SINKER SECTION DESIGN TO REDUCE BUCKLING RELATED FAILURES

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INTRODUCTION

Deep hole in tubing (HIT) failures in Reciprocating Rod Lift are a common and expensive problem in unconventional wells today and analysis is pointing towards aggressive buckling mechanisms being a primary cause of the failures. It is worth mentioning that there are likely a combination of factors that are accelerating failures in this region. For example, aggressive corrosive environments, solids (Abrasion), and even deviation in some cases. In the end, in most of these deep hole in tubing failures, rod on tubing contact and some amount of side loads due to buckling are present.

Buckling mechanisms are also likely causing other harm in the Reciprocating Rod Lift system, namely, deep body failures due to bending forces, connections failures due to vibrations and shock loads, and loss of net stroke due to the energy loss of buckling. There are various studies and papers available on these topics and more research would help understand these topics further. It is important to provide some background on the bending force mechanism mentioned above. It can be seen in Finite Element Analysis (FEA) of buckling scenarios, that the bending produces concentrated effective stress near upset due to the stiffer connection area resisting the bends and the bending being concentrated directly outside of the connection (Fig 1).

Overall, it is understood that there are various negative effects associated with compressive loads and buckling. These effects, especially deep holes in tubing are what lead to the following research, product development, and failure reduction efforts.

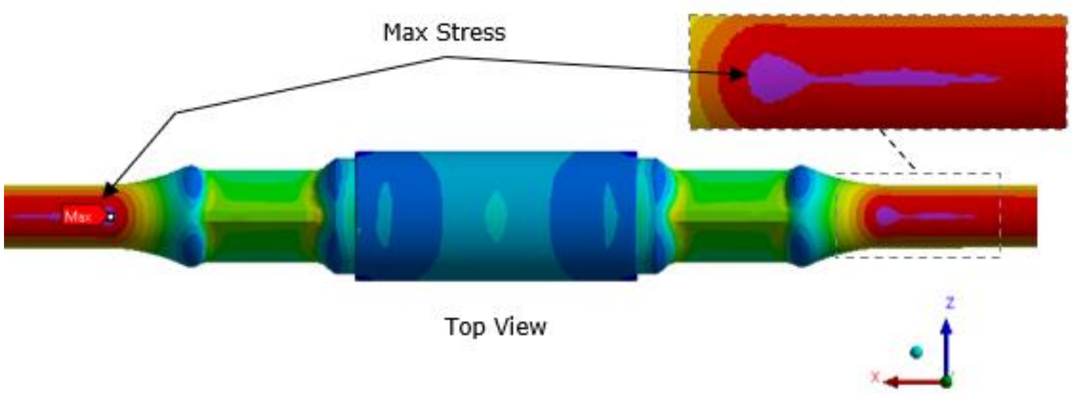


Figure 1. Finite Element Analysis Output of a Sucker Rod Bending Scenario

BUCKLING BASICS

Buckling of a sucker rod string is essentially deflection of a slender column under a compressive load. In reciprocating rod lift, due to the nature of the pumps used and various operational conditions, there will almost always be a measurable compressive load on the rods directly above the pump. This is why sinker sections are used. There are an endless number of operational changes that can reduce the compressive load induced on the rods by the pump (full pump fillage, separate solids, etc.), but this beyond the scope of this paper. When attempting to explain the buckling behavior of a sucker rod, Euler’s Critical Load equation below is very helpful for understanding what compressive load causes a rod to buckle and what can be done to prevent it.

$$P_{cr} = \frac{\pi^2 E\ I}{(KL)^2}$$

Where:
P_{cr} = Critical Buckling Load (Load at which the column buckles) in pounds
E = Young’s Modulus in MPSI
I = Moment of Inertia in Inches^4
L = Unsupported Column Length in Inches
K = Effective Length Factor

Young’s Modulus varies slightly depending on which type of steel, but for the purposes of this explanation and sucker rod applications, it can be assumed to be constant. Unsupported column length is determined by where the sucker rod is being supported and can be assumed to be supported at each coupling or at the top/bottom of tapers by contacting the tubing walls, but this likely is not reality and difficult to predict. The rod is effectively supported at the top of the well, the pump, and the guides. The effective length factor varies from 1-4 depending on end support type (hinged, fixed, free, etc.) but for this paper, will be assumed to be 1 as most advanced research suggests is most accurate. Moment of Inertia depends only on the size of the rod experiencing the load and is calculated using the following equation for circles:

$$\frac{\pi D^4}{64}$$

Where:
D = Diameter of the rod

There are many derivations and expansions upon Euler’s to get closer to real life scenarios. These include several equations derived by Lukasiewicz in his paper On Lateral and Helical Buckling of a Rod in a Tubing that account for a pressure stabilization effect and predict both lateral and helical buckling (Lukasiewicz 2006) and the algorithms that operate in the background of common rod design programs today. In short, it seems that Euler’s is likely to predict buckling before it is occurring, but the main variables are still important to understand how to prevent buckling and a relative comparison of the efficacy of different strategies. Below is a table of Euler’s Critical Loads (Table 1) of common rod/sinker bar sizes and guiding configurations calculated using the following equation and the following table (Table 2) of effective lengths based on assumptions of being supported at guides and/or couplings:

$$P_{cr} = \frac{\pi^2 (27.56)\ (.015532)}{(L)^2}$$

(Table 1)

Euler's Critical Buckling Load (lbf)		Guiding				
		Slick	4 Per	5 per	6 per	8 per
Rod Size	1 5/8"	1034	N/A	N/A	N/A	N/A
	1 1/2"	751	N/A	N/A	N/A	N/A
	1 1/8"	237	3142	4242	5563	14060
	1"	148	1961	2648	3473	8778
	7/8"	87	1150	1552	2036	5145
	3/4"	47	621	838	1099	2777

(Table 2)

Effective Length L (Inches)	Guiding				
	Slick	4 Per	5 per	6 per	8 per
	300	83	70	60	40

Or expressed in PSI as is typically output by rod design software in Table 3 below:

(Table 3)

Euler's Critical Buckling Load PSI		Guiding				
		Slick	4 Per	5 per	6 per	8 per
Rod Size	1 5/8	499	N/A	N/A	N/A	N/A
	1 1/2	425	N/A	N/A	N/A	N/A
	1 1/8	238	3161	4268	5596	14145
	1	188	2497	3372	4422	11176
	0.875	145	1912	2581	3386	8556
	0.750	106	1406	1897	2488	6286

Euler's equation and these calculations show there are only a few variables that can realistically be adjusted to reduce buckling given a compressive load; increase cross sectional area of the rod or support the rod by adding guides. These tables also show that adding guides has a much larger effect on eliminating buckling (and in many cases is necessary to eliminate buckling due to unavoidable compressive loads in the sinker tapers). An important comment is that guides do wear over time and perform as a less ideal support. Guides not being accounted for as a support are a primary limitation in buckling tendency calculations in rod design software available today. Essentially, the ideal case to eliminate buckling is infinite centralization and support (Fig 2 & 3). Sinker sections also reduce the compressive load and therefore buckling, but only for rods above the sinker sections, so you may still have buckling in the sinker section and need attempt to treat the problems it causes in other ways (specialty tubing, etc.).

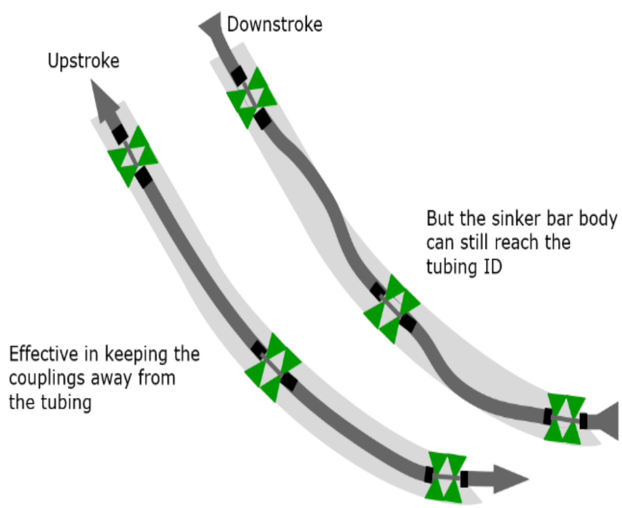


Figure 2. Sinker Bar buckling under compression

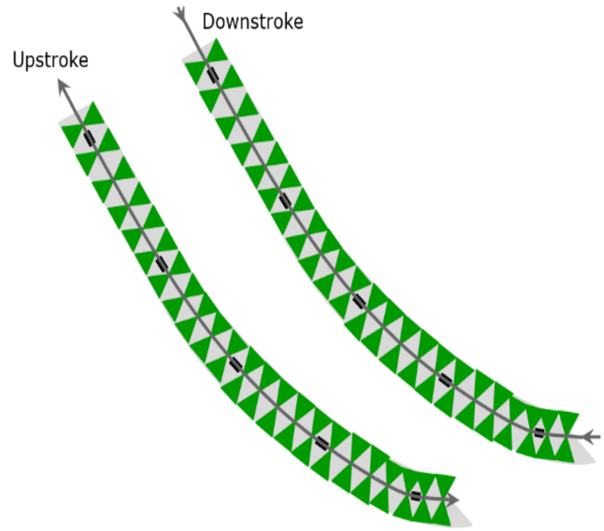


Figure 3. Ideally centralized rod

<u>SINKER SECTION DESIGN STRATEGIES</u>

There are a large variety of different sinker section strategies that are currently employed by operators to optimize several different factors, and the below section will summarize those strategies and the advantages and disadvantages of each. Before summarizing the various sinker section strategies, it is important to mention a few rod design best practices to model worst case scenario compressive loads for calculating buckling tendency. Generally, consider the below points and apply several or all which are feasible for the well in question:

- Modeling 75-95% pump fillage
- Modeling low fluid level/pump intake pressure, although this is highly variable on other design parameters, so running iterations with a wide range is recommended
- Always consider max strokes per minute possible
- Consider higher pump friction depending on field average or expected value
- In cases of uncertainty, design with the goal of 1000 psi (+-200) bottom minimum stress above the sinker section

In addition to attempting to model a realistic worst-case scenario, it is important to remember the goal of sinker section design; eliminate the negative effects of buckling. If buckling is eliminated in all sections of the rods string, then there will be no negative effects.

Sinker Bar

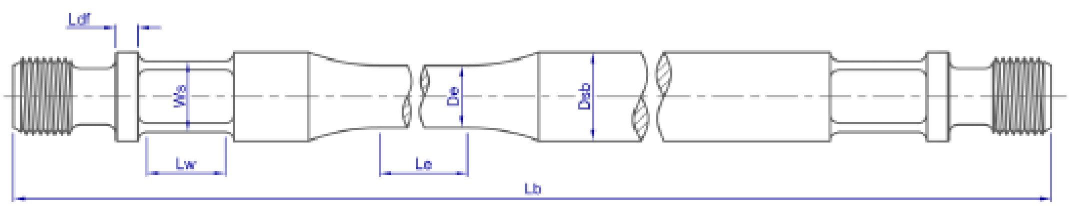
The “standard” design for sinker sections. Range from 1 ¼” - 2” body diameter, with 1 ½” and 1 5/8” being the most common in unconventional wells. Commonly paired with stabilizer bars (3-4ft 1” Body x ¾” or 7/8” Pin, 1-3 per guided pony rods) and ¾ or 7/8 slimhole (SH) couplings to achieve constant body diameter. Figure 4 below shows standard dimensions for sinker bars and the following bullets also summarize the advantages and disadvantages of sinker bar:

Sinker Bars Full API

Product Description:

Tenaris standard products are with four wrench flats and elevator neck. There are also available with only two wrench flats and/or without the elevator neck.
Products according to API 11B.

Dimensions:



Nominal Size: Rod	Nominal Size: Units	Dsb	Ldf (max)	Ws	De	Lw (min)	Le (min)	Sucker Rod Thread Pin Size	Polished Rod Thread Pin Size
1 1/4"	in	1.25 +0 -0.03	0.75	1 ±0.03126	0.875 +0.009 -0.018	1.25	4	5/8"	3/4"
	mm	31.75 +0 -0.76	19.05	25.4 ±0.794	22.23 +0.23 -0.46	31.75	101.6		
1 3/8"	in	1.375 +0 -0.03	0.75	1 ±0.03126	1 +0.009 -0.018	1.25	4	5/8"	3/4"
	mm	34.93 +0 -0.76	19.05	25.4 ±0.794	25.4 +0.23 -0.46	31.75	101.6		
1 1/2"	in	1.5 +0 -0.03	0.75	1.313 ±0.03126	1 +0.009 -0.018	1.25	4	3/4"	7/8"
	mm	38.1 +0 -0.76	19.05	33.34 ±0.794	25.4 +0.23 -0.46	31.75	101.6		
1 5/8"	in	1.625 +0 -0.03	0.75	1.313 ±0.03126	1 +0.009 -0.018	1.25	4	7/8"	-
	mm	41.28 +0 -0.76	19.05	33.34 ±0.794	25.4 +0.23 -0.46	31.75	101.6		
1 3/4"	in	1.75 +0 -0.03	0.75	1.5 ±0.03126	1 +0.009 -0.018	1.25	4	7/8"	-
	mm	44.45 +0 -0.76	19.05	38.1 ±0.794	25.4 +0.23 -0.46	31.75	101.6		

Figure 4. Sinker Bar Data Sheet

- Relatively high pounds/foot to minimize length of sinker section
- SH couplings achieve near constant outer diameter and distribute side loads
- Only able to reduce buckling by adding stabilizer bars at each end (Max 3 guides) and leaving considerable risk of buckling induced tubing wear through body section
- Can be limited on loading of typically low-grade steel at pins and elevator necks or even SH couplings if not upgraded to a HS base material

- Risk of flow losses in tight clearances between sinker bar and tubing internal diameter (ID), especially in systems producing above 300 barrels of fluid/day and operations that run above 1300 in/min polished rod speed

1” Guided Sucker Rod

The next most common sinker section design of the past is using standard 1” guided sucker rods (or 7/8” in 2 3/8” tubing applications). These are typically guided with 4 guides per rod but may have as much as 8 guides per rod in some cases. Guided 1” has the below associated benefits and drawbacks:

- Small Erodible Wear Volume (EWV) due to the 2” OD coupling (Fig. 5)
- Not suitable for slim hole applications (2-3/8” tubing), and must downsize to 7/8” rod and sacrifice pounds/foot and EWV even further
- Presence of guides avoids metal on metal contact between rods and tubing and provide supports to prevent buckling under moderate compressive loads
- Relatively low pounds/foot
- Guides help create uniform bending of the sucker rod and reduce near upset stress concentrations
- Rod failures in sinker section are rare due to increased strength of upsized pin and base steel

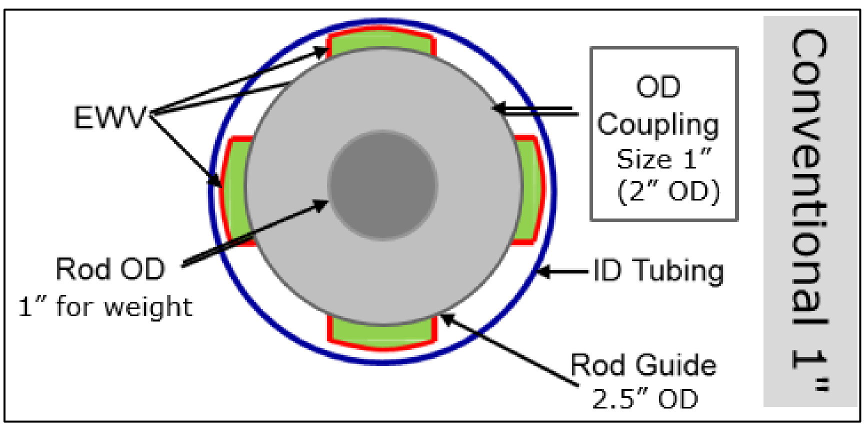


Figure 5. 1” Guided Sucker Rod, EWV

Sinker Rod (1” Body x 3/4” Pin Sucker Rod)

The most up and coming of the sinker sections. It seeks to maximize the benefits of both designs. Commonly available in 8 guides per rod (as is recommended as a standard by the authors) and paired with ¾ SH (1.5” OD) couplings to maximize EWV of the guides. Further information is shown in the product data sheet below (Fig 7). As above, the various advantages and disadvantages are summarized below:

- Very high EWV due to the 1.5” OD coupling (Fig. 6 & 8)
- Suitable for slim hole applications (2-3/8” tubing) with proper sized guides
- Higher guides per rod and EWV further delay metal on metal contact between rods and tubing and provide more and longer lasting supports to prevent buckling
- Relatively low pounds/foot (Table 4)
- Coupling OD and body diameter closer to uniform to distribute side loads and bending forces across rod
- Higher guides per rod further allows uniform bending of the sucker rod and reduce near upset stress concentrations
- Suitable for pump in curve applications due to the above characteristics
- Smaller connection that may be susceptible to failures if overloaded or not properly designed and operated
    - Although, sinker rods are typically a higher-grade steel than sinker bars

(Table 4)

Sinker Type (All SH Couplings)	Pounds/Foot
1 5/8" x 7/8" Pin	7.1
1 5/8" x 7/8" Pin w/ 1" 4ft Stabilizers	6.5
1 1/2" x 3/4 Pin	6.1
1 1/2" x 3/4 Pin w/ 1" 4ft Stabilizers	5.6
1 1/4" Bar	4.3
1 1/8" x 7/8" Pin	3.5
1" Rod	2.9
1" x 3/4" Pin	2.9
7/8" Rod	2.2

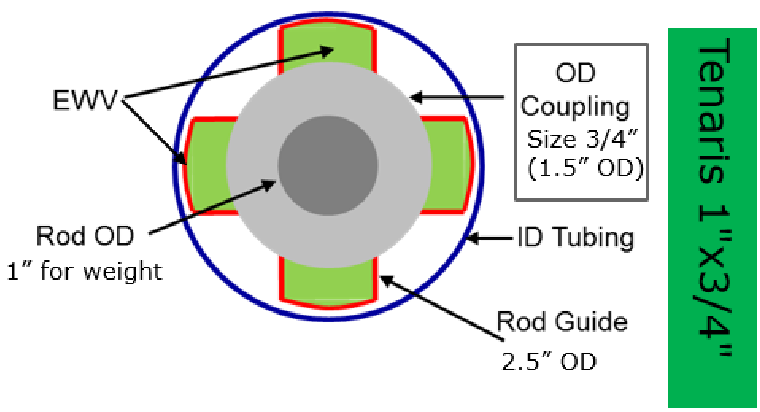


Figure 6. Sinker Rod EWV Visualization

API grade Sinker Rods

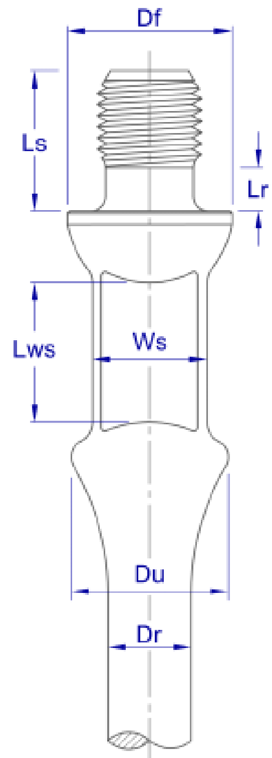
Dimensions:

API Grade Sinker Rod is a Tenaris special product designed to support lateral loading in compressive sections of the string in Beam Pumping applications.

Nominal Size			Dr	Df	Ws	Lws (min)	Du	Lr	Ls
Rod	Pin	Units							
1"	3/4"	in	1	1.5	1	1.25	1.5	0.594	1.437
			+0.009 -0.018	+0.005 -0.01	±0.031		+0.004 -0.122	+0.031 -0	+0.063 -0.00
		mm	25.4	38.1	25.4	31.75	38.1	15.09	36.51
			+0.23 -0.43	+0.13 -0.25	±0.8		+0.1 -3.1	+0.79 -0	+1.59 -0

Sucker Rods Nominal Lengths: 25, 30 ft (7.62 , 9.14 m)

*Other lengths might be available upon request.



Steel Grades:

Different steel grades are available, depending on the type of load and the corrosion level in the wells. All this materials comply with API 11B.

Chemical Composition:

Typical chemical compositions (wt%) are listed in the following table:

Grade	C (%)	Mn (%)	Si (%)	S (%)	P (%)	Cr (%)	Ni (%)	Mo (%)	Other (%)
D alloy	0.40-0.45	0.75-1.00	0.15-0.35	0.025 max	0.025 max	0.80-1.10	0.25 max	0.15-0.25	-
D Special	0.29-0.37	0.70-0.95	0.15-0.35	0.025 max	0.025 max	0.80-1.10	1.65-2.00	0.20-0.30	V: 0.04-0.08
D Special KD	0.20-0.25	0.80-1.00	0.15-0.35	0.015 max	0.025 max	0.70-0.90	1.15-1.50	0.25-0.30	V: 0.03-0.07

Figure 7. Sinker Rod Product Data Sheet

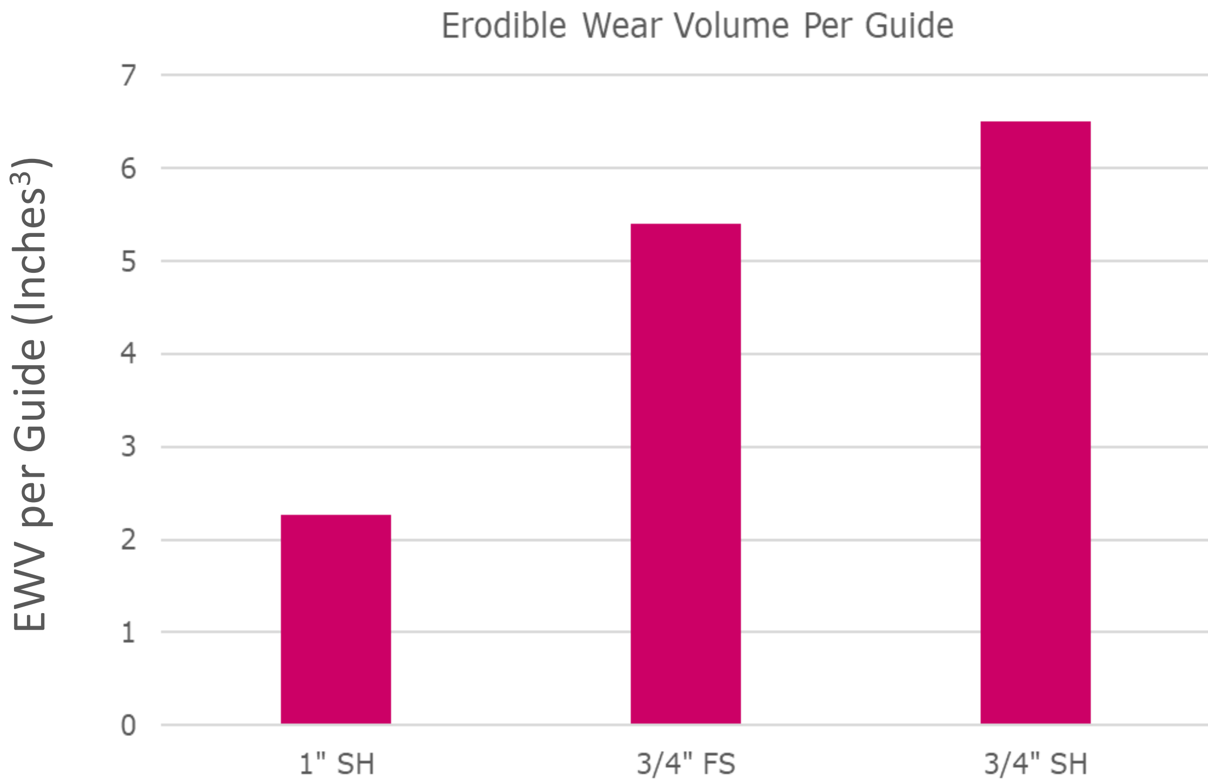


Figure 8. Erodible Wear per Guide Comparison Based on Coupling Size

Due to specific characteristics of sinker rod, some design recommendations are below:

- ¾" SH couplings are recommended to maximize EWV
    - Because coupling-tubing contact may eventually happen, low friction couplings are recommended for an extra layer of protection
    - High strength couplings are recommended due to reduced ¾ SH strength
- 8 guides per rod is standard recommendation in order to achieve all of the previously mentioned benefits of a higher guide per rod design
- Perform loading calculations based on the nominal pin diameter as it will be the weakest link in the system (This is also true, but not common for sinker bars)
- Average ratio of sinker bar (1 ½") to sinker rod (1") is approximately 1:2, depending on the sucker rods size above the sinker taper
- Pair with a hydrodynamic guide to limit erosion-corrosion mechanisms and the pressure drops along the sinker section

Additionally, there are some similar, but non sinker section specific design considerations that may help alleviate the negative effects of buckling.

- Adding guided rods above the sinker section where impossible or impractical to completely eliminate compressive loads on sucker rods with sinkers
- It is imperative to eliminate all compressive loads, not just buckling, in fiberglass rod sections due to the higher sensitivity to compressive loads and risk of failure

INDUSTRY TRENDS & NEXT STEPS

The sinker rod is becoming increasingly popular across all basins with 500+ installs over 15+ operators being tracked by the authors since late 2021 but has particularly grown rapidly in the Permian and Bakken. A large majority of the installs have been to combat deep tubing failures, but there has also been significant value in for improving performance (failure reduction and production) on hybrid fiberglass strings.

Run times before first hole in tubing failure by one Bakken operator have averaged 441 days on 36 installs in 2022. Further analysis is required on the hole in tubing failures that have occurred to understand if they happened near the sinker section and clearly define failure mechanisms and root causes. Another Bakken operator has reported the SH Sinker Rod (2 3/8” tubing) has been the best solution to date for reducing tubing wear by achieving 9 months+ run times in high tubing failure frequency wells.

Operators in Permian Basin are also reporting strong performance in both 2-7/8” & 2-3/8 size sinker rods. Data available for the 2-7/8” installs show one HIT. Other failures in these installs are non-HIT nor Sinker Rod related. For SH sinker rods, a total of 13 installs that commenced deployment as early as Nov 2022 have shown zero failures. Four of those installs show HIT as previously failed component. For all these installs, monitoring and analysis shall continue.

One operator in Permian incorporated sinker rods strongly into their fiberglass hybrid string design. This approach helped to further understand the limits in the application range for the sinker rod. Some of the features and benefits claimed by the operator are:

- Sinker taper length up to 2000ft with guided 7/8” or 1” rod immediately above
- Help plunger downstroke/fall at high polished rod velocity and flowrates
- Hydrodynamic rod guide to prevent corrosion-erosion mechanisms

Overall, engineering analysis over the incidents described at the opening of this document is clearly improving and leading to developments on sinker section design, but there is plenty further work to be done including the below points:

- Perform Computation Flow Dynamics (CFD) of various sinker section designs to understand if any strategies are impeding flow
- Research or trials of larger diameter sinker bars
- Rod design software improvements to account for guides as supports and account for effective stress associated with bending and buckling
- Explore higher fatigue resistant sinker rods to increase loading capacity of pins in situations where very long tapers are required
- Explore the need for more erodible wear volume near the connection to further delay coupling on tubing contact
- Tribocorrosion (Wear + Corrosion) testing of guides and specialty tubing (boronized, internally plastic coated, etc.) to understand their effect on guide wear
- Understand how sinker section design affects pumps landed in the curve
- Investigate the effects of buckling and associated vibrations on sucker rod connection failures and system efficiency

CONCLUSIONS

- Deep hole in tubing failures plague the industry and likely are being accelerated or caused by buckling mechanisms among other negative effects
- Some compressive loads are almost always guaranteed to occur above your pump in reciprocating rod lift applications
- Euler's Critical Buckling Load equation is a useful tool to understand critical buckling loads of different sinker/rod sizes and guide configurations
    - Showing that adding supports in the form of guides is much more effective at increasing critical buckling loads than increasing rod diameter
- Modeling realistic worst case compressive load scenarios is important to effectively manage buckling
- Rod design programs seem relatively reliable at performing buckling calculations, but do not consider guides as supports
- Various sinker strategies are being used today, and there doesn't seem to be a one size fits all approach
    - Sinker rod seems effective and promising for mitigating buckling and protecting the tubing from wear
- Rod guide wear must be factored into sinker rod buckling application analysis
- Improvement through research and development on sinker section design is not finished and there are many steps to continue improvement

REFERENCES

Lukasiewicz, S.A., and C. Knight. "On Lateral and Helical Buckling of a Rod in a Tubing." *J Can Pet Technol* 45 (2006) doi: https://doi.org/10.2118/06-03-TN1

ACKNOWLEDGEMENTS

The authors would like to thank Tenaris Product Engineering team for their continued support in understanding buckling and its negative effects and developing sinker related technology.