TESTING OF HYDRAULIC TUBING ANCHORS

Walter Phillips
Black Gold Pump & Supply

ABSTRACT

Hydraulic tubing anchors have been around for over 30 years, however the technology has greatly improved in recent years. To better understand the dynamics of hydraulic anchors, a test rig was constructed to approximate down-hole conditions in terms of depth and holding capacity. The test assembly allows for controlling the perceived depth by way of pressurizing the tubing, or internal bore of the hydraulic anchor. Varying the pressure in the "tubing" simulates the pressures seen at any depth. The holding capacity of the anchor is tested by a hydraulic jack, which is placed under the anchor. The jack, having a known bore, can easily correlate PSI to lifting force placed on the anchor. Numerous tests were conducted at varying depths to find the lifting force required to dislodge, or cause the anchor to slip. Anchor test data as well as analysis of the interface between the anchor and casing are presented.

BACKGROUND

Tubing anchors are used to stabilize pump and tubing movement relative to the rod-string and casing. As the down-hole pump cycles, fluid loads are transferred from the rods onto the tubing. The resulting load differential causes the tubing to stretch and contract. In unanchored tubing, this tubing stretch reduces the net pump travel. In addition to lost production, cyclic stretching and movement can cause unnecessary wear on the casing and rod string in addition to the tubing string. In the 1950's, it was shown that unanchored tubing actually buckles and can become helically coiled around the rod string, which remains essentially straight under tension (Lubinski). This compounds the issue of rod on tubing wear because it drastically increases the side-loading on the contact points.

Two basic types of anchors are considered in this paper. Mechanical type anchors engage serrated metal blocks, or "slips" onto the inner casing wall via a screw type, or positive engagement mechanism. A second type of anchor, and primary focus of this analysis, utilizes the fluid pressure in the tubing string to energize a piston. This piston then pushes the serrated blocks onto the inner wall of the casing for a positive engagement. Mechanical anchors are well known and used throughout the industry, but are problematic in certain well conditions, in particular deep or deviated wells where their setting procedure can be difficult or impossible. Safety is also a concern as there are a series of potentially dangerous surface operations that take place in the placement and removal of the mechanical anchor. The Hydraulic anchor does not require any surface manipulation in conjunction with installation or removal.

SETTING AND UNSETTING ANCHORS

Setting a typical mechanical type anchor requires the tubing to be rotated at surface. Rotating the tubing engages a threaded cone, or wedge, that gradually expands the serrated "slips" until they provide a positive grip on the casing wall. In addition, this type of mechanical anchor must be pre-loaded to set the anchor and tubing into tension to account for many factors such as temperature, tubing dynamics, etc. (Lubinski, Samayamantula) The mechanical anchor does not compensate for these factors during normal operation of the well, and so the correct preload is essential. Furthermore, if the anchor becomes unset as a result of improper installation, a significant mechanical intervention is required to reset the anchor. These installation operations pose a potential safety concern with rig crews.

A hydraulic anchor does not require any setting procedure at the surface in order to engage the anchor. As the tubing fills with fluid, the bottom-hole differential pressure between the tubing and casing increases. This pressure induces a force on the piston in the hydraulic anchor mandrel, pushing the serrated blocks, or "slips", against the casing wall. The hydraulic anchor is designed such that it will move down the casing as fluid load induced tubing stretch increase. Serrations, or teeth, in the slips allow the anchor to move downward but will prevent the anchor from moving up while engaged. Effectively the hydraulic anchor compensates for the variability in tubing stretch caused by a number of factors such as fluid loading and temperature. The claim that the anchor will move down, but not up, is tested and validated in this paper, although the full analysis as it relates to functioning well conditions is left to future work.

Unsetting a mechanical anchor is accomplished by relieving the pre-tension on the tubing, and then rotating the tubing to unscrew the engagement mechanism. Under certain conditions this is not possible and so shear pins are used to actively disengage the anchor mechanism. In rare cases the mechanical anchors can become stuck due to sand, corrosion, or any number of other factors. Pulling on a stuck anchor to release the shear pins poses a serious safety concern for rig crew personnel. In very rare cases, the size and design of the mechanical anchor can cause gas flow issues in the casing annulus (Rowlan)

Unsetting a hydraulic anchor is accomplished by equalizing the pressure in the tubing to minimize or eliminate the pressure acting on the anchor piston. This is typically done through a tubing drain or by unsetting the pump, if possible. Once the tubing pressure is equalized, the positive force on the anchor piston is eliminated and the anchor releases. Conversely, the casing annulus may be filled with fluid to equalize pressure in the tubing, but this is not a commonly required practice. It is advised that hydraulic anchors are always run in conjunction with some secondary means to drain the tubing.

CASE HISTORY

Hydraulic anchors have not seen widespread acceptance because they have traditionally been very problematic. The hydraulic anchor, by necessity, requires a rubber-sealed piston in the side of the tubing. Down-hole conditions are not optimal for this type of rubber seal, and so hydraulic anchors generally fail as a hole in tubing (HIT). This problem presented itself when a large producer began running hydraulic anchors in some very deep and extreme conditions. Although hydraulic anchors have been deployed with great success for many years in less extreme conditions, these particular wells exposed many design flaws. The runtime of the wells were cut short because of the hydraulic anchor failures, and necessitated a solution. The anchor program was assessed and determined that the general concept of the tool was sound, but the design and manufacturing process were the primary cause of failure. The hydraulic anchor was completely redesigned to improve tolerances, implement best practices on the sealing surfaces, utilize the appropriate sealing materials for down-hole conditions, and improve finishing processes regarding plating and adhesion. These design modifications have dramatically improved the runtimes of these wells to the point where the hydraulic anchor is no longer a significant source of well intervention. Overall, the program is relatively new, so true runtime results are still pending. Nevertheless, significant improvements over the failure rates of the previous hydraulic anchors are immediately evident in reduced failures. To date approximately 500 redesigned hydraulic anchors have been installed. Detailed analysis of anchors pulled for incident well work indicates the previous modes of failure have been addressed.

The remainder of this paper discusses controlled testing for various aspects of the anchor-to-casing interface and its dynamic holding power. In particular, the claim that the hydraulic anchor moves down, but not up is tested. Real world results show this is likely the case because there is no significant rod on tubing wear, which would be indicative of buckling tubing, as described by Lubinski. These controlled tests merely demonstrate the anchor's capabilities under optimal conditions and attempt to quantify the forces involved. The purpose is to better understand the tool's limitations and to aid in designing real-world well applications.

ANCHOR DYNAMICS

The hydraulic anchor is affected by a number of forces that differ from those governing the application of traditional mechanical anchors. Since the hydraulic anchor works on a pressure drop across the tubing wall, close attention must be paid to the fluid dynamics and pressures in the wellbore. This paper assumes a full column of fluid in the tubing string. Significant gaseous flows, particularly foam, in the casing annulus can degrade the performance of the anchor by applying pressure to the casing side of the anchor piston. Alternate methods of determining fluid loading and pressure at the anchor should be used if "non-standard" down-hole conditions are present.

Forces acting on the anchor itself are fairly straightforward. Fluid load, caused by the plunger, acts longitudinally on the tubing string, causing the anchor to move relative to the casing. The pressure drop across the anchor piston imparts a lateral force, engaging the anchor onto the casing wall. This normal force acting on the anchor-to-casing contact points works through friction and shear to counteract the longitudinal forces caused by the cyclic fluid loading. Please refer to Figure 1 for a detailed illustration of these forces.

The relationship between the anchor forces described above and in Figure 1 is detailed through the following basic equations.

$$F_o = \Delta p_{plunger} * A_{plunger}$$
$$F_a = \Delta p_{anchor} * A_{piston}$$
$$F_{contact} = F_a * q$$
$$F_a \perp F_{contact}$$
$$F_o \parallel F_{contact}$$

Fluid loading is also defined in RP-11L terminology as:

$$F_o = 0.340 * G * D^2 * H$$

F_o	Fluid load as defined in the API RP-11L. Also the longitudinal force the anchor works to counteract
F_a	Lateral force applied to the casing wall by the anchor piston, also called Anchor Thrust
$F_{contact}$	The perpendicular force at the anchor/casing contact interface generated by applying the anchor force
q	Coefficient of anchor resistance. Includes frictional and shear components.
G	Specific gravity of the fluid
D	Diameter of the pump plunger (in)
H	Fluid level as measured from surface (TVD)
Δp_{anchor}	Differential pressure drop across the tubing wall at the anchor (PSI). This pressure drop is determined from fluid densities, tubing and casing pressures, gas gradients, etc.
$\Delta p_{plunger}$	Differential pressure across the plunger, at the pump depth (PSI). This pressure increase is a primary component of the fluid loading (F_o).
A_{piston}	Area of the anchor's piston (in^2)
$A_{plunger}$	Area of the anchor's piston (in^2)

The resistive force, $F_{contact}$, generated by the mechanical interface between the anchor and casing wall is the primary focus of this paper. As long as $F_{contact}$ is greater than F_o, the anchor should be held in place. $F_{contact}$ however, has a measurable limitation and varies with the applied perpendicular force generated by the anchor, F_a. Determining the limitations of $F_{contact}$ will help to ensure proper anchor application by helping to identify well conditions where F_o is greater than the ultimate holding power of the anchor.

Conditions affecting the above forces and equations include the following:

Fluid density

Fluid density has an impact on the absolute thrust, or holding power, generated by the anchor. Fluid density also affects the fluid loading on the tubing and so the ratio between Anchor Thrust (F_a) and Fluid Load (F_o) remains constant. In other words, a lighter fluid will produce less anchor thrust, but will also reduce the fluid loading in proportion so that the anchor does not need to work as hard. The ratio of Fluid Loading to Anchor Thrust remains constant regardless of fluid density, assuming the fluid density is generally uniform.

Fluid Level

Fluid level has a significant effect on the pressure drop across the tubing wall. A relatively high fluid level will reduce the absolute thrust generated by the anchor piston. A fluid level at, or slightly below, the anchor is the best-case scenario for the anchor design. If the fluid level is expected to be significantly above the anchor placement, attention should be given to ensure true vertical fluid level from surface would generate enough of a pressure drop at the anchor to adequately engage the anchor piston. This paper does not specifically call out the effects of fluid level in test data because that is a well specific variable. When designing a hydraulic anchor application, the user should correct for the highest expected fluid level under operating well conditions.

Tubing & Casing Pressure

Tubing and casing pressure also affect the performance of the anchor. As long as the tubing pressure is greater than the casing pressure, the anchor should be positively affected. If however the casing pressure is increased above the tubing pressure, this will work to counteract the pressure drop across the anchor piston. Other conditions, such as foam or substantial gradient in the casing annulus, can work against the anchor piston. Increasing backpressure on the tubing will increase the absolute holding power of the anchor, but will also increase the fluid loading. This is not a generally recommended practice, but may be used in certain circumstances to test or ensure the anchor function.

Temperature

Temperature affects the length of the tubing string, but since the hydraulic anchor is not preloaded, this is not as much of a concern as it is with mechanical anchors. For the purposes of this paper, temperature effects are ignored when applied to designing hydraulic anchor applications. It should be noted briefly that the test results presented were gathered over a number of days where the ambient temperature ranged as much as 15-20°F. Temperature impact on these test results is assumed to be negligible.

Hammer Effect

The “Hammer” effect is the rapid longitudinal loading and unloading of the anchor-to-casing interface caused by the opening and closing of the pump valves. Although this is effect not explicitly considered in this paper, it should be briefly discussed. The anchor loading test methodology, discussed below, does not adequately simulate the extreme loading and unloading cycles that are seen in an operating well. The purpose of the tests are to achieve a reasonable understanding of the forces involved in anchor design and to establish a basic minimum requirement for effective installations of these anchors. Even though this methodology does not simulate the hammer affect, the use of a hydraulic jack loosely approximates the behavior by applying increasing pressure in bursts. It is insufficient to draw any conclusions from these test results, but is mentioned as a possible area of future investigation.

TEST METHODOLOGY

Hydraulic anchors are primarily affected by the culmination of two dynamic forces; the pressure inside the tubing acting on the anchor piston, and the cyclic fluid loading on the tubing itself. The goals of these tests are to determine the effective holding power of the hydraulic anchor at a range of depths. By holding one of these forces constant, we are able to adjust the other until the anchor noticeably moves. There are many other factors that contribute to the effective holding power of a hydraulic anchor, but the purpose of these tests are to establish ground rules for applying anchors to overall well conditions.

The testing methodology allows for simulating both depth and plunger-induced fluid loading on the tubing string as follows. Anchor depth is simulated by capping the anchor while applying hydraulic pressure via a hose. Adjusting the pressure applied to the internal bore of the anchor can approximate varying depths and fluid densities. For example, applying 2165 PSI to the internal bore of the hydraulic anchor can simulate an anchor depth of 5000 ft. This is assuming water at 0.433 PSI/ft, and a fluid level at or below the anchor. For simplicity and clarity, water with a specific gravity of 1.0 (API 10) is used for all data presented here. When designing anchors for actual wells, the fluid density, fluid level, and casing/tubing pressures should be considered.

Transferring fluid loading from the plunger to the tubing string causes longitudinal loading on the hydraulic anchor. Fluid loading is simulated by a hydraulic bottle jack, which is placed under a pressurized anchor. The jack is then actuated to simulate the longitudinal fluid loading on the tubing string, specifically at the anchor-to-casing contact points. The pressure in the jack can be easily converted to load by the known area of the jack’s piston. A sizable jack is used such that it is capable of loads much greater than would be seen in real world fluid loading conditions. This overprovisioning of the hydraulic jack allows for testing the slippage point of the contact interface between the hydraulic anchor and casing wall.

Please refer to Figure 2 for a detailed illustration of the main anchor test assembly used to preform these tests. While pressuring the internal bore of the anchor accurately simulates depth and given well conditions, the use of a jack to simulate longitudinal forces is not entirely accurate. The jack induces a compressive force at the bottom of the anchor housing, whereas the real world forces are mostly in tension above the anchor, but can also turn to compression as the anchor "walks" down the casing. Since the anchor housing is solid and short, we are reasonably satisfied this is an appropriate means of testing. Imparting a true tension force in a test apparatus would require a significant piece of test equipment, and was ruled out for safety concerns. For this paper, the compressive forces applied below the anchor are assumed to be roughly equivalent to the real world tension forces above the anchor.

Initial test runs were performed using simple analog gauge readings at discrete anchor pressures. Because the piston area magnifies pressure readings, when converted to load, it was decided the subjective gauge reading element should be eliminated. Subsequent tests were conducted in a partially automated fashion in that pressure samples, from both the jack and anchor bore, were continuously gathered electronically during a run. This allowed data intervals to be analyzed and filtered for quality, in addition to eliminating human transcription errors between test samples and runs. Upon implementing the continuous data acquisition graphing, a flaw was uncovered in the hydraulic relief valve supplying pressure to the anchor. If anchor pressure release valve were not sufficiently tightened, it would gradually bleed off pressure. This effect was far more pronounced at higher pressures, but barely perceptible on the analog gauges. Since stable pressures in the anchor are critical to proper correlation of readings, this condition became easily identified and corrected, resulting in higher quality data.

Once the anchor is setup in the test rig, the operator begins the data acquisition system, which begins plotting data sample points. The operator then manually sets one of the test pressure parameters constant and varies the other until the anchor noticeably slips. Individual test run data could then be analyzed for anomalies and the approximate slippage points recorded. Multiple runs, with varying parameters are graphed to illustrate the limits of various anchors. Gathering data in this manner ensures repeatable results and the volume of samples eliminates any transcription or gauge reading errors.

Anchor Slippage

Anchor slippage is subject to interpretation in these tests and is defined here for clarity. The point at which an anchor slips is the point at which the anchor moves, but the force on the jack remains roughly constant. Because the anchor teeth cause a minor deformation in the surface of the casing wall, the anchor might noticeably move for a given jack pressure, but that is not necessarily the force at which the anchor will continuously move. A component of that initial motion is absorbed in minor metal deformation as the teeth "bite" into the casing wall. Identifying the anchor slippage point using continuous data acquisition and graphing removed the subjectivity on when an anchor truly slipped. This slippage point was easily identifiable because the jack pressure flat-lined where subsequent pumping of the jack did not result in an increased longitudinal force. The definition of anchor slippage proved problematic in one particular test case, which is discussed in the Results & Analysis section.

TEST CASE DESCRIPTIONS:

Test Case A

Anchor slippage points at a given depth. The operator sets the pressure inside the anchor to a given depth approximate. This anchor pressure is held constant for the duration of the test run. The operator then increases pressure on the bottle jack until the anchor noticeably slips. This test is repeated for multiple different depths. Figure 5 through Figure 8 show some example data gathered from these test cases over various configurations.

Test Case B

Anchor slippage points at a given lifting force. This is a validation on the data gathered in Test Case A. The pressure in the jack is then set to the value determined from Test #1, while the anchor pressure is higher than the corresponding test case. The operator then reduces the pressure inside the anchor to the corresponding depth being tested. Because the anchor has been set into the casing wall from the higher pressure at the start, the operator then operates the jack until the anchor slips and jack pressure stabilizes. This test is again repeated for each test case from Test Case A. A variant of this test was performed by gradually relieving pressure on the anchor while observing a corresponding drop in pressure on the jack. Although this does not yield immediately useful data, because the jack pressure does not directly correspond to the actual slippage point. It is interesting to observe that this relationship is also very linear with respect to depth and longitudinal force (See Figure 6).

Test Case C

Compare holding forces with, and against, the serrated anchor teeth, also called “slips.” This tests the differential forces required to move the anchor up, vs. down. The operator places the anchor in the test rig “upside down” which loads the anchor in the opposite direction. The same method as Test #1 is then used to complete each test run. Data from Test #1 is used for comparison of the directional holding capacity of the serrated anchor “slips.” This test case proved valuable in understanding the odd behavior of one particular anchor size and is discussed in the Results & Analysis section.

Figure 5 and Figure 6 represent data samples from the same data and test run, consisting of test cases A and B for 5-1/2” casing. Removing the time component illustrates the strict correlation between depth and load. The distinct stair step of Figure 6 represents the increasing depth of Test Case A. The smooth bumps represent the decreasing depth of Test Case B. Since the anchor is effectively set into the casing wall prior to reducing the anchor/tubing pressure, the jack has a slightly more difficult time “slipping” the anchor. Manually identified slippage points are overlaid on Figure 6 and the slope of the lines are nearly identical for both Test Case A and B. The process of manually identifying slippage points is shown in Figure 8. Briefly, the flat graph area following a jack operation is identified as the point at which increasing jack pressure is entirely dissipated through anchor movement.

Two common hydraulic anchors were selected representing two different piston sizes. Corresponding joints of K55 casing were used for the test. Mechanical anchor were not tested using this apparatus (Figure 2), although they could be. Mechanical anchors employ shear pins to release the anchor in case of emergency. The holding power of a properly set mechanical anchor is assumed to be substantial and adequate. Real world evidence indicates this is the case and so testing would not yield useful data for comparison against the variable holding capacity of the hydraulic anchor. Testing an improperly set mechanical anchor, or comparing the casing wall impact between the two types of anchor would be interesting, but is beyond the scope of this paper.

RESULTS & ANALYSIS

The results presented herein are provided in PSI with example depths based on a SG of 1.0 for water. Actual working depths associated with the PSI values provided would range depending on fluid densities. Gaseous flows through the production tubing are beyond the scope of this paper. These results merely indicate the holding performance of various anchors under controlled conditions.

Test results gathered through the data acquisition system were consistent, with one large exception (discussed below). The holding power for a given anchor piston size was linear with respect to the pressure applied to the piston. Through Test Case B, the linearity of this relationship was confirmed by approaching the slippage from a different starting point. In short, the slope of the load vs. depth line is roughly the same regardless of how the test is performed, although the line is offset according to the test conditions leading up to the slippage point. This confirmed our basic expectations in that, all things being equal, the holding power of the anchor is directly related to the pressure applied and the resistance of the anchor-to-casing interface.

The direction of the anchor teeth proved to be a critical component of how effective the anchor was at engaging the casing. Although this statement seems intuitive, the profile of the hydraulic anchor’s teeth is much less aggressive than the profile found in mechanical anchor teeth. Prior to starting the tests, the concern was raised that the tooth profile might not have as significant of an affect as claimed. This was not the case, and it turns out that the holding power is in fact significantly less in the direction of the teeth. In effect, the anchor can “walk down” the casing wall, as claimed, provided the appropriate internal pressure and fluid loading. Evidence of this can be seen in Figure 3 and Figure 4 where the holding power of the upside down teeth is noticeably less than the holding power against the teeth.

When testing the large piston hydraulic anchor, a series of anomalies were uncovered and presented in Figure 7. Whereas the test behavior of the smaller anchor was very consistent, the large piston anchor quickly exceeded the limitations pressure transducer used on the jack. Although this occurred at very low anchor pressures (corresponding to relatively shallow depths), consistent results were unattainable. Jack pressures were increased without the apparent flat-line that indicated true slippage on the smaller anchor. It is noted that these anomalies occurred at very high fluid loading values, much higher than would be encountered in most reasonable well conditions at these shallow depths.

The large piston anchor also exhibited odd behavior as the apparatus was allowed to sit for a short time at pressure. Subsequent jack operation actually resulted in a drop in jack pressure, which was unexpected. One theory as to the cause of this behavior was dry casing, specifically the anchor teeth were observed to be shearing metal from the casing wall. Oil was applied to the inner casing wall and retested, but lubrication had little effect on the observed anomalies. The direction of the large piston anchor's teeth was reversed, and Test Case C performed on a fresh surface of casing. Results from this test case were consistent and repeatable (shown in Figure 8). Considering the issues against the teeth indicates they have a very significant effect at higher lateral forces.

Although good quality test results were unattainable for the larger anchor, we are satisfied that the holding power far exceeds any real world conditions for all reasonable depths. An alternative measure of identifying anchor slippage was employed and a number of test runs were performed. Although this is not consistent with the previous slippage definition used, it is presented for perspective. These samples are identified on Figure 3 and Figure 4.

CONCLUSIONS

Test results largely support real world observations regarding the performance of the hydraulic anchors. Holding power is substantial, but care needs to be given when designing an anchor for a specific well application. Unlike the mechanical anchor, there are no preload calculations or required surface manipulation on installation. The hydraulic anchors do however, require specific knowledge of casing size and well conditions to properly size both the physical anchor dimensions and verify its holding capacity for the expected fluid loading. If a single anchor is determined not to have enough holding power for the given well conditions, a second or third anchor can be used. The results presented here can be used to more accurately determine if the well conditions exceed anchor capacity. Historically, the recommended practice is to ensure the anchor thrust is greater than 130% of the fluid loading, both expressed in pounds (LBS). This could be amended with respect to each anchor piston size, and to consider the downward motion of the anchor. Since the 130% method has proven to be successful in real world conditions, it is determined this is an adequate rule of thumb. If however, a more detailed assessment of a wells anchor design is required, all aspects of the well should be taken into account and compared against the data gathered from these tests. Fluid loading for a given depth and anchor should never exceed the tested value. Since these values represent explicit slippage points, the actual functional limits should be reduced accordingly.

Further testing of unique anchor configurations would be useful. In particular, testing smooth slips and more aggressive teeth profiles would help to better understand the mechanical interface at the casing wall. Simulating down-hole conditions such as sand and other solid particulate contamination would likely reduce the holding power of the anchor. Although this was not tested, it is believe that solids between the casing wall and anchor teeth affect the performance of the anchor, although the significance of this is still unclear. It is also believe that this would be more pronounced at lower anchor pressures where the anchor force is insufficient to displace the solid particulates. This is believed to result in a non-linear holding power with respect to depth. Oil was applied to the casing wall for a number of tests and was found to have little effect on the overall holding power. This is likely because the anchor is not a pure friction anchor. The serrated teeth actually bite into the casing wall creating minor deformations.

In conclusion, the hydraulic anchor provides a number of operational benefits from its simplicity. Recent design and manufacturing improvements have significantly improved the reliability of this type of anchor. Although experience has proven valuable in designing anchor applications for given wells, these test results provide deeper insight for the marginal cases.

REFERENCES

Lubinski, A., & Blenkarn, K. A. (1957, January 1). Buckling of Tubing in Pumping Wells, Its Effects and Means for Controlling It. Society of Petroleum Engineers.

Samayamantula, J. & Roderick, R. (2013) Tubing Anchor Catcher Applications And Abstract Operation. 2013 Sucker Rod Pumping Workshop

Rowlan, L. & Skinner, K. (2013) Gas Locked Pumps are NOT Gas Locked! 2013 Sucker Rod Pumping Workshop
API RP-11L

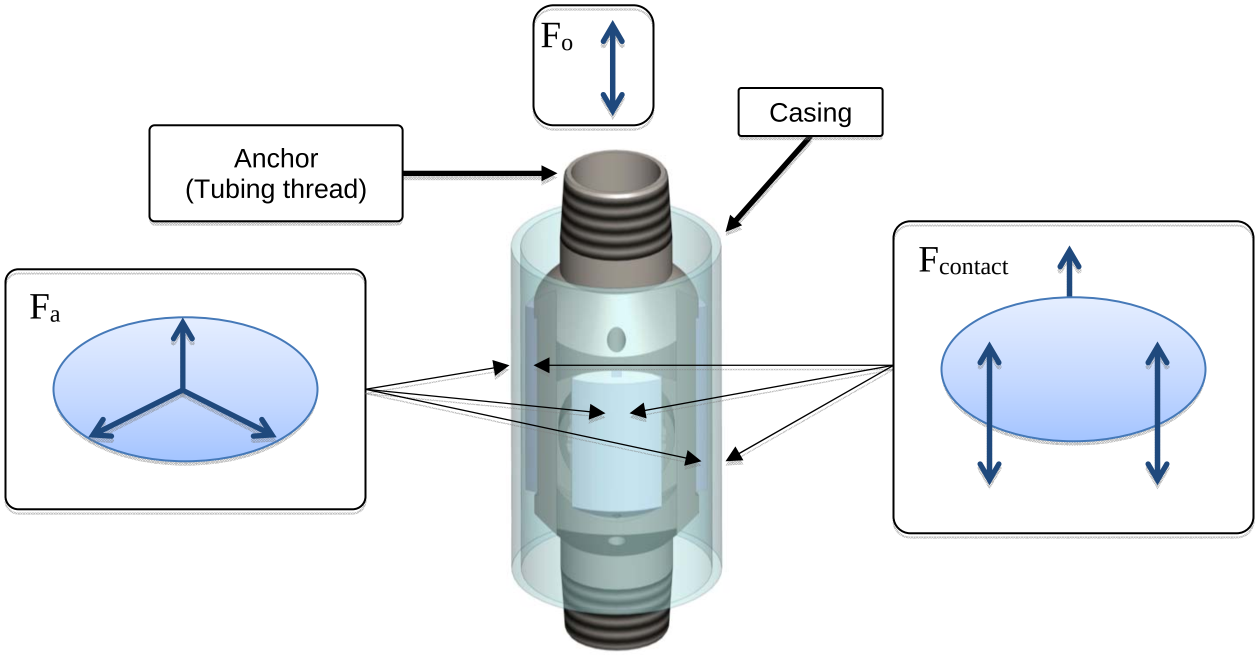

Figure 1 - Hydraulic anchor forces

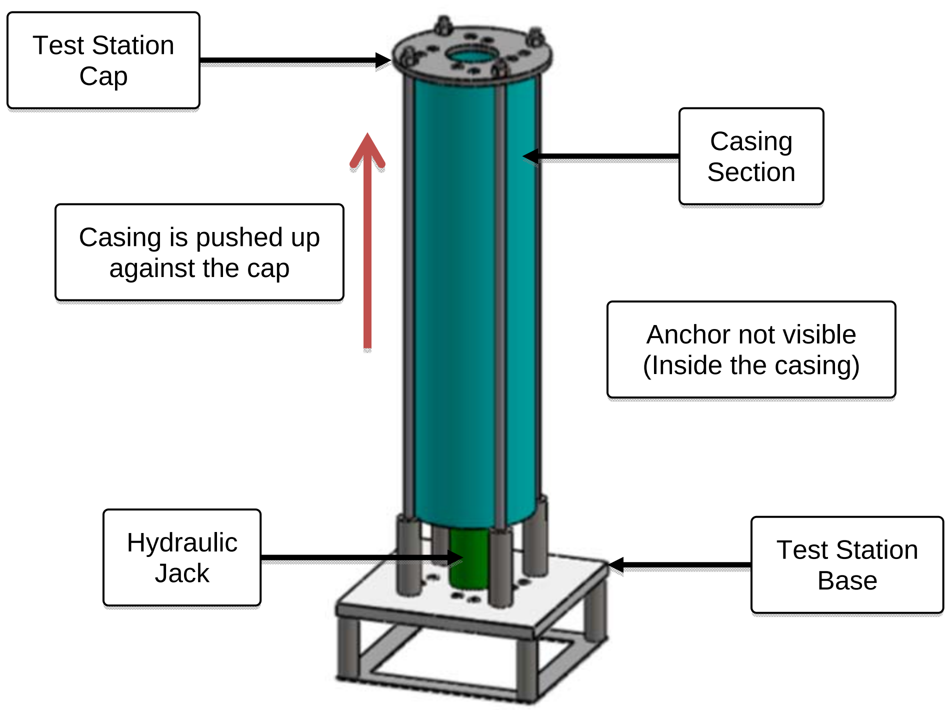

Figure 2 - Hydraulic anchor test station

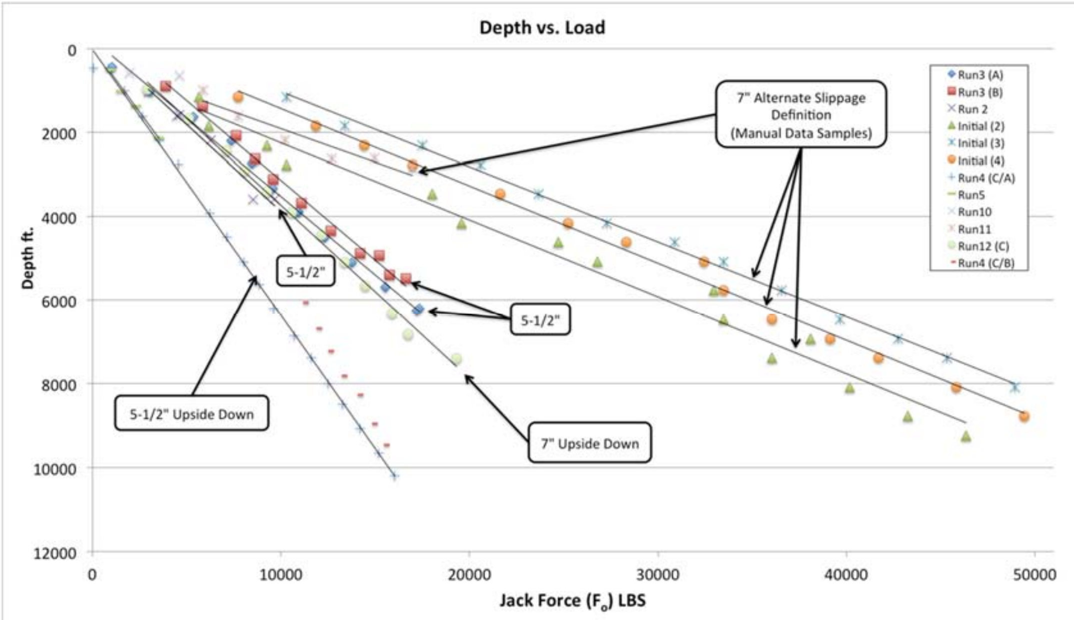

Figure 3 - Full filtered test results (Y-axis presented in the negative direction). The standard 7" anchor data points use an alternate definition of "slippage" where the anchor noticeably moves, rather than where the jack pressure flat-lines. It is a bit more subjective and so multiple test runs are displayed for that configuration. The slopes of those lines are relatively consistent indicating that the relationship between depth and load is stable.

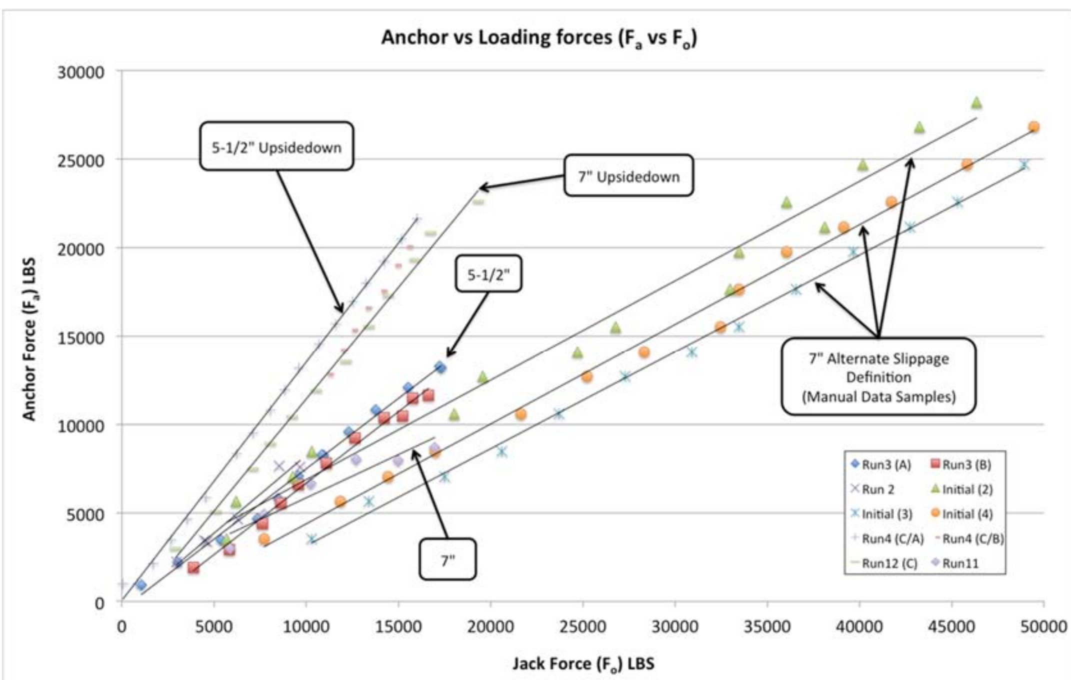

Figure 4 - Anchor depth is converted to force acting on the anchor piston (Y axis, plotted in the positive direction). The affect of anchor piston area is eliminated. Upsidedown anchor tests are nearly parallel, which indicate the anchor contact forces are consistent in this direction. The 7" anchor results are not parallel with the 5-1/2", but this is likely due to the inconsistent definition of anchor "slippage" which was a result of the large increase in force with respect to depth for the larger piston.

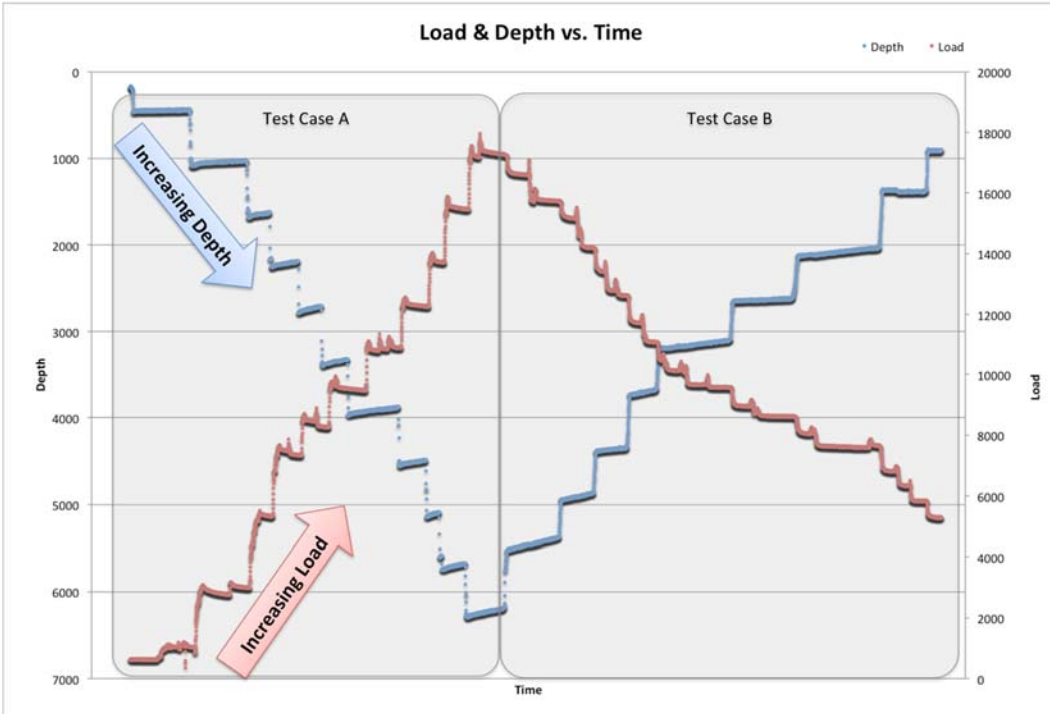

Figure 5 - Combined Test Case A & B, 5-½" K55 casing. Raw data collected over time, as gathered from the pressure transducers. Time samples are roughly 2 per second. Higher sampling frequencies were not deemed necessary for these tests. This test was conducted in a continuous fashion in that the anchor was not reset between each change in depth pressure.

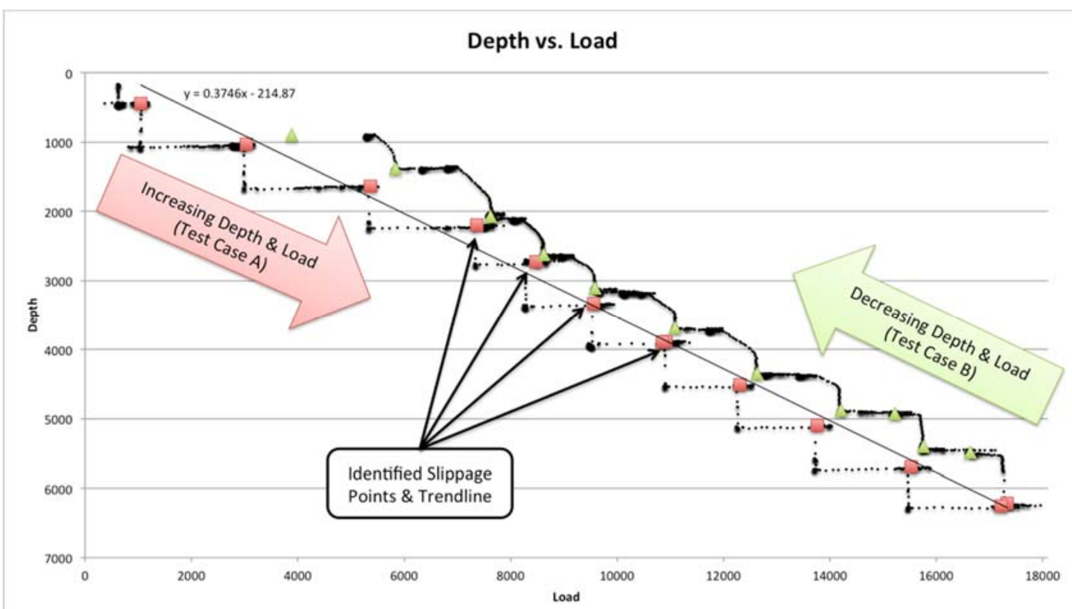

Figure 6 - Combined Test Case A & B, 5-½" K55 casing. Same data as Figure 5 with the time component removed. Data samples are plotted against each other representing Depth vs. Load over the course of the test.

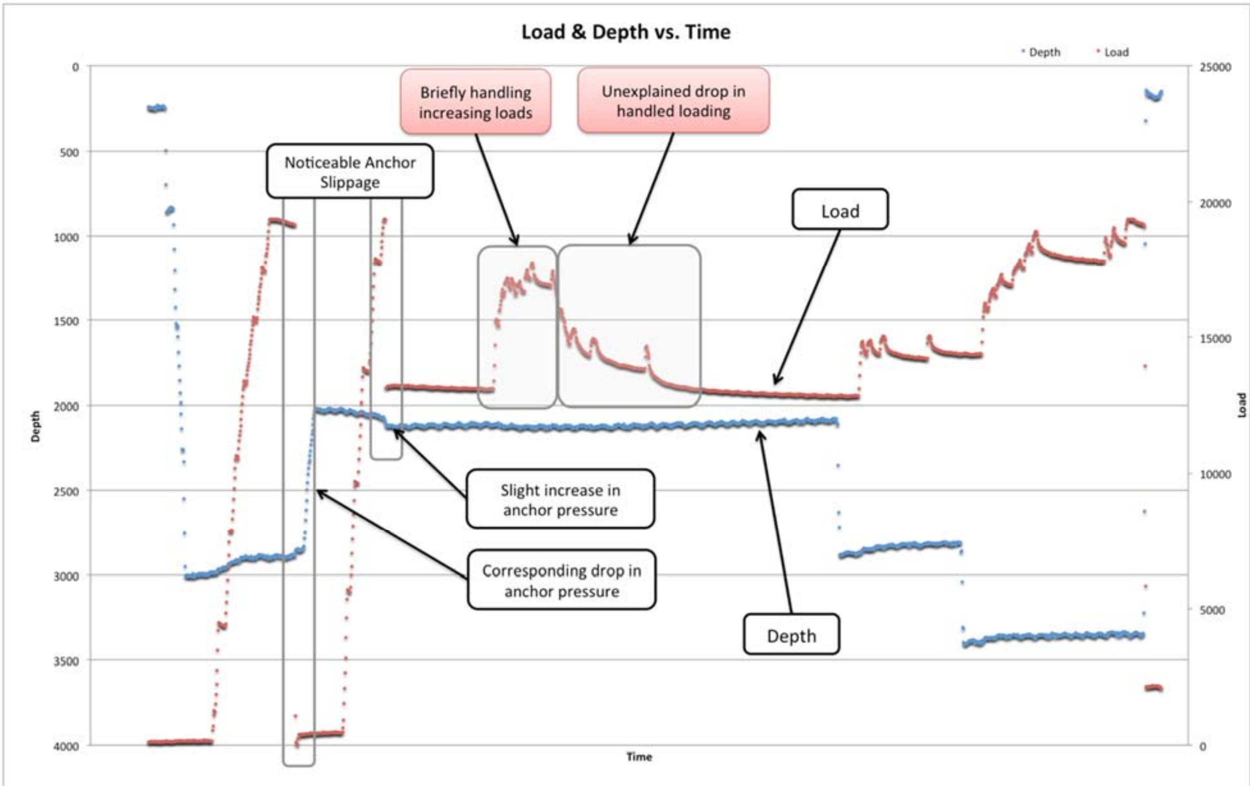

Figure 7 - Combined Test Case A & B, 7-½" K55 casing. Raw samples gathered over time. This test exhibited a number of anomalies, which are identified on the graph. First, a noticeable and significant movement was observed at about 1000ft depth. A corresponding drop in anchor pressure was observed and is likely a result of piston expansion, probably due to irregular casing wall I.D. Once the anchor is set, increasing loads were observed with audible metal fatigue and shear. A stable slippage point could not be found by operating the jack. Subsequent jack operation actually dropped loading pressure, presumably as the casing wall sheared. It should be noted that the loading at which this occurred was approximately 15,000 LBS, which is substantially higher than would ever be seen from fluid loading, let alone at this depth.

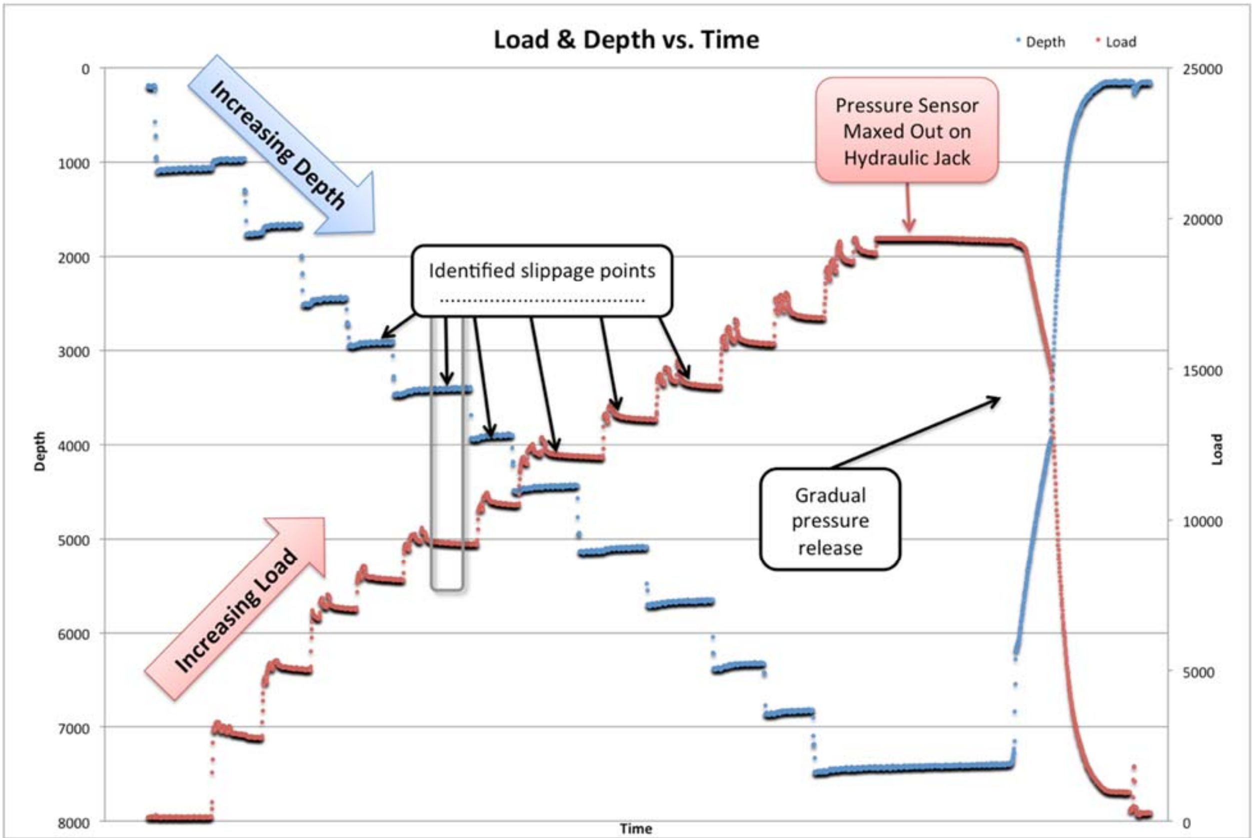

Figure 8 - Test Case C, 7" K55 casing, upside-down (with the anchor teeth). Time gathered samples. Identifying slippage points is accomplished by observing the flat sections, following jack operation. These points are considered "filtered" and are used for analysis as presented in Figure 3 and Figure 4.