UNIVERSITY OF LISBON

INSTITUTO SUPERIOR TECNICO

Hydrodinamics of floating systems

Project 2

Task 1

Analysis of a mooring cable

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Task 1: Static analysis of an elastic cable

Introduction:

The objective of the work is to make a preliminary design of the mooring system, to analyze the stiffness induced by the mooring lines and the mooring-induced damping coefficients. Computing the load-excursion relations and considering only the horizontal force acting on the total system for an uniform cable line with one material related to the x-z plane.

It will test three different materials and water depths to discover how the combination of both influences stress. Furthermore, in this research, it will be determined how the vessel displacement affects the tension in the mooring cable and the relation between maximum motion and water depth.

Step 1: Choice of main cable line features.

In this project, the static method will be adopted in combination with the elastic cable line theory with various materials. Chain, wire, and fiber rope composed of polyester are among the materials to be considered. The table below shows the stiffness per unit length, EA, weight per unit length, w, and breaking strength of the cable for each material. The chain grade will be assumed to be ORQ, the wire configuration will be spiral strand, and the attributes from the polyester will be supplied by Material Properties.

Material	Stiffness (EA) [N]	Weight per length [N/m]	CBS [N]
Chain	90,000 * D^2	0.1875 * D^2	21.1*(44-0.08*D) * D^2
Wire	90,000 * D^2	0.043 * D^2	900 * D^2
Polyester	(2,100*π) D^2	0.0067 * D^2	250 * D^2

Table 1 materials selection

Where D is the cable's diameter in millimeters. According to the IACS specifications, the table's diameter can range from 80 mm to 210 mm. As a result, in the catenary and taut designs, the cable from all materials will be assumed to have a diameter of 100 mm.

The water depth and external influences are also assumed in this project. The calculations will be performed for water depths of 150 m, 500 m, and 1000 m, and the horizontal steady force caused by wind, wave, and current will be 80KN, 200KN, and 350KN, respectively.

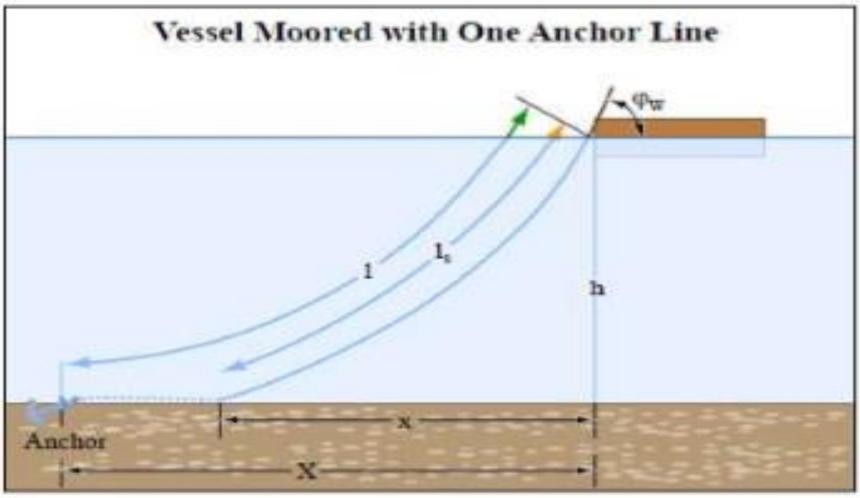
Step 2 & 3: Calculation of the relation between horizontal tension T_H, vertical tension T_Z, total tension force T and the angle ϕ_w with the horizontal distance X from the anchor point to the fairlead.

Based on the computed relations found above:

- Calculate the horizontal distance between the anchor point and the fairlead (X). In relation of that, assuming that the values of the horizontal steady force are (80,200,350) KN for the respectives water depth (150,500,1000)m.
- Calculate the necessary horizontal force from the vessel on the chain, permitting to move the anchor absuming is a gravity anchor
- Calculate the relation between the vessel's motion δ and the mooring line tension T.
- Calculate the maximum horizontal motion of the vessel when a suction anchor is used.

Catenary configuation

There are two methodologies for calculating the correct procedure required by the problem.
Catenary configuration and Taut configuration.
The difference resides in the expressions to find the relation between the X and T.



The first used is the Catenary configuration, with the main purpose to obtain the relation between the vessel's motion and the mooring line tension (δ versus T).
As a result, the following approach was used to compute this:

Was assumed that the horizontal force ranged from 1 to 1,000 kN and that the cable length was 3.5 times the local water depth (h).

After that, using a solver, the following equation was solved to give the value of T for various materials, water depth, and horizontal forces.

$$T_{horizontal} = EA * \left(\left({T}/{EA} + 1\right)^2 - 2 * {w * h}/{EA}\right)^{0.5} - EA \quad \text{(I)}$$

The force T is absumed real and positive, so the vertical force T_z can be calculate by the following Pythagoras theorem

$$T_z = \sqrt{T^2 - T_{horizontal}^2} \quad \text{(II)}$$

Tz, on the other hand, equals lmin*w (III), where lmin is the length of the cable between the fairlead and the touchdown points. As a result, atan (Tz/Th) may likewise be used to compute the angle phi. With all of this information, the total horizontal distance (X) may be determined using the equation below:

$$X = (l - lmin) * (1 + Th/AE) + x$$
$$x = (Th/w) * asinh(w * lmin/Th) + Th * lmin/EA \quad \text{(IV)}$$

When utilizing a gravity anchor, the required horizontal force from the vessel on the chain to move the anchor may be simply estimated by using the equation (IV) and assuming l = lmin = 3.5*h.

Three stages are required to establish the relationship between delta and T. The first step is to determine the vessel's starting displacement (X0). The range in which delta can change is computed in the second step. The third step is to compute T for a given X by interpolating the preceding findings. In this situation, the X will equal the total of X0 and delta. The first step is to use the relationships between X and Th to interpolate them with the necessary horizontal force. The horizontal force as input was equivalent to the forces caused by wind, wave, and current. As a result, with a water depth of 150 m, a horizontal force of 80 kN was applied. This procedure was done for various materials and water depths. As a result, each material and water depth has a distinct X0.

According to the presentation appointments, the delta range fluctuates with water depth, and its values are shown in the table below. The intended delta was calculated by taking the average of the findings and was designed for a semi-submersible.

Extreme Excursions as a Percentage of Water Depth

Water Depth (m)	Mooring Type	Semi-submersible	Ship
30	Chain/wire	30-45%	40-55%
150	Chain	15-25%	30-40%
500	Chain/wire	25-30%	20-30%
1000	Fibre ropes	5-10%	5-15%

Finally, it is essential to ensure that the mooring system is in line with the classification societies. The minimal safety factor for an unbroken cable, according to the guidelines, is 1.8. As a result, the force T must be less than the CBS divided by 1.8. As a result, if this value is less than 1.8, it can offer the maximum displacement of a platform for different materials and water depths by picking the lowest safety factor greater than 1.8 and interpolating the supplied T to obtain the delta. Furthermore, if the safety factor is less than 1.8, the mooring cable cannot be utilized. As a result, the material or diameter need be altered to accommodate it.

Results for Catenary configuration:

The material developed by choosing the diameter and the characteristics given in Table X are shown in the table below. Also, using the graphs that connect the horizontal force to the X, the horizontal distance between the anchor point and the fairlead for the given horizontal steady force created may be calculated. They were calculated using the formulae described in section related to catenary configuration and are displayed below for various water depths.

Material properties

	EA	w	CBS
Steel	9e+08	1875	7.596e+06
Wire	9e+08	430	9e+06
Polyester	6.5973e+07	67	2.5e+06

For h = 150m and Th = 80 kN

- Chain: X = 424 m
- Wire: X = 455 m
- Polyester: X = 483 m

For h = 500m and Th = 200 kN

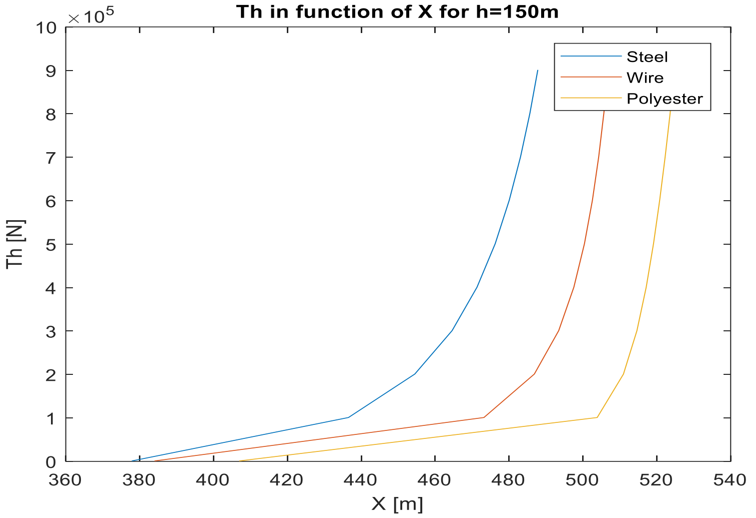
- Chain: X = 1410 m
- Wire: X = 1540 m
- Polyester: X = 1662 m

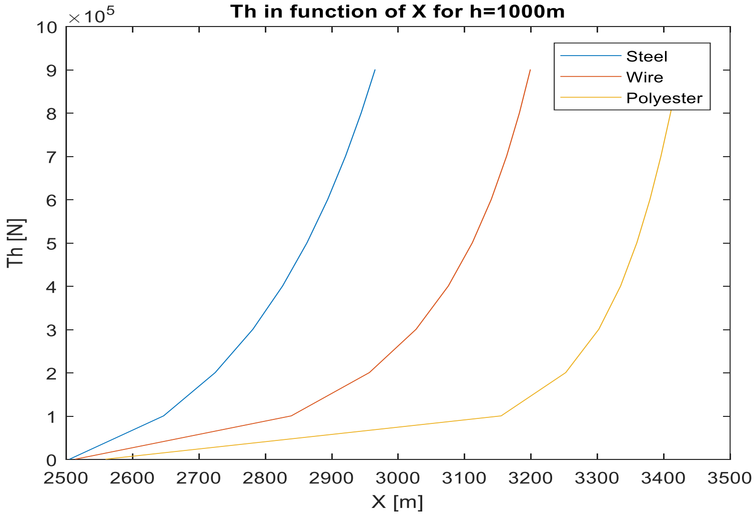
For h = 1000m and Th = 350 kN

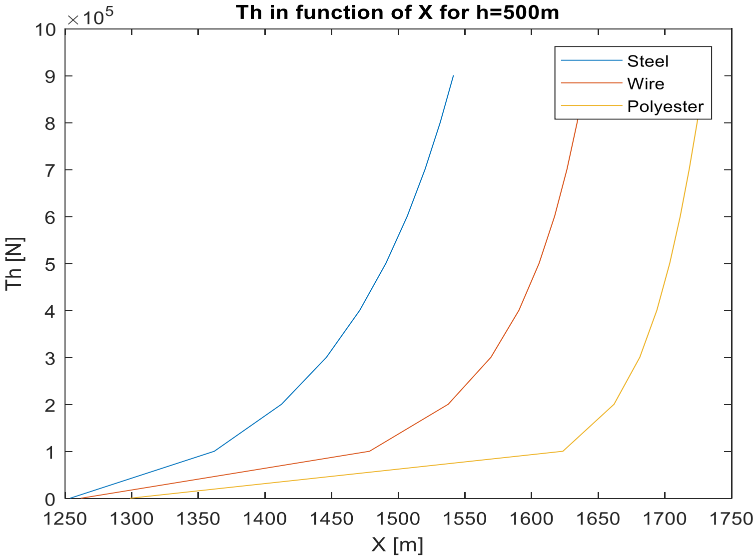
- Chain: X = 2803 m
- Wire: X = 3050 m
- Polyester: X = 3317 m

For better analysis and explanation of the data obtained, plotted graphs are shown below.

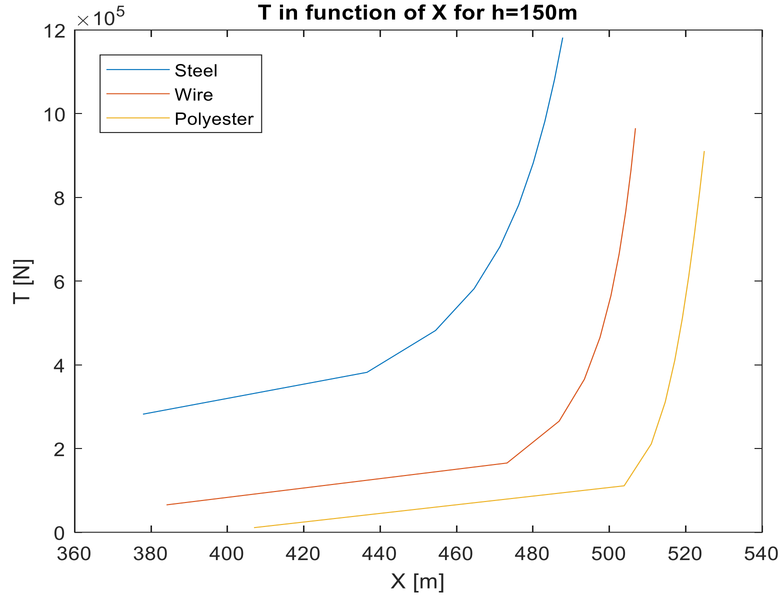
For Th in function of X with differents water depth:

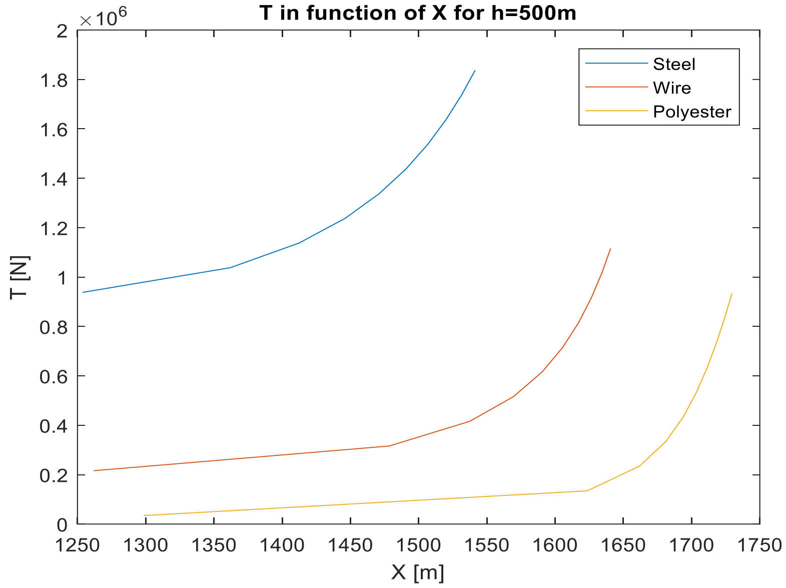


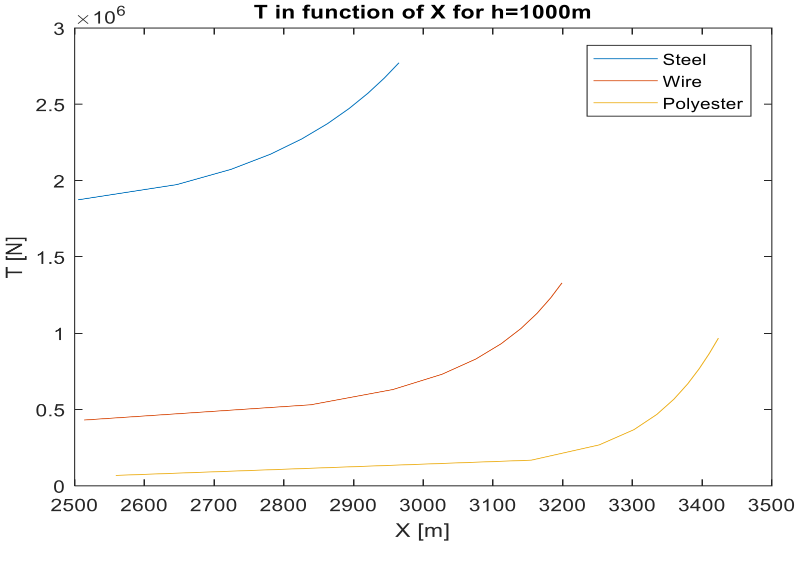




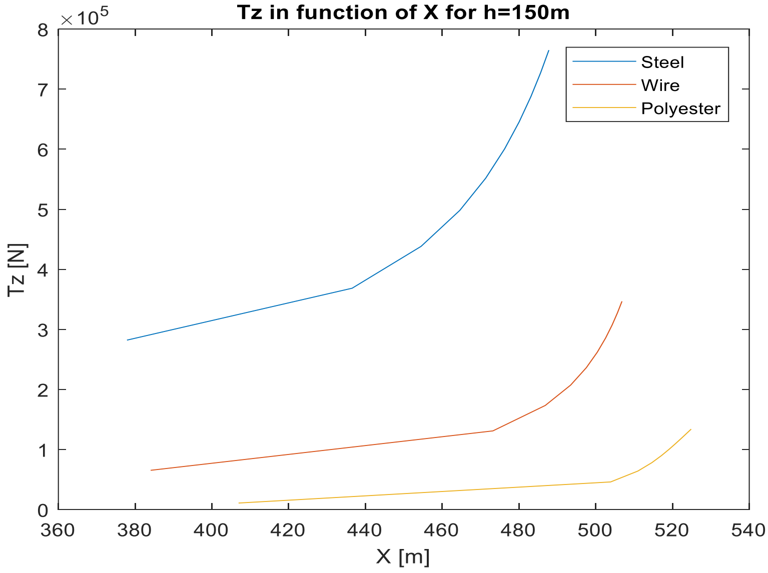
For T in function of X with differents water depth:

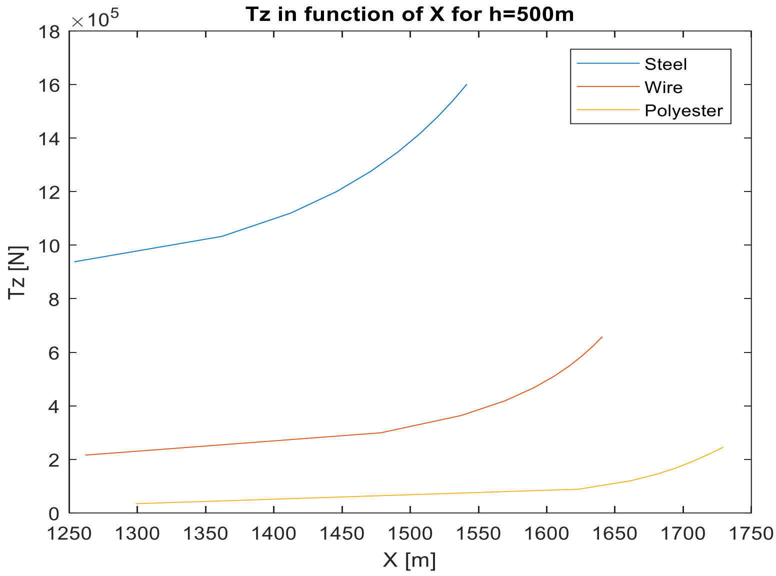


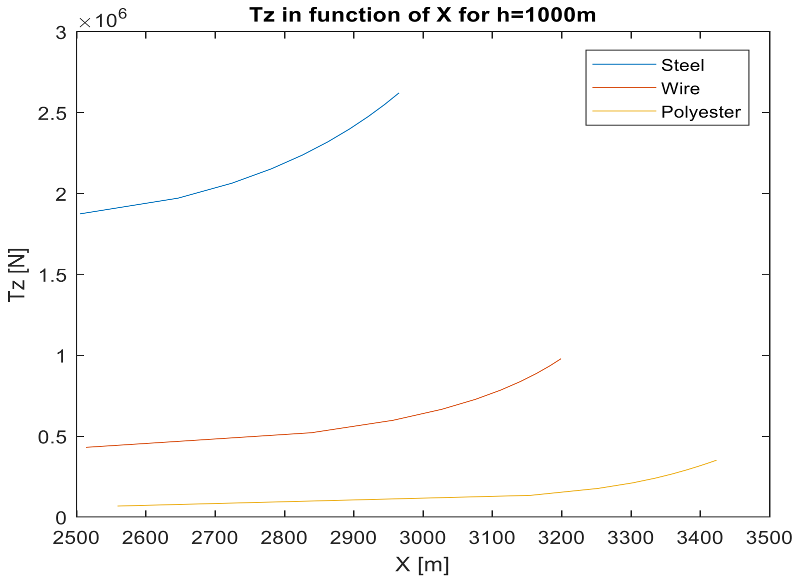




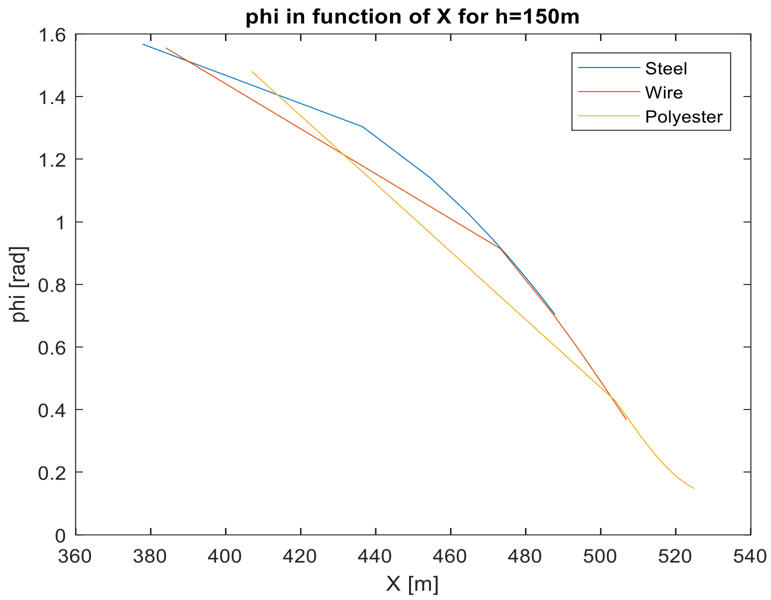
For Tz in function of X with differents water depth:

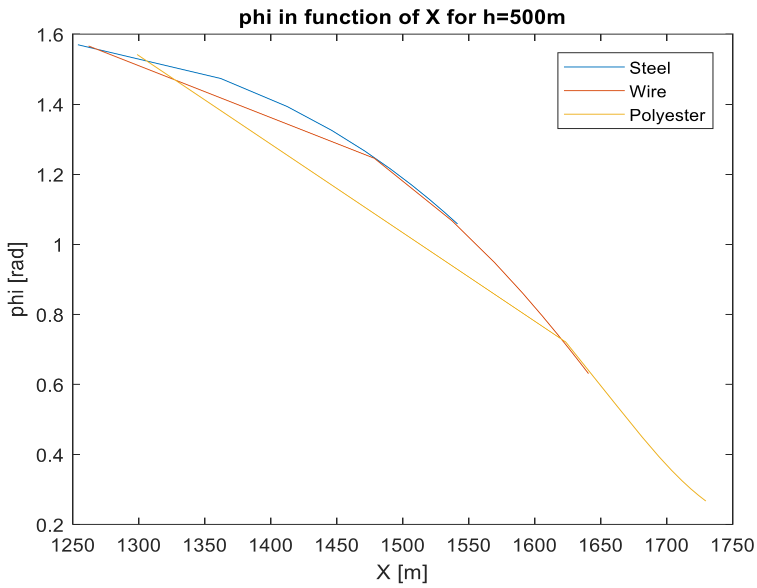


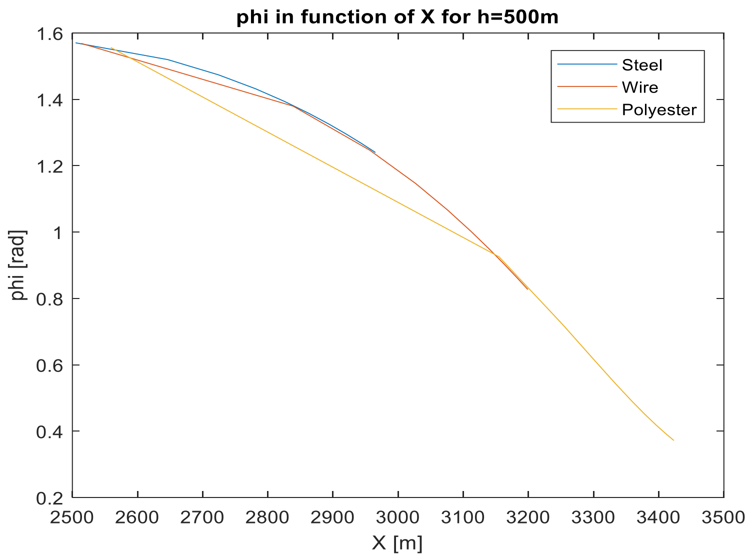




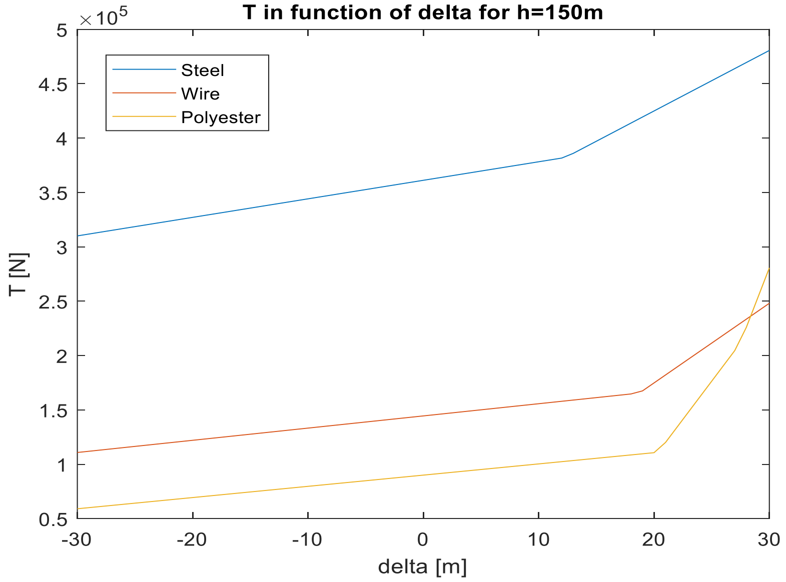
For Phi in function of X with differents water depth:

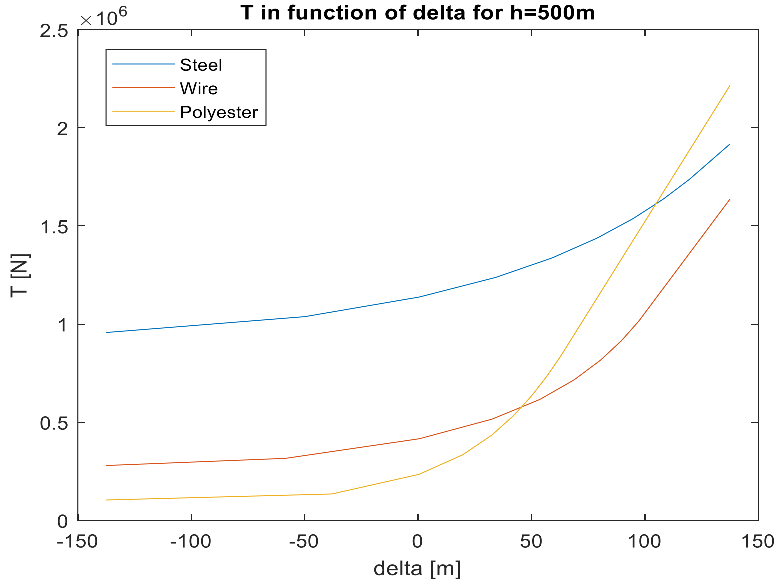


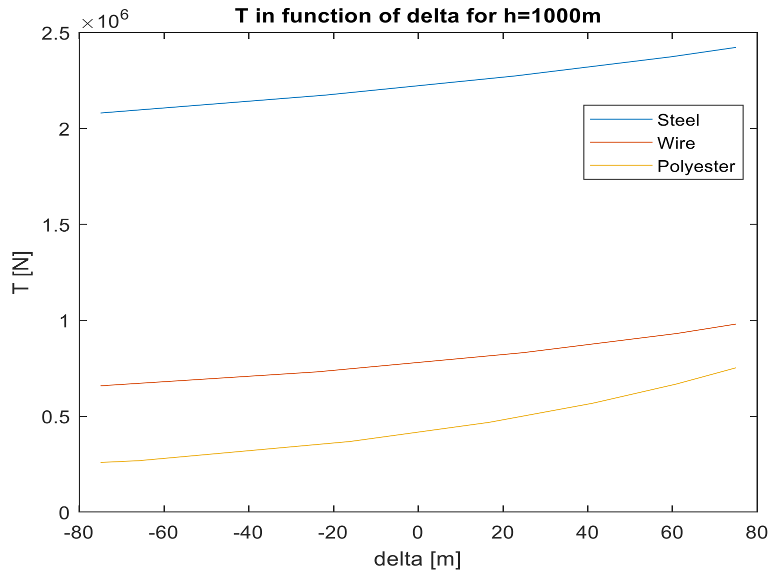




For T in function of delta with differents water depth:







The following tables show the impact in the choice of materials in the respective depths taking into account the main parameters calculated.

h=150m

	Steel	Wire	Polyester
X0 [m]	424.21	454.48	483.52
delta_max [m]	30	30	30
T_max [N]	4.8062e+05	2.4809e+05	2.8065e+05
SF_min [-]	15.805	36.277	8.9078

h=500m

	Steel	Wire	Polyester
X0 [m]	1411.9	1536.9	1661.5
delta_max [m]	137.5	137.5	92.5
T_max [N]	1.9175e+06	1.6367e+06	1.3842e+06
SF_min [-]	3.9615	5.4989	1.8061

h=1000m

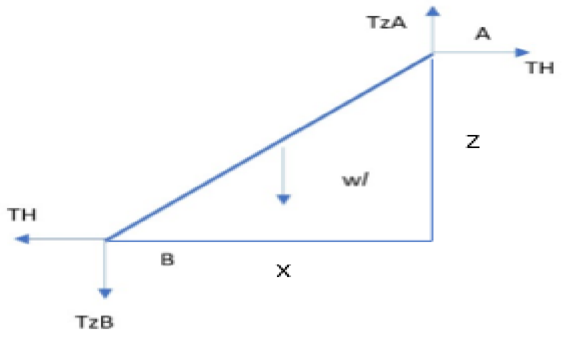
	Steel	Wire	Polyester
X0 [m]	2803	3050.7	3318.3
delta_max [m]	75	75	75
T_max [N]	2.4222e+06	9.7978e+05	7.5182e+05
SF_min [-]	3.136	9.1857	3.3253

The delta is determined around the starting displacement equal to that horizontal force, as mentioned in the catenary technique procedure. Furthermore, the following visuals might be made using Figure X and how the T fluctuates with X. With this information, a minimum safety factor of 1.8 was determined in order to determine the vessel's maximum horizontal motion. If the safety factor, T/CBS, reaches 1.8, the related delta of this T will be used as the delta maximum. If the delta achieves its greatest value in the range (for example, -30m to 30m) without falling below 1.8, the delta maximum will be the largest value of delta in the range. Finally, if the value for any delta in the interval is less than 1.8, the system cannot be employed.

Based on these tables and graphs, it is reasonable to deduce that any material might be used in a depth of 150m if just the force aspect is considered. If the cost of each is taken into account, the choice might be different.

The wire rope is the ideal choice for the 500m and 1000m distances since it has the highest minimum safety factor of any material. However, if the diameter of the polyester was larger, the findings at a water depth of 1000 m may be different. This is owing to the fact that the minimum safety factor would increase, as would the ship's maximum displacement.

Taut configuration



The equations below were used to solve the problem associated with this arrangement. It was assumed that the vertical force ranges between w*l and 5*w*l, where l is 3.5 times the depth of the water. The horizontal force for each condition was determined by calculating the equation below for the specified water depth and material.

$$Z = h = (Th/w) * (sqrt(1 + (Tza/Th)^2) - sqrt(1 + (Tzb/Th)^2)) + (Tza^2 - Tzb^2)/(2 * w * EA)$$

Where, Tza = Tz and Tzb = Tza – w*l and following the determination of Th, the total horizontal length (X) may be calculated using the equations below for each material and water depth.

$$X = (Th/w) * (asinh(Tza/Th) - asinh(Tzb/Th)) + Th * (Tza - Tzb)/(w * EA)$$

The approach for determining the relationship between delta and T and the maximum horizontal motion of the vessel is the same as for the catenary solution.

Results for Taut configuration:

The material created by adopting a diameter and the attributes indicated in the table are shown in the table following. Using the graphs that connect the horizontal force to the X, the horizontal distance between the anchor point and the fairlead for a particular horizontal steady force produced may be calculated. They were calculated using the formulae described in related to the method used and are displayed below for various water depths.

Material properties

	EA	w	CBS
Steel	9e+08	1875	7.596e+06
Wire	9e+08	430	9e+06
Polyester	6.5973e+07	67	2.5e+06

For h = 150m and Th = 80 kN

- Chain: X = 424 m
- Wire: X = 455 m
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For h = 500m and Th = 200 kN

- Chain: X = 1410 m
- Wire: X = 1540 m
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For h = 1000m and Th = 350 kN

- Chain: X = 2803 m
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For better analysis and explanation of the data obtained, plotted graphs are shown below.

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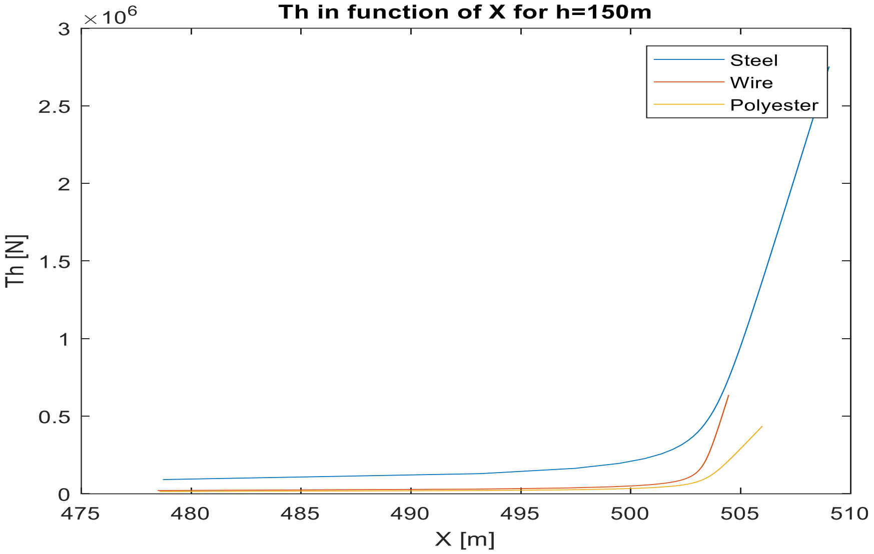
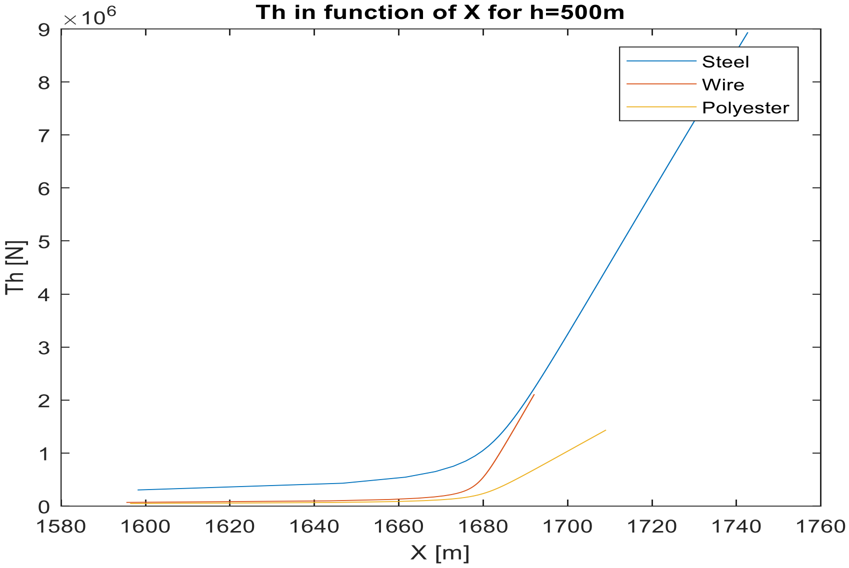
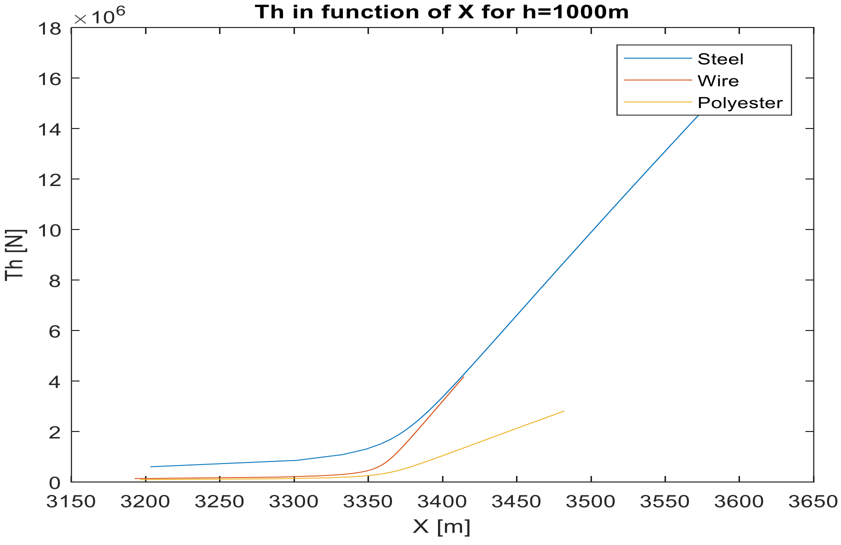
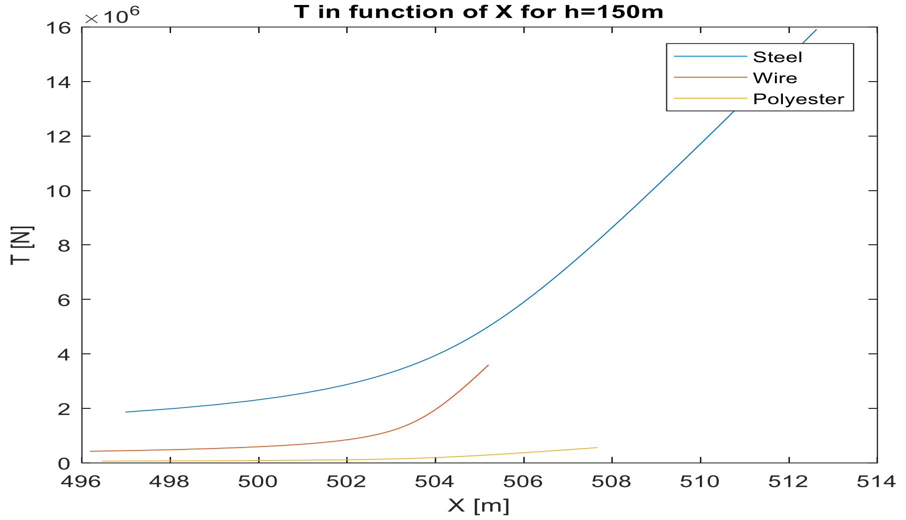
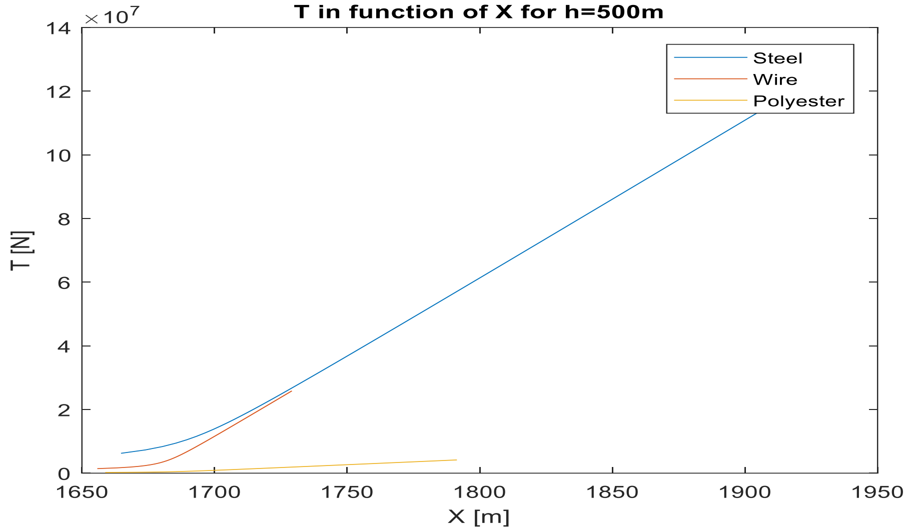


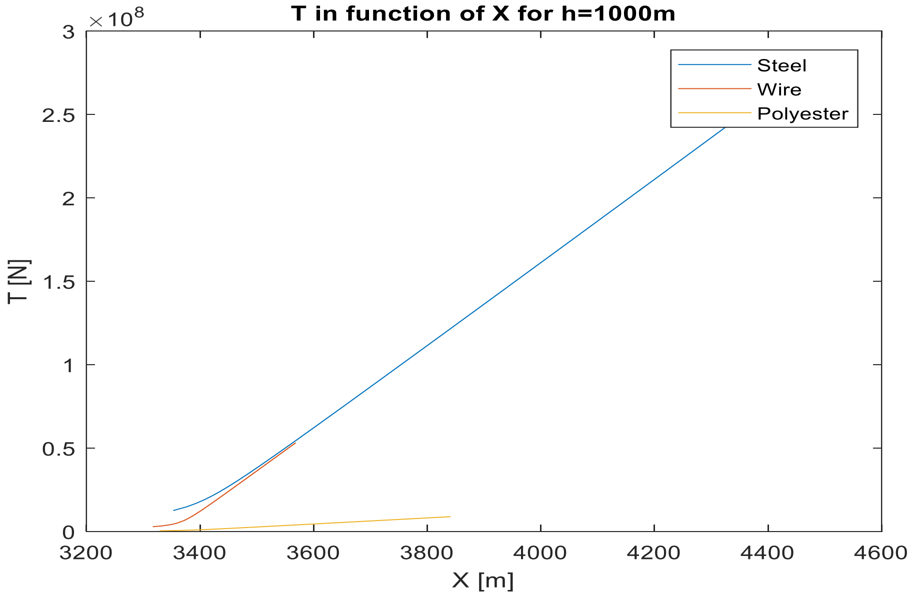




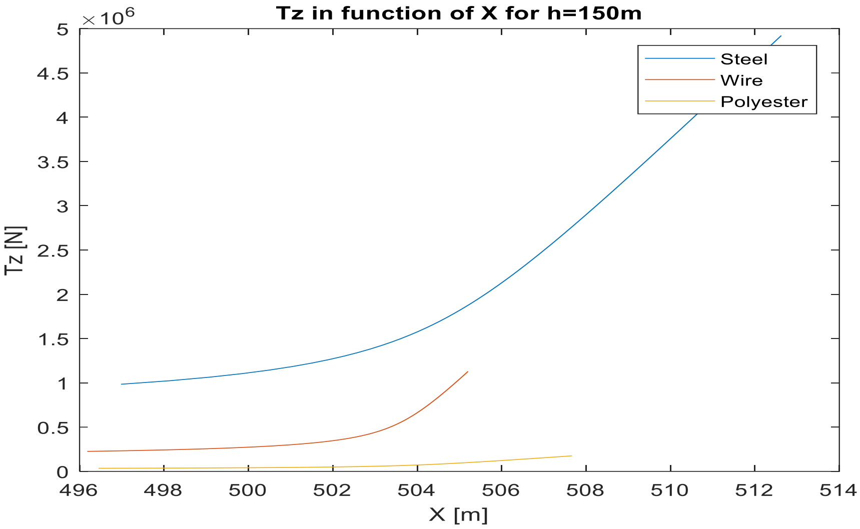
For T in function of X with differents water depth:

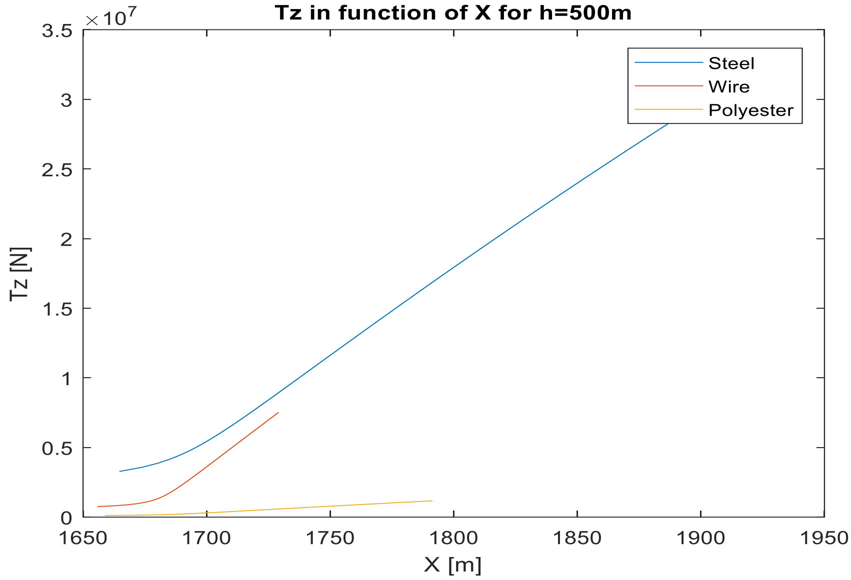


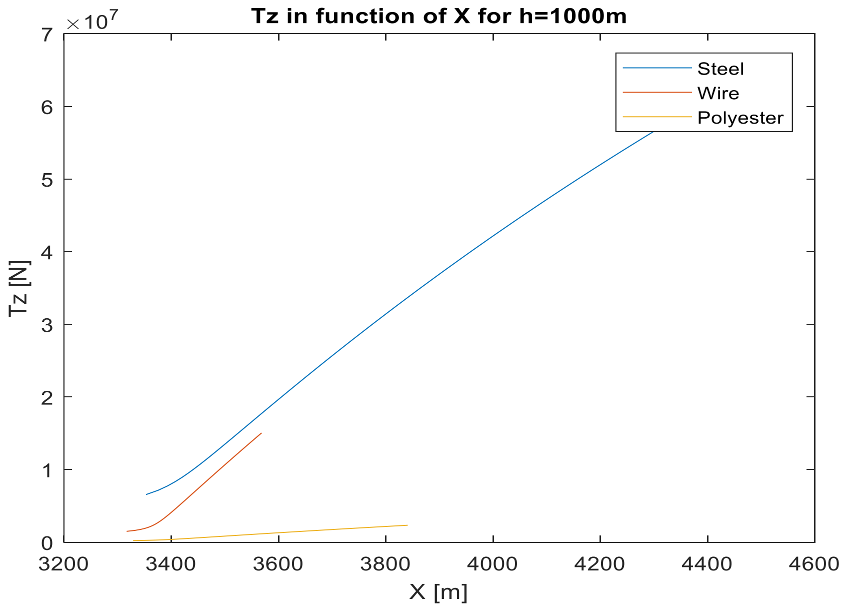




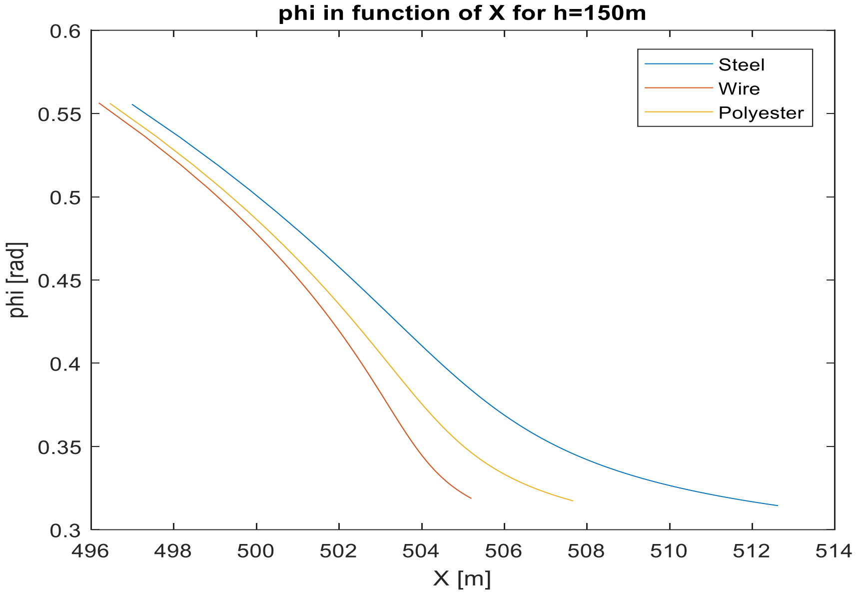
For Tz in function of X with differents water depth:

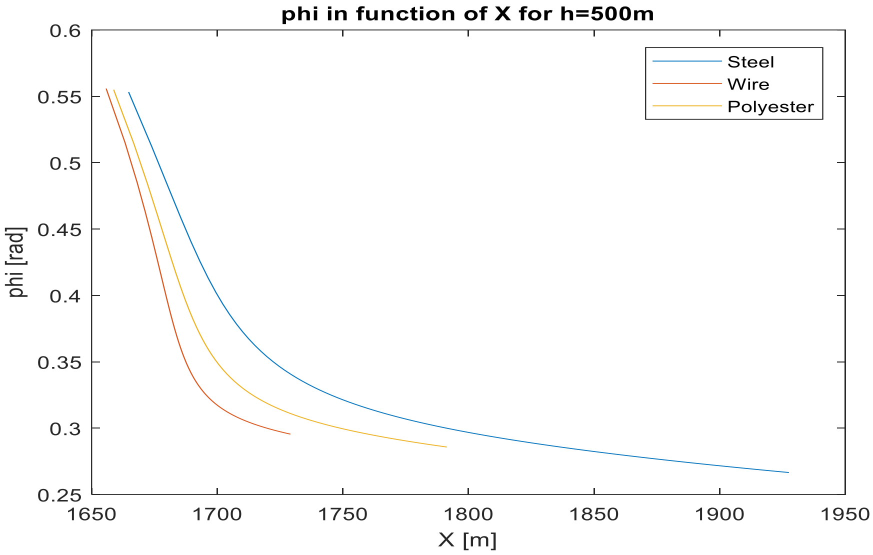


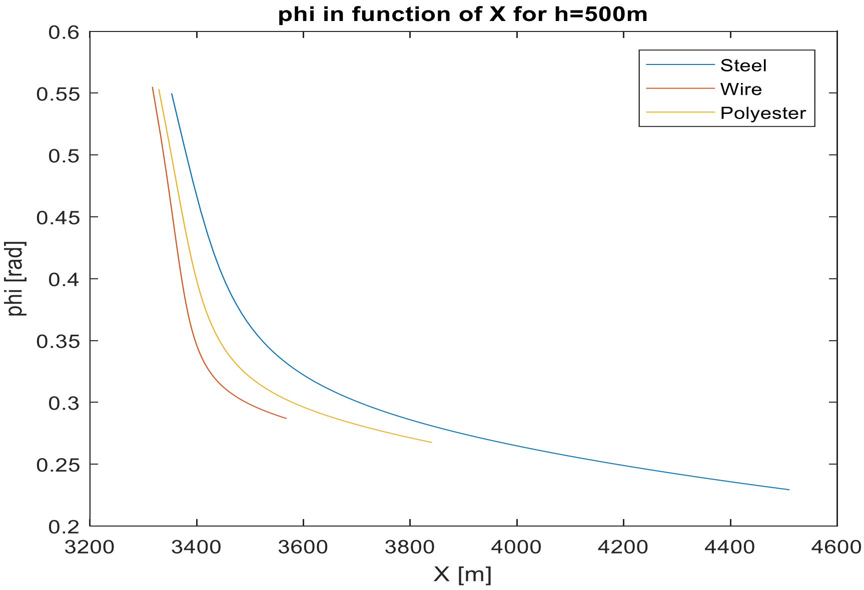




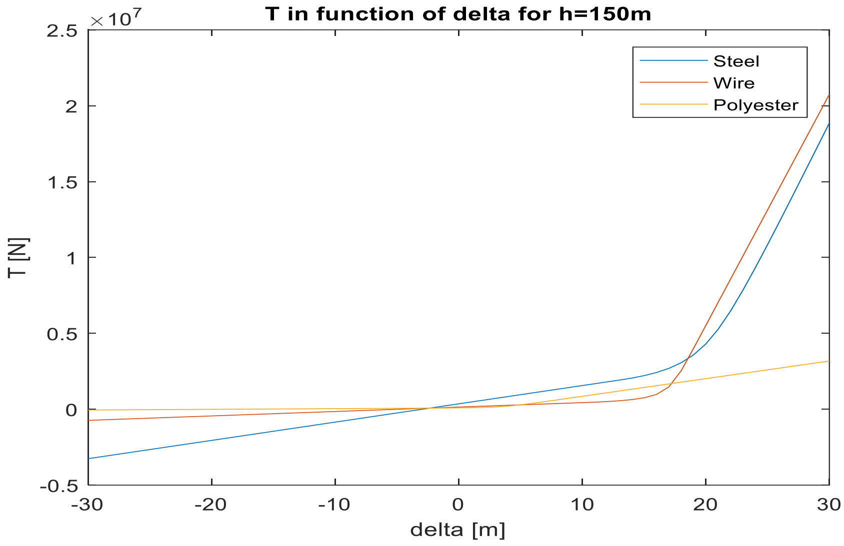
For Phi in function of X with differents water depth:

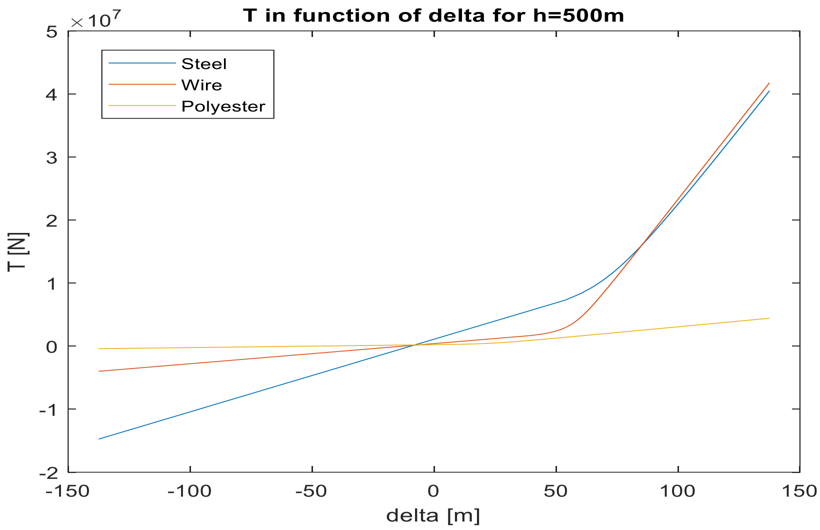


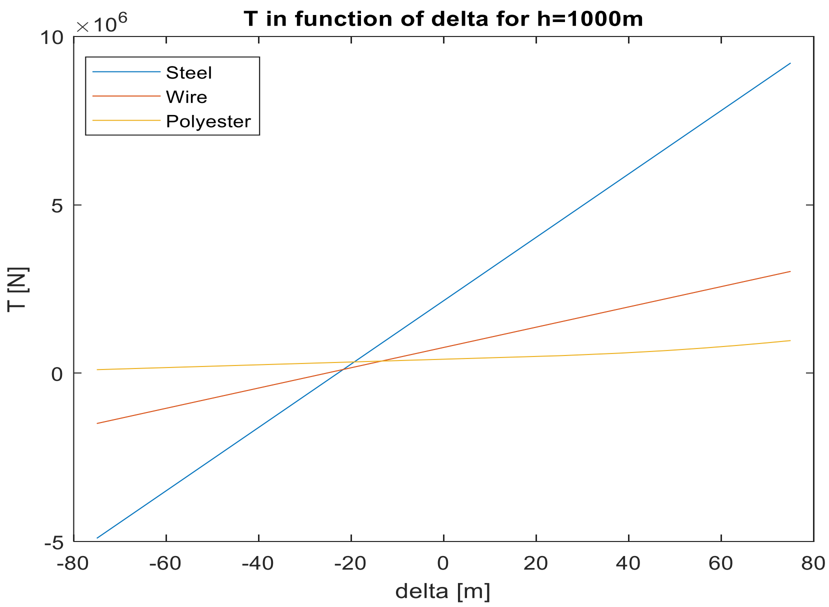




For T in function of delta with differents water depth:







The following tables show the impact in the choice of materials in the respective depths taking into account the main parameters calculated.

h=150m

	Steel	Wire	Polyester
X0 [m]	484.45	486.46	500.15
delta_max [m]	30	30	30
T_max [N]	1.8861e+07	2.0755e+07	3.1768e+06
SF_min [-]	0.40273	0.43362	0.78696

h=500m

	Steel	Wire	Polyester
X0 [m]	1620.1	1624	1661.1
delta_max [m]	137.5	137.5	137.5
T_max [N]	4.0495e+07	4.1769e+07	4.4223e+06
SF_min [-]	0.18758	0.21547	0.56532

h=1000m

	Steel	Wire	Polyester
X0 [m]	3242.3	3247.5	3321.7
delta_max [m]	75	75	75
T_max [N]	9.2097e+06	3.0234e+06	9.6976e+05
SF_min [-]	0.82478	2.9768	2.578

The delta is computed around the beginning displacement equivalent to that horizontal force, as specified in the section relating to the technique utilized. Furthermore, the following visuals might be made utilizing Figure above and how T fluctuates with X. With those information, the table above might be used to determine the vessel's maximum horizontal motion with the constraint of the safety factor being more than 1.8. If the safety factor is less than 1.8, the mooring system cannot be utilized in that depth of water with that material.

Some details in the graphs and table should be highlighted. To begin with, when a linear interpolation function was utilized, the tension in the wires tended to be negative. As a result, it follows the behavior of the curve for positive delta values and extrapolates this to negative ones. However, given the catenary solution, it is clear that T cannot be negative, because when the catenary curve finishes, the taut curve starts. As a result, the graph indicates significantly larger results than the true value and should only be evaluated for positive tension levels. Second, as can be seen, this taut arrangement can only be used at depths of 1000m with wire and polyester materials, as it is the only configuration with an SF greater than 1.8. As a result, in order to comply with the standard, the diameter of the cable must be changed for the other depth in order to satisfy the safety factor.

Conclusions

This preliminary design is an analysis of the feasibility of a proposed project or system. It tries to objectively and logically discover the strengths and weaknesses of a current business or new endeavor, the possibilities and challenges inherent in the natural surroundings, the resources necessary to carry out, and, finally, the chances for success. Since a result, the diameter of 100 mm for all materials in the catenary design appeared to be a good choice, as the safety factor adhered to the IACS criteria for all water depths.

Additionally, the findings suggest that in some circumstances, the safety factor may be reduced if it was greater than necessary. For instance, the chain diameter for a depth of 100 m. However, the same conclusions do not apply to the taut configuration since there was a circumstance where the safety regulation did not follow the rules. Furthermore, the safety factor found in this configuration demonstrates that the diameters were virtually the bare minimum required, as the safety factor was constantly close to 1.8. Thus, increasing the diameter would increase the CBS and thus enhance the safety of the mooring system.

References

1. Deepropemanual.pdf
2. Preliminarydesignofmooringsystems.pdf
3. Staticanalysisofacable.pdf
4. Handbookofoffshoreengineering.pdf
5. Task1solutionnotes.pdf
6. Material properties. https://www.tensiontech.com/papers/deep-mor/synthetic-fibre-yarn-properties-table-2

ANNEX

Main code

```
% Analysis of a mooring cable;
% Author: Davide Melozzi;
% ist1102230;
clc
clear variables

% Water depths
h=[150,500,1000]; %[meters]

% Wind Force
WF=[80,200,350]*10^3; %[N]

% Diameter of the Cable accordin to IACS
D=100; %[mm]

%% Step 1: Material properties
material=["steel","wire","Rope"];
AE=zeros(1,length(material)); %varies in row with D and collum with material
w=zeros(1,length(material));
breaking_str=zeros(1,length(material));
for i=1:length(material)
    [AE(i),w(i),breaking_str(i)] = Step1(material(i),D);
end
T_print = table(AE(:),w(:),breaking_str(:));
T_print.Properties.VariableNames = {'EA' 'w' 'CBS'};
T_print.Properties.RowNames = {'Steel';'Wire';'Polyester'};
disp('Material properties')
disp(T_print)
disp(' ')
%% Step 2.1: Finding X
Th=(1:100:1000)*10^3; %[N]

%water depth equal to 150m
X_150=zeros(length(Th),length(material));
T_150=zeros(length(Th),length(material));
Tz_150=zeros(length(Th),length(material));
phi_150=zeros(length(Th),length(material));

for j=1:length(material)
    for i=1:length(Th)
        [T_150(i,j),Tz_150(i,j),X_150(i,j),phi_150(i,j)]=Step21(AE(j),w(j),Th(i),h(1));
    end
end

figure
plot(X_150,T_150)
xlabel('X [m]')
ylabel('T [N]')
title('T in function of X for h=150m')
legend('Steel','Wire','Polyester')
disp('end')

figure
plot(X_150,Tz_150)
xlabel('X [m]')
ylabel('Tz [N]')
```

```
title('Tz in function of X for h=150m')
legend('Steel','Wire','Polyester')

figure
plot(X_150,Th)
xlabel('X [m]')
ylabel('Th [N]')
title('Th in function of X for h=150m')
legend('Steel','Wire','Polyester')

figure
plot(X_150,phi_150)
xlabel('X [m]')
ylabel('phi [rad]')
title('phi in function of X for h=150m')
legend('Steel','Wire','Polyester')

%water depth equal to 500m
X_500=zeros(length(Th),length(material));
T_500=zeros(length(Th),length(material));
Tz_500=zeros(length(Th),length(material));
phi_500=zeros(length(Th),length(material));

for j=1:length(material)
    for i=1:length(Th)
        [T_500(i,j),Tz_500(i,j),X_500(i,j),phi_500(i,j)]=Step21(AE(j),w(j),Th(i),h(2));
    end
end

figure
plot(X_500,T_500)
xlabel('X [m]')
ylabel('T [N]')
title('T in function of X for h=500m')
legend('Steel','Wire','Polyester')
disp('end')

figure
plot(X_500,Tz_500)
xlabel('X [m]')
ylabel('Tz [N]')
title('Tz in function of X for h=500m')
legend('Steel','Wire','Polyester')

figure
plot(X_500,Th)
xlabel('X [m]')
ylabel('Th [N]')
title('Th in function of X for h=500m')
legend('Steel','Wire','Polyester')

figure
plot(X_500,phi_500)
xlabel('X [m]')
ylabel('phi [rad]')
title('phi in function of X for h=500m')
legend('Steel','Wire','Polyester')
disp('end')

%water depth equal to 1000m
X_1000=zeros(length(Th),length(material));
```

```
T_1000=zeros(length(Th),length(material));
Tz_1000=zeros(length(Th),length(material));
phi_1000=zeros(length(Th),length(material));

for j=1:length(material)
    for i=1:length(Th)

[T_1000(i,j),Tz_1000(i,j),X_1000(i,j),phi_1000(i,j)]=Step21(AE(j),w(j),Th(i),h(3));
    end
end
figure
plot(X_1000,T_1000)
xlabel('X [m]')
ylabel('T [N]')
title('T in function of X for h=1000m')
legend('Steel','Wire','Polyester')
disp('end')

figure
plot(X_1000,Tz_1000)
xlabel('X [m]')
ylabel('Tz [N]')
title('Tz in function of X for h=1000m')
legend('Steel','Wire','Polyester')

figure
plot(X_1000,Th)
xlabel('X [m]')
ylabel('Th [N]')
title('Th in function of X for h=1000m')
legend('Steel','Wire','Polyester')

figure
plot(X_1000,phi_1000)
xlabel('X [m]')
ylabel('phi [rad]')
title('phi in function of X for h=500m')
legend('Steel','Wire','Polyester')
disp('end')


%% Step 2.2
Tz_anchor=zeros(length(h),length(material));
Th_anchor=zeros(length(h),length(material));
for i=1:length(h)
    for j=1:length(material)
        ls=3.5*h(i);
        Tz_anchor(i,j)=ls*w(j);
        if h(i)==150
            if Tz_anchor(i,j)>max(Tz_150(:,j))

X_anchor=interp1(Tz_150(:,j),X_150(:,j),Tz_anchor(i,j),'linear','extrap');
                Th_anchor(i,j)=interp1(X_150(:,j),Th(:),X_anchor,'linear','extrap');
            else
                X_anchor=interp1(Tz_150(:,j),X_150(:,j),Tz_anchor(i,j),'linear');
                Th_anchor(i,j)=interp1(X_150(:,j),Th(:),X_anchor,'linear');
            end
        elseif h(i)==500
            if Tz_anchor(i,j)>max(Tz_500(:,j))

X_anchor=interp1(Tz_500(:,j),X_500(:,j),Tz_anchor(i,j),'linear','extrap');
```

```
                Th_anchor(i,j)=interp1(X_500(:,j),Th(:),X_anchor,'linear','extrap');
            else
                X_anchor=interp1(Tz_500(:,j),X_500(:,j),Tz_anchor(i,j),'linear');
                Th_anchor(i,j)=interp1(X_500(:,j),Th(:),X_anchor,'linear');
            end
        else
            if Tz_anchor(i,j)>max(Tz_1000(:,j))

X_anchor=interp1(Tz_1000(:,j),X_1000(:,j),Tz_anchor(i,j),'linear','extrap');
                Th_anchor(i,j)=interp1(X_1000(:,j),Th(:),X_anchor,'linear','extrap');
            else
                X_anchor=interp1(Tz_1000(:,j),X_1000(:,j),Tz_anchor(i,j),'linear');
                Th_anchor(i,j)=interp1(X_1000(:,j),Th(:),X_anchor,'linear');
            end
        end
    end
end

disp(Th_anchor)
%% Step 3

%for h=150m
delta_150=(-0.2*h(1):1:0.2*h(1));
X0=interp1(Th,X_150,WF(1));
T_delta_150=zeros(length(delta_150),length(material));
for j=1:length(material)
    for i=1:length(delta_150)
        if X0(j)+delta_150(i)<min(X_150(j,:)) || X0(j)+delta_150(i)>max(X_150(j,:))
            [T_delta_150(i,j)] =
interp1(X_150(:,j),T_150(:,j),X0(j)+delta_150(i),'linear','extrap');
        else
            [T_delta_150(i,j)] = interp1(X_150(:,j),T_150(:,j),X0(j)+delta_150(i));
        end
    end
end

figure
plot(delta_150,T_delta_150)
xlabel('delta [m]')
ylabel('T [N]')
title('T in function of delta for h=150m')
legend('Steel','Wire','Polyester')

Delta_max=[0,0,0];
T_max=[0,0,0];
SF_min=[0,0,0];
for j=1:length(material)
    index = Safety_factor(breaking_str(j),T_delta_150(:,j));
    if index==0
        Delta_max(j)=delta_150(end);
        T_max(j)=T_delta_150(end,j);
        SF_min(j)=breaking_str(j)/T_delta_150(end,j);
    else
        Delta_max(j)=delta_150(index);
        T_max(j)=T_delta_150(index,j);
        SF_min(j)=breaking_str(j)/T_delta_150(index,j);
    end
end
T_print = table([X0(1);Delta_max(1);T_max(1);SF_min(1)],...
    [X0(2);Delta_max(2);T_max(2);SF_min(2)],...
    [X0(3);Delta_max(3);T_max(3);SF_min(3)]);
```

```
T_print.Properties.VariableNames = {'Steel';'Wire';'Polyester'};
T_print.Properties.RowNames = {'X0 [m]' 'delta_max [m]' 'T_max [N]' 'SF_min [-]'};
disp('h=150m')
disp(T_print)
disp(' ')


%for h=500m
delta_500=(-0.275*h(2):1:0.275*h(2));
X0=interp1(Th,X_500,WF(2));
T_delta_500=zeros(length(delta_500),length(material));
for j=1:length(material)
    for i=1:length(delta_500)
        if X0(j)+delta_500(i)<min(X_500(j,:)) || X0(j)+delta_500(i)>max(X_500(j,:))
            [T_delta_500(i,j)] =
interp1(X_500(:,j),T_500(:,j),X0(j)+delta_500(i),'linear','extrap');
        else
            [T_delta_500(i,j)] = interp1(X_500(:,j),T_500(:,j),X0(j)+delta_500(i));
        end
    end
end
figure
plot(delta_500,T_delta_500)
xlabel('delta [m]')
ylabel('T [N]')
title('T in function of delta for h=500m')
legend('Steel','Wire','Polyester')

Delta_max=[0,0,0];
T_max=[0,0,0];
SF_min=[0,0,0];
for j=1:length(material)
    index = Safety_factor(breaking_str(j),T_delta_500(:,j));
    if index==0
        Delta_max(j)=delta_500(end);
        T_max(j)=T_delta_500(end,j);
        SF_min(j)=breaking_str(j)/T_delta_500(end,j);
    else
        Delta_max(j)=delta_500(index);
        T_max(j)=T_delta_500(index,j);
        SF_min(j)=breaking_str(j)/T_delta_500(index,j);
    end
end
T_print = table([X0(1);Delta_max(1);T_max(1);SF_min(1)],...
    [X0(2);Delta_max(2);T_max(2);SF_min(2)],...
    [X0(3);Delta_max(3);T_max(3);SF_min(3)]);
T_print.Properties.VariableNames = {'Steel';'Wire';'Polyester'};
T_print.Properties.RowNames = {'X0 [m]' 'delta_max [m]' 'T_max [N]' 'SF_min [-]'};
disp('h=500m')
disp(T_print)
disp(' ')

%for h=1000m
delta_1000=(-0.075*h(3):1:0.075*h(3));
X0=interp1(Th,X_1000,WF(3));
T_delta_1000=zeros(length(delta_1000),length(material));
for j=1:length(material)
    for i=1:length(delta_1000)
        if X0(j)+delta_1000(i)<min(X_1000(:,j)) || X0(j)+delta_1000(i)>max(X_1000(:,j))
            [T_delta_1000(i,j)] =
interp1(X_1000(:,j),T_1000(:,j),X0(j)+delta_1000(i),'linear','extrap');
```

```
        else
            [T_delta_1000(i,j)] = interp1(X_1000(:,j),T_1000(:,j),X0(j)+delta_1000(i));
        end
    end
end
figure
plot(delta_1000,T_delta_1000)
xlabel('delta [m]')
ylabel('T [N]')
title('T in function of delta for h=1000m')
legend('Steel','Wire','Polyester')

Delta_max=[0,0,0];
T_max=[0,0,0];
SF_min=[0,0,0];
for j=1:length(material)
    index = Safety_factor(breaking_str(j),T_delta_1000(:,j));
    if index==0
        Delta_max(j)=delta_1000(end);
        T_max(j)=T_delta_1000(end,j);
        SF_min(j)=breaking_str(j)/T_delta_1000(end,j);
    else
        Delta_max(j)=delta_1000(index);
        T_max(j)=T_delta_1000(index,j);
        SF_min(j)=breaking_str(j)/T_delta_1000(index,j);
    end
end
T_print = table([X0(1);Delta_max(1);T_max(1);SF_min(1)],...
    [X0(2);Delta_max(2);T_max(2);SF_min(2)],...
    [X0(3);Delta_max(3);T_max(3);SF_min(3)]);
T_print.Properties.VariableNames = {'Steel';'Wire';'Polyester'};
T_print.Properties.RowNames = {'X0 [m]' 'delta_max [m]' 'T_max [N]' 'SF_min [-]'};
disp('h=1000m')
disp(T_print)
disp(' ')
```

Taut

```
clc
clear variables
close all

% Water depths
h=[150,500,1000]; %[meters]

% Wind Force
WF=[80,200,350]*10^3; %[N]

% Diameter of the Cable accordin to IACS
D=[100,100,100]; %[mm]

%% Step 1: Material properties
material=["steel","wire","Rope"];
AE=zeros(1,length(material)); %varies in row with D and collum with material
w=zeros(1,length(material));
breaking_str=zeros(1,length(material));
for i=1:length(material)
    [AE(i),w(i),breaking_str(i)] = Step1(material(i),D(i));
end
```

```
T_print = table(AE(:),w(:),breaking_str(:));
T_print.Properties.VariableNames = {'EA' 'w' 'CBS'};
T_print.Properties.RowNames = {'Steel';'Wire';'Polyester'};
disp('Material properties')
disp(T_print)
disp(' ')
%% Step 2

%for h=150 m
disp('1')
Tz_150=zeros(100,3); %[N]
Tz_150(:,1)=linspace(w(1)*3.5*h(1),w(1)*5*3.5*h(1));
Tz_150(:,2)=linspace(w(2)*3.5*h(1),w(2)*5*3.5*h(1));
Tz_150(:,3)=linspace(w(3)*3.5*h(1),w(3)*5*3.5*h(1));
Th_150=zeros(100,3); %[N]
X_150=zeros(100,3); %[m]
for j=1:length(material)
    for i=1:length(Tz_150)
        [Th_150(i,j)] = find_Th_taut(AE(j),w(j),Tz_150(i,j),h(1));
        [X_150(i,j)] = find_X_taut(AE(j),w(j),Th_150(i,j),Tz_150(i,j),h(1));
    end
end
disp('1')
T_150=sqrt(Th_150.^2+Tz_150.^2);
phi_150=atan(Tz_150./Th_150);

figure
plot(X_150,T_150)
xlabel('X [m]')
ylabel('T [N]')
title('T in function of X for h=150m')
legend('Steel','Wire','Polyester')
disp('end')

figure
plot(X_150,Tz_150)
xlabel('X [m]')
ylabel('Tz [N]')
title('Tz in function of X for h=150m')
legend('Steel','Wire','Polyester')

figure
plot(X_150,Th_150)
xlabel('X [m]')
ylabel('Th [N]')
title('Th in function of X for h=150m')
legend('Steel','Wire','Polyester')

figure
plot(X_150,phi_150)
xlabel('X [m]')
ylabel('phi [rad]')
title('phi in function of X for h=150m')
legend('Steel','Wire','Polyester')

%for h=500 m
Tz_500=zeros(100,3); %[N]
Tz_500(:,1)=linspace(w(1)*3.5*h(2),w(1)*10*3.5*h(2));
Tz_500(:,2)=linspace(w(2)*3.5*h(2),w(2)*10*3.5*h(2));
Tz_500(:,3)=linspace(w(3)*3.5*h(2),w(3)*10*3.5*h(2));
Th_500=zeros(100,3); %[N]
```

```
X_500=zeros(100,3); %[m]
disp('1')
for j=1:length(material)
    for i=1:length(Tz_500)
        [Th_500(i,j)] = find_Th_taut(AE(j),w(j),Tz_500(i,j),h(2));
        [X_500(i,j)] = find_X_taut(AE(j),w(j),Th_500(i,j),Tz_500(i,j),h(2));
    end
end
disp('1')
T_500=sqrt(Th_500.^2+Tz_500.^2);
phi_500=atan(Tz_500./Th_500);

figure
plot(X_500,T_500)
xlabel('X [m]')
ylabel('T [N]')
title('T in function of X for h=500m')
legend('Steel','Wire','Polyester')
disp('end')

figure
plot(X_500,Tz_500)
xlabel('X [m]')
ylabel('Tz [N]')
title('Tz in function of X for h=500m')
legend('Steel','Wire','Polyester')

figure
plot(X_500,Th_500)
xlabel('X [m]')
ylabel('Th [N]')
title('Th in function of X for h=500m')
legend('Steel','Wire','Polyester')

figure
plot(X_500,phi_500)
xlabel('X [m]')
ylabel('phi [rad]')
title('phi in function of X for h=500m')
legend('Steel','Wire','Polyester')
disp('end')

%for h=1000 m
Tz_1000=zeros(100,3); %[N]
Tz_1000(:,1)=linspace(w(1)*3.5*h(3),w(1)*10*3.5*h(3));
Tz_1000(:,2)=linspace(w(2)*3.5*h(3),w(2)*10*3.5*h(3));
Tz_1000(:,3)=linspace(w(3)*3.5*h(3),w(3)*10*3.5*h(3));
Th_1000=zeros(100,3); %[N]
X_1000=zeros(100,3); %[m]
disp('1')

for j=1:length(material)
    for i=1:length(Tz_1000)
        [Th_1000(i,j)] = find_Th_taut(AE(j),w(j),Tz_1000(i,j),h(3));
        [X_1000(i,j)] = find_X_taut(AE(j),w(j),Th_1000(i,j),Tz_1000(i,j),h(3));
    end
end
disp('1')
T_1000=sqrt(Th_1000.^2+Tz_1000.^2);
phi_1000=atan(Tz_1000./Th_1000);
```

```
figure
plot(X_1000,T_1000)
xlabel('X [m]')
ylabel('T [N]')
title('T in function of X for h=1000m')
legend('Steel','Wire','Polyester')
disp('end')

figure
plot(X_1000,Tz_1000)
xlabel('X [m]')
ylabel('Tz [N]')
title('Tz in function of X for h=1000m')
legend('Steel','Wire','Polyester')

figure
plot(X_1000,Th_1000)
xlabel('X [m]')
ylabel('Th [N]')
title('Th in function of X for h=1000m')
legend('Steel','Wire','Polyester')

figure
plot(X_1000,phi_1000)
xlabel('X [m]')
ylabel('phi [rad]')
title('phi in function of X for h=500m')
legend('Steel','Wire','Polyester')
disp('end')
%% Step 3
%for h=150m
delta_150=(-0.2*h(1):1:0.2*h(1));
X0=[0 0 0];
T_delta_150=zeros(length(delta_150),length(material));
for j=1:length(material)
    if WF(1)<min(Th_150(:,j)) || WF(1)>max(Th_150(:,j))
            X0(j)=interp1(Th_150(:,j),X_150(:,j),WF(1),'linear','extrap');
        else
            X0(j)=interp1(Th_150(:,j),X_150(:,j),WF(1));
    end
    for i=1:length(delta_150)
        if X0(j)+delta_150(i)<min(X_150(:,j)) || X0(j)+delta_150(i)>max(X_150(:,j))
            [T_delta_150(i,j)] =
interp1(X_150(:,j),T_150(:,j),X0(j)+delta_150(i),'linear','extrap');
        else
            [T_delta_150(i,j)] = interp1(X_150(:,j),T_150(:,j),X0(j)+delta_150(i));
        end
    end
end

figure
plot(delta_150,T_delta_150)
xlabel('delta [m]')
ylabel('T [N]')
title('T in function of delta for h=150m')
legend('Steel','Wire','Polyester')

Delta_max=[0,0,0];
T_max=[0,0,0];
SF_min=[0,0,0];
for j=1:length(material)
```

```
    index = Safety_factor(breaking_str(j),T_delta_150(:,j));
    if index==0
        Delta_max(j)=delta_150(end);
        T_max(j)=T_delta_150(end,j);
        SF_min(j)=breaking_str(j)/T_delta_150(end,j);
    else
        Delta_max(j)=delta_150(index);
        T_max(j)=T_delta_150(index,j);
        SF_min(j)=breaking_str(j)/T_delta_150(index,j);
    end
end
T_print = table([X0(1);Delta_max(1);T_max(1);SF_min(1)],...
    [X0(2);Delta_max(2);T_max(2);SF_min(2)],...
    [X0(3);Delta_max(3);T_max(3);SF_min(3)]);
T_print.Properties.VariableNames = {'Steel';'Wire';'Polyester'};
T_print.Properties.RowNames = {'X0 [m]' 'delta_max [m]' 'T_max [N]' 'SF_min [-]'};
disp('h=150m')
disp(T_print)
disp(' ')


%for h=500m
delta_500=(-0.275*h(2):1:0.275*h(2));
X0=[0 0 0];
T_delta_500=zeros(length(delta_500),length(material));
for j=1:length(material)
    if WF(2)<min(Th_500(:,j)) || WF(2)>max(Th_500(:,j))
            X0(j)=interp1(Th_500(:,j),X_500(:,j),WF(2),'linear','extrap');
        else
            X0(j)=interp1(Th_500(:,j),X_500(:,j),WF(2));
    end
    for i=1:length(delta_500)
        if X0(j)+delta_500(i)<min(X_500(:,j)) || X0(j)+delta_500(i)>max(X_500(:,j))
            [T_delta_500(i,j)] =
interp1(X_500(:,j),T_500(:,j),X0(j)+delta_500(i),'linear','extrap');
        else
            [T_delta_500(i,j)] = interp1(X_500(:,j),T_500(:,j),X0(j)+delta_500(i));
        end
    end
end
figure
plot(delta_500,T_delta_500)
xlabel('delta [m]')
ylabel('T [N]')
title('T in function of delta for h=500m')
legend('Steel','Wire','Polyester')

Delta_max=[0,0,0];
T_max=[0,0,0];
SF_min=[0,0,0];
for j=1:length(material)
    index = Safety_factor(breaking_str(j),T_delta_500(:,j));
    if index==0
        Delta_max(j)=delta_500(end);
        T_max(j)=T_delta_500(end,j);
        SF_min(j)=breaking_str(j)/T_delta_500(end,j);
    else
        Delta_max(j)=delta_500(index);
        T_max(j)=T_delta_500(index,j);
        SF_min(j)=breaking_str(j)/T_delta_500(index,j);
    end
```

```
end
T_print = table([X0(1);Delta_max(1);T_max(1);SF_min(1)],...
    [X0(2);Delta_max(2);T_max(2);SF_min(2)],...
    [X0(3);Delta_max(3);T_max(3);SF_min(3)]);
T_print.Properties.VariableNames = {'Steel';'Wire';'Polyester'};
T_print.Properties.RowNames = {'X0 [m]' 'delta_max [m]' 'T_max [N]' 'SF_min [-]'};
disp('h=500m')
disp(T_print)
disp(' ')

%for h=1000m
delta_1000=(-0.075*h(3):1:0.075*h(3));
X0=[0 0 0];
X0(1)=interp1(Th_1000(:,1),X_1000(:,1),WF(3));
X0(2)=interp1(Th_1000(:,2),X_1000(:,2),WF(3));
X0(3)=interp1(Th_1000(:,3),X_1000(:,3),WF(3));
T_delta_1000=zeros(length(delta_1000),length(material));
for j=1:length(material)
    if WF(3)<min(Th_1000(:,j)) || WF(3)>max(Th_1000(:,j))
            X0(j)=interp1(Th_1000(:,j),X_1000(:,j),WF(3),'linear','extrap');
        else
            X0(j)=interp1(Th_1000(:,j),X_1000(:,j),WF(3));
    end
    for i=1:length(delta_1000)
        if X0(j)+delta_1000(i)<min(X_1000(:,j)) || X0(j)+delta_1000(i)>max(X_1000(:,j))
            [T_delta_1000(i,j)] =
interp1(X_1000(:,j),T_1000(:,j),X0(j)+delta_1000(i),'linear','extrap');
        else
            [T_delta_1000(i,j)] = interp1(X_1000(:,j),T_1000(:,j),X0(j)+delta_1000(i));
        end
    end
end
figure
plot(delta_1000,T_delta_1000)
xlabel('delta [m]')
ylabel('T [N]')
title('T in function of delta for h=1000m')
legend('Steel','Wire','Polyester')

Delta_max=[0,0,0];
T_max=[0,0,0];
SF_min=[0,0,0];
for j=1:length(material)
    index = Safety_factor(breaking_str(j),T_delta_1000(:,j));
    if index==0
        Delta_max(j)=delta_1000(end);
        T_max(j)=T_delta_1000(end,j);
        SF_min(j)=breaking_str(j)/T_delta_1000(end,j);
    else
        Delta_max(j)=delta_1000(index);
        T_max(j)=T_delta_1000(index,j);
        SF_min(j)=breaking_str(j)/T_delta_1000(index,j);
    end
end
T_print = table([X0(1);Delta_max(1);T_max(1);SF_min(1)],...
    [X0(2);Delta_max(2);T_max(2);SF_min(2)],...
    [X0(3);Delta_max(3);T_max(3);SF_min(3)]);
T_print.Properties.VariableNames = {'Steel';'Wire';'Polyester'};
T_print.Properties.RowNames = {'X0 [m]' 'delta_max [m]' 'T_max [N]' 'SF_min [-]'};
disp('h=1000m')
disp(T_print)
```

```
disp(' ')


function [X] = find_X_taut(AE,w,Th,Tz,h)
l=3.5*h;
Tza=Tz;
Tzb=Tza-w*l;
X=(Th/w)*(asinh(Tza/Th)-asinh(Tzb/Th))+Th*(Tza-Tzb)/(w*AE);
end
function [Th] = find_Th_taut(AE,w,Tz,h)
l=3.5*h;
Tza=Tz;
Tzb=Tza-w*l;
syms Th
eq=h==(Th/w)*(sqrt(1+(Tza/Th)^2)-sqrt(1+(Tzb/Th)^2))+(Tza^2-Tzb^2)/(2*w*AE);
sol=solve(eq);
Th=double(sol); Th(Th<0)=[];
end
```

Safety factor

```
function [index] = Safety_factor(CBS,T)
SF=1.8;
for i=1:length(T)
    if SF>CBS/T(i)
        index=i-1;
        break
    else
        index=0;
    end
end
end
```