) to align it with the downhole pump equipment (Figure 3B). If the well has doglegs, however, the bearings in the line-shaft of the pump will experience wear and tear, which will reduce the pump life and efficiency (Figure 3C).

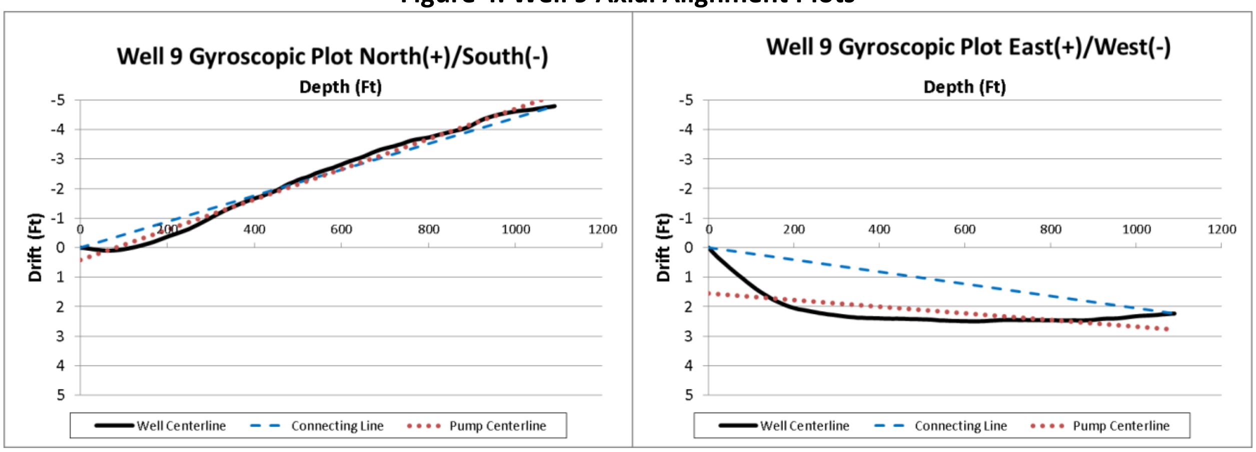
Figure 3.
Pump Response to Well Alignment



SRP developed an internal use spreadsheet to evaluate axial alignment using inputs for pump setting depth, well diameter, and column pipe diameter. The spreadsheet uses closure distance and azimuth bearing data measured by the gyroscopic survey of a well to plot the well centerline (Figure 4) in the North/South view and the East/West view. The spreadsheet then calculates the distance from the well centerline to the pump centerline (AWWA standard) and from the well centerline to the connecting line (Roscoe Moss standard) for each depth interval of the gyroscopic survey. It compares the difference between these distances with the maximum allowable tolerance defined by the well diameter and column pipe diameter inputs. If the difference exceeds the tolerance, then the well is out of axial alignment and the column pipe will not be straight and must bend through that portion of the well. The spreadsheet displays the depth intervals of the well that exceed the axial alignment tolerance with highlighted cells.

The spreadsheet is dynamic, in that it adjusts its calculations to accommodate user-defined depths and diameters. This is critical because while several turns in the well centerline to total depth can cause axial misalignment, if those turns are below the pump setting depth then they are much less relevant to practical operating conditions. Figure 4 displays axial alignment plots from the discussed spreadsheet for Well 9 in the North/South view and the East/West view. The solid black line is the well centerline (gyroscopic survey), the dotted red line is the pump centerline (AWWA standard) and the dashed blue line is the connecting line (Roscoe Moss standard).

Figure 4. Well 9 Axial Alignment Plots



The two oriented perspectives of Well 9 show dramatically different plumbness and alignment scenarios. In the North/South view, the well is plumb in the first 100 feet and then deviates consistently to the south. It eventually reaches almost 5 feet of drift but due to the alignment consistency, the connecting line, pump centerline, and well centerline are close to each other and relatively straight. By contrast, in the East/West view, the well drifts two feet to the east in the upper 200 feet and then straightens out to an almost vertical orientation for the rest of the well with a relatively small final drift at total depth. This results in a dogleg at about 200 feet and a large spatial difference between the well centerline and the two specification lines. Consequently, relatively high amounts of drift over a large distance can become negligible (e.g. 5 feet at total depth), whereas an appreciable amount of drift in the upper 200 feet can make a considerable impact to axial alignment even though the final well drift was relatively small (e.g. 2 feet at total depth). The impact of a shallow dogleg around 200 feet was also observed in well 1 and well 5. Each of these wells also has relatively low drift at total depth (approximately 1 foot or less) but the shallow doglegs in these wells resulted in increased axial alignment concerns in the lower portion of the wells.

The axial alignment analysis of the nine wells drilled between 2005 and 2013 is summarized in Table 3. Total well depth ranged from 640 to 1,310 feet with an average of 988 feet. The pump setting depth ranged from 260 to 580 feet with an average of 372 feet, considerably less than the total well depth. The maximum axial alignment depth determined from the spreadsheet ranged from 310 to 1,180 feet with an average of 681 feet. This is also considerably less than the average total well depth but significantly deeper than the actual pump setting depth. This evaluation resulted in a determination that all nine pump setting depths are within acceptable axial alignment. The analysis for well 9 indicated that it was extremely close to axial alignment constraints, so this well benefitted from a shallower pump setting depth of 290 feet to accommodate the maximum axial alignment depth of 310 feet. Although well 8 exceeded the plumbness standard, it contained no shallow doglegs and was well within acceptable axial alignment, which further emphasizes the importance of axial alignment versus drift.

Table 3. Axial Alignment Data Summary for the Nine Recent Wells

	Minimum	Maximum	Average
Well Diameter (inches)	20	24	21.8
Column Pipe Diameter (inches)	8	14	12.4
Total Well Depth (feet)	640	1310	988
Actual Pump Setting Depth (feet)	260	580	372
Maximum Axial Alignment Depth (feet)	310	1180	681

Recommendations

The initial goal of the plumbness and alignment study was to develop a revised technical specification for plumbness and alignment that is achievable, measureable, and considers practical operating conditions. Based on the study results, the following plumbness and alignment standards and considerations will be incorporated into future SRP well drilling specifications:

- The current plumbness tolerance of 6 inches per 100 feet of well depth appears achievable. The plumbness tolerance is especially important in the upper portion of the well to avoid shallow doglegs. Exceedances of the plumbness tolerance can be waived if the well meets the axial alignment tolerance described below.

- The axial alignment spreadsheet developed by SRP will be used in place of a dummy test to determine acceptance of well alignment for line-shaft pumps. Depending on the specific length, shape and weight of the dummy tool, it is possible for a well to successfully pass a dummy test and still contain doglegs or S-curves that will bind a line-shaft pump. Therefore, a dummy test is not considered a dependable measurement method for determination of axial alignment and future reliability of a line-shaft pump. The dummy test may still be appropriate to assess axial alignment for certain hydrogeologic environments, well diameters, and for wells that are to be equipped with a submersible pump.

- To accommodate practical operating conditions, the axial alignment tolerance incorporates the AWWA and the Roscoe Moss standards in coordination with current SRP operating procedures. The axial alignment will be determined with the pump centerline method where the pump is centered at the top of the well. This method mimics SRP installation procedures where the pump can wander at depth yet needs to be centered at the surface to connect to the existing distribution piping. The well must maintain axial alignment to the proposed pump setting depth using the proposed column pipe diameter. The proposed pump setting depth and column pump diameter will be determined from aquifer test analysis of the completed well with consideration of the appropriate pump submergence and local water level trends.

- If the well fails the axial alignment tolerance, it is assumed that the misalignment in the well may result in premature pump wear, so the drilling contractor will be required to compensate SRP appropriately.

Further Studies and Applications

During the course of this investigation, several opportunities for further studies and useful applications emerged. First, the gyroscopic survey tool that SRP currently uses may be near the end of its useful life and will be evaluated for potential replacement in the near future. It is very important to reliably measure the plumbness and alignment of water wells, so additional evaluations will be conducted to assess available logging tool technology and capabilities. This importance was highlighted by the unexpected variability of gyroscopic survey results for well 8 using separate logging tools.

Second, the axial alignment spreadsheet developed during the study will be used to evaluate pump setting depths and pump diameters on existing SRP wells. Due to the legal considerations and public responsibility of SRP as a utility, the spreadsheet is proprietary and will be unavailable for non-SRP distribution. However, the conceptual descriptions provided herein should be adequate for other entities to develop similar well evaluation models or analytical tools. In addition to providing a baseline assessment of recently-installed wells, the SRP alignment spreadsheet will be utilized to evaluate existing wells. If an existing pump is determined to be "misaligned", the spreadsheet will provide an indication of the appropriate setting depth to which the pump can be raised (or the appropriate column pipe diameter reduction) to achieve axial alignment. This will result in less frequent maintenance, reduced costs, and increased reliability for the well system. When pumps are identified as "misaligned", but can't be altered due to existing infrastructure conditions, they will be tracked to evaluate whether the magnitude of misalignment should be considered excessive. This data will be monitored over time and used to revise the SRP axial alignment spreadsheet and SRP's well drilling specification in the future.

Third, a small percentage of SRP well sites are equipped with submersible pumps because of large drift conditions in the well. The axial alignment spreadsheet allows these wells to be evaluated so the submersible pumps can be replaced by line-shaft pumps where appropriate, resulting in greatly reduced future pump equipment and maintenance costs, and down time.

This plumbness and alignment study yielded results that were unexpected and extremely valuable. The results will support our primary goal of developing a more robust and applicable technical specification for plumbness and alignment in new wells, and it will also enable us to evaluate pump setting depths and axial alignment in older active wells. Informed decisions can then be made for possible modification of existing pump equipment or the conversion of current submersible pump sites to line-shaft pump sites. Insight realized from this study will enable SRP and other well owners to avoid premature pump wear and unnecessary pump maintenance, which will provide significant cost savings and increased well system reliability in the future.

Acknowledgments and Citations

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