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Towards an objective method of verifying the bend radius of HDD installations

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ABSTRACT:
Particularly in high pressure pipes the bend radius (or pipeline stress) is a critical factor in the pipeline integrity management. As HDD techniques and mapping technologies evolve, the permitted margins of error decrease and specifications are tightened, shifting more risk towards the drilling contractor. However, often due to poor understanding of the concept and definition of 'bend radius', upfront agreement on measuring method and permissible deviations seems to lag behind in this evolution. As a result, post installation discussions tend to end up in a mud slinging contest if bend radius specifications are undercut.

Reduct's Pipeline Mapping Systems are used frequently to gather accurate data required to calculate bend radii. However, parties tend to dismiss the results if they are unfavorable and question both the accuracy and calculation method. As a result, Reduct conducted an extensive field test to prove that the technology is sufficiently accurate and to define an operational method yields results within a 5% error margin. This paper describes the test method and result analysis.

Reduct believes the test results provide a firm and fair framework within which drilling contractors and network operators can define objective a-priori verification standards. Reduct has developed a simple software tool that calculates the key verification drivers based on the method outlined below. Further information can be found on our website or on our stand in the Exhibition Hall.

Introduction

Horizontal Directional Drilling is increasingly becoming an exact science as tools and skills evolve. As a result, pipeline owners gradually tighten the specifications of HDD installations and this includes deviations from specified bend radii. Reduct's gyroscopic mapping systems are among the few tools that provide high quality and high frequency data necessary for accurately calculating the bend radius of an installed pipe.

However, data accuracy and the bend radius calculation method are still subject of heated discussions and this is not surprising because particularly for the driller there is a lot at stake. Part of the problem is caused by the multiple interpretations of the definition of 'bend radius' and poor a-priori agreement between parties on post installation measuring method and allowable deviation. I believe there is sufficient consensus on a few key elements, such as the fact that the bend radius assessment should take the 3-dimensional directional change into consideration and that the final product pipe data should be assessed, not the pilot data. However, on a number other key elements consensus still needs to be found. This document discusses Reduct's view on these elements.

Aside from the mathematical principles behind calculating bend radii, a very important element to consider when setting drilling accuracy specifications is the state of the art of HDD steering systems. Under normal circumstances, the driller has manageable control over steering the pilot bore and reaming of the hole. The pullback should not change the bending radius of a pipe significantly, but sometimes it happens beyond his control due to adverse ground conditions and other environmental forces. Since the pipeline owner is only interested in the position of the product pipe all blame for errors rest on the driller. As a driller on a critical job you therefore will want to know what caused any measured errors; steering errors or errors introduced during pullback. To get an answer to that question it is essential to map both the pilot and final product pipe and compare results. The question of liability and force majeure may then work to the driller's advantage.

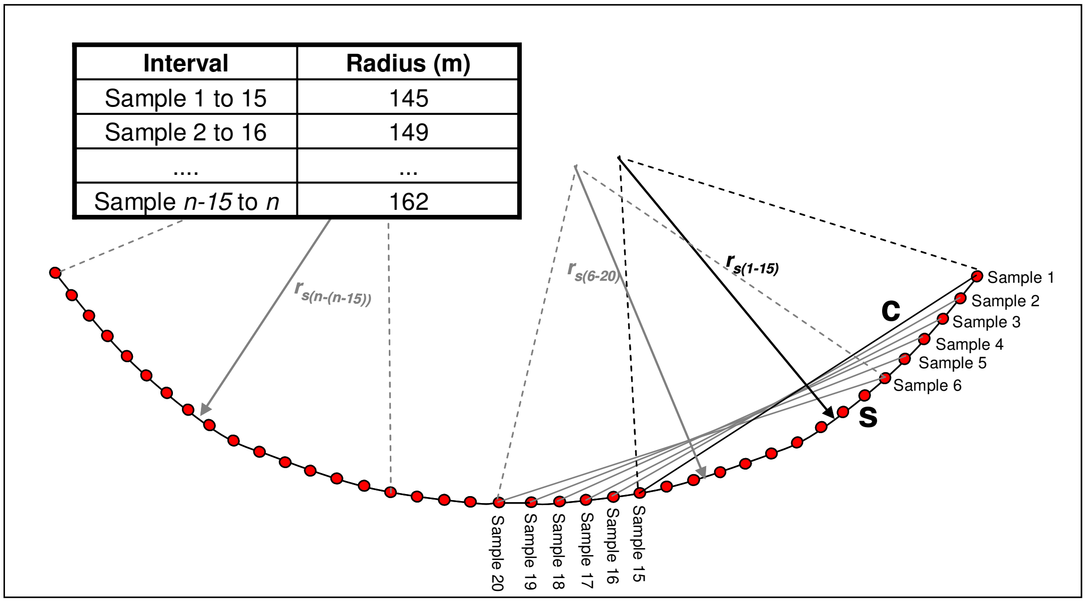
Assuming that the driller's skill is reflected in the accuracy of the pilot profile, the inevitable question arises how accurately a pilot can be drilled. Again, there is no definitive answer to this question, but one thing is for sure, it's not millimeter accurate. A 'reasonable absolute deviation' from the planned profile is usually allowed but if the steering within this margin is too abrupt the bend radius specification may still be briefly undercut, in the worst case resulting rejection by the operator.

The Bend Radius calculation methods

Basically, two calculation methods exist to derive a bend radius from consecutive positional data.

The first method calculates the bend radius by means of consecutive sample angles. The key requirement for using this method is that the raw data is 'perfect', i.e. even the smallest wobble of measuring unit due to welds, debris and other noise will have a significant impact on the bend radius calculation. Therefore, this requires the definition of a complicated and unbiased filter that applies to the sampling frequency. The validity of the filter is very difficult to test for larger radii (say >350m).

The second method (used by Reduct), uses the arc length (*s*) over a certain interval and calculates the bend radius by comparing the length of curve **s** to the straight line length **c** between the first and last sample of the chosen interval.



Interval	Radius (m)
Sample 1 to 15	145
Sample 2 to 16	149
....	...
Sample *n-15* to *n*	162

Figure 1: Illustration of the arc length method

The discussion below is based on this second method.

The measurement interval

The measurement interval is defined as the number of samples over which the bend radius is calculated. Generally it can be stated that the bend radius graph, given a certain level of 'noise' of the raw data used, is more erratic when shorter intervals are chosen, and smoother when longer intervals are chosen.

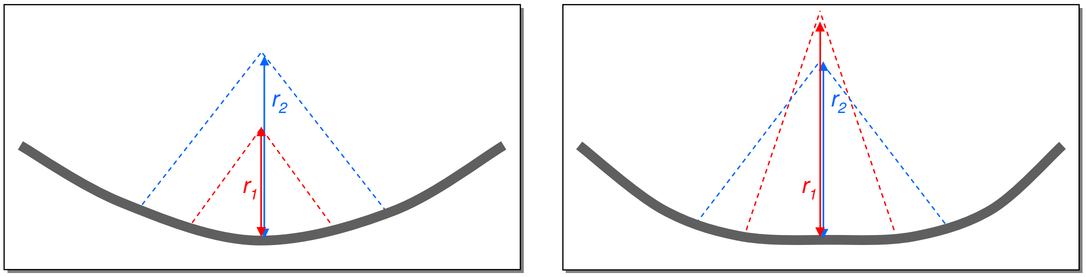


Figure 2: Shorter intervals a more erratic: they yield lower lows and high highs

As the bend radius of a pipe increases, the curve draws nearer to the straight line between the first and last sample of a given interval (i.e. the curve become straighter). The absolute rate at which the curve draws closer to the straight line decreases as the radius increases. The table below shows the incremental distances between radius curves per 100m radius up to 1200m radius over a range of measurement intervals from 20m to 100m.

Change in height (h) per radius change of 100m

Interval (m)	Radius (m)											
in mm	100	200	300	400	500	600	700	800	900	1000	1100	1200
20	0.251	0.083	0.042	0.025	0.017	0.012	0.009	0.007	0.006	0.005	0.004	
30	0.568	0.188	0.094	0.056	0.038	0.027	0.020	0.016	0.013	0.010	0.009	
40	1.018	0.335	0.167	0.100	0.067	0.048	0.036	0.028	0.022	0.018	0.015	
50	1.607	0.525	0.261	0.157	0.104	0.074	0.056	0.043	0.035	0.028	0.024	
60	2.343	0.759	0.377	0.226	0.150	0.107	0.080	0.063	0.050	0.041	0.034	
70	3.239	1.038	0.514	0.308	0.205	0.146	0.110	0.085	0.068	0.056	0.046	
80	4.308	1.362	0.674	0.402	0.268	0.191	0.143	0.111	0.089	0.073	0.061	
90	5.569	1.734	0.855	0.510	0.339	0.242	0.181	0.141	0.113	0.092	0.077	
100	7.047	2.155	1.059	0.631	0.419	0.299	0.224	0.174	0.139	0.114	0.095	

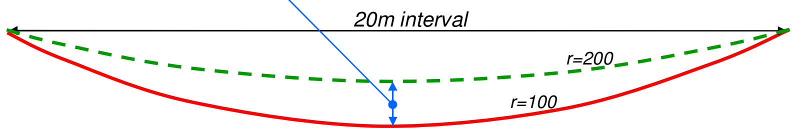


Table 1: Incremental change is distance between curves

The example circled is the distance between the 100m and the 200m radius curve that go through a 20m interval. For HDD purposes, one should interpret this as follows: the client specified a minimum diameter of 200m but a 100m radius was measured, thus the driller deviated 25.1cm from the specified profile over a 20m interval. Using the same logic, the deviation 500m specified curve and a 400m drilled curve over a 40m interval is 0.100m, or 10 cm.

The further one goes to the right in the table, i.e. as the radius of the curve become larger, the smaller the distances between curves become and the less meaningful short measurement intervals become. For example, at an interval of 20m the distance between a 700m and an 800m curve in only 9mm, which will be hard to measure during steering. However, at an interval of 70m, the deviation is a more measurable 110mm.

If HDD contractors are required to adhere to a minimum bend radius on a project and the curve analysis method is accepted by both parties, then it is essential that the a relevant measurement interval is agreed a-priori.

Below table presents the relevant intervals if parties agree on 100mm (light and dark green) and 200mm (light green) as the maximum deviation.

Distance between curves per radius change of 100m

		Radius (m)											
in	mm	100	200	300	400	500	600	700	800	900	1000	1100	1200
Interval (m)	20	0.251	0.083	0.042	0.025	0.017	0.012	0.009	0.007	0.006	0.005	0.004	
	30	0.568	0.188	0.094	0.056	0.038	0.027	0.020	0.016	0.013	0.010	0.009	
	40	1.018	0.335	0.167	0.100	0.067	0.048	0.036	0.028	0.022	0.018	0.015	
	50	1.607	0.525	0.261	0.157	0.104	0.074	0.056	0.043	0.035	0.028	0.024	
	60	2.343	0.759	0.377	0.226	0.150	0.107	0.080	0.063	0.050	0.041	0.034	
	70	3.239	1.038	0.514	0.308	0.205	0.146	0.110	0.085	0.068	0.056	0.046	
	80	4.308	1.362	0.674	0.402	0.268	0.191	0.143	0.111	0.089	0.073	0.061	
	90	5.569	1.734	0.855	0.510	0.339	0.242	0.181	0.141	0.113	0.092	0.077	
	100	7.047	2.155	1.059	0.631	0.419	0.299	0.224	0.174	0.139	0.114	0.095	

Table 2: Distance between curves over a set interval per radius change of 100m

So if the minimum bend radius requirement of an HDD profile is 500m and the permitted maximum deviation is 100mm, then a minimum interval of 50m needs to be used. Similarly, if the permitted deviation is 200mm, then a minimum interval of 70m should be chosen.

Although the above method of agreeing on bend radius measurement principles are not yet commonly used today, it is clear to see from this table that the larger the chosen interval the more room for error the driller has. The maximum permitted deviation should therefore be agreed in light of the complexity of the drill, the soil conditions and possibly the steering method used.

The raw data accuracy

The quality of the raw data is essential in calculating bend radius values, regardless of the calculation method.

Reduct Pipeline Mapping Systems collects data using inertial sensors technology. Although this technology is quite accurate, small deviations from reality are possible. The question then begs how these small deviations impact the bend radius calculation.

The method to test this empirically is by mapping a certain segment of pipe repeatedly and comparing the <u>*spread of the bend radii*</u> of

1. the individual results (Filter 1[1]),
2. averaging 2 consecutive forward (A to B) and backward (B to A) measurements and then calculating the bend radius (Filter 2),
3. averaging 4 consecutive forward and backward measurements and then calculating the bend radius (Filter 3),
4. and finally repeating the averaging exercise for all measurements (Filter 4).

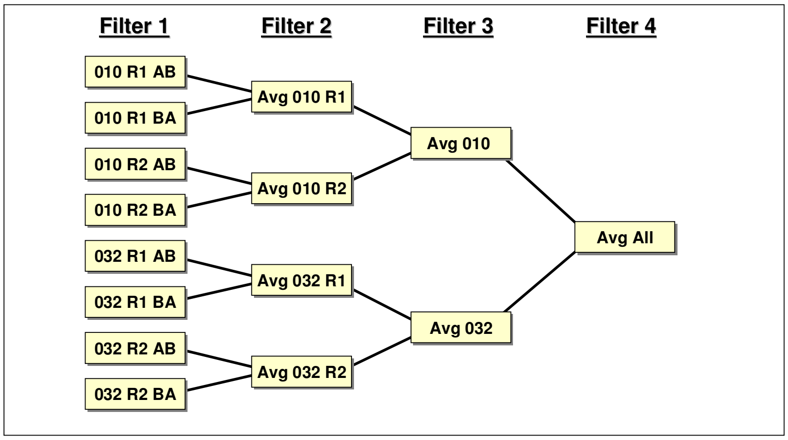


Figure 2: Empirical raw data quality test

A priori it can be stated that **IF** the Filter 1 data contains a high level of noise, the arc ***s*** will be longer and thus the bend radius smaller. It is then expected that filter 2, 3 and 4 contain smoother data yielding shorter arcs and thus higher bending radii.
On the contrary, **IF** the Filter 1 data contains low levels of noise, the filter 2, 3 and 4 bend radii curves will lie within the spread of the individual measurements.

The test data concerns a 980m pipeline segment. Two Reduct Pipeline Mapping Systems (4 runs each) were used (serial numbers 010 and 032) to eliminate technical error/noise. The interval selected to compare the results was ‘only’ 30m to accentuate peaks and falls.

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[1] The Reduct probes sample at 100Hz, i.e. 100 samples per second. At a typical traveling speed of 1.5m/sec, that translates to one sample per 1.5 cm. The bend radius is calculated on a sample frequency of 1m, hence once about 66 samples. Individual results are therefore already filtered one time.

Figure 3 below shows the overall results of all bend radius measurements. Immediately the high level of repeatability is noticeable, particularly for radii less than 1000m.

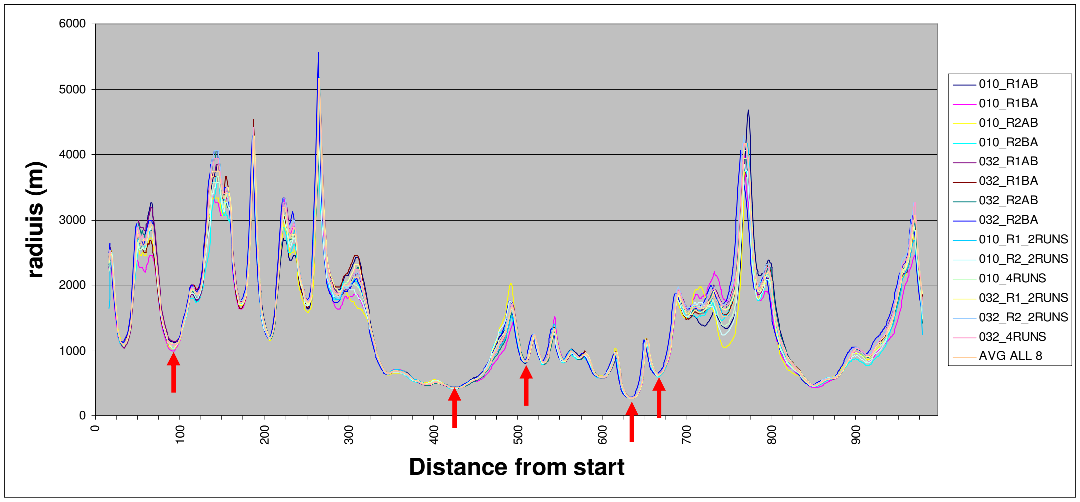

Figure 3: Mapping results of all individual runs and the averages

The true analysis of the quality of the measurements is done by means of comparing the *spreads* of the bend radii at the various filter levels. The *absolute spread* is expected to be larger at higher bending radii than at lower, so five ‘dips’ (red arrows) at different bending radii have been selected for detailed spread analysis.

Figure 4 gives an example of the detailed results of the spread analysis for the ‘dip’ at approximately 1050m radius (left red arrow in Figure 3) .

- The spread at Filter 1 is 144m, or 14.5% of the lowest vale in the spread. The orange and blue lines depict the two different systems used.
- The spread at Filter 2 is down to 60m, or 5.7% of the lowest vale in the spread.
- The spread at Filter 2 is down to 36m, or 3.4% of the lowest vale in the spread.

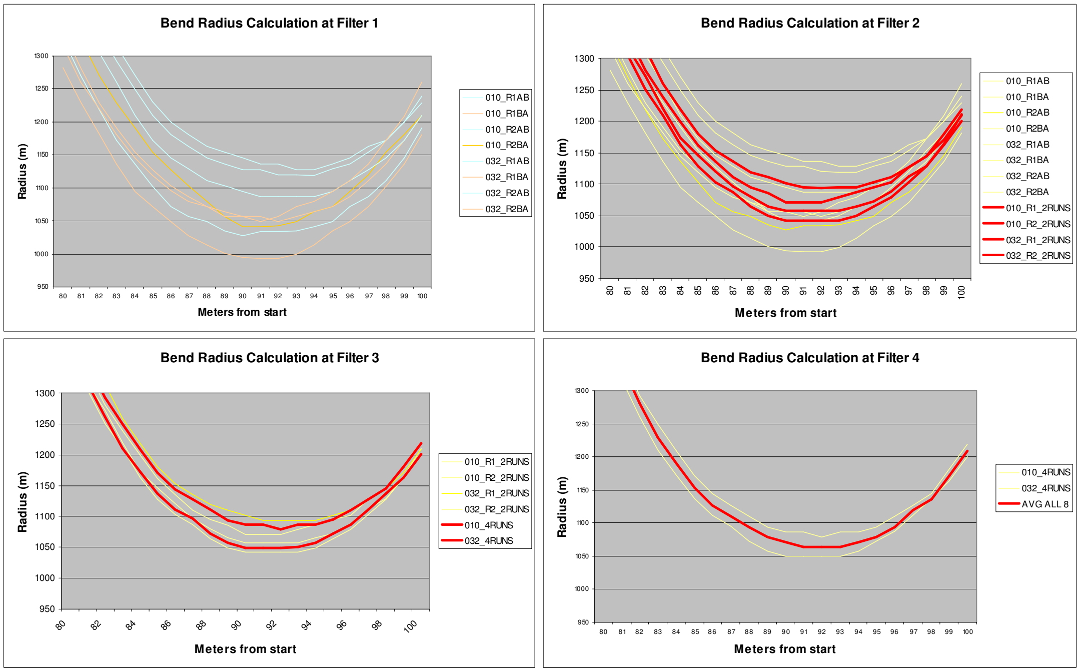

Figure 4: Spread analysis at about 1050m radius

Table 3 presents the results obtained in similar fashion as above for the 5 different dips indicated by the red arrows in Figure 3.

Spread results	Filter 1	After Filter 2	After Filter 3
@ r ~ 1050m	144m (14.5%)	60m (5.7%)	36m (3.4%)
@ r ~ 825m	59m (7.4%)	40m (4.9%)	22m (2.7%)
@ r ~ 625m	43m (7.3%)	31m (5.1%)	20m (3.3%)
@ r ~ 425m	33m (8.2%)	20m (4.8%)	2m (0.5%)
@ r ~ 275m	12m (4.5%)	10m (3.7%)	5m (1.9%)

Table 3: Spread analysis results at various radius dips
Note: Spreads for larger intervals will decrease and for shorter intervals will increase.

Some other observations resulting from the spread analysis:

- Results confirm that the *absolute spread* increases with an increase in radius.
- The percentage of spread varies significantly at the Filter 1 level, but converges to about 5% at Filter 2 (averaging 2 runs and then calculation bend radius).
- The improvement in spread from Filter 2 to Filter 3 is less spectacular.
- Filter 2, 3 and 4 lie more or less in the middle of the Filter 1 results. As explained before, this means that:
    1. the individual results of the Reduct Pipeline Mapping Systems contain very LOW levels of noise, and
    2. that the calculating method yields a good representation of reality.

Measurement tolerance
For practical operational reasons, it is best to focus on Filter 2 as a standard for measuring bend radius. This means that when accurate measurement tools are used, an average is taken of two measurements of the same pipeline segment, once from entry to exit point and once from exit to entry point. This average is then used to calculate the bend radii of the pipeline segment.

At Filter 2 and a 30m interval, the spread is generally 5% so that could be a good indication of measurement tolerance. So for example, if the measured radius is 300m, then the tolerance range is 285m to 315m and for 600m the tolerance range is 570m to 630m.

Conclusion
As more and more elements become measurable and information becomes available to both pipeline owner and drilling contractor, the necessity of understanding and agreeing on a measurement principle for bend radius upfront is essential. This paper shows that key elements such as measurement interval are vital to justifiably accepting or rejecting an HDD.

In addition, this paper shows that bend radius data generated by Reduct Pipeline Mapping Systems is highly accurate and reliable and two passes will generate a tolerance level of 5%. Furthermore the Arc Length calculation method is an acceptable method for calculating bend radii in the HDD environment.

Although the results presented above provide a sufficient basis for calculating HDD bend radii, the most important change that needs to happen is that contractor and network owner include the key drivers of post-installation bend radius verification in the job specification so that the current ambiguity is significantly diminished. Reduct has developed a simple software tool that calculates the key verification drivers based on the method outlined below. Further information can be found on our website or on our stand in the Exhibition Hall.