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ASSESSING THE EFFECTS OF DROPPED OBJECTS ON SUBSEA PIPELINES AND STRUCTURES

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ABSTRACT

Subsea pipelines, flowlines, and structures are periodically subject to anchor snags and impact with dropped objects. The primary objective when these events occur is determining how to assess the resulting damage. This typically involves making critical decisions in relatively short time frames. The challenge for most operating companies is being forced to make these decisions with limited information, while also attempting to assess the consequences of failure.

This paper provides detailed discussions on how analysis methods and full-scale testing have been used to assess damage to subsea pipelines and structures. Specifically, information is provided on insights gained during dropped objects studies that included experimental efforts involving 1 MJ drops (24,000 lbs dropped from approximately 30 feet), as well as finite element dynamic simulations that included interaction between a dropped object, a subsea pipeline, and soil. The value of the work presented in this paper is that pipeline operators can better position themselves to appropriately respond to pipeline damage using a methodology that has permitted the continued safe operation of subsea pipeline systems.

INTRODUCTION

On occasion subsea pipelines get damaged. When this occurs, pipeline operators are charged with the task of assessing the damage. The process associated with this assessment effort typically involves some form of data collection (sometimes including surveying the position of the pipeline), assessing the damage, making a temporary assessment, and then issuing a final judgment based on the long-term needs of the pipeline system.

The purpose of this paper is to provide the reader with insights and suggestions on how to make an assessment based on sound engineering principles. Over the past several years the author has been involved in numerous pipeline damage assessments, several of which have involved the replacement of large sections of damage pipe material.

In this paper we show that it is possible to make an assessment of damage to a pipeline using a specific evaluation process. Operators can evaluate damage severity with confidence in order to repair the pipeline, replace certain sections, or restore service to its original condition if a benign level of damage occurred..

To a certain extent, this paper is a survey of techniques used to evaluate damage. There is no single resource, standard, or document that provides guidelines for assessing damage to subsea pipelines. By and large, most operators have experts on staff, or bring in outride consultants, who have experience in this type of work. An objective of this presentation is to provide insights and guidance to industry in assessing subsea pipeline damage. Of equal importance, information is presented on analytical and experimental techniques that can be used to assess pipeline damage.

This paper is structured as follows. The *Background* section provides insights on the critical aspects associated with assessing pipeline damage including a list of recommended steps. The *Numerical Methods* section discusses how finite element methods can be used to assess impact damage. More specifically, discussions are provided on how evaluating damage relative to impact energy can be used to identify critical parameters for comparing damage. The *Experimental Techniques* section discusses several aspects of using testing as a means for evaluating pipeline damage. The first pass information that is provided includes discussions on how finite element modeling is used to calculate impact energy based on the deformed configuration of the pipeline. However, information is also included on the use of dynamic modeling techniques for evaluating high speed impact problems that include the use of soil in the finite element model. The final section, *Conclusions*, provide insights on how all aspects of the presented information can be used to execute an assessment process that increases the potential for future safe operation of the pipeline system.

BACKGROUND

When subsea pipelines are damaged, operators are required to make an assessment of the damage. This typically involves flying the pipeline using a subsea ROV (remotely operated vehicle) to make a first level assessment of the damage. If the line was impacted by an anchor, some level of survey work is also performed, typically involving efforts to determine how far the pipeline was displaced from its original position. To assess localized damage associated with anchor impingement and direct contact with the pipeline, dent profile measurements can be made to assess the general and residual stress state.

It is critically important during the initial evaluation efforts that the potential failure modes be considered. As a point of reference, larger thin-walled pipes that are deformed can be susceptible to collapse when subjected to external pressure loading. The *six step process* listed below was developed to ensure that the evaluation process did not fail to address subject matters that could lead to the failure of the pipeline.

1. Identify critical parameters associated with potential failure modes (e.g. ovality, strain, displacement, etc.).

2. Collect information required to assess critical parameters (e.g. ROV videos, surveys, etc.).
3. Perform calculations to quantify the magnitude of the critical parameters.
4. Determine allowable limits on critical parameters based on industry-accepted standards.
5. Compare calculated values to allowable limits.
6. Based on results of Step #5, determine path forward (i.e. continue operation, re-rate, repair, or replace).

Identify Critical Parameters

This step is listed first for a reason. As in the design process, it is critically important when assessing pipeline damage to address potential failure modes. The drivers for failure in subsea pipelines include, but are not limited to, ovality, excessive strain and displacement, and curvature. Identifying critical parameters typically requires the expertise of pipeline engineers who have been involved in either design work or contributed in some manner to prior failure analyses.

Data Collection

Once the critical parameters have been identified, it is necessary to collect data that will permit the parameters to be quantified. Examples of activities associated with data collection include ROV videos and survey data to assess pipeline displacement. When actual data are collected, such as survey points, it is important to quantify the level of uncertainty in the measurements. This is critically important, especially if decisions regarding removal of damaged section of the pipeline are required. Without good quality data it is not possible to make accurate decisions about the level of pipeline damage.

Perform Calculations

Once the critical parameters have been identified and the necessary data have been collected to permit an assessment, calculations are required. API RP 1111 [1] is commonly used as a first-pass means for determining permissible in-place ovality, curvature, and bending strains. As stated previously, the quality of the calculations is directly related to the accuracy of the collected data.

As a point of reference, consider when survey data are used to calculate global curvature of a displaced pipeline. In calculating bending strain based on curvature (refer to Fig. 1), consideration for the standard deviation in the measurements should be considered. As noted in Fig. 2, when the standard deviation is considered three possible strain levels are calculated (i.e. mean value in addition to plus and minus the standard deviation values). Once the three radii of curvature are calculated, three bending strain values can be determined. Figure 3 provides results from a prior study. Also included in this figure are the maximum permitted in-place bending strains using the methods specified in API RP 1111 as functions of pipe ovality. As noted for the presented data, two of the three strain values exceed the maximum (permitted) in-plane strains. From a review of this information, one would be forced to conclude that the displaced condition of this pipeline is unacceptable.

Determine Limits

Determining limits based on industry standards is critically important to the evaluation process. Examples of appropriate references include API RP 1111 and ASME B31.8 [2]. As discussed previously, examples of established limits include those associated with curvature, bending strain, and ovality.

Figure 4 is a plot showing bending strain as a function of the applied bending moment. The plotted results are from a finite element model that integrated the effects of internal pressure, axial tension, and bending. As noted in this figure, a safety factor is imposed on the bending strain to ensure that collapse of the pipe does not occur. The results presented are from an actual project involving a pipeline that had been displaced from it original trenched position by an anchor impact.

Compare Calculations to Limits

Once the calculations are complete and acceptable limits have been identified and determined, the next logical step is making a comparison between the two values. Once this takes place, those involved in the evaluation process are better positioned to make a decision based on a sound technical basis. If the calculated values exceed the determined limits, the operator must make a decision as discussed in the next section of this paper.

Path Forward Options

Depending on the outcome from the comparison efforts, operators are required to make a decision. The common responses include repairing the pipeline, replacing the pipeline, permitting temporary operation pending further repairs/replacements, or continuing operation as-is with no concern for any future remediation activities.

It should be noted that evaluating pipeline damage typically involves two phases of work: *preliminary assessment* and *assessment for long-term service*. For a subsea pipeline, a preliminary assessment might include ensuring that the pressure in the pipeline does not drop below a certain value so as to ensure that collapse of the pipeline does not take place. On the other hand, long-term assessment will usually include reviewing the age of the pipeline, operating history, plans for future service, and risk analysis evaluation including determining the consequences of failure.

ANALYSIS METHODS

Numerical analysis of some form is typically performed in assessing the damage to subsea pipelines. The level of analysis is related to the quantity (and perhaps quality) of information that can be gathered. The available information ranges from detailed survey data with actual dent profile measurements to as little information as detected using a sonar scan that only included the displaced and approximate position of the original pipeline. Engineers must be careful to appropriately use the information they are provided and avoid the propensity to extract greater levels of information from the collected data that is readily apparent. Examples include making detailed assessments using survey data with limited accuracy (i.e. high levels of uncertainty accompanied with large standard deviations).

Fundamentally, the entire purpose in evaluating the level of damage imparted to a pipeline is to make a decision regarding acceptability in terms of future service. If the damage is relatively benign and within acceptable damage tolerances, operation of the pipeline can continue. However, if serious damage has been imparted to the pipeline, the line will require changes in operating conditions, repair, or replacement. Figure 5 provide a five step process that details the minimum considerations required for a damaged pipeline assessment. There are three central elements to the assessment process. The first involves identifying critical parameters. For subsea pipelines, one of the obvious critical parameters is ovality. If an excessive level of ovality exists, it is possible for the external pressure generated by the hydrostatic pressure of the seawater to collapse the pipe when it has either low internal pressure levels or is subject to bending loads. Other obvious parameters include curvature and bending strain. The second element involves performing calculations to quantify the magnitude of the critical parameters. Calculations typically occur in the form of either analytic solutions (i.e. closed-form) or through numerical methods such as finite element analysis. Regardless of the means of calculation, determining the magnitude of the critical parameter is essential for the assessment process. The third key element of the assessment process involves determining allowable limits for the critical parameters. These are typically determined using either company policies, standards such as ASME B31.8 for gas transmission pipelines, or recommended practices such as API RP 1111 *Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design)*.

Closed-form Solutions

Initial analysis efforts typically involve calculations based on analytic or closed-form solutions. Examples include calculating bending strain from curvature as presented in Fig. 1 (Survey data are required to complete this type of activity). For pipelines damaged through impact with subsea anchors evaluating the strain in the deflected pipeline is on of the most effective, yet simple, means for assessing severity. As mentioned previously, the process involves taking the displaced geometry of the pipeline from survey data points and then calculating curvature. From curvature bending strain is calculated.

Another useful expression relates dent depth and force is presented by Palmer et al [3]. This equation is used to determine how much force is imparted into a pipeline to generate a specified dent depth.

$$u_d = \frac{3}{32\pi} \frac{P^2}{Y^2 t^3} \qquad (1)$$

where:

U_d Dent depth (inches)

P Force of indentation (lbs)

Y Yield strength (psi)

t Pipe wall thickness (inches)

Figure 6 provides data that was used to generate a load-deflection curve for the denting of a 12.75-inch x 0.406-inch Grade X65 pipe. As shown in this figure, the calculated residual dent depth for the 100 kip indentation load is within 5 percent of the actual measured experimental value. This equation can also be used to estimate the energy level associated with a given indentation event.

Other relations are important when discussing dropped objects that include calculating the kinetic energy of a dropped object based on the mass and velocity at impact. As will be discussed, numerical methods are better suited for solving these types of problems.

Numerical Methods

When discussing dropped objects, one must consider damage imparted to impacted structure. The include subsea pipelines and flowline, manifold, trees, and jumpers. One of the more basic metrics to evaluate damage considers energy methods. There are several options for analytically evaluating structural damage generated by dropped objects using numerical methods. The first involves integration of a load-deflection curve. This type of data is most likely to be generated using a finite element analysis that considers a quasi-static loading process. The second, and more sophisticated method, calculates absorbed energy using a dynamic finite element model based on an explicit numerical integration scheme. If one considers the use of the ABAQUS general-purpose finite element software, the quasi-static model would require the use of ABAQUS Standard, while the time-dependant dynamic model would employ ABAQUS Explicit. The sections that follow discuss these two analysis methods.

Quasi-static Evaluation

Figure 6 provides a plot showing load-deflection data for a 12.75-inch x 1.375-inch, Grade X65 pipe based on results from a FEA model. Also provided in this figure is the Palmer equation presented previously in Equation 1 that shows good correlation with the analysis results.

The objective in this model was to determine the energy imparted to a subsea flowline from a dropped object. If the load-deflection curve presented in Fig. 6 is integrated, the resulting energy level is 675 kJ. This implies that if a dropped object having a kinetic energy of 675 kJ impacts this respective flowline, a residual dent depth on the order of 5 inches is likely.

What are not considered in this quasi-static analysis are two important factors.

- Flowline and pipelines typically rest on top of or are buried in the soil. When they are impacted the overall response includes the stiffness (i.e. energy capacity) of the soil. In a quasi-static analysis, it is appropriate to integrate springs into the FEA model to capture the contributing stiffness.
- The time dependant response of the system. This includes the response of the soil, but also how the impact generates a peak load that exceeds the value observed in the quasi-static analysis.

The quasi-static simulation is a very useful tool for determining the energy capacity of the particular structure; however, as will be presented in the next section, the explicit integration scheme permits a far more rigorous evaluation technique to assess the combined dynamic response of the dropped object, soil, and pipelines.

Dynamic Simulation

Analyses that consider the time-dependant response of a system require a greater level of expertise than required for the quasi-static evaluation. However, if the assessment requires evaluation of the entire impacted system including the response of the supporting soil, the explicit technique is required.

Results are presented for a finite element model that integrated time-dependant soil properties. Due to the cohesive nature of the soil, a rapid load rate generates a greater level of resistance when compared to a relatively slow application of load. A parallel analogy is considered when dropping an object into a body of water. If the impact with the water occurs at a high rate of speed, the projected area is initially stopped by the sudden impact with the surface of the water. However, if the object is lowered slowly into the water, the only resistance to gravity is the buoyancy force, which is significantly less than the resisting impact force. The soil shear strength increases by 50%. if a strain rate is 10,0000 times the quasi-static load rate. This time-dependant data was used as input into the finite element model.

The intent of this discussion is not to provide detailed discussions on explicit finite element modeling techniques, but rather demonstrate how this approach can be used to evaluate the effects of dropped objects on subsea pipelines. The ideal means for making a presentation of this type is to show results from a prior analysis. Figure 7 shows the overall schematic for the FEA model including the impactor (e.g. dropped object), pipeline, and the soil. It is noted that for computational efficiency a symmetry plane is invoked. Energy impact levels of 10 kJ, 100 kJ, and 1 MJ (1000 kJ) were evaluated. The 10 kJ value generated minimal damage, while the 1 MJ value effectively ruptured the 16-inch diameter pipeline. An internal pressure level of 1,755 psi was considered (pressure level corresponding to 72% of the Specified Minimum Yield Strength, SMYS).

Figure 8 includes the following plots:

- Force as a function of time
- Force as a function of displacement
- Velocity and displacement as functions of time

There are several important observations in viewing these plots. The first is the magnitude of impact force that is imparted to the pipeline. A force exceeding 350,000 lbs was calculated. Another observation is the relatively short duration of impact where the peak load was calculated to be on the order of 0.005 seconds. This rapid impact is accompanied by a rapid deceleration as observed with the velocity as a function of time plot.

Figure 9 provide von Mises contour plots for times spanning from 0.001 to 0.05 seconds. It is noted that the stress in the pipe decreases with time. This occurs because of the rebound of the dropped object after the initial impact.

One of the significant observations in reviewing the numerical method techniques is that analysis can be used to assess a wide range of variables including impact energy, geometry of the impacted structure, geometry of the dropped object supporting conditions such as the soil, and a variety of other parameters. Through parametric studies, those studying impact mechanics can better understand the effects of different variables and be better positioned to understand what damage might be imparted to their respective structure. From an economic standpoint, numerical modeling is significantly less expensive and time intensive than experimental techniques, especially those involving full-scale testing as discussed in the following section.

EXPERIMENTAL TECHNIQUES

Analytical methods have been discussed and presented in relation to studying dropped objects. Much of the work that has been presented has been validated using experimental methods. Testing that involves quasi-static loads typically permits measurements of load versus deflection. However, when full-scale drop tests are performed with energy levels of sufficient magnitude (e.g. 1 MJ), the magnitude of impact force exceeds the capacity of conventional load cells. Therefore, in order to better understand the overall response associated with impact, studies typically involve a combination of sub-scale and full-scale studies. The sections that follow provide the details associated with both types of testing based on prior studies conducted by the author.

Sub-scale Testing

The primary intention in performing the sub-scale testing is to determine the magnitude of impact force during a dropped object event. Prior to testing, an informal survey of several experienced engineers was conducted to assess the potential range of peak loads encountered during impact. It was apparent based on the variability of responses (everything from 2g to 10g) and lack of available test data, that testing was required.

The purpose in testing was to determine the magnitude of impact forces associated with a range of test conditions. The purpose was to assess a range of variables including support conditions (rigid, sand, and end supports). As shown in Figure 10, testing involved a 6-foot section of 12-inch NPS pipe placed in a trough that was filled with sand. A 150-lb steel block was dropped from a height of 5 feet. Data were recorded by a data acquisition system (DAQ) at 5,000 scan per second. The results from this test are plotted in Figure 11. The following observations are made in reviewing the plotted data.

- Steel on steel configuration results in an acceleration of 76.4 g's
- Steel on soil configuration results in an acceleration of 63.9 g's
- The simply-supported spanned steel on steel configuration results in an amplification of 51.5 g's

From these results it is clear that changing the support structure reduces the corresponding acceleration value. Considering that subsea pipelines are either buried or rest on the sea floor. as well as having a certain spanning condition, one could assume that the acceleration load imparted to a pipeline will be less than the values reported herein. These results clearly demonstrate that the conditions associated with the surrounding pipe support significantly affect the response of the pipeline during impact.

Full-scale Testing

Once the sub-scale testing was completed, the investigative efforts focused on testing associated with large scale drop tests. After reviewing possible options, the maximum possible test condition involved dropping 24,000 lbs from 30 ft. This corresponds to 720,000 ft-lbs (976 kJ), or approximately 1 MJ. This represents a relatively significant energy level. Correspondingly, a kinetic energy of 1 MJ can be calculated assuming that an object weighing 18,500 lbs impacts a structure traveling at a velocity of 50 feet per second.

As a point of reference, calculations were performed on various potential dropped objects. Figure 12 provides an example calculation sheet with the following dropped objects being considered.

- CAT: 14,000 lbs with a terminal velocity of 32 feet per second (302 kJ)
- Basket: 25,000 lbs with a terminal velocity of 31 feet per second (506 kJ)
- Tree: 101,500 lbs with a terminal velocity of 22 feet per second (1035 kJ)

As noted, a dropped tree possesses an energy level at impact of approximately 1 MJ. This value includes the submerged weight of the tree, as well as the drag associated with the minimally-projected surface area,

Over the past several years, the author has been involved in several full-scale drop tests. Figure 13 provides a series of photos from testing performed by dropping a range of weights from a height of 30 feet. The energy levels in this study ranged from 51 kJ to 976 kJ. The intent was to determine the level of damage imparted to a 12-inch nominal diameter subsea flowline (1.375-inch wall thickness). As noted in Figure 13 that involved a 300 kJ drop, minimal damage was inflicted to the outside surface of the flowline. Even the 1 MJ drop did not inflict damage to the pipeline that would have made it inoperable. It should be noted that none of this testing was performed with internal pressure in the pipe, which is obviously not representative of actual in-service conditions. However, one could also argue that subsea soil has significantly greater compliance than onshore soil and that a greater percentage of the energy would go into the soil during impact. High speed video captured the impact of the drop tests at a rate of 2,000 frames per second. A review of the video showed that during impact the pipe deflection elastically into the soil to a depth of 12 inches.

The overall observations from the full-scale study included:

- The flowline pipe demonstrated significant robustness
- The soil contributes energy absorbing capacity during the impact
- The external insulation provided additional energy absorption and protection for the pipeline
- Visual inspection will not reveal the full extent of damage to pipe, especially when insulation material is present

CONCLUSIONS

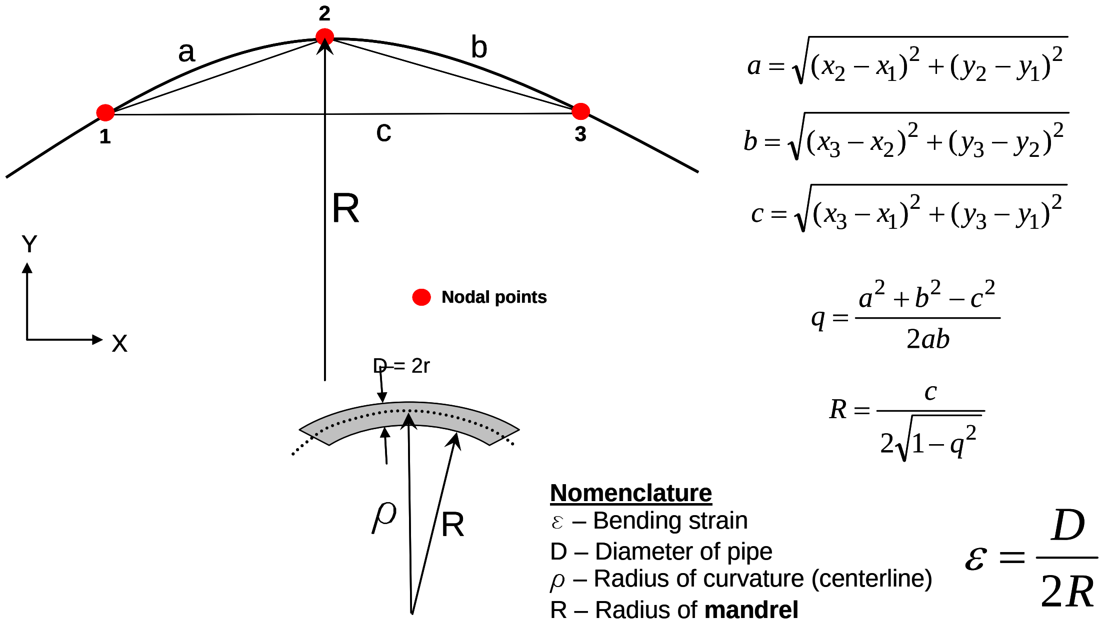
This paper has presented insights on how to assess damage imparted to subsea structures, including pipelines, during dropped object impacts. While making an assessment after damage has occurred is important, the better approach is to evaluate the potential damage that can be imparted to a given structure. Finite element methods with elastic-plastic material properties are ideally-suited for this type of task. The critical location for each structure can be identified and the analysis can determine the load-deflection response at that particular location. By numerically integrating this curve, the energy capacity can be calculated.

Experimental efforts also have their place; however, testing is expensive and requires knowledgeable staff, especially in the area of high speed data acquisition. If testing is done, the program should be well-designed and seek to capture information that can compliment analysis efforts. The authors experience is that testing should be used to confirm analysis results and not exclusively replace analysis efforts. When differences between testing and analysis exist, the analyst must make adjustments to the analytical model to address any differences. More often than not, the supporting conditions should be considered, especially the time-dependant response of the soil.

As greater levels of deepwater activity continue, the potential for dropped object impacts will only increase. It is advisable to perform assessments to address the energy capacity of subsea structures prior to impact incidences so that decisions on the consequence of damage can be made based on sound technical merits. It is envisioned that programs of this type will draw heavily on the details and methodology presented in this paper.

REFERENCES

1. Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design) API Recommended Practice 1111, Third Edition, American Petroleum Institute, Washington, D. C., July 1999.
2. American Society of Mechanical Engineers, *Gas Transmission and Distribution Piping Systems*, ASME B31.8, New York, New York, 2003 edition.
3. Palmer, A. C., and King, R. A., *Subsea Pipeline Engineering*, PennWell Corporation, Tulsa, Oklahoma, 2004.



$$a = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$b = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}$$

$$c = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2}$$

$$q = \frac{a^2 + b^2 - c^2}{2ab}$$

$$R = \frac{c}{2\sqrt{1 - q^2}}$$

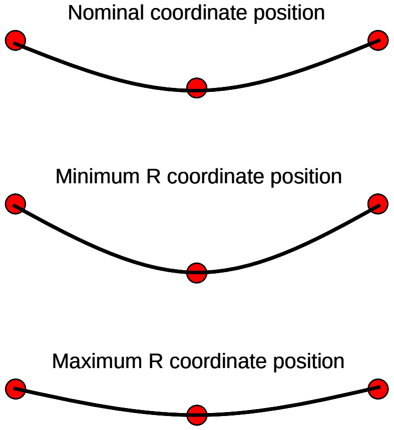
Nomenclature

ε – Bending strain
D – Diameter of pipe
ρ – Radius of curvature (centerline)
R – Radius of **mandrel**

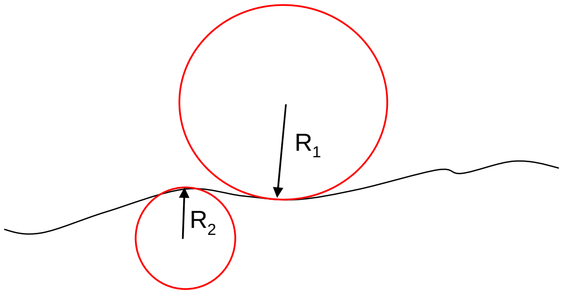
$$\varepsilon = \frac{D}{2R}$$

Figure 1 – Calculating curvature and bending strain from three points in space

How does standard deviation affect the curvature of a pipeline?



Using three points, a *radius of curvature,* R, can be calculated along the length of a pipeline. The image below shows a **RED CIRCLES** demonstrating how the radius of curvature can change along he length of the pipeline.



Sample pipeline position based on survey data

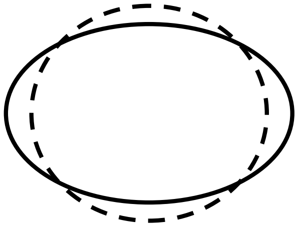
Figure 2 – Demonstrating the effects of standard deviation in measurement on curvature

Nominal position of survey data: $\varepsilon = 0.480$ percent

Minimum radius of curvature and maximum strain: $\varepsilon = 1.521$ percent

Maximum radius of curvature and minimum strain: $\varepsilon = 0.101$ percent

The above data demonstrate the potential for changing the calculated bending strain based on changes in survey data relative to the standard deviation. If one is to consider and allowable strain of 0.45 percent, two of the calculated values exceed this limit.



Pipe shown with and without ovality.

Ovality	Allowable Bending strain (percent)
0.00%	0.5346
0.50%	0.5036
1.00%	0.4754
1.50%	0.4496
2.00%	0.4260
5.00%	0.3175

Ovality limits the amount of bending strain that can be induced in a pipeline due to the potential for collapse due to external pressure.

Figure 3 – Evaluating the effects of standard deviation on allowable bending strain

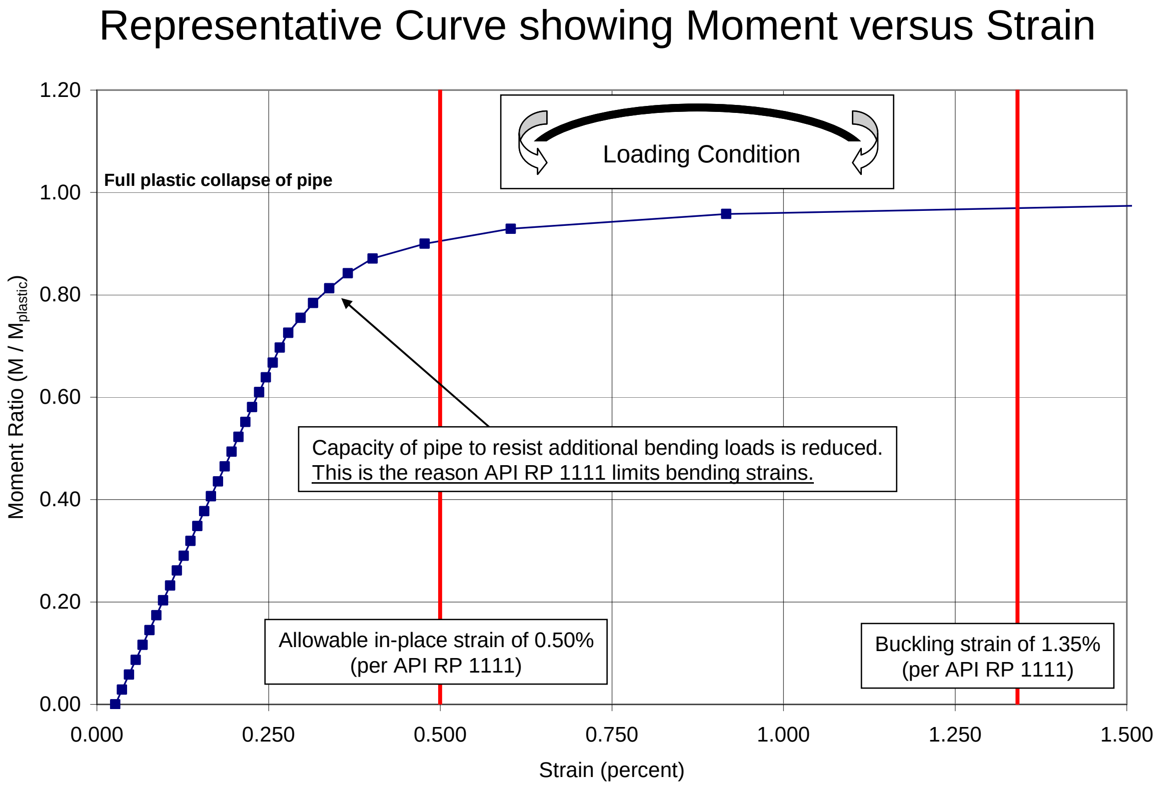
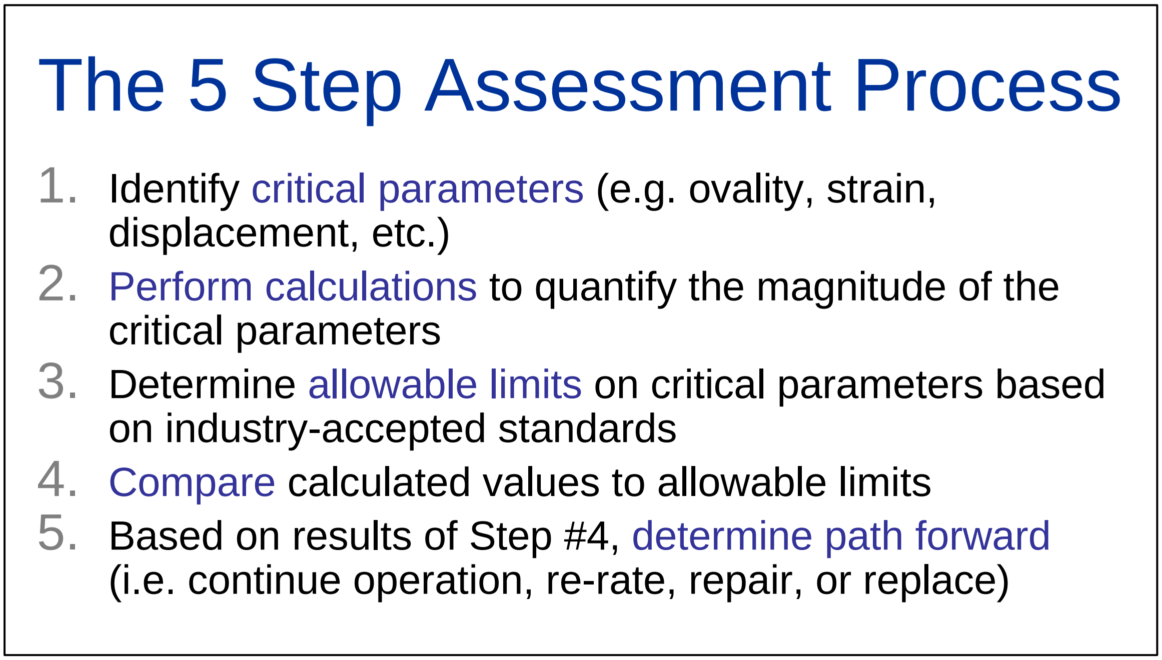


Figure 4 – Moment-strain relation for pipe subjected to internal pressure, tension, and bending loads



The 5 Step Assessment Process

1. Identify critical parameters (e.g. ovality, strain, displacement, etc.)
2. Perform calculations to quantify the magnitude of the critical parameters
3. Determine allowable limits on critical parameters based on industry-accepted standards
4. Compare calculated values to allowable limits
5. Based on results of Step #4, determine path forward (i.e. continue operation, re-rate, repair, or replace)

Figure 5 - Five step process for a damaged pipeline assessment

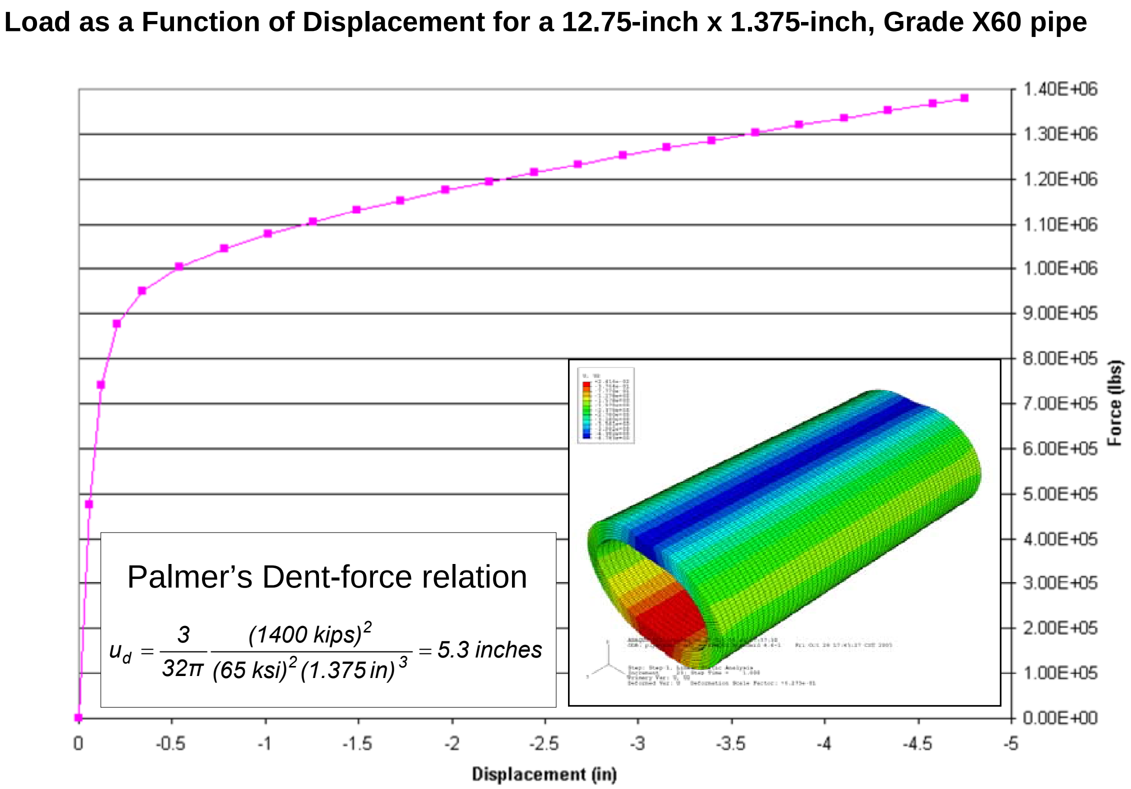


Figure 6 – Load-deflection curve for quasi-static FEA model

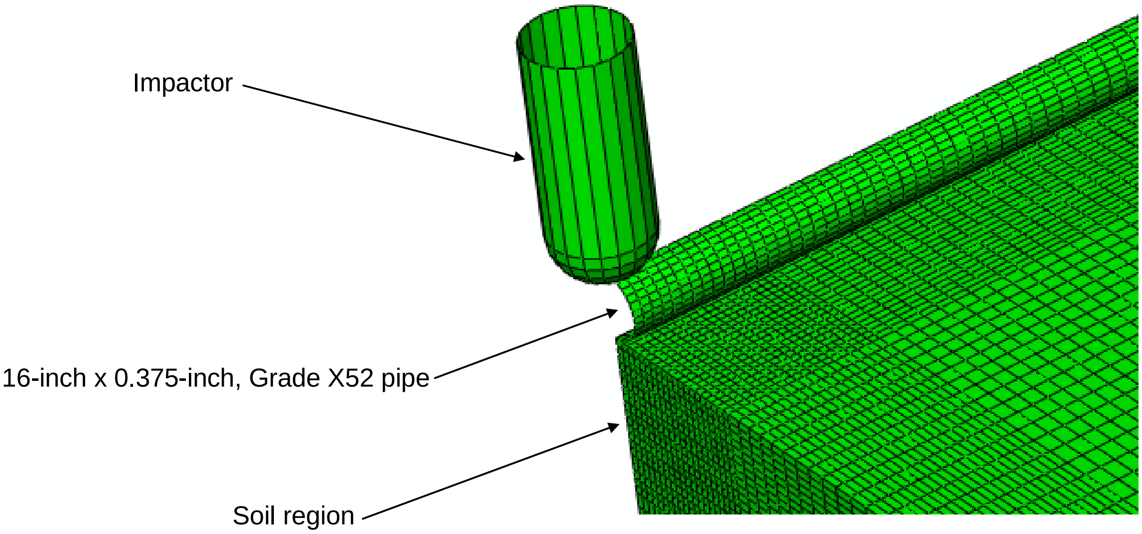


Figure 7 – Diagram showing components in the ABAQUS Explicit FEA model

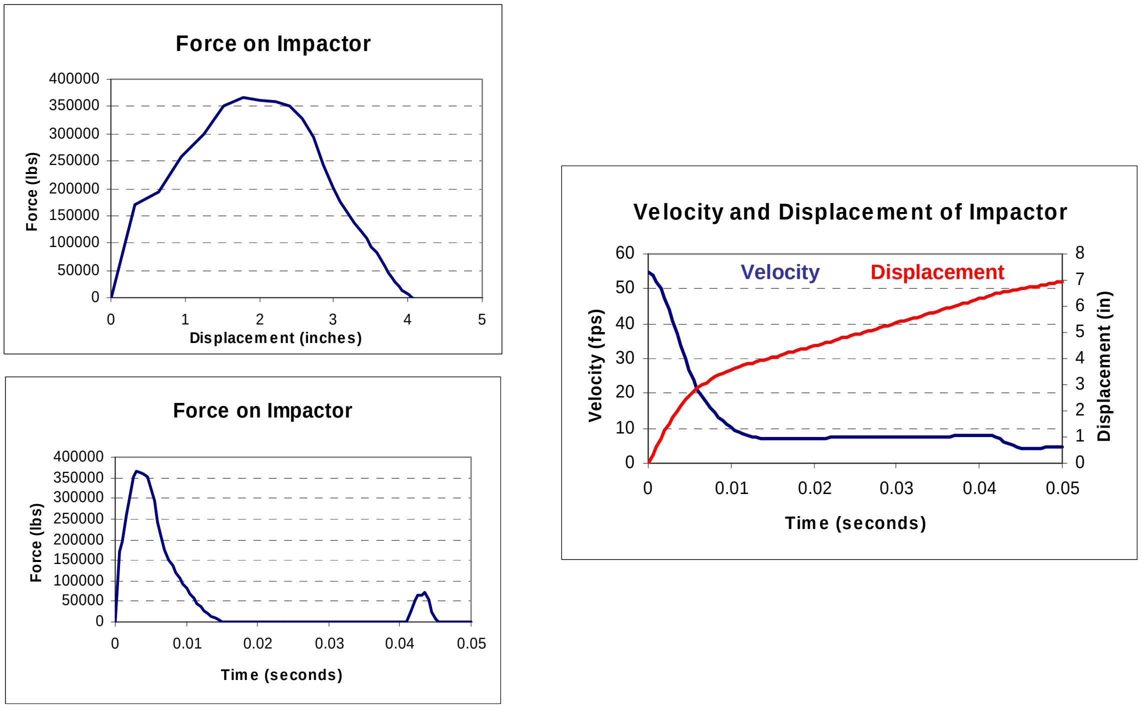


Figure 8 – Explicit analysis results considering force, time, displacement, and velocity for 100 kJ

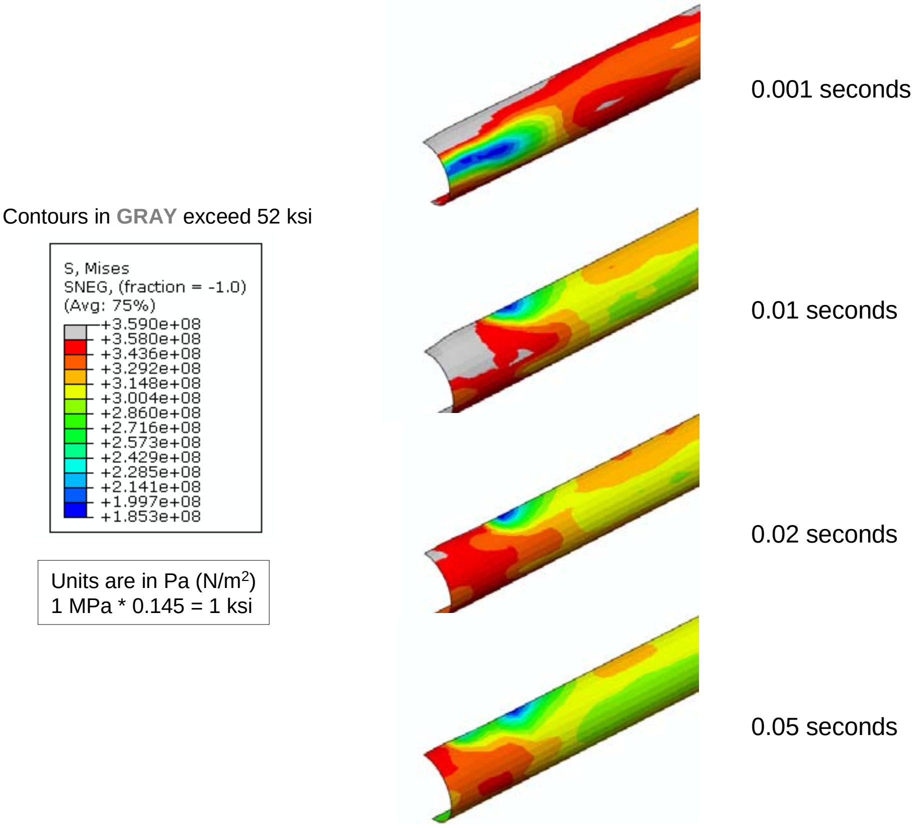
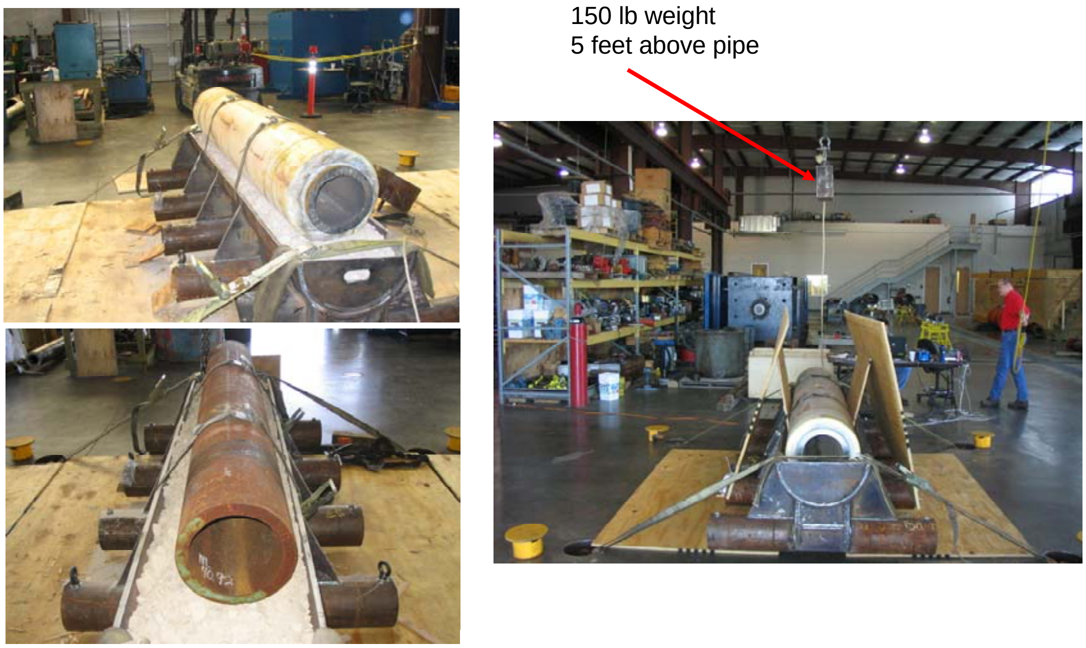


Figure 9 – von Mises stress contour plots for Explicit analysis at 100 kJ energy level



150 lb weight
5 feet above pipe

Figure 10 – Set-up for sub-scale drop tests

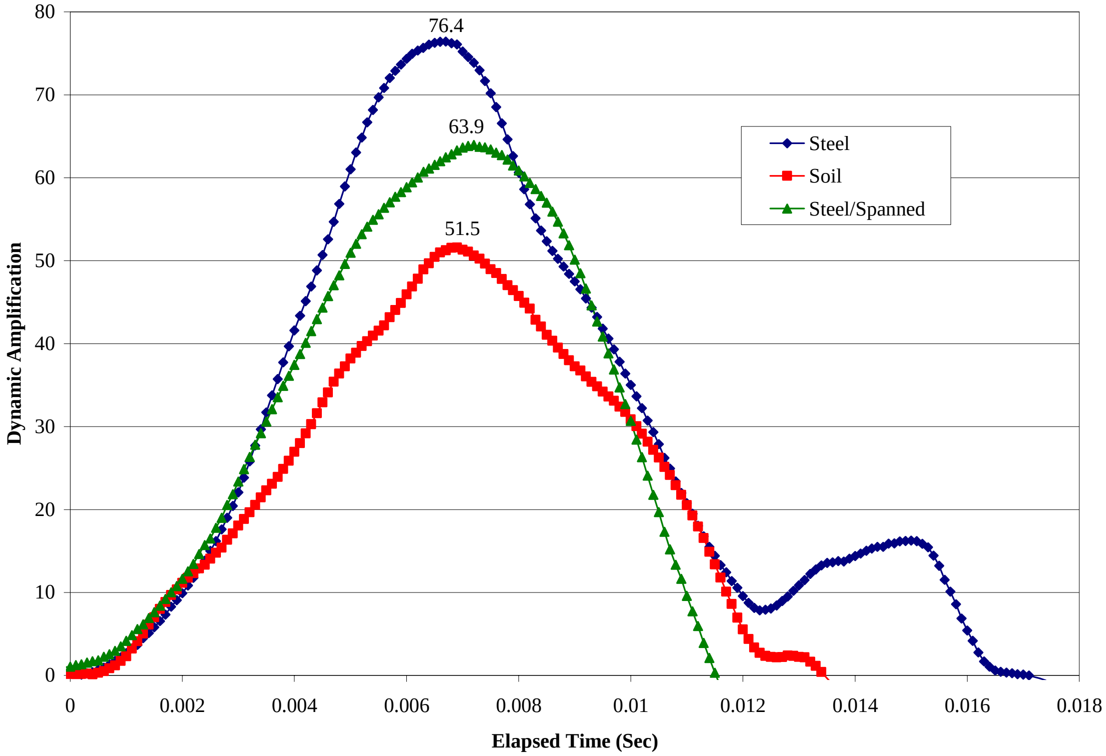


Figure 11 – Acceleration levels measured during dropped object (150 lbs dropped from 5 feet)

2. TREE DROPPED OBJECT:

$m := \lambda \cdot 101500\,\mathrm{lb}$ Mass

$L_1 := 12.6\,\mathrm{ft}$ Dimension 1

$L_2 := 13.6\,\mathrm{ft}$ Dimension 2

$L_3 := 13\,\mathrm{ft}$ Dimension 3

$A_1 := L_1 \cdot L_3$ $A_1 = 163.8\,\mathrm{ft}^2$ Frontal Area 1

$A_2 := L_1 \cdot L_2$ $A_2 = 171.4\,\mathrm{ft}^2$ Frontal Area 2

$A_3 := L_2 \cdot L_3$ $A_3 = 176.8\,\mathrm{ft}^2$ Frontal Area 3

$\rho := 62.4 \cdot \frac{\mathrm{lb}}{\mathrm{ft}^3}$ Density of Water

$C_D := 1.16$ Drag Coefficient

$g := 32.2 \cdot \frac{\mathrm{ft}}{\mathrm{s}^2}$ Gravity

$V_{t1} := \sqrt{\frac{2 \cdot m \cdot g}{C_D \cdot \rho \cdot A_1}}$ $\boxed{V_{t1} = 21.9\,\frac{\mathrm{ft}}{\mathrm{s}}}$ Terminal Velocity 1

$V_{t2} := \sqrt{\frac{2 \cdot m \cdot g}{C_D \cdot \rho \cdot A_2}}$ $V_{t2} = 21.4\,\frac{\mathrm{ft}}{\mathrm{s}}$ Terminal Velocity 2

$V_{t3} := \sqrt{\frac{2 \cdot m \cdot g}{C_D \cdot \rho \cdot A_3}}$ $V_{t3} = 21.1\,\frac{\mathrm{ft}}{\mathrm{s}}$ Terminal Velocity 3

Figure 12 - Calculation of terminal velocity for dropped tree

Figure 13 - Photographs from 1 MJ full-scale drop test