ExxonMobil

Santa Ynez Unit

Offshore Power System Repair: Amended Project
OPSR:A

Cable Retrieval Risk Assessment
(Analysis of Risk of Damage to Existing Components from a Dropped Cable During Retrieval)

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Study Summary

PMBCI examined the risk of physical damage to the active SYU cables and pipelines from the dropping of the failed “C” cable with or without the recovery tools attached during retrieval from the seabed. The study evaluated two water depths and three locations: 1) seaward of the shelf break in about 450 feet of water depth and 2) at two gas pipeline crossings of the “C” cable west of the Harmony platform each in about 1250 feet of water depth. The study methodology included the following three steps: 1) analysis of the falling cable dynamics; 2) analysis of the collision impact dynamics and 3) estimation of pipeline or cable damage. As a result of the analysis, five cable laydown modes were examined and three were found to be plausible under study conditions.

1) Stiff Catenary Laydown – (Very shallow water only < 50 ft) [Not considered plausible]
2) Hammerhead Laydown – (Does not occur under assumptions used) [Not considered plausible]
3) Spaghetti Pile Without Clamp – (All water depths)
4) Spaghetti Pile With Clamp – (All water depths)
5) Plunging Stalk – (Deep water only > ~400 ft)

The plausible damage to either a pipeline or a power cable was determined using elastic collision impact analysis. The results of this analysis obtained the following conclusions:

a) None of the pipelines or submarine power cables can be damaged by stiff catenary laydown mode.
b) None of the pipelines or submarine power cables can be damaged by the hammerhead laydown mode.
c) None of the pipelines or submarine power cables can be damaged by the spaghetti pile without clamp laydown mode.
d) None of the pipelines can be damaged by the spaghetti pile with clamp laydown mode.
e) All of the submarine power cables can be damaged by the spaghetti pile with clamp laydown mode.
f) All of the pipelines can be damaged by the plunging stalk mode.
g) All of the submarine power cables can be damaged by the plunging stalk mode.

As shown above, a plausible risk to the operating pipelines and power cables exists at each of the study locations, specifically in the deeper water. It should be noted that the spaghetti pile mode would more easily impact a long linear target such as the submarine cable. For the spaghetti pile with clamp or the plunging stalk modes to damage a pipeline or power cable, they would have to have a direct hit on the component. A tabular summary is provided in the report.

Study Premise

ExxonMobil commissioned PMBCI to examine the risk of damage to the SYU power cables and pipelines if the existing failed “C” cable is dropped during retrieval from the seabed while either the existing cables and pipelines are still in active service or the same operation after all of the cables and pipelines have been decommissioned and removed from service at the end of the SYU field life.

The primary risk examined in this study is that of possible physical damage caused by a dropped object such as the cable being retrieved with or without the recovery tools attached. One phase of this study will be to examine the loading required to cause such a failure. For the situation where the existing power cables or pipelines are still in service, an impact sufficient to cause plastic (e.g. inelastic permanent) deformation of the cable jacket armor wires or the pipeline is defined (for the purposes of this study) as failure. Depending on the actual damage, this type of deformation could require the repair of the cable or pipeline. For the situation where the cables and pipelines have been decommissioned, no repair would be required.

The study assumes, as an obvious conclusion, that the cable being retrieved, and the recovery clamp or end fittings to be employed are not themselves heavy enough to cause damage if they were lowered gently to the sea bottom. The major part of the study will focus on the estimation of the kinetic energy of the falling body. Due to the required calculation assumptions, the unknown physical condition of the cable to be retrieved, and for consistency with common engineering practice for heavy lift marine rigging and salvage operations, a safety factor of at least 3.0 is recommended. Without an adequate safety factor it is not practical to predict that a given scenario avoids damage with consequent risks of loss of service, pollution, and increased risks associated with or arising in additional or corrective work.

Site and Operations

The study evaluates the retrieval of the failed “C” power cable (5.83 inch diameter 35 kv submarine power cable) that has been removed from service and will be replaced as part of the OPSR:A Project. The cable runs between the shore and the Heritage offshore platform passing South of the Hondo and Harmony platforms as shown on the marine survey drawings (reference Pre-Lay Cable Route Survey, September 2001).

The OPSR:A Project purposes to retrieve the portion of the cable from the conduit terminus to the shelf break. The inshore portion of the cable will be retrieved to about 400-450 feet of water to the seaward side of the shelf break in the OCS. As a future operation, the OCS portion of the failed “C” cable could be retrieved from the shelf break to the first gas pipeline crossing west of Harmony platform and then from the second crossing of the gas pipeline to the Heritage platform.   Another future operation could be the removal of the entire OCS portion of the failed “C” cable at the end of the SYU field life after the facilities have been shut down.

In the area of the shelf break the purposed approach is for the seaward portion of the “C” cable to be cut at the tension machine on the vessel and lowered to the sea bottom with a nominal 100 pound pulling head attached for future recovery. The cable is nominally parallel and adjacent to the “B” power cable, the “A” power cable, and the 12-inch POPCO pipeline at this location. The first objective of this study is to evaluate if damage could occur to these in-service power cables or pipelines if the “C” cable were dropped at this point.

The future retrieval operation of the OCS portion of the “C” cable would proceed by lifting the inshore end of the cable at the 400-450 water depth and recovering it onto the cable recovery vessel through a traction device. A nominal 3-knot current from approximately West to East will contribute to the cable catenary tension during recovery.

For this analysis the recovery of the cable on the OCS will proceed to a point to the East and slightly South of the Harmony platform. The point will be selected such that the catenary lift-off point remains short of where the “C” cable crosses under the 12-inch gas pipeline West of the Harmony platform. The cable will be cut at this point and lowered to the sea bottom with a nominal 100 pound pulling head attached.

The second objective of this study is to determine if this cable were dropped at this point would it damage any of the in-service power cables or pipelines at that location. The cables at that location are the “A”, “B”, and “D” submarine power cables. The pipelines are the 20-inch oil emulsion pipeline, the 12 inch treated water pipeline, the 14-inch oil emulsion pipeline, and the 12-inch sales gas pipeline.

For this analysis the recovery of the cable on the OCS will continue West of the second crossing of the 12 inch gas pipeline located West of the Harmony platform to the Heritage platform. At this location, the cable will be cut on the sea bottom and lifted with a 200-pound cable clamp.

The third objective of this study is to determine if the cable, with the clamp tool attached, were dropped at this point would it damage any of the in-service cables or pipelines at this location. The “E” power cable, 12-inch gas pipeline, and 20 inch oil emulsion pipelines are at this location.

Study Methodology

The study methodology included the following three steps to address the study objectives:

1.) Falling Cable Dynamics

> *For each of the three locations, how can the cable fall? How fast will it go? With what kinetic energy will it strike the seafloor or one of the study target cables or pipelines? In simple terms, how hard does it hit?*

2.) Collision Impact dynamics

> *The “C” cable being retrieved and the lifting clamp or end fitting will be falling on the study target bodies with kinetic energies predicted in step 1. The force imparted to the target body will be predicted as a collision of elastic bodies. The work done to bring the falling body to rest is the integral of the force exerted with respect to the falling body deformation. The same amount of work is done by the equal and opposite forces deforming the target body.*

3.) Pipeline or Cable Damage Estimate

> *The pipelines are analyzed by a linear finite element analysis to determine the magnitude of force applied in the anticipated patterns that would result in initiation of a failure <u>if acting alone</u>. As it is not practical to evaluate other actual stresses as may be present, a safety factor of three is recommended to provide rational assurance that damage will not result from combined stresses due to both the predicted impact event and “ambient” stresses from operating and service conditions.*
>
> *The cables spiral armor will be effective principally in resisting transverse cuts or abrasion. It will not be effective in preventing lateral loads from being transferred to the conductors. The HV Kerite conductor insulation is a material with physical behavior characteristics like a high durometer rubber and a tensile strength of 550 psi. The target cables are primarily subject to damage either by a stabbing type of impact in which the armor wires are pushed aside, perhaps by broken armor wires protruding from the falling cable, or by direct*

> *crushing forces transmitted through the armor to the conductor core. This high rate impact load can cause a longitudinal splitting and consequent failure if the peak tensile stresses exceed the tensile strength.*
> *A linear finite element analysis of the conductor has been performed to determine the loading that would initiate such a failure. A safety factor of at three is recommended to insure the validity of safe loading predictions. No data is available for the known characteristic of most insulating materials to exhibit reduced dielectric strength under high shear stress loadings therefore the suggested safety factor of three may not be adequate to prevent dielectric breakdown if the cables are energized at the time of impact.*

Falling Cable Dynamics

Analyses of the cable catenaries with loading from typical water currents were performed for a wide variety of conditions at 450 and 1250 water depths. These analyses indicated that to avoid exceeding allowable cable tension the horizontal force at the traction (upper) end must be limited. The maximum cable tension without current loading would be at the upper end. Due to the current forces transverse to the cable, both the horizontal and vertical forces are markedly increased and the maximum cable tension will occur in the sag bend rather than the upper end. The profile that must be adopted to prevent excessive tension in the three knot current is steeper at the upper end than might be used for a “no-current” cable laying or recovery operation. The manufacturers suggested maximum cable tension of 21,680 pounds should be observed. As the cable is known to have failed, the possibility of a local physical defect either due to fault currents or galvanic action is considered high. Although the cable is being retrieved without expectation of reuse, higher tension than the manufacturer has recommended could cause a tensile failure at a local physical defect. There is no assurance that such a failure will not occur at an even lower load. All normal precautions to stay clear of highly tensioned multipart lines should be observed. If such an unanticipated tension failure does occur at a tension less than the recommended 21,680 pound limit, the results will be very similar to the cases considered at the previously described three locations.

The cable could be dropped due to a rigging failure or handling error at any of the three study locations. The first analysis is for a 3-knot current loaded catenary in 450 feet of water, within permissible maximum tension limits. Two time steps for a direct integration time-history dynamic analysis are shown in Figure 1. This analysis does not converge to a solution as instabilities develop from the inability of the modeled cable to sustain compressive loads.

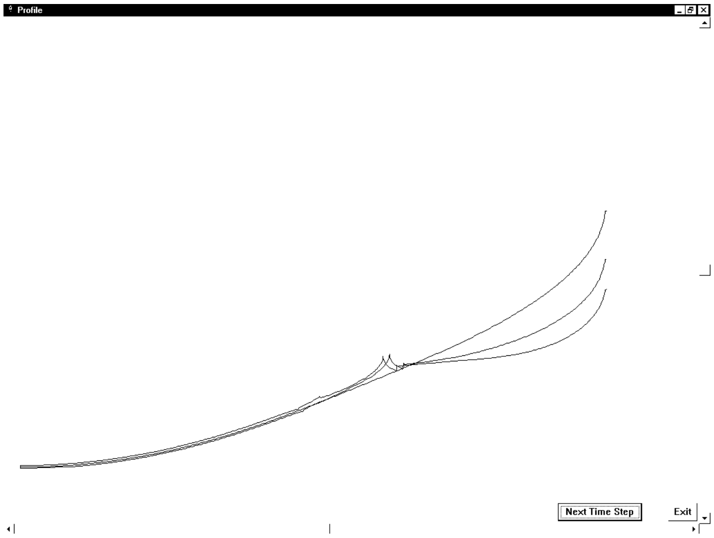


Figure 1 – 450-foot water depth simple catenary dynamic analysis predicts instability

Several useful inferences may be drawn even though a full direct solution fails. These will be discussed further after looking at other examples. The water depth for this case is 450 feet. The lift-off point is 842.28 feet from the able head, which is 11.17 feet above the waterline.

A second analysis using a similar profile for 1250 feet of water follows. This current loaded profile is for minimum tension while retaining control of the lift-off point. The lift-off point is 341.34 feet from the cable head, which is 11.14 feet above the waterline. Note that for this minimum tension case in 1250 feet of water, the cable head is nearly vertical. Five time steps from the cable release are shown in Figure 2. Just as in the 450-foot water depth case, compressive instabilities develop, and the solution fails to converge.

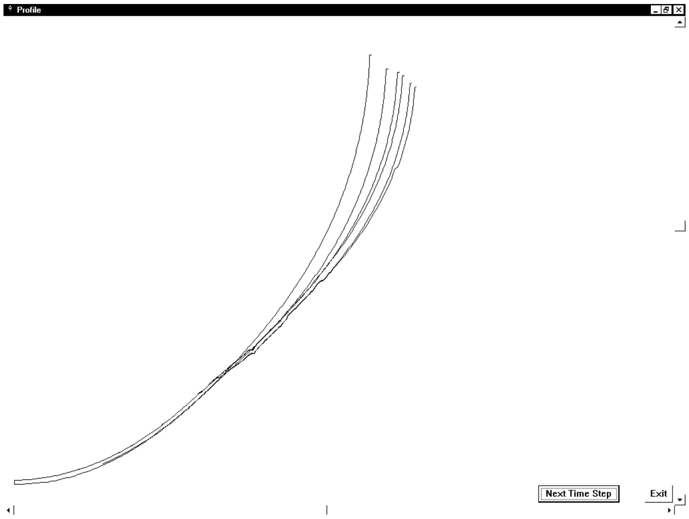


Figure 2 – 1250-foot water depth minimum tension simple catenary dynamic analysis predicts instability

By contrast, the current loaded profile for maximum tension was also evaluated. The lift-off point is 1482.88 feet from the cable head, which is 11.38 feet above the waterline. For this maximum tension case in 1250 feet of water the cable head is still at a high angle. Two time steps from the cable release are shown in Figure 3. Just as in the other cases, compressive instabilities develop, and the solution fails to converge.

The maximum tension profile for 1250 feet of water follows.

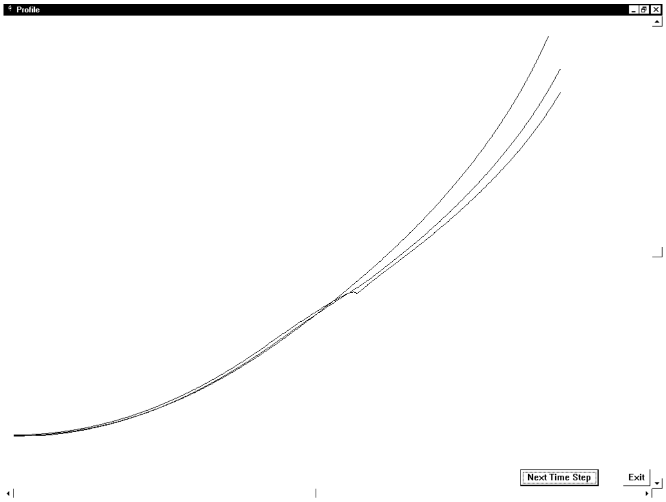


Figure 3 – 1250-foot water depth maximum tension simple catenary dynamic analysis predicts instability

These analyses and others all failed to converge to simple solutions with the cable on bottom and in every case the development of instability due to axial compression was the reason.

The "C" cable has three HV insulated conductors and a single layer of 46 BWG #4 galvanized steel wires coated with 55 mils of high density polyethylene. The coated armor wires are in a single left lay layer with a 39-inch spiral pitch. The armor wires are not contained within a sheath or connected together.

Traditional rational analysis to proceed beyond the above evaluation suggests five specific modes to consider for the manner in which the dropped cable may reach the sea bottom:

1.) Stiff Catenary Laydown Mode

If the cable were able to sustain the compression that arises without significant local buckling or out of plane deformation, it would come down with in-plane lateral motion only. A single touchdown point would move along the seabed from the prior-to-release lift-off point to the cable head.

A number of factors work against development of this case. The single layer spiral armor will cause the slacking cable to spiral and compression will amplify the inherent spiral. This effect will cause out of plane motion to initiate. The spiral armor itself is unable to sustain direct compression and it can open up forming basket(s). At any local defect such as where a basket exists or armor wires are displaced from their normal lay or wires have been broken, corroded, or damaged in any way, a weak spot is formed where compressive force will cause a concentration of p-delta moment amplification effects.

The simple stiff catenary laydown can only occur in very shallow water (perhaps less than 50 feet of water depth). This mode is not expected in the study water depth range. Further analysis of this mode was not pursued as it is not expected to occur.

2.) Hammerhead Laydown Mode

This laydown mode is the same as above except that the cable end fixture acting as a concentrated weight causes the cable end to fall faster such that it hits bottom ahead of the adjacent cable.

This mode is also not expected to develop in the study water depths. The Stiff Catenary Laydown from which this mode would develop does not occur and the cable end fittings employed are not heavy enough to have significant effect.

3.) Spaghetti Pile Mode Without Clamp

As the cable cannot sustain compressive loading without lateral displacement and bending it will curl into a spaghetti pile. As the curling cable falls, there will be multiple touchdown points in unpredictable locations and sequences along and to both sides of the nominal cable path. In all cases the touchdown velocity will be approximately the terminal velocity for lateral motion of the cable. The individual impact points may be very slightly higher than the nominal terminal velocity as adjacent cable segments are inclined with respect to the general motion.

This mode is expected to occur at all the study location water depths. The lateral distribution of the impact points could be higher in the deeper water but remains unpredictable. As the cable reaches its terminal velocity in less than its own diameter there is no other significant difference between the 450 and 1250-foot water depths.

A typical impact point kinetic energy for the spaghetti pile would be approximately:

$$E_k = \frac{m \cdot v^2}{2} = \frac{\left(\frac{200}{32.2}\right) \cdot \left(3.75^2\right)}{2} = 43.7 \quad ft \cdot lbf$$

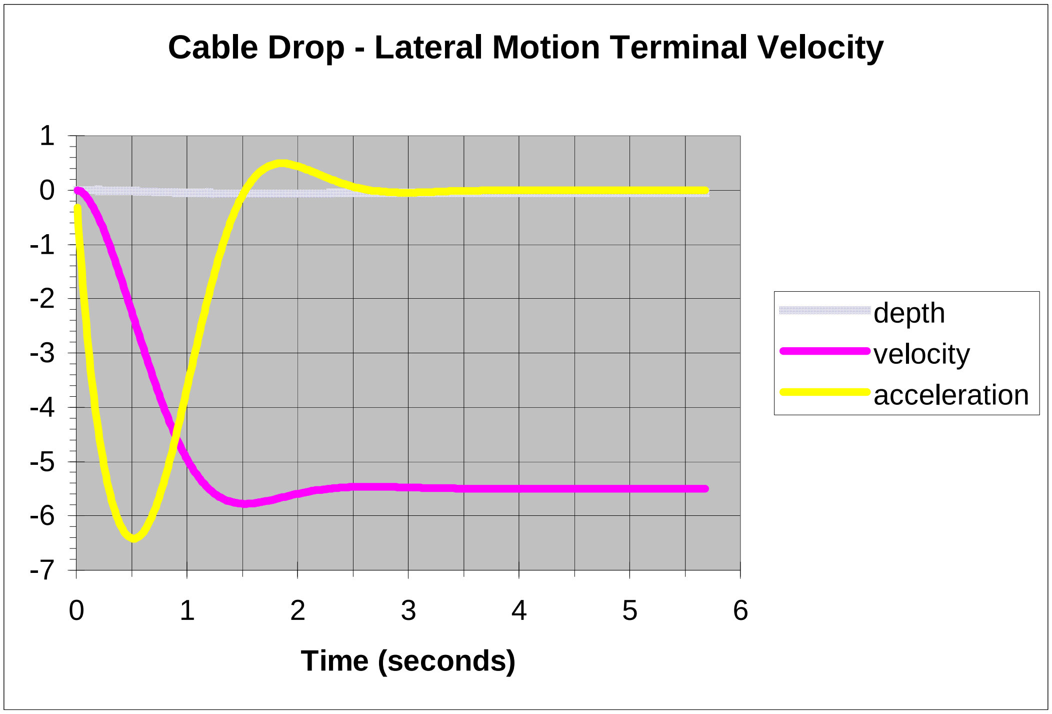


Figure 4 – Dynamic Terminal Velocity Study by Morison's Equation

The terminal velocity for the "C" cable free falling in seawater at 70° F is 5.50 feet per second. The cable diameter is 5.38 inches. The values for Cd and Cm are 0.70 and 1.6.

As can be seen in Figure 4, starting from rest the terminal velocity is reached in about 2.5 seconds and with a lateral motion of less than the cable diameter.

[5.5 feet per second is 3.75 miles per hour; about walking speed.]

4.) Spaghetti Pile Mode With Clamp

This mode is the same as the previous mode except that a 200-pound end clamp is located a few feet from the end of the cable. The edge of this clamp can strike the pipe like a knife-edge and at a slightly higher kinetic energy.

At the end clamp the kinetic energy could be:

$$E_k = \frac{m \cdot v^2}{2} = \frac{\left(\frac{400}{32.2}\right) \cdot \left(4.00^2\right)}{2} = 99.4 \ \ ft \cdot lbf$$

5.) Plunging Stalk Mode

The axial hydrodynamic forces, which are commonly ignored in many cases, are substantially less than the lateral forces described by Morison's Equation. If a segment of cable is falling in the direction of its longitudinal axis then its terminal velocity is governed by the weaker axial flow surface boundary layer effects and it will fall faster and for a much greater distance before reaching terminal velocity.

Figure 5 shows a 400-foot "stalk" falling vertically. It reaches terminal velocity at 67.3 feet per second (45.9 miles per hour) when the drag equals the submerged weight of 3500 pounds after plunging 122 feet. Note this is radically different from the lateral terminal velocity.

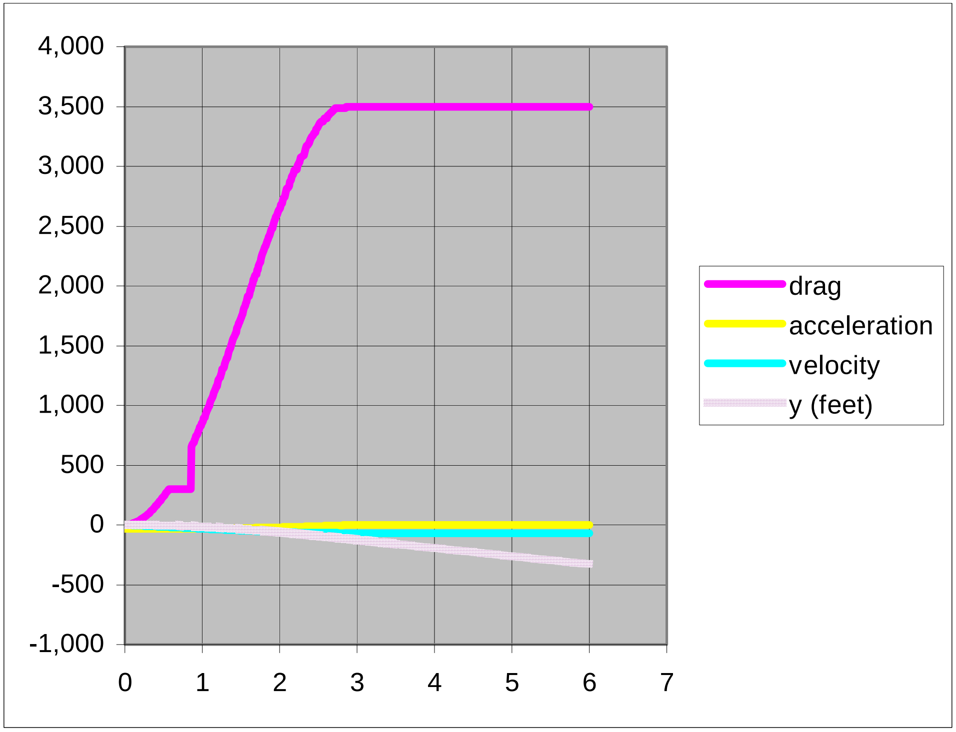


Figure 5 – Axial Flow Terminal Velocity Study

The kinetic energy for a 400-foot stalk at terminal velocity, as could develop in 1250 feet of water, is:

$$E_k = \frac{m \cdot v^2}{2} = \frac{\left(\frac{400 \cdot 18.85}{32.2}\right) \cdot \left(67.3^2\right)}{2} = 530293 \;\; ft \cdot lbf$$

This is a plausible worst case for the 1250 water depth locations. At the 450-foot water depth the plausible stalk length is more like 150 feet.

$$E_k = \frac{m \cdot v^2}{2} = \frac{\left(\frac{150 \cdot 18.85}{32.2}\right) \cdot \left(39.9^2\right)}{2} = 69898 \;\; ft \cdot lbf$$

<u>This mode is more plausible in deeper water depths. It is also more likely to be initiating at points of existing cable damage.</u>

<u>Elastic Collision Impact Dynamics</u>

1) 400 foot Plunging Stalk Impact

Weight of impacting object (in force units): $W := 7540 \cdot \text{lbf}$

Velocity of the impacting object: $V := 67.3 \cdot \text{fps}$

Stiffness of object being impacted: $k_1 := 1.5 \cdot \text{kpi}$

Stiffness of the impact object - This value is typically just estimated. As a guide line, some selected values of k $_2$, and the corresponding combined stiffness k, follows: $k_2 := 150 \cdot \text{kpi}$

for $k_2 = k_1$ **k = 1/2*k$_1$ (for equal stiffnesses)**
$k_2 = 2{*}k_1$ $k = 2/3{*}k_1$
$k_2 = 3{*}k_1$ $k = 3/4{*}k_1$
$k_2 = 7{*}k_1$ $k = 7/8{*}k_1$
$k_2 = 10^{15}$ **k = k$_1$ (for infinitely stiff impact object)**

Calculate the kinetic energy at impact as a function of the velocity at impact, V:

$$E_F(V) := \frac{W}{2 \cdot g} \cdot V^2 \qquad E_F(V) = 6368.645 \text{in} \cdot \text{kips}$$

Derive the formula for converting energy of a moving object into an impact force on the body being impacted:

The energy absorbed by the impacted object, as well as the energy absorbed by the impacting object , is equal to the area under each one 's force/deflection curve. Since the area is a triangle, the energy , $E = \frac{1}{2} \cdot R \cdot y$, where R is the force, which is equal between the two objects, and y is the deflection. The total energy is equal to the sum of the energy absorbed by both.

Therefore $E = \frac{1}{2} \cdot R \cdot y_1 + \frac{1}{2} \cdot R \cdot y_2$ and by substitution $E = \frac{1}{2} \cdot R \cdot \frac{R}{k_1} + \frac{1}{2} \cdot R \cdot \frac{R}{k_2}$

Simplifying $E = \frac{1}{2} \cdot R^2 \cdot \left(\frac{1}{k_1} + \frac{1}{k_2}\right)$ and $R = \sqrt{\frac{2 \cdot E}{\frac{1}{k_1} + \frac{1}{k_2}}}$

And further simplifying $R = \sqrt{2 \cdot \frac{k_1 \cdot k_2}{k_1 + k_2} \cdot E}$

Where the effective stiffness of the two body combination is: $k := \frac{k_1 \cdot k_2}{k_1 + k_2}$ $k = 1.5 \text{kpi}$

Calculate the impact force as a function of the combined stiffness and the speed of the impacting body: $R(k, V) := \sqrt{2 \cdot k \cdot E_F(V)}$

Therefore for the 400 foot plunging stalk at a 1250 foot water depth:

The resulting impact force between bodies is: $R(k, V) = 137.538 \text{kips}$

2) Similarly, for the 150 foot plunging stalk at a 450 foot water depth:

The resulting impact force between bodies is: $R(k, V) = 49.93 \text{kips}$

3) For the Spaghetti Pile Mode with Clamp Mode:

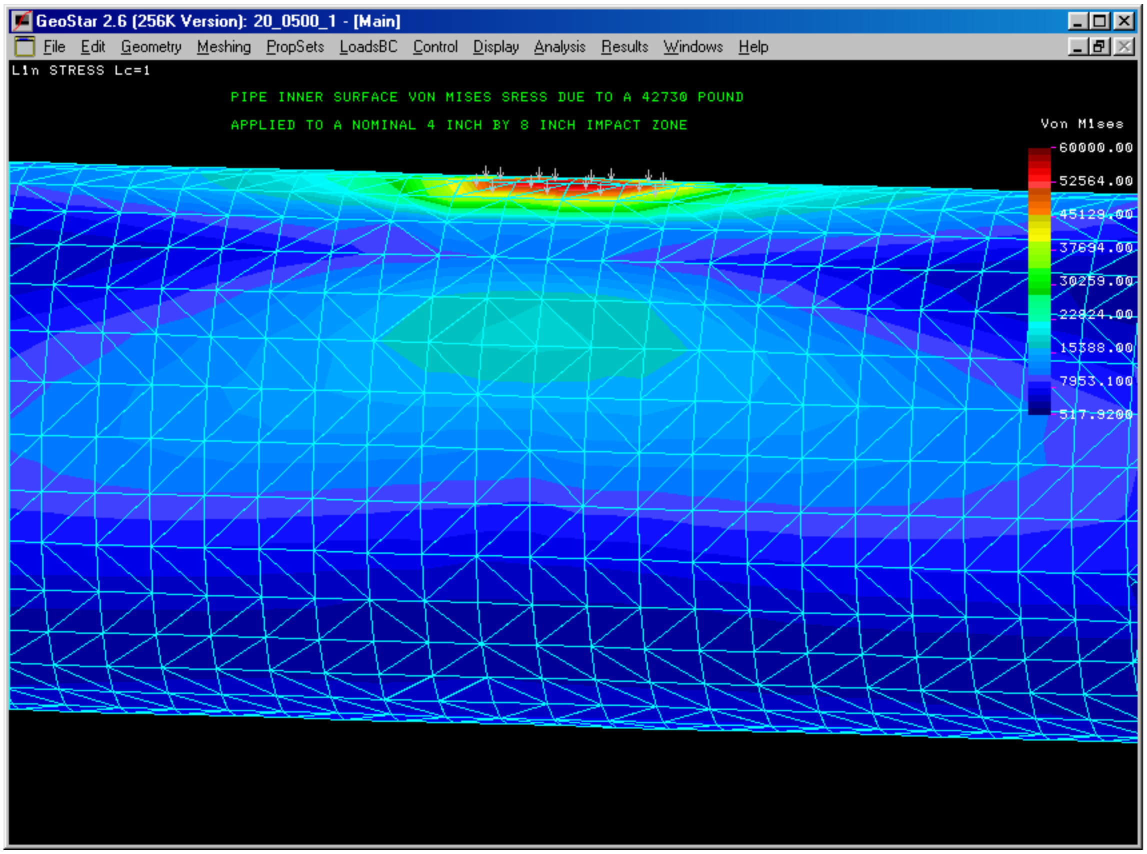
The resulting impact force between bodies is: $R(k, V) = 1.883 \text{kips}$

4) For the Spaghetti Pile without Clamp Mode:

The resulting impact force between bodies is: $R(k, V) = 1.248 \text{kips}$

Pipeline and Cable Damage Estimates

The most easily damaged pipeline would be the 20-inch diameter pipe with a 0.5-inch wall thickness (oil emulsion line). The force required to yield the pipe is 42,730 pounds. With a safety factor of 3.0, as recommended, this says the applied force should be limited to 14,243 pounds. As shown in Figure 6, this is substantially less than the plunging stalk forces of 137,530 or 49,930-pound forces for the 400 and 150-foot cases, respectively. Damage to the 20-inch pipeline at any of the three study locations is therefore plausible.



PIPE INNER SURFACE VON MISES SRESS DUE TO A 42730 POUND
APPLIED TO A NOMINAL 4 INCH BY 8 INCH IMPACT ZONE

Figure 6 – Finite Element Analysis for 20ϕ0.500 60-ksi-yield stress pipeline for load to cause yield, distributed over an impact zone for the plunging stalk mode

Conversely, for the general case of the spaghetti pile mode, the 1,248 pounds is insufficient to cause damage to the most easily damaged pipeline.

For the spaghetti pile with clamp impact case, the force required to yield the pipe is 31,796 pounds as shown in Figure 7. This force is less than the case shown in Figure 6 since the clamp impact is applied for the finite element analysis as a concentrated line load transversely to the pipe axis rather than spread over a larger impact area. This simulates the knife edge effect of the clamp edge striking the pipe at an angle. With the recommended safety factor of 3.0, the applied load should be limited to 10,599 pounds. As this is substantially more than the 1,883 pounds for the clamp impact in the spaghetti pile with clamp mode, no pipeline damage will occur.

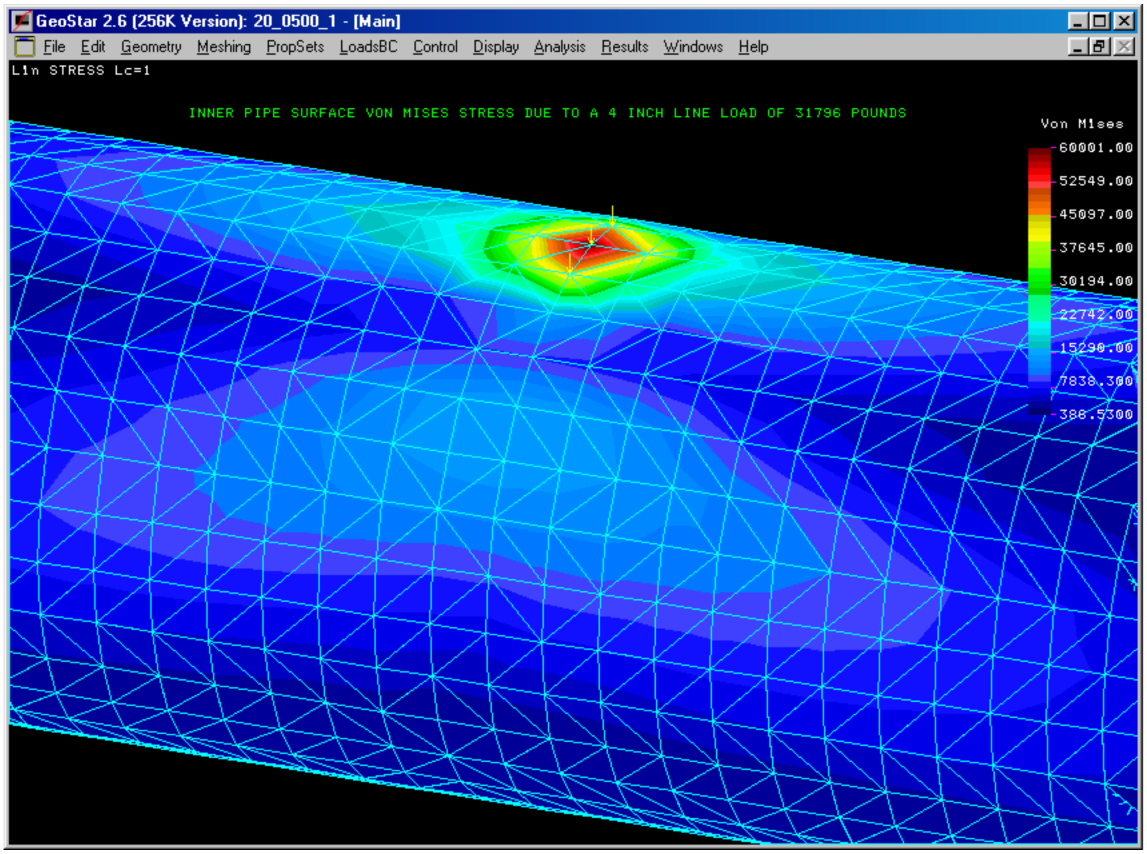


Figure 7 – Finite Element Analysis for 20ϕ0.500 60-ksi-yield stress pipeline for load to cause yield, applied like a knife-edge for the spaghetti pile with clamp mode.

The pipeline most resistant to impact damage would be the nominal 12-inch pipe with a 0.625-inch wall thickness (gas pipeline). The load required to yield the pipe is 107,500 pounds. With the safety factor of 3.0, the load should be limited to 35,833 pounds. The impact pattern assumed on the pipe is shown in Figure 8.

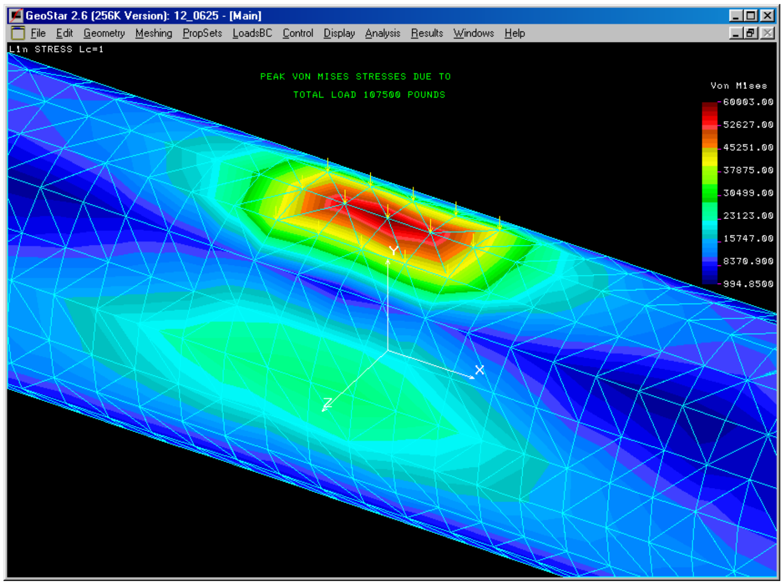


Figure 8 - Finite Element Analysis of 12.75ϕ0.625 60 ksi yield pipeline for load to cause yield, distributed over an impact zone for the plunging stalk mode

The 137,530-pound and 49,930 pound forces from the 400 and 150 foot plunging stalk modes, respectively, both exceed 35,833 pounds. Therefore, any of the pipelines at any of the study locations can plausibly be damaged by an impact in the plunging stalk mode.

Finite element analysis of the cable primary conductor assembly reveals the HV Kerite insulation reaches a 550-psi Von Mises stress with a 5223 pound per inch transverse loading. The spiral armor is deemed to be effective to distribute the knife-edge load for about one inch, or 4 armor wire diameters.

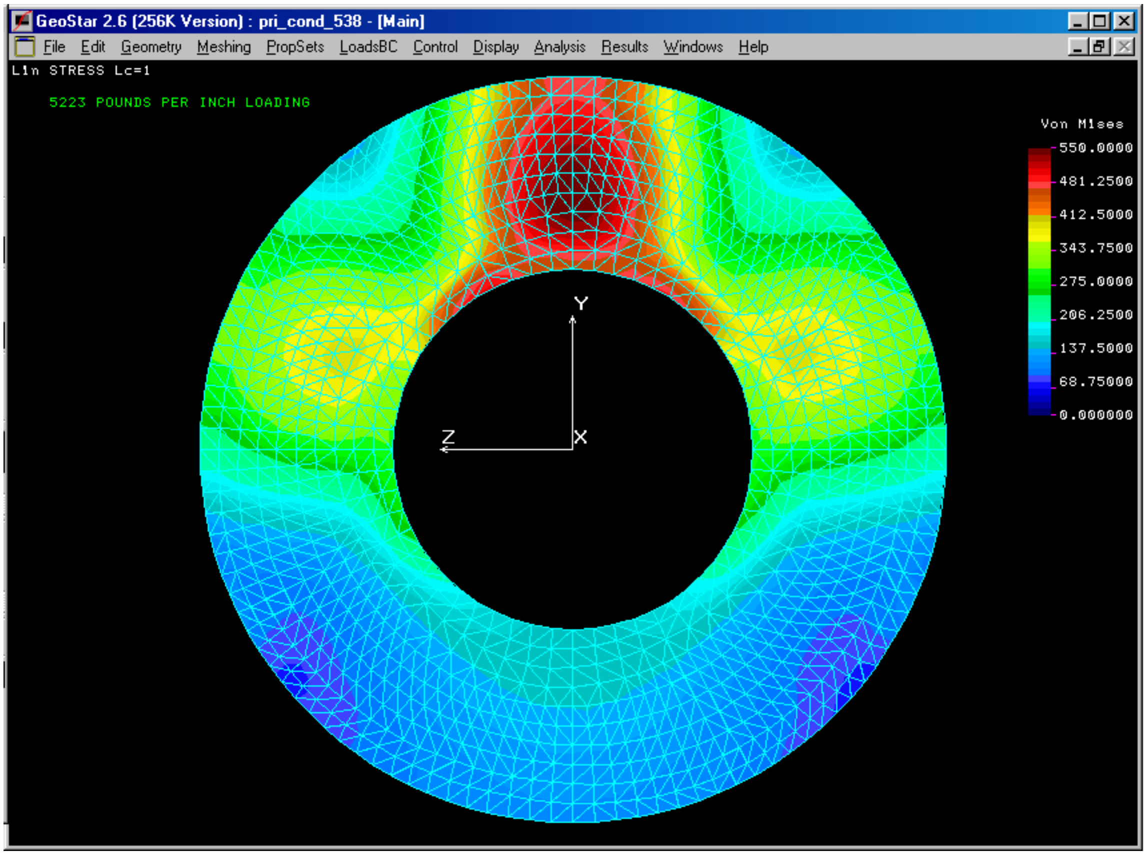


Figure 9 –

The cable analysis stress plot in Figure 9 shows a loading of 5,223 pounds per inch will cause a longitudinal splitting of the HV Kerite insulation layer of the conductors. With a safety factor of 3.0, the loading should be limited to 1,741 pounds. This means that the spaghetti pile with clamp mode impact (1883 pounds) or either plunging stalk mode impact can fail any of the cables.

A summary tabulation of plausible damage is shown in the following table:

location – water depth	Item	Plausible damage during retrieval operation from dropped “C” cable				
		stiff catenary laydown mode (mode 1)	hammerhead laydown mode (mode 2)	spaghetti pile mode without clamp (mode 3)	spaghetti pile mote with clamp (mode 4)	plunging stalk mode (mode 5)
1 - 450	12 inch POPCO	no	no	no	no	yes
1 - 450	“A” cable	no	no	no	yes	yes
1 - 450	“B” cable	no	no	no	yes	yes
2 - 1250	“A” cable	no	no	no	yes	yes
2 - 1250	“B” cable	no	no	no	yes	yes
2 - 1250	“D” cable	no	no	no	yes	yes
2 - 1250	20 inch oil emulsion	no	no	no	no	yes
2 - 1250	12 inch treated water	no	no	no	no	yes
2 - 1250	14 inch oil emulsion	no	no	no	no	yes
2 - 1250	12 inch sales gas	no	no	no	no	yes
3 - 1250	“E” cable	no	no	no	yes	yes
3 - 1250	12 inch gas	no	no	no	no	yes
3 - 1250	20 inch oil emulsion	no	no	no	no	yes