Static Towing Assembly Guidelines (STAG)

(First edition 2020)

Issued by the

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First edition April 2020

The Oil Companies International Marine Forum (OCIMF)
Vision: A global marine industry that causes no harm to people or the environment.

Mission: To lead the global marine industry in the promotion of safe and environmentally responsible transportation of crude oil, oil products, petrochemicals and gas, and to drive the same values in the management of related offshore marine operations.

We do this by developing best practices in the design, construction and safe operation of tankers, barges and offshore vessels and their interfaces with terminals and considering human factors in everything we do.

Contents

Glossary

Catenary The downward curve in a towline between a tug and a tanker naturally formed by its own weight.

Coupled mooring analysis A mooring analysis that takes into account the interactions between the tug and tanker and the towline, so that the vessel motions are influenced by the non-linear behaviour of the towline.

Cyclic loading The continuous and repeated application of a load on a towing assembly.

Elongation The total extension (elastic and plastic) of a line.

Grommet A continuous loop formed by splicing together the ends of a length of rope.

Hard eye Thimble as part of the assembly to protect the wire or fibre.

Lay length The length along the axis of a rope in which a strand makes one complete spiral around the rope axis.

Minimum Breaking Load (MBL) The minimum force at which a new line or component, will break when tested.

Proof load defined as the maximum tensile force that can be applied that will not result in deformation

Residual strength testing Testing to destruction a sample length of line that has been in use, in order to determine its current breaking load.

Shock load A sudden and significant increase in the load on a towing assembly.

Soft eye Loop of rope without the support of a thimble.

Stiffness The rigidity of the line and its ability to resist deformation.

Working Load Limit (WLL) The maximum load that a component should be subjected to in operational service, calculated from the limiting environmental criteria.

Abbreviations

ASD	Azimuth Stern Drive
D/d	Diameter of bend divided by diameter of line
F(P)SO	Floating (Production) Storage and Offloading facility
GOTO	Guidelines to Offshore Tanker Operations
HMPE	High Modulus Polyethylene
HMSF	High Modulus Synthetic Fibre
IWRC	Independent Wire Rope Core
MBL	Minimum Breaking Load
OEM	Original Equipment Manufacturer
SPM	Single Point Mooring
UV	Ultraviolet
WLL	Working Load Limit

Bibliography

CI-2001-04: Fibre Rope Inspection and Retirement Criteria (Cordage Institute)

CI-1500-02: Test Methods for Fibre Rope (Cordage Institute)

Guidelines for Offshore Tanker Operations (GOTO) (OCIMF)

Mooring Equipment Guidelines (MEG4) (OCIMF)

1 Introduction

1.1 Purpose and scope

This information paper supplements the OCIMF publication *Guidelines to Offshore Tanker Operations* (GOTO) and should be read along with the relevant guidance for static towing operations.

The purpose of this information paper is to provide technical guidance on selecting fit for purpose towing assemblies that minimise risk of injury to crew members or damage to equipment, and to optimise the effectiveness of static towing operations.

This paper discusses the technical factors that tug operators should consider, in collaboration with terminal operators, when selecting the components of towing assemblies for static towing operations at both Single Point Mooring (SPM) and Floating (Production) Storage and Offloading (F(P)SO) terminals.

The recommendations in this information paper come from extensive industry data gathering and a technical study. This study had pre-determined inputs, which do not represent all the variables found in static towing operations. Variables include tug size, constant pull or on-demand pull, tanker size, equipment specifications and environmental conditions. Therefore, it is recommended that operators carry out their own due diligence when designing a towing assembly.

OCIMF does not recommend using ship's lines in static towing operations. This information paper's guidance applies to dedicated, fit-for-purpose towing assemblies.

There is no international standard or, until now, any industry best practice guidance on static towing assemblies. Assembly configurations and compositions vary considerably across the industry and are usually selected based on operational experience. However, existing static towing assembly designs are rarely supported by technical studies.

1.2 Static towing philosophy

Static towing is an operation that aims to safeguard offshore F(P)SO and SPM terminals against physical contact from visiting tankers. The scope of these operations is detailed in the relevant sections of GOTO. Tug operators performing static towing should have a formal process in place for conducting safety risk assessments. Refer to GOTO section 10 for detailed guidance on risk management during static towing operations.

Figure 1.1: *Tandem static towing operations*

Industry studies have concluded that static towing operations at offshore terminals should be conducted over the bow wherever possible. Where static towing operations are conducted over the stern, tug masters and mooring masters should have a clear understanding of the conditions that could cause girting of the tug and the actions required to mitigate such risk (see section 5 below).

Towline assemblies for static towing operations should be designed bearing in mind the characteristics of the selected tug, the towing method, the dimensions and equipment fitted to the tankers to be assisted, the expected environmental conditions at the terminal and any specific aspects of the location, such as limited swing room etc.

2 Towline assemblies

2.1 Composition and configuration

Towline assemblies consist of a main towline, a pennant and may also include a stretcher. The main towline is installed on the tug's winch with the pennant connected to the free end of the towline. This is passed to the tanker to be towed. If fitted, the stretcher is placed between the main towline and the pennant.

Main towlines are deployed from the tug's winch on the bow or main deck, depending on the tug's design. Towlines can be constructed of steel wire or synthetic fibre.

Towing pennants are short lengths of wire rope or synthetic line used to prevent damage to the main towline, where it is made fast on the assisted tanker's stern.

A stretcher is a heavy-duty hawser. It is also referred to as a shock line or towing spring. A stretcher may comprise of a single leg or grommet (doubled length), of synthetic line with high strength and elasticity. The purpose of a stretcher is to reduce the dynamic loading caused by wind waves and swell, protecting the assembly from high shock loads and fatigue.

The components of the towline assembly can be joined together using either hard (steel or alloy) or soft (synthetic line) shackles. Synthetic lines can also be directly spliced eye to eye or joined by a cow-hitch or a soft shackle.

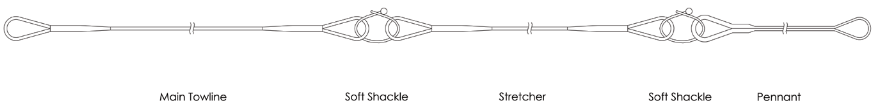


Figure 2.1a: *Synthetic towline assembly*

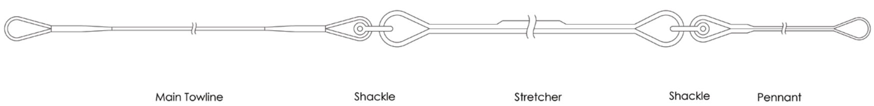


Figure 2.1b: *Wire towline assembly*

As shown in figure 2.1, a single leg or a grommet stretcher can be used in either synthetic or wire towline assemblies.

The relative motions between the tanker and tug vary, according to the towing assembly design. A coupled mooring analysis in which the vessels relative motion and towline tensions are calculated simultaneously should be used to evaluate the performance and the maximum dynamic peak load at the limiting conditions.

2.2 Main towlines

Main towlines can be made from either steel wire rope or High Modulus Synthetic Fibre (HMSF). The strength (Minimum Breaking Load (MBL)) of both types is typically 3 times the bollard-pull of the tug. The tow assembly should be designed so that the maximum peak load does not exceed 50% of the MBL of the main tow line.

2.2.1 Steel wire ropes

Steel wire ropes have high tensile strength, durability and rigidity. A typical steel wire towline is made of high quality, preformed, galvanised drawn wire, and formed in a 6 x 36 Independent

Wire Rope Core (IWRC) construction. Although capable of enduring high tensions and repetitive contact with poor surface conditions, wire towlines do have several drawbacks. Their weight makes them difficult to handle and broken wires can cause hand injuries. They require regular lubrication and can damage deck hardware, such as chocks and fairleads.

2.2.2 Synthetic lines

HMSF is often used as an alternative to steel wire and has grown in popularity because of its comparable strength, with the added advantage of its light weight and ease of handling. Because HMSF lines generally have similar strength and elongation to steel wire of similar diameters, they can be used interchangeably with little modification to the towing vessels winch equipment. However, a thorough management of change process should be followed. The most critical factors in maintaining safe working conditions for HMSF lines include minimising abrasion damage and preventing permanent twist from developing in the line.

Synthetic lines can be jacketed or non-jacketed. Jackets made from materials other than HMSF are not recommended. Non-jacketed lines provide flexible handling and, are easier to inspect and splice but they are more vulnerable to abrasion. Jacketed lines are less flexible, are more difficult to inspect and splice but offer more resistance to abrasion and contamination by, for example, oil and grease or rust particles. Jacketed lines also have better spooling performance on winches.

2.2.3 Selecting towlines

When determining the suitability of a line for a static towing operation, many factors need to be considered. Even in calm water the actual loads on the towline can greatly exceed the bollard pull of the tug. Towlines connected to large tankers must exert significant forces to safely control them. When one end of the towline assembly pulls away from the assisted vessel, the line stretches and the tension increases, absorbing kinetic energy and slowing the movement. During this slowing, the line is subject not only to the displacement of the tanker, but also the force required to decelerate the movement or momentum. By spreading out this deceleration over a larger distance or longer time, high peak loads or shock loads can be significantly reduced.

To avoid high peak loads in the towing assembly, include a stretcher or increase the length of the towline. Due to their weight, wire ropes benefit more from the catenary effect of a longer tow line. However, due to the wires weight and when operating in shallow waters, there is a risk of the towline coming in to contact with the seabed (piping) if the tug loses position and during deployment and retrieval of the towline.

A coupled mooring analysis is recommended for the specific towing vessel, tanker and weather conditions as shown in the technical study report in Appendix A. This study shows that tow line lengths of 200m can be used in sea conditions up to 1.5m significant height. For higher sea states, increase the towline length further, or include a stretcher.

Line strength ratings are the maximum load or force they can withstand without failure. However, HMSF lines need to be selected carefully, since they can degrade quickly if continuously loaded from 0 to 50% of the MBL. It is therefore recommended to add a stretcher to reduce the amplitude of this load cycle for waves above 1.5m significant height.

2.3 Stretchers

A stretcher is a short length, typically 20m, of relatively elastic line. It is built into a towline assembly that includes a low extension wire rope or HMSF towline to help absorb the shock loads and thus reduce peak loads in the assembly. A stretcher can be a single line with an eye at each end or it can be a grommet. If hard shackles are used as connectors, the stretcher should be fitted with thimbles on both eyes to reduce damage and maintain an adequate D/d ratio. The shackles connected must fit the thimbles.

Whether a stretcher is needed depends on the towline length and environmental conditions.

It is good practice to select a stretcher with similar strength (MBL) to the main towline.

2.3.1 Stretcher stiffness

Stiffness is influenced by:

- Material.
- Length.
- Stretcher configuration (grommet v single leg).
- Frequency/period of motion (dynamic stiffness).
- Length of eye.
- Length of splice.
- Rope construction.
- Rope MBL.

The optimal stiffness depends on wave conditions and the stiffness of the main towline. The stiffness characteristics of the different materials are shown in figure 2.2.

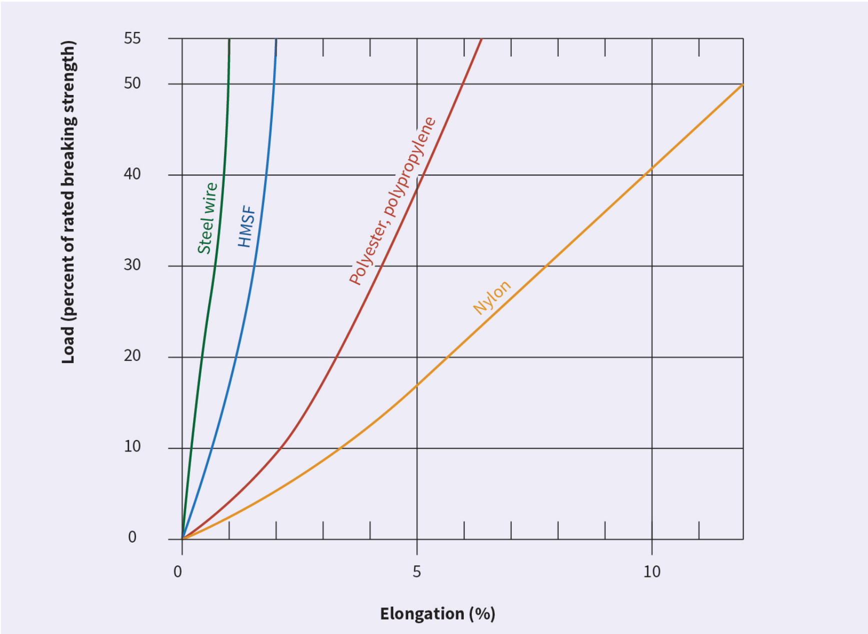


Figure 2.2: *Typical load/extension stiffness characteristics of wire and synthetic fibre lines*

HMSF lines and steel wire lines, which both have an elongation of around 2-3% are not suitable as stretchers, because the near vertical load elongation curve can result in very high shock loads. A stretcher material with elongation (>10%) at the MBL is most effective.

Lines with high elongation, such as nylon lines, have several advantages and disadvantages when compared to less elastic lines such as those made of polyester. A higher elongation lowers the peak load on the line itself, which in turn lowers the risk of breakage on the entire towline assembly and effectively reduces the fall rate of the margin of safety. This lower peak load also causes less stress on the connection system, which means that the deformation or failure of other hardware, such as shackles, bitts and fairleads, is less likely. The disadvantages can include less control of the payload position, especially when coupled with render recovery towing winches, and a high level of stored energy within the line, resulting in high recoil rates if there is a component failure in the system.

As per the MARIN study in appendix A, if a 20m nylon stretcher is used, the tug can maintain its 200m towline in up to 2.5m significant wave height and only needs to increase the deployed towline length for sea conditions above that.

2.4 Pennants

Pennants are used to avoid excessive wear on the main towline or stretcher and provide ease of handling for the tanker's crew. Pennants are fitted with a large, soft eye at the free end, which makes it easier for the tanker's crew to handle and provides safer connection and disconnection of the tow.

Because the towing pennant is made fast on board the assisted tanker through a fairlead, it is more likely to suffer from wear and mechanical damage than other components. Pennants are easily replaced and there should be a replacement strategy in place.

In general, wire pennants should be selected for wire towlines and synthetic pennants should be selected for synthetic towlines. This will avoid a reduction in strength due to induced twisting.

2.4.1 Wire pennants

Wire pennants are more durable than synthetic pennants.

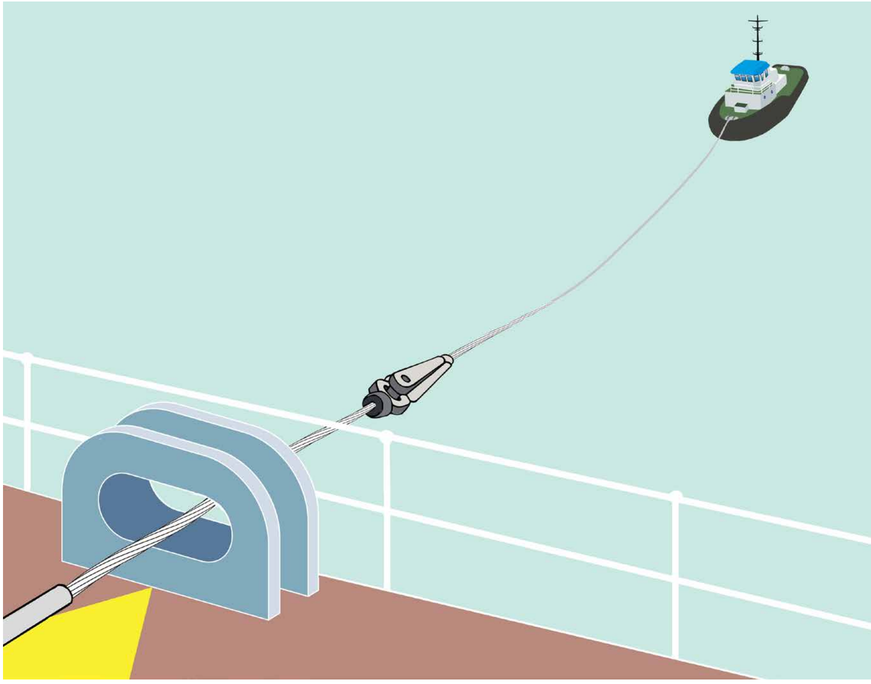


Figure 2.3: *Steel wire towing pennant*

When used with a steel wire towline, steel wire towing pennants should be of the same lay direction as the towline. Because it is the weak link (see section 2.6.1), the wire pennant's MBL should be not greater than the MBL of the main towline.

Care should be taken to ensure the pennant eye is large enough to fit over a set of bitts on the tanker stern.

2.4.2 Synthetic line pennants

Synthetic line pennants are easier to handle than wire.

Any synthetic pennant should be protected against chafing.

The MBL of a spliced synthetic towing pennant should be not less than the MBL of the main tow line because of anticipated wear and tear on the pennants, which may also warrant a greater initial MBL than the main tow line.

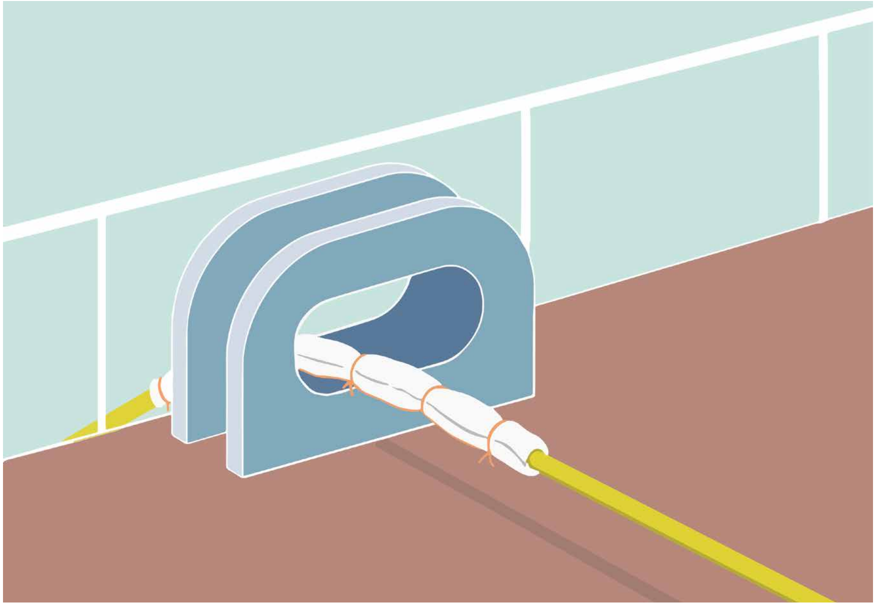


Figure 2.4: *Chafe protection for HMSF towline pennant*

2.4.3 Grommets

If synthetic towing pennants are selected, it is recommended that they are constructed as endless grommets, because:

- The two legs of a grommet have a larger combined surface area which reduces contact pressure at each leg in the fairlead
- They experience reduced movement because they have a larger surface area and are more rigid
- It is possible to rotate the grommet end for end to spread wear
- The larger surface area provides greater heat dissipation in the fibers

These factors will increase the pennant's service.

Figure 2.5: *Grommet pennant*

(**Note:** Grommets with a splice in only one leg are imbalanced, with one side (with splice) being stiffer than the other. Under cyclic loading this imbalance increases relative movement in the connection and increases heat andabraision damage.)

2.4.4 Determining grommet strength

The ultimate strength of a grommeted pennant depends on the resulting D/d ratios (see 2.6 below) created at its connection ends as these are the known weak points. Grommet configurations, although having a two-part line configuration, will not offer twice the single line breaking strength. The strength of the line greatly depends on the material chosen and its resistance to bend loss. Consult the line manufacturers to make sure appropriate connection D/d ratios are specified during towline assembly design as well as to understand the line performance and degradation caused by bending.

Figure 2.6 provides general bend loss behaviour for wire and HMSF lines. For example, a grommet pennant, made of 40mm HMPE fibre line, with an eye-to-eye connection to a single-leg stretcher, made of 80mm polyester fibre line, will result in a D/d ratio of 2:1 experienced by the pennant. According to figure 2.6, the grommet strength efficiency factor will be slightly higher than 1.3. If the single-line MBL is 110t, then the estimated grommet breaking force would be about 145t (1.32 x 110t). The connection experiencing the sharpest bend is assumed to be the weak point and needs to be considered when designing the component's breaking strength.

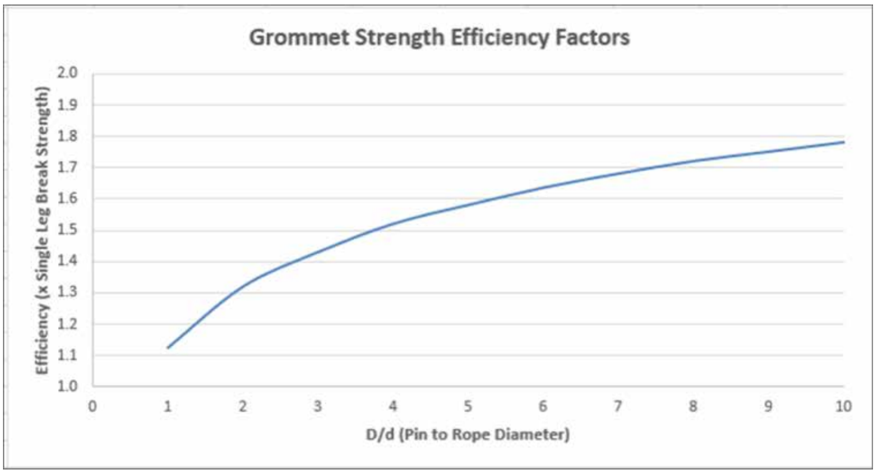


Figure 2.6: *D/d efficiency factors*

(**Note:** The long standing industry estimate of grommet efficiency factors being 1.7 has been found to be overly optimistic when considering grommet in a real life connection method and when subject to cyclic loading. Real life grommet factors as low as 1.1 have been measured.)

2.4.5 Messenger lines

Messenger lines should be of suitable strength to lift the towing assembly up to the vessel.

2.5 Connection methods

All lines experience instant strength loss when loaded around a curved surface. This is proportional to the diameter of the bend and the properties of the line's base material. The reduction in load carrying capability is due to the interruption and unbalancing of line strands traveling across the bend. Testing and research have shown that line strength depends on the ratio of hardware or connection size to line diameter (D/d). More severe bends (with smaller surface radii) will result in greater instant strength loss. A D/d ratio below 2:1 will result in significant strength loss.

The components of the towline assembly can be connected in several different ways.

2.5.1 Cow-hitch

A cow-hitch connection joins two synthetic lines of similar diameter without a requirement for splicing, thimbles or other hardware. It connects two eyes directly but also allows disconnection or line replacement. If one of the connecting lines is of a short length, either a pennant or a stretcher, then a cow hitch connection can be easily performed on deck.

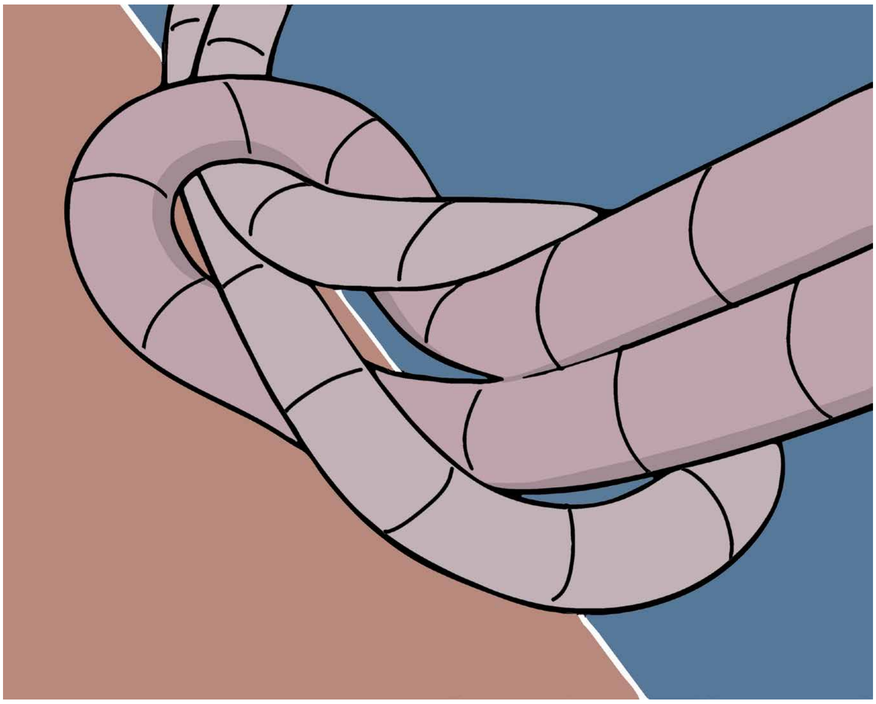


Figure 2.7: *Cow hitch connection*

For easy disconnection, a short piece of line called a pigtail can be placed between each eye and used to pull the two eyes apart (figure 2.8).

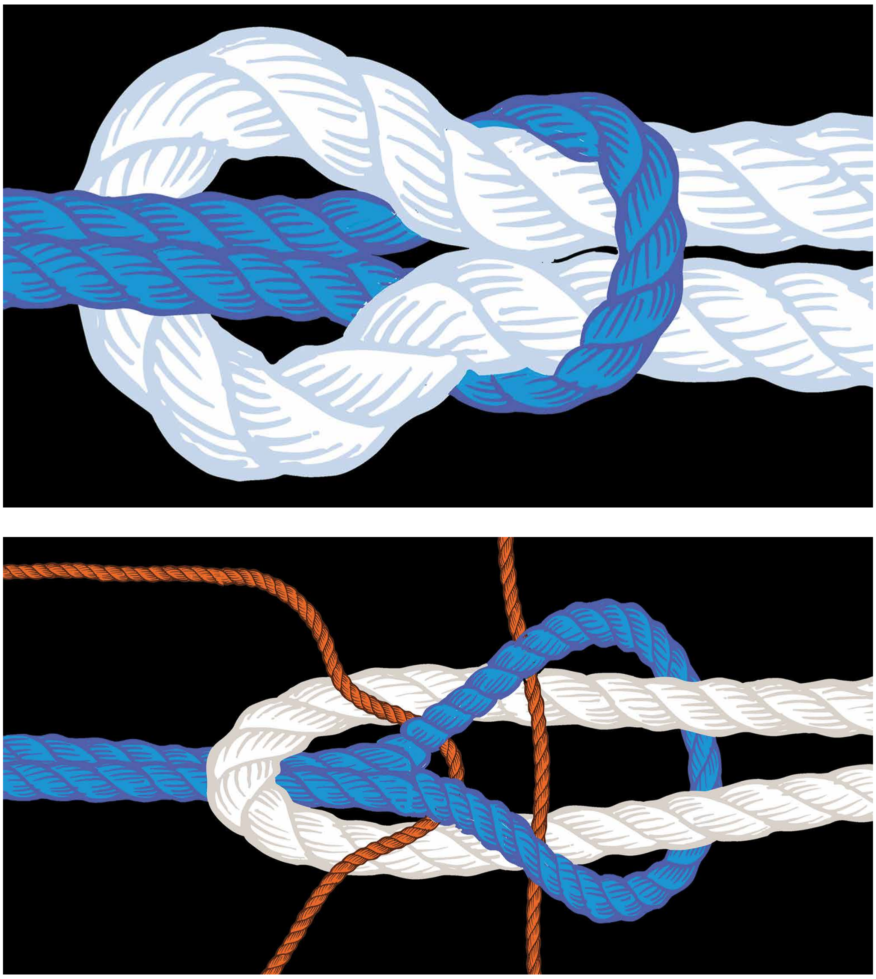


Figure 2.8: *Cow hitch connection with pigtail*

When a small diameter line is cow hitched to a larger diameter line, there is a risk that the smaller line will cut into the larger line due to increased stresses caused by pinching. Regular visual inspection is recommended to check that the connection area has not been overloaded or significantly damaged. If a seizing is placed in the top of the eye of the smallest line, this can help to bring both lines to similar diameters, as well as reducing abrasion in the eye. It is recommended to always provide chafe protection on the individual eyes before cow-hitching. This improves the D/d ratio of the two lines connected and protects against pinching.

Testing has shown that up to 15% of the assembly's original strength can be lost if a cow hitch connection is used. The strength loss can vary depending on the line type and the paired sizes. Consult the line manufacturer when designing the towing assembly. This is especially critical if the strength rating of each towline component is designed to match one another (e.g. 1:1:1).

Never use a cow-hitch to connect a wire to a synthetic line.

2.5.2 Spliced eye-to-eye

This method of joining synthetic lines requires splicing two eyes together, making a permanent connection. Towlines can be ordered this way or spliced in the field by competent personnel. For pennant or stretcher replacements, a new eye will need to be created. This connection method has the highest strength efficiency when connected lines are sized appropriately because there is not much strength reduction in using this method when compared to the cow hitch method.

Figure 2.9: *Eye to eye connection*

2.5.3 Hard shackles

Hard shackles can also be used to connect towline assembly components. Shackles should be sized appropriately so they are not the weakest link in the assembly, and they should provide a suitable bow or pin size for the connecting line eye. Their Working Load Limit (WLL) should be the same or greater than the tug's bollard-pull. The use of mooring shackles or links is not recommended for static towing applications because of their relatively large size, their inability to withstand side loading and their single securing mechanism. Hard shackles can be used to connect towlines to synthetic stretchers and steel wire pennants.

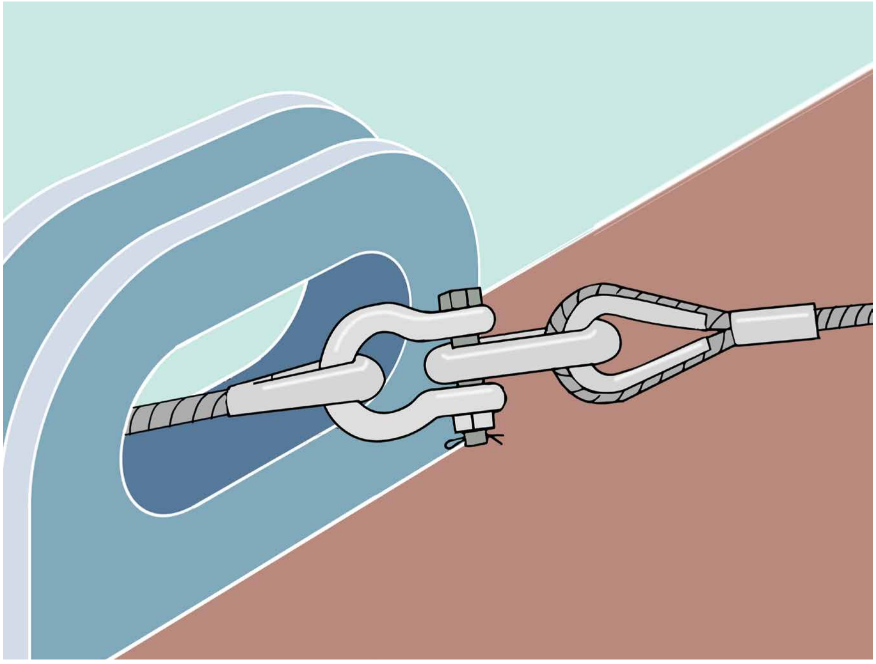


Figure 2.10: *Towline assembly master link*

One option is to use a heart shaped thimble with gusset plate and a master link with a safety bow shackle. If using a master link, it should be rated at the same WLL as the shackle.

Forged high tensile alloy shackles with galvanised body and safety locking pin are recommended (figure 2.11). These shackles should have a proof load of at least 2 x Working Load Limit (WLL).

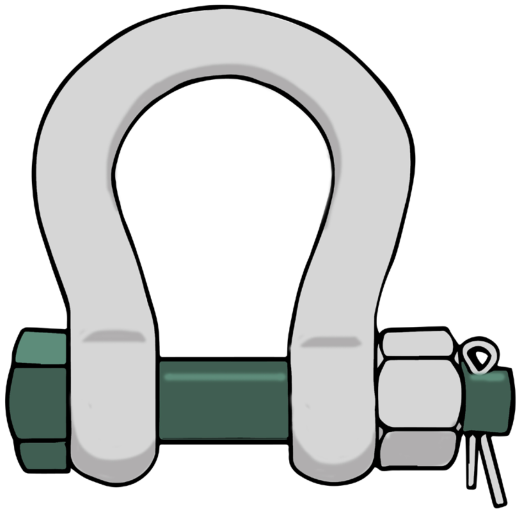


Figure 2.11 *Bolt type anchor shackle*

Safety type shackles have two independent locking mechanisms for the shackle bolt, usually a nut and a split pin. Screw pin shackles and other shackles such as a forelock shackle, with only a single locking mechanism for the pin are not recommended.

Wide body sling shackles may be used as an interface between a wire towline or pennant with the soft eye of a stretcher.

Do not use shackles if the shackle is free to rotate and might apply the load across the legs of the shackle rather than the axial line between the pin and the back of the shackle. Ideally, the pin will go into a wire line closed socket. If the shackle rotates, its efficiency can be reduced by as much as 50%.

2.5.4 Soft shackles

Lighter connection methods in the form of soft shackles are recommended for synthetic assemblies. These are easier to handle and are a safer option: in case of a failure, the soft shackle does not have the same risk of recoil due to component failure as a hard shackle.

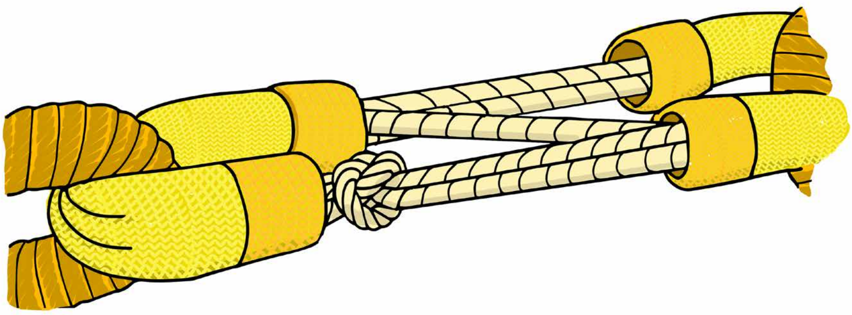


Figure 2.12: *Soft shackle in use*

A soft shackle is a synthetic fibre line connection for the main towline. It replaces a conventional cow hitch, thimble and shackle or similar hardware. It consists of a short length of synthetic line with an eye termination at one end and a stopper knot on the other end. The eye rests on the neck of the stopper knot and tightens as load is applied to the towing assembly.

A shackle has a multi-loop configuration. It should always be assembled to the manufacturer's specifications. The shackle's MBL can be set as needed, based on the MBL of the line used and the number of loops (or wraps).

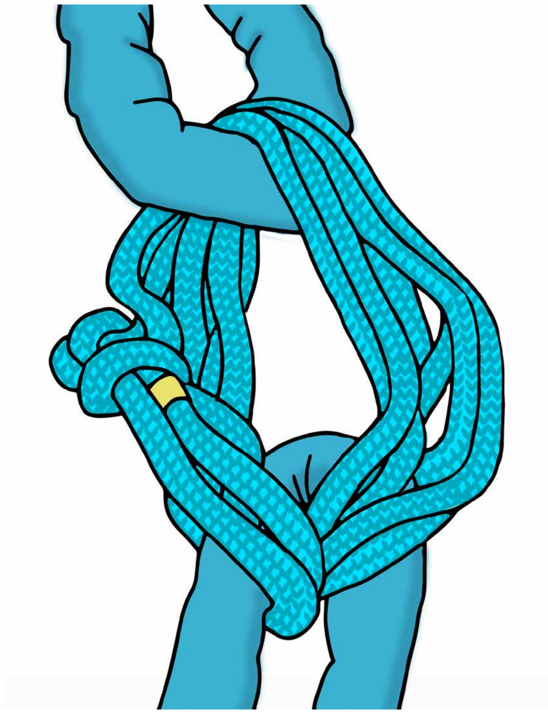


Figure 2.13: *Soft shackle*

The soft shackle should be the calculated weak link in a towing assembly and specified accordingly.

To ensure equipment operates as designed, only use Original Equipment Manufacturer (OEM) certified soft shackles in towing assemblies.

2.6 Recommendations on towline assembly specification and configuration

2.6.1 Weak links

During static towing operations dynamic conditions may result in loads that exceed the strength of the towline assembly and cause it to part. It is recommended that a weak link is incorporated into the towline assembly so that a known component fails first – usually the towing pennant or soft joining shackles. It should always be an easily replaceable component, but never the main towline. It is preferred that the tow winch brake be set to render at 50% of the main towline MBL. However, it is recognised that this is difficult to apply on practice. Therefore, the following configurations are recommended:

- HMSF towing assemblies made up of an HMSF main towline, a synthetic stretcher and a HMSF grommet pennant joined by soft shackles; the soft shackles should be the weak link.
- Wire towing assemblies made up of a wire main towline, a synthetic stretcher, and a wire pennant joined by hard shackles; the wire pennant should be the weak link.

2.6.2 Synthetic assemblies

Table 2.1 shows examples of the recommended synthetic assembly configuration of increasing strength.

	Main Tow Line	Connection A (soft shackles)	Stretcher	Connection B (soft shackles)	Pennant
Multiplier (1)	3	3	3+	2.25 (weak link)	3+
Bollard Pull	250m x 44mm HMSF	3 loops of 24mm HMSF	20m x 80mm 8-strand polyester/ polypropylene mix	2 loops of 24mm HMSF (3)	10m x 34mm HMSF grommet (4)
50t	159t MBL (2)	184t MBL	158t MBL	123t MBL	150t MBL
	250m x 52mm HMSF	3 loops of 28mm HMSF	20m x 96mm 8-strand polyester/ polypropylene mix	2 loops of 28 mm HMSF	10m x 42mm HMSF grommet
75t	220t MBL	242t MBL	225t MBL	161t MBL	225t MBL
	250m x 62mm HMSF	4 loops of 26mm HMSF	20m x 88mm double braid nylon grommet	3 loops of 26mm HMSF	10m x 48mm HMSF grommet
100t	298t MBL	281t MBL	336t MBL	211t MBL	300t MBL
	250m x 68mm HMSF	4 loops of 30mm HMSF	20m x 96mm double braid nylon grommet	3 loops of 30mm HMSF	10m x 52mm HMSF grommet
125t	368t MBL	362t MBL	390t MBL	272t MBL	375t MBL
	250 x 76mm HMSF	4 loops of 32mm HMSF	20m x 104mm double braid nylon grommet	3 loops of 32mm HMSF	10m x 62mm grommet
150t	448t MBL	408t MBL	447t MBL	306t MBL	506t MBL

Table 2.1: *OCIMF recommendation for synthetic towing assemblies*

Notes:

1. The Multiplier is the factor that relates the components MBL to the bollard pull of the tug.
2. The MBL s are indicative only for each component specification and will vary. Consult manufacturer for actual rated values.
3. Both Connection A and Connection B are soft shackles of the same line for standardisation but with Connection B having one less loop to provide the “weak link” required. Failure at this location would allow the tanker to use main engines without risking fouling the propeller.

2.6.3 Wire rope assemblies

Table 2.2 shows examples of the recommended wire rope assembly configuration of increasing strength

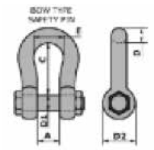
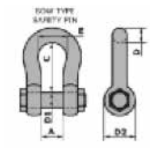
Bollard Pull	Main Tow Line	Connection	Stretcher*	Connection	Pennant
Multiplier	3	WLL = Bollard Pull	3+	WLL = Bollard Pull	2.5+ (weak link)
					
50	300m** x 46mm 6 × 36WS IWRC 1960	Safety dee, bolt type or bow shackle WLL 50t	20m x 80mm diameter 8 strand polyester/ polypropylene mix	Safety dee, bolt type or bow shackle WLL 50t	10m** x 42mm 6 x 36WS IWRC 1960 with a 2m soft eye by termination each end using a steel ferrule
Typical MBL	151t		158t		126t
75	300m** x 56mm 6 × 36WS IWRC 1960	Safety dee, bolt type or bow shackle WLL 75t	20m x 96mm diameter 8 strand polyester/ polypropylene mix	Safety dee, bolt type or bow shackle WLL 75t	10m** x 52mm 6 × 36WS IWRC 1960 with a 2m soft eye by termination each end using a steel ferrule
Typical MBL	233t		225t		185t
100	300m** x 66mm 6 × 36WS IWRC 1960	Safety dee, bolt type or bow shackle WLL 100t	20m x 88mm diameter double braid nylon grommet	Safety dee, bolt type or bow shackle WLL 100t	10m** x 60mm 6 × 36WS IWRC 1960 with a 2m soft eye by termination each end using a steel ferrule
Typical MBL	302t		336t		256t
125	300m** x 74mm 6 × 36WS IWRC 1960	Safety dee, bolt type or bow shackle WLL 125t	20m x 96mm diameter double braid nylon grommet	Safety dee, bolt type or bow shackle WLL 125t	10m** x 66mm 6 × 36WS IWRC 1960 with a 2m soft eye by termination each end using a steel ferrule
Typical MBL	370t		390t		310t
150	300m** x 82mm 6 × 36WS IWRC 1960	Safety dee, bolt type or bow shackle WLL 150t	20m x 104mm diameter Double braid nylon grommet assembly	Safety dee, bolt type or bow shackle WLL 150t	10m** x 74mm 6 × 36WS IWRC 1960 with a 2m soft eye by termination each end using a steel ferrule
Typical MBL	433t		447t		390t

Table 2.2: *OCIMF recommendation for wire rope towline assemblies*

Notes:

1. *Using a stretcher is optional, especially if there are no wave or swell conditions
2. **Typical deployed operating length. The actual length purchased can be determined to suit operators winch capacity and maintenance strategy
3. The MBL's for the rope sizes are indicative only. Check with rope manufacturer for actual values
4. The stretcher should have a thimble eye to reduce damage. Ensure the shackle can connect to the thimble.
5. There are many different shackle specifications. Ensure the proof load of the shackle selected is 2 x WLL.

3 Factors affecting towline assemblies

3.1 Heat build up

Towline assemblies can heat up when in use due to:

- internal friction in the towline assembly. Because of its elastic properties, the stretcher will heat up more and faster than pennants and main towlines.
- external friction from contact with another object.

3.1.1 Internal friction

Internal friction is the force resisting motion between the fibres in a line while it undergoes a deformation. This deformation can be axial cycling between maximum and minimum loads or cyclic bending over a curved surface including within the connection points. Internal friction can be minimised by manufacturing lines with suitable fibre and coatings.

Modelling of internal friction in synthetic stretchers has indicated a measurable increase in temperature. However, because of the very low radial thermal conductivity of polymers in general and the nature of the connection between stretcher and mainline or pennant (there is more material in the spliced area, which gives a lower stress amplitude and therefore less heat generation), the heat in the stretcher is not transferred to the main line or to the pennant. It may, however, degrade the stretcher and lead to its premature failure.

3.1.2 External friction

External friction occurs between a line and a surface when these move against each other. This may lead to temperature rise in both the surface and the line. Examples are a pennant running through a fairlead, the main towline through a staple or at the connection point between the stretcher, tow line and pennant, where different materials are in physical contact. The frictional force and the heat generated will increase in proportion to line movement and contact pressure. Both friction and heat can be reduced by water cooling using either sea or fresh water.

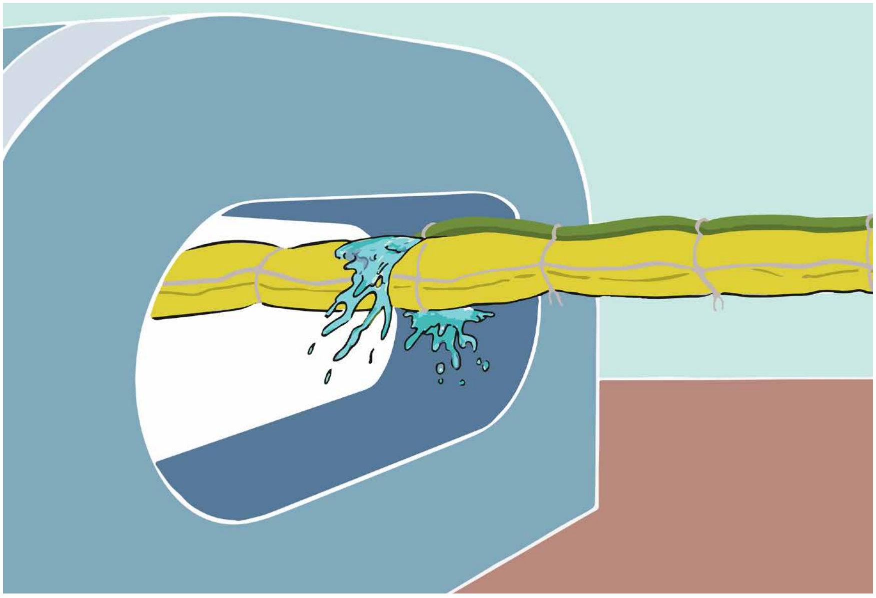


Figure 3.1: *Water cooling to reduce external friction and heat build-up*

External friction between a towline and a steel fairlead will lead to heat build-up in both components. Modelling the heat build-up for an HMSF grommet-type pennant with synthetic jacket rubbing against a steel fairlead has shown that the rise in temperature in the pennant will be lower than the surface temperature of the steel fairlead. This is because of the low radial conductivity of the synthetic materials. For the same reasons as above, the heat in the pennant is not transferred to the stretcher or main towline. The effect of external friction can be minimised by using a suitable protective line cover, sleeve, or coating.

Significant friction burn can occur when a synthetic line is pulled down through loose layers on the winch-drum. Care should be taken to reel the line onto the drum evenly and under tension

For both internal and external friction, heat build-up will be reduced when the towing arrangement is exposed to wind and/or water.

3.2 Improper towline installation onto the winch

Proper installation of a towline on a drum requires adequate back tension on the first layers. This is to prevent the towline from diving or knifing on the winch drum if the line experiences a sudden high load, forcing itself between the lower layers. Working out this line dive can be difficult, especially while performing a tow. Proper back tension during installation will induce memory into the line and prevent the line from diving on the drum.

Care must be taken that no significant twist is induced onto the tow line as it is spooled onto the winch. As long as the towline is spooled correctly it is not necessary to remove and respool after each operation.

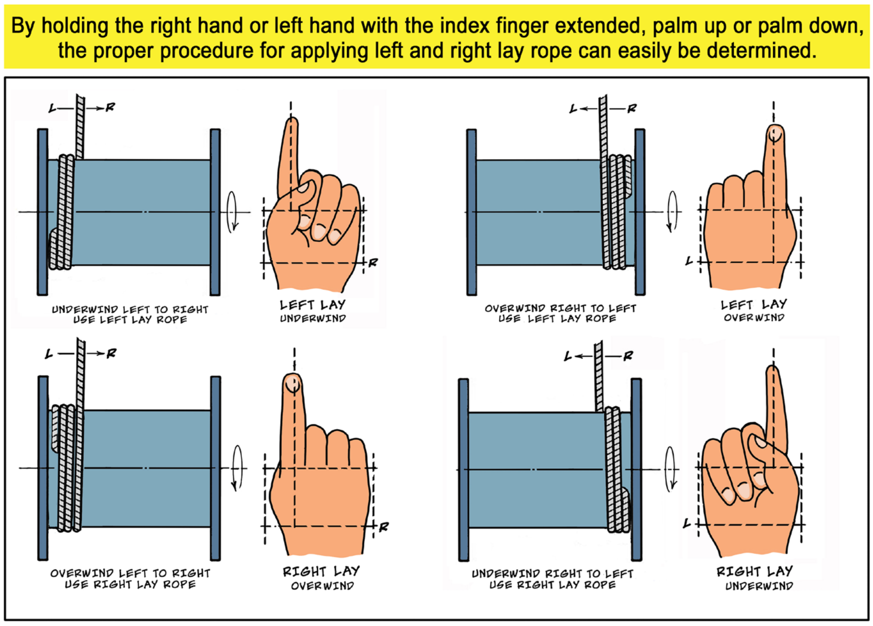


Figure 3.2: *Correct installation of wire rope to winch drum*

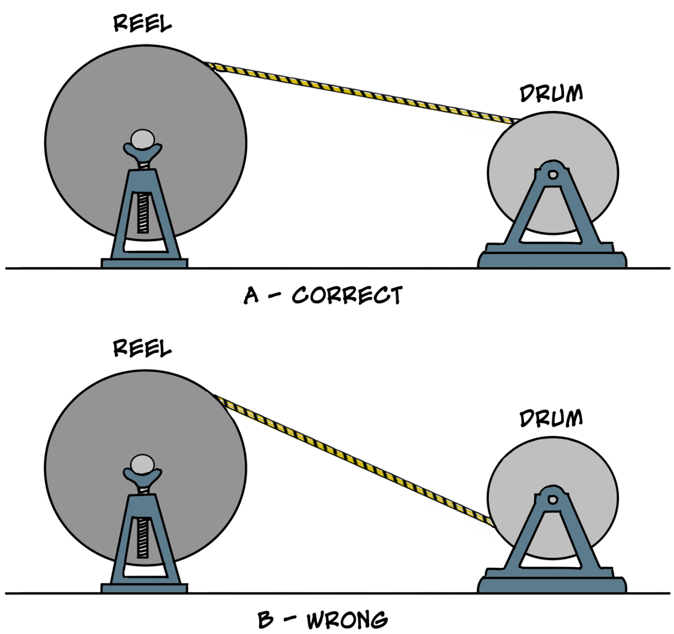


Figure 3.3: *Installing a wire rope to a winch from a cable drum*

3.3 Cyclic and shock loading

Wire and synthetic lines that are load cycled repeatedly will gradually lose strength, even when this is within their normal working load range. The extent of the strength loss depends on the level of the loads in relation to the MBL and on the line's material and construction. Various mechanisms can lead to the breakdown of synthetic fibres under cyclic tension, the most common is internal fibre to fibre abrasion.

A shock load is a sudden high load that is transferred into a line from a low load or static load situation. This can cause a peak load that is higher than the recommend load limit or in extreme cases residual break load, which can cause line failure.

Shock loading can cause significant loss of strength or durability, which can be difficult to detect visually. This can lead to subsequent line failure even when operating below the maximum load limits.

Keeping track of a line's usage history, particularly load monitoring data, is the best way to determine the likelihood that shock loading has occurred. Operators should consult with manufacturers to determine at what point the towline and/or towline assembly components should be retired from service when subjected to shock loading. This may be after a single high shock load or after several smaller shock loads over a defined period of time.

3.4 Line rotation and torque

Braided or plaited fibre lines are made of equal numbers of left- and right-hand strands. If the line is twisted, half the strands will tighten, and the other half will slacken. However, fibre line yarns are "mobile" and will migrate to accommodate variations in tension. This is especially true with highly elastic yarns such as nylon.

Fibre lines can accommodate high levels of twist without significantly reducing tensile strength. However, allowing a twist to stay in the line will have a long-term effect on the line's fatigue life, because the same strands will be repeatedly loaded more than strands of opposite lay. It is good practice to remove any twist and to avoid connecting the line to any laid rope. A good rule of thumb is to allow no more than one turn per lay length. Experience has shown that twist from regular towline handling and usage will not reach high risk levels. Regular use includes winding off winch, connection to towline components with dissimilar construction, using of a laid messenger line connected to tanker or, contact with surfaces such as bitts or fairleads.

Excessive twisting of steel wire ropes has a negative effect. When a steel wire line is fixed at both ends, and a tension is applied, the wire line will stretch, and the outer wires will pull down more tightly on the wires below. This is ultimately damaging but is the way the wire line is designed to work.

However, if one end of the wire line is free to rotate, the line will tend to unwind when tension is applied. This exposes the line's core and the lubricants to the sea, which could easily wash out the grease. The wires are usually pre-formed, with the helix set into the wire. If it unwinds enough, the helix will become damaged and the wires will not return to their original position once the load is removed. When a wire line is connected to a fibre line that has no resistance to twisting, the fibre line acts like a swivel and, allows the wire to unwind and wind as load is applied and released. As a fibre line becomes more and more twisted, its resistance to additional twist will increase and it will reach an equilibrium point. A wire pennant connected to a synthetic towline tends to twist or spin violently if the towing vessel is moving in a swell. This twisting or spinning caused by the inherent torque in the wire, can result in excessive movement of the wire pennant within the tanker chock and can damage the outer strands of the wire pennant when it impacts the surface of the chock. Swivels will not prevent this and should not be used in static towing assemblies.

A towing assembly that consists of a wire main tow line, fibre stretcher and wire pennant is recommended because the wire line will twist the fibre until it has a similar resistance to the wire line. Load variation in the stretcher will also be dampened by the wire line catenary.

Appendix B contains an example formula for calculating the torsion effect in a wire line.

3.5 Physical damage

3.5.1 Chafing or abrasion

All synthetic fibre towing assembly components can become damaged if exposed to contact surfaces, particularly while under tension. Damage to steel wire is less likely, but broken strands are still possible.

Steel fairleads should be clean, smooth and rust-free. Rough surfaces will significantly speed up the rate of abrasion and reduce the service life of pennants and other components. Fitting sleeves or liners to fairleads can improve contact surfaces. Such inserts can change the frictional and heat dissipation properties of the contact surfaces and should not be fitted without a thorough management of change process and consultation with the line manufacturer to ensure compatibility.

Lines can better resist external abrasion damage when fitted with abrasion resistant sleeves (either braided, cloth or web) or individual strand jackets.

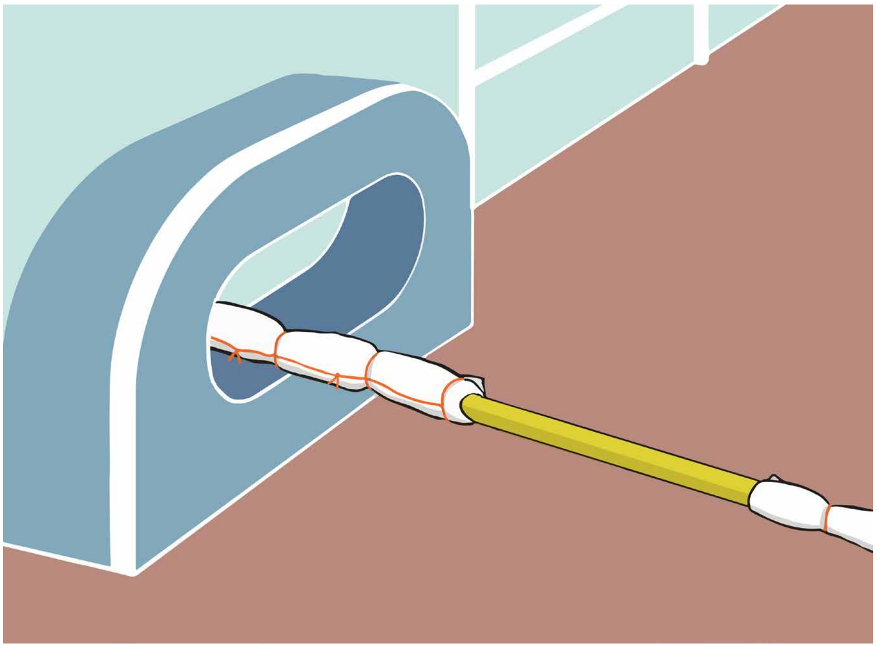


Figure 3.4: *Synthetic towline pennant with chafing protection*

3.5.2 Exposure to elements

Corrosion affects a wire's residual strength, leading to a shorter service life. Corrosion protection on wire lines is recommended, both by galvanising individual wires and by applying an appropriate lubricant as required throughout the wire's service life.

Wire rope itself is not affected by ultra-violet (UV) radiation. However, some lubricants can be, so seek the line manufacturer's advice.

All synthetic lines are degraded by UV radiation, but it only affects the line's outer fibres, which can discolour and become brittle. Ropes with larger diameters, particularly over one inch, are less affected. UV radiation has a minor effect on towlines over their lifetime. Covers and coatings protect load-bearing cores against UV radiation.

HMSF lines may have relatively low melting points and published critical temperatures. However, this does not mean they are less viable in hot climates. Studies have shown that HSMF lines undergo only negligible degradation in high-temperature environments.

Exposing the ropes to temperatures below 75°C does not significantly affect the residual strength of HMSF fibre lines. At higher temperatures above 75°C, HMSF fibres will soften, which can reduce their strength.

Synthetic towline components should be kept clear of high heat surfaces such as hot exhaust pipes or areas where welding takes place.

3.5.3 Contact with chemicals

While synthetic lines are generally resistant to most industrial chemicals, avoid exposure. If they are at risk of chemical exposure, seek advice from the line manufacturer to make sure there will be no detrimental effects. Wire lines should also be kept clean because contact with chemicals can deteriorate grease or cause corrosion.

Note: To help reduce the effects of chafing, lubricating the tanker chock with grease is common practice and is recommended for both synthetic and wire pennants. Grease used for this application are not considered chemicals within the context of these guidelines.

4 Towing winches

4.1 Winches

Recent developments in towing winch design, such as render-recovery systems, may influence the optimum design of towline assemblies. Render recovery systems are designed to prevent slack line and overload events, so they might be more effective than stretchers in this case.

There are three types of towing winch in use.

- Conventional winch
- Constant tensioning winch
- Render-recovery winch

All towing winches have a brake arrangement and a drive arrangement. During operation, the winch can be used in render (brake) mode, recovery (drive) mode or in a dynamic mode.

4.2 Conventional winches

Recovery is performed by engaging the drive. The pull force and speed of recovery are directly related to the applied motor power and gear ratio. Render is performed, with the drive disengaged, by varying the brake force. The speed and brake force are directly related only to the brake type and efficiency.

Main features:

- Passive winch
- Moderate recovery pull (20% to 40% of the tug's static bollard-pull) at the working layer
- Line render and recovery rates of around 20% of the tug's free running speed (or 3 knots)
- High hold capacity static brakes (250% of the tug's static bollard-pull)
- Optional brake tension monitoring
- Low cost and complexity

Limitations:

- No powered rendering capability under load
- Limited shock-load mitigation by brake slippage only
- No slack wire prevention
- Changes between brake and drive mode are manual and can lead to operational delays or errors

4.3 Constant tensioning winches

Unlike conventional winches, constant tensioning (or self-tensioning) winches are continuously operated in the drive mode, but with limited render and recovery capability. Render and recovery speed and force are directly related to the applied motor power and gear ratio. The maximum render and recovery speeds are limited by the maximum speed of the motor and power of the system.

Main features:

- Active winch
- Moderate recovery pull (20% to 50% of the tug's static bollard-pull) at the working layer.
- Moderate powered rendering capability
- Adjustable automatic constant tension recovery, up to the power limit of the winch drive
- High hold capacity static brakes (250% of the tug's static bollard-pull)
- Moderate cost and complexity

Limitations:

- Limited capability in dynamic mode. In environmental conditions where dynamic mode cannot support the loads experienced, passive operation is necessary.
- Limited shock-load mitigation

4.4 Render-recovery winches

These winches are designed to operate continuously in dynamic mode in harsh environmental conditions. Dynamic brakes can be used for extended rendering, if needed. During operation, both the drive and a dynamic brake can be engaged.

Main features:

- Active winch
- Increased recovery pull (80% to 150% of the tugs static bollard-pull) at the working layer
- Increased powered rendering capability
- Active control of towline including slack wire prevention
- Increased active shock load control
- High hold capacity static brakes (250% of tug's static bollard-pull)

Limitations:

- Effectiveness of shock-load mitigation is determined by the response time of the dynamic system
- The elasticity of stretchers (if used) can hinder performance
- High power consumption
- High cost and complexity of drive systems

5 Girting

5.1 Girting prevention

Girting occurs when a tug is towed broadside by a towline under tension and is unable to manoeuvre out of that situation. Girting is the most common reason that tugs capsize. If the towline is leading abeam and has enough tension it can overcome the tug's righting lever and cause deck edge immersion followed by capsizing. Girting can develop very quickly and with very little warning. It often results in fatalities because crewmembers can become trapped in the capsizing tug.

It is essential that all persons involved in controlling the tow operation are aware of girting risks and the causal factors, including a failure to maintain towing deck watertight integrity.

If a situation occurs which results in excessive tension on the towline, activating the towline emergency quick release may be necessary. Winch operators should have a clear understanding of how to activate this equipment. Depending on the arrangement, this may trip the towing hook, release the winch brake or allow the towing winch to freewheel, each of which will release the tension in the towline and allow the tug to return upright and regain control. As a further safety measure, the towline should be attached to the winch drum by a weak link connection in case the towline has to be fully paid out and released. The winch drum must never be secured in a way that prevents the winch from rendering or releasing.

Girting is particularly hazardous to conventional single screw tugs. Tractor and azimuth stern drive (ASD) tugs are less likely to girt because the tug master can produce significant thrust in all directions to maintain the tow alignment. Towing from a point near amidships on a conventional tug is inherently unstable and can result in situations where the load on the towline can heel the tug over to a large and dangerous angle.

5.2 Tug equipment

To reduce the risk of girting, tug operators should consider the following options:

5.2.1 Gob wires

A gob wire (also known as a gog wire) is used to move the effective towing point closer to the tug's stern. This prevents the towline from being taken across the tug's beam, and therefore reduces the danger of girting.

Fixed gob:

A fixed gob consists of wires or chains, secured on the centreline towards the aft end of the main deck and attached to the towline by a wide-bodied shackle or a suitable sheave.

Running gob:

An adjustable gob wire might provide the best flexibility when towing. Leading from a separate winch drum, the wire is fed through a sheave or wide-bodied shackle fitted to the centreline at the aft end of the main deck, and then connected to the towline. This arrangement can be adjusted to allow the towline to leave the vessel from a position close to the tug's pivot point to aid manoeuvring. However, care must be exercised when using an adjustable gob wire as it cannot be heaved in once the towline is under tension.

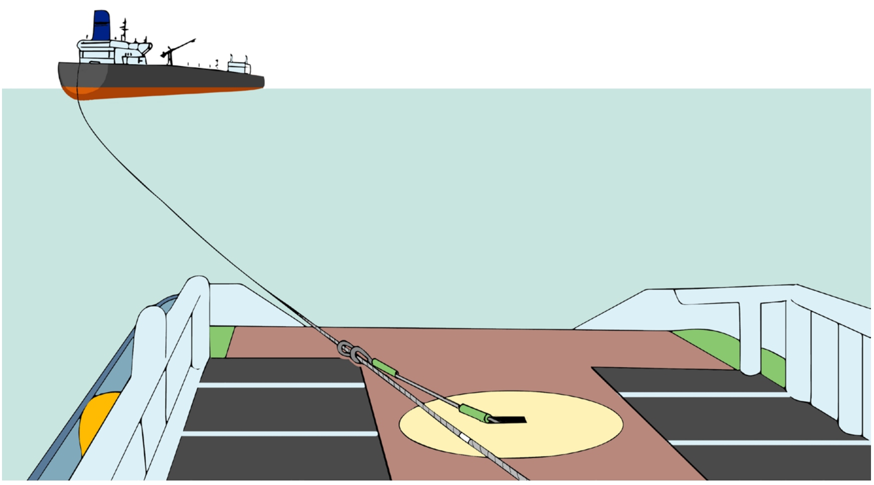


Figure 5.1: *Gobbing arrangement*

5.2.2 Towing pins

Towing pins are remotely controlled, retractable vertical pins, which may have locking tops. They are used to limit the transverse movement of a towline close to the stern. Towing pins can be fitted as a single pair or as two pairs.

Note: due to size of apperture towing pins can introduce a limitaton on the size of tow line, stretcher and pennant diameter, as well as the connection type

5.2.3 Norman pins

Normal pins are solid vertical metal posts or rollers either at the stern or on each quarter designed to prevent the towline from moving away from the stern. These may be remotely controlled, retractable powered pins or fitted manually.

5.2.4 Dynamic winches

Dynamic winches are render-recovery winches with auto-abort features that help mitigate the risk of deck edge immersion by monitoring tug list and deck edge immersion and automatically rendering if the tug is in danger

5.2.5 Bow winches

The risk of girting is significantly reduced when conducting static towing operations over the bow of the tug.

6 Management of towline assemblies

6.1 Towing assembly management plan

All towing assembly components will degrade over time due to wear and tear. To ensure the assembly is always fit for purpose, the tug operator should develop a towing assembly management plan.

This programme should include:

- Identification and certification of all components
- Training and competence requirements for maintenance tasks such as splicing
- Schedules and instructions for inspections and maintenance
- Record keeping including hours of use and load monitoring such as a towing log
- Establishment of clear retirement criteria for all components
- Storage instructions for components in line with manufacturers recommendations

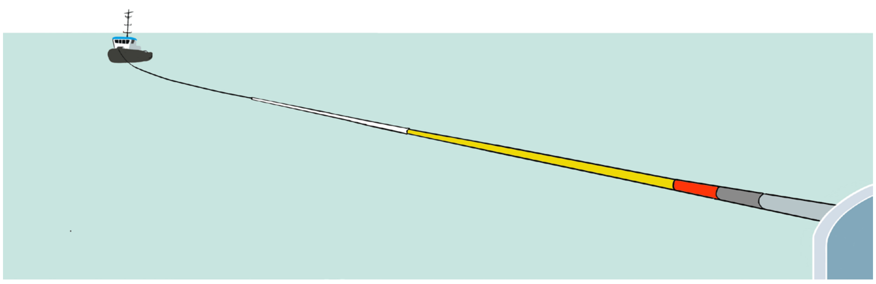


Figure 6.1 *Synthetic towline assembly*

Users should continue to revise and refine the programme based on experience. Not having an adequate maintenance program or failing to follow it, may result in an unexpected failure of the towing assembly.

6.2 Certification and tagging

All towing lines should be supplied with appropriate certification. This should be carefully filed to support the tug's maintenance and line tracking requirements. Certificates include detailed specifications and descriptions of the line supplied based on spliced break tests.

Towline components should be tagged with durable and readable tags for easy identification. This tag provides important information about the line and should be located near the splice of a towline or working line. The tagging system should correspond directly with the certificate and should not be removed. In this way lines can be tracked through their service life.

Care should be taken in identifying the true breaking strength based on a certificate. The certified strength may be based on testing procedures that do not represent real life conditions, for example the test uses small D:d ratios in the connection, or the sample is tested unspliced, or tested dry.

6.3 Line inspection

There are no definitive rules or precise evaluation methods for determining when a line should be retired because many variables affect line strength. Load history, bending radius, abrasion, chemical exposure, and other factors can make retirement decisions difficult. Therefore, users and inspectors need to be trained in assessing line condition. Routinely conducting line inspections will help to identify accelerating wear as well as decrease the risks associated with putting damaged sections back into service. In general, the amount of potential strength loss in synthetic lines is directly related to the amount of broken fibre in the line's cross section. Consult the line manufacturer to determine the inspection criteria.

The tug operator should determine how frequently the following towline inspections should be performed based on historical performance data analysis. All inspections should be performed by a line manufacturer's representative or other competent personnel, either from within the operator's organisation or by a third party.

6.3.1 Deployment inspection

As the line is being deployed and retrieved, it is recommended that the crew externally inspect the line for signs of general deterioration or mechanical damage and to verify that the line is correctly installed onto the winch drum. Any visible change in condition should be reported.

6.3.2 Periodic inspection

A competent crew member should perform an external and internal line inspection. The frequency of the inspections should at least consider any statutory requirements, environmental conditions, experience gained from previous inspections, and the number of operations and hours of use.

Inspect each line along its entire length. However, in the case of a long length, the competent person can choose to inspect only the working length. In such cases, if a greater working length is needed after the previous inspection and before the next one, inspect that additional length before use.

Areas that should be inspected include:

- Winch anchor point and the section of line close to it.
- Sections of line in wear zones, particularly sections that run through deck fairleads and pedestal rollers.
- Sections that spool on the winch drum, particularly cross-over zones.
- Any section at, or near, a rope termination.

Use the information gained from a periodic inspection is decide whether:

- The line can safely remain in service until the next periodic inspection; or
- The line should be discarded immediately; or
- The line should be discarded within a specified time frame.

6.3.3 Detailed inspection

A detailed external and internal inspection along the full length of the line should be performed by a competent crew member, third party inspector or manufacturer's representative. They should submit a formal report to tug staff and management stating repair requirements, repairs carried out and recommendations such as end-for-end or retire.

6.4 Line maintenance

In general, any retirement-criteria damage on a localised section of line needs to be cut and removed from the overall length, and the remaining length or lengths need to be re-spliced. Any splicing work should be performed by competent personnel or by a manufacturer's representative. When damage occurs at or near the eye of the line, the best solution is to cut away the affected outboard length of line, including the existing eye, and to splice a new eye into the remaining line's length. If damage occurs at or near the middle of the line's overall length, the line should be retired from service. Removing the damaged section and the line consumed in the splice will make the line shorter. Consider the minimum length requirements of the application when deciding to re-splice or retire a line. Before performing any irreversible maintenance, consult your company's policy and/or the manufacturer to determine if re-splicing a damaged line is permitted.

Wire lines in service may suffer corrosion damage. Corrosion reduces the strength of the line by reducing its metallic cross –sectional area. It also accelerates fatigue by causing irregular surfaces from which stress cracking can spread. Severe corrosion can also cause decrease the lines elasticity. The wire ropes used in wire towing lines should be protected by applying appropriate lubricant, which should be reapplied as required through the service life of the line.

6.4.1 Wear zone management

Typically, the outboard or working end of the line suffers the greatest strength loss because it is subjected to more demanding conditions, such as repeated and dynamic loading, mishandling, and fairlead and bollard abrasion. To maximise the service life of towing lines, it is recommended to vary the line sections exposed to high stress and increased wear throughout their use.

While these methods are valuable tools in line maintenance, it is important that detailed records be maintained of any actions taken to ensure that crews understand the condition and service history of all line components onboard over their life.

6.4.2 Surface conditioning

Towing fittings such as fairleads or pins deteriorate over time if not periodically maintained. Mixed use of synthetic fibre and wire lines is not recommended because wire lines can burr and score fittings which may damage fibre lines if used in the same service location.

All metal surfaces in contact with the synthetic line should be smooth with no snags, burrs, rust, or wire line scoring. Repair any damaged surface before re-deploying synthetic towing lines through, or around, the damaged deck equipment.

6.4.3 Line cropping

Lengths of line can be removed (also called line cropping) for residual strength testing or to repair damaged lines. If inspections reveal a high amount of localised abrasion, cutting, or damage near line ends, it may be recommended to remove short, damaged sections from service. Removing weakened outboard lengths and migrating undamaged line sections towards the working end allows the lines to safely stay in use. New eye splices should always be performed by competent personnel.

6.4.4 End-for-ending

The inboard end of the towline on the winch drum accumulates only limited wear. It can retain a high percentage of its original breaking strength even after many operations. By reversing the line on the drum, or end-for-ending, worn or damaged sections are moved to a less demanding position. The recommended end-for-ending period depends on the nature of the towing service, how frequently it is used, the tugs ability to perform the end-for-end process, and other factors, but it should be at, or near, the midpoint of the towline's expected service life. Reinstall the line back onto the winch carefully, following the tug operator's procedures (see above section 4.2).

6.5 Residual strength testing and line condition analysis

A residual strength testing programme allows operators to refine their towline management plan. This is the most reliable method for extending towlines service life while ensuring operational safety. Periodic break tests of used samples allow the tug operator to understand how the lines are degrading relative to their actual usage. It is critical to document inspections and line usage both to identify trends and to understand anomalies resulting from localised damage or extreme loading conditions.

To conduct testing, a 15-20 metre length of line, depending on the line diameter, needs to be cropped and shipped to a testing facility. This length is repurposed as a test sling, inspected, and pulled to destruction. It is important to specify how the sample sling must be tested to ensure consistent and accurate results. Residual strength testing of synthetic lines usually follows the Cordage Institute's CI-1500 test method for used lines. A formal report should be returned and documented, containing inspection and test results. The report findings will affect how the retirement criteria are updated to reflect actual conditions of service.

6.6 Retirement of towlines

The tug operator should define a line's initial service life (the number of towing operations or hours of use) to indicate when it should be retired. The timing of maintenance events and the frequency of residual strength tests can then be based on this initial service life. Performing break tests of used samples allows the tug operator to understand how the lines are degrading.

With a clear understanding of static tow conditions and line wear, a predictive model can indicate the loss of strength at any point during the line's service life.

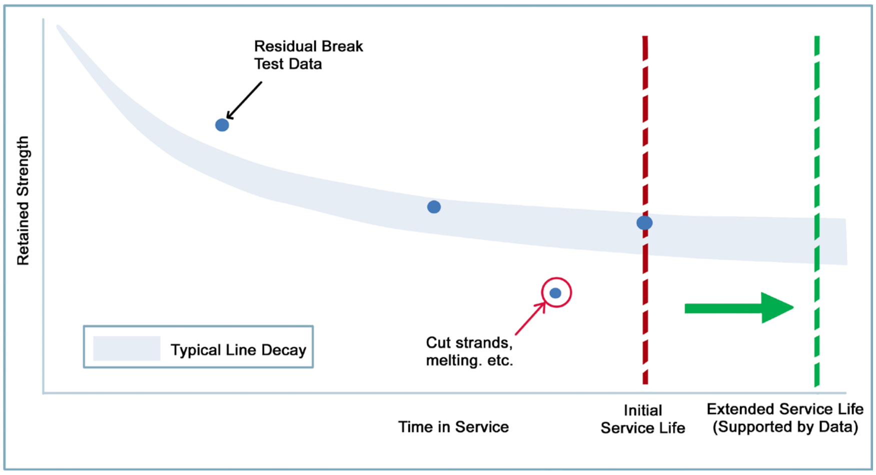


Figure 6.2: *Example of a towline service life model*

Using the data from periodic residual strength testing, the tug operator can make an informed decision to either reduce or extend the expected service life.

Refer to the OCIMF *Mooring Equipment Guidelines (MEG)* for detailed information on line inspection, maintenance, residual strength testing and retirement criteria.

6.6.1 Retirement criteria for wire ropes

Wire ropes should be closely inspected for:

- External and internal corrosion
- Mechanical damage
- Heat damage

Wire ropes should be withdrawn from service if any of the following defects are found:

- Wire protrusion in loops, if in groups
- Core protrusion
- Strand protrusion or distortion
- Fracture of strands
- Kinks or tightened loops
- Local decrease of rope diameter (sunken strand) due to break or distortion of the core
- Uniform decrease in rope diameter (due to external wear/abrasion, internal wear and core deterioration), if decrease is 7.5% of nominal diameter or higher
- External corrosion, with wire surface heavily pitted and slack wires
- Internal corrosion, with corrosion debris exuding from valleys between outer strands
- Wire breaks discard if the number of visible wire breaks is more than 4 breaks in a length that is 6 times the rope diameter or more than 8 breaks in a length that is 30 times its diameter
- Local increase of rope diameter due to core distortion, if diameter increases by 5% or more.

6.6.2 Retirement criteria for synthetic lines

It is recommended that tug operators develop a programme for line maintenance, inspection and retirement. This will reduce unnecessary degradation of the line and ensure lines are operated within safety margins over their service life. Inspection and discard guidance is covered by industry standards such as CI-2001: Fiber Rope Inspection and Retirement Criteria, but the line manufacturer should provide further product specific instructions.

Appendix A: Static Towing Simulations Report by Marin

A1 *Marin Static Towing Simulations Report*, 2019

CONTENTS **PAGE**

REVIEW OF TABLES, FIGURES AND PHOTOS

Tables in the report:

Tables in the Table section:

Figures in the report:

Figures in the Figure section:

EXECUTIVE SUMMARY

OCIMF requested MARIN to study the effect of a stretcher on a towline assembly during static tow. An industry survey showed that stretchers are not always utilized in towline assemblies. This study aimed to understand below what towline length and above which weather conditions, the stretchers become advantageous to reduce the peak line loads. This was accomplished by carrying out a number of dynamic mooring simulations with MARIN's software aNySIM.

Two different configurations were considered in the study: 1) FPSO system – a turret moored FPSO that has a VLCC connected in tandem with the tug pulling on the VLCC and 2) SPM system – a VLCC connected to a CALM buoy with the tug pulling on the VLCC. The standard deviation and maximum towline loads were very similar between the FPSO and the SPM systems.

Many different towlines were used. This included variations in towline lengths (150-400 m), towline materials (steel wire or synthetic lines) and 3 different stretchers. The simulations were carried out in different environments with the wave significant heights ranging from 1 m to 3.5 m and for 2 stern tug bollard pull levels of 15 t and 30 t. A total of 1280 fast time simulations were carried out.

The simulations showed that for wave H_s less than 1.5 m, all the different line configurations will be feasible. However, for waves greater than 1.5 m, the shorter line lengths of 150 and 200 m will need a stretcher. Without the stretcher, the safe working loads were exceeded.

The maximum towline tensions (tones) for a wave H_s of 2.5 m is also shown in the table below (FPSO system). The towline loads decrease with increasing length of the towline. For a given towline length, the maximum loads also decrease when using a stretcher with the lowest loads seen for the nylon stretcher which has the lowest stiffness.

The towline tensions also increase with the 30 t tug force compared to the 15 t tug. This increase is greater for the steel wire. Steel wire generally have a lower stiffness due to the "catenary" effect of their higher mass. However, with the higher 30 t tug force, the catenary effect is reduced and its stiffness is comparable (for the shorter lengths, even higher) to the synthetic line.

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
		Tug Force = 15 t							
H_s = 2.5 m V_w = 30 kn	150	225	145	170	62	225	157	140	64
	200	154	137	109	58	144	117	108	61
	300	69	49	47	34	105	86	65	54
	400	33	31	30	28	63	56	53	40
		Tug Force = 30 t							
H_s = 2.5 m V_w = 30 kn	150	265	192	220	80	232	202	163	75
	200	234	227	140	75	197	149	144	67
	300	148	114	105	71	135	84	79	69
	400	84	69	64	52	76	75	70	58

The standard deviations of the towline loads were always higher when using the synthetic lines compared to the steel wire with the 15 t tug force. The maximum loads were also generally, but not always, slightly higher when using the synthetic lines. However, when pulling with a 30 t tug force the standard deviations of the towline loads were higher for the shorter (150 m, 200 m) steel wire lines. The maximum loads are also generally higher when using the steel wire.

The relative motions between the tanker and tug vary with the design of the towline assembly. Therefore, a couple mooring analysis in which the vessel motions and line loads are solved simultaneously is needed to derive the motions and line loads on a particular application. Based on industry practice and the results of the technical study discussed in this report it is possible to provide some generic guidance for static tow operations:

- It is good practice to select a stretcher with similar strength to the main towline.
- The strength (MBL) of the towline on offshore tugs is typically about 3 times the bollard pull of the tug.
- The stiffness of the stretcher can be varied by choosing its material and length. The optimal stiffness depends on wave conditions and the stiffness of the main towline.
- This study shows that towline lengths of 200 m can be used in sea conditions up to 1.5 m significant height. For higher sea states the towline length should be increased further, or a stretcher should be included.
- If due to towline length limitations or other considerations, it is not possible to deploy the recommended towline length, a stretcher should be included. A stretcher material with large stretch (>10%) at the MBL is most effective.
- If a 20 m Nylon stretcher is used, the tug can maintain its 200 m towline in up to 2.5 m significant wave height and only needs to increase the deployed towline length for sea conditions above that.

1 INTRODUCTION

OCIMF has requested MARIN to study the effect of a stretcher on a towline assembly during static tow. An industry survey shows that these stretcher are not always utilized in towline assemblies. This study aims to understand below what towline length and above which weather conditions, the stretchers become advantageous to reduce the peak line loads. The study will focus on an ASD tug with HMPE and steel wire towline assemblies of various length for increasing weather conditions. All simulations will be carried out with and without stretcher.

1.1 Objectives

The main objective of the study is to identify when an d what length of stretcher would be m ost effective at reducing peak loads in towlines, while maintaining a high level of control for the static tow.

1.2 Content of the report

In this report the following topics are addressed:

- Description of the sign conventions
- Description of the applied software
- Description of the simulation model
- Discussion of the Environments and simulation matrix.

2 SIGN CONVENTION

2.1 Units

The following metric (SI) units are used throughout this report unless otherwise stated:

- Motions and dimensions are given in meter [m]
- Angles are given in degrees [deg]
- Forces are given in 1,000 Newton [kN]
- Moments are given in 1,000 Newton meter [kNm]

2.2 Local Coordinate System (LCS)

The applied sign convention and coordinate system are in accordance with the OCIMF recommendation. An overview of this standard is given in Figure 2-1. The origin of the Local Coordinate System (LCS) is located at the intersection of the keel, centreline and halfway L_{pp}. A right handed coordinate system is applicable. The order of rotations is Yaw-Pitch-Roll.

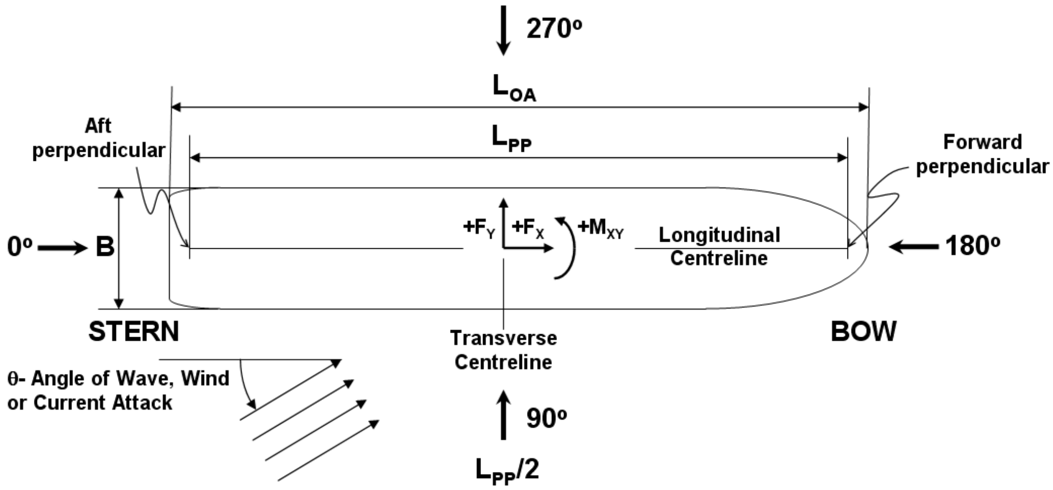


Figure 2-1: General OCIMF convention

The motions are positive in the following directions:

positive surge	(x)	: towards the bow
positive sway	(y)	: towards port side
positive heave	(z)	: upwards
positive roll	(ϕ)	: starboard side down
positive pitch	(θ)	: bow down
positive yaw	(ψ)	: bow towards port side

The forces and moments are positive in the following directions:

positive longitudinal force	(F_x)	: towards the bow
positive lateral force	(F_y)	: towards port side
positive vertical force	(F_z)	: upwards
positive roll moment	(M_x)	: starboard side down
positive pitch moment	(M_y)	: bow down
positive yaw moment	(M_z)	: bow towards port side

The relative environmental headings are defined as follows:

0 degree heading	: stern on
90 degrees heading	: starboard side on
180 degrees heading	: bow on
270 degrees heading	: port-side on

2.3 Global Coordinate System (GCS)

The origin of the Global Coordinate System (GCS) is located in the Still Water Line (SWL). A right handed coordinate system is applicable. At the start of each simulation, the local coordinate system and global coordinate system have the same orientation.

3 APPLIED SOFTWARE

3.1 Linear diffraction analysis programs DIFFRAC / DRIFTP

The added mass, damping, wave loads and wave drift forces are calculated using MARIN's linear diffraction theory programs DIFFRAC and DRIFTP. In DIFFRAC / DRIFTP the linearised velocity potential problem is solved using a three-dimensional source distribution technique.

The mean wetted part of the vessel hull is approximated by a large number of panel elements. The distribution of source singularities on these panels forms the velocity potential describing the fluid flow around the vessel hull.

The pressure distribution on the hull is calculated from the velocity potential. The added mass and damping coefficients, as well as the first order wave forces (DIFFRAC) and second order wave drift forces (DRIFTP) are then determined from the pressure distribution and written to a hydrodynamic database. All calculations in DIFFRAC / DRIFTP are carried out in the frequency domain.

3.2 Time-domain simulation tool aNySIM

The time-domain simulation program aNySIM can simulate the behaviour of (multiple floating) bodies under the action of combined swell, wind seas, current and wind. The effect of mooring lines and other mechanical components on the floater motions can also be taken into account. In the simulations, the combined low frequency and wave frequency motions of each body are calculated in 6 degrees of freedom in the time-domain, using a retardation function approach.

Equations of motion

The equations of motion derived within potential theory describe the fluid reactive forces on a floating structure under arbitrarily external loads varying in time. For 6 degrees of freedom these equations can be written as shown below:

$$\sum_{j=1}^{6} (M_{kj} + m_{kj})\ddot{x}_j + \int_{-\infty}^{t} R_{kj}(t-\tau)\dot{x}(\tau)d\tau + C_{kj}x_j = F_k(t) \qquad k = 1, 2 \ldots 6$$

in which:

x_j	Motion in j-th mode
$F_k(t)$	Arbitrarily in time varying external force in the k-th mode of motion
M	Inertia matrix
m	Added inertia matrix
R	Matrix of retardation functions
C	Matrix of hydrostatic restoring forces

The retardation functions R, as well as the added inertia coefficients m, are determined using the results of the diffraction calculations.

Wave exciting forces

The low frequency and wave frequency wave exciting forces and moments are also calculated using the diffraction calculations. First order wave load coefficients in combination with a specified wave spectrum are used to calculate the first order wave loads. The second order wave drift forces are calculated using the quadratic transfer functions (QTFs) from the diffraction calculations.

Wind and current loads

The wind and current loads on the vessel are calculated within aNySIM using dimensionless coefficients. Body dimensions and the wind / current conditions (velocity and direction) are considered in the simulations.

Mooring lines

Mooring lines are modelled in aNySIM as catenary elements with an axial stiffness. Bending stiffness is not taken into account. Mooring lines can be composed of multiple segments, each with its own set of properties. Drag and inertia loads from the water on the mooring lines are not taken into account.

Springs

Spring elements can be used to connect two bodies. The forces always act in line with the spring element. The stiffness can be specified either by means of a combination of a linear stiffness and a quadratic stiffness, or by means of a load-elongation curve. Damping can be specified as a combination of linear damping and quadratic damping.

4 SIMULATION MODEL

The objective of this study was to look at the impact of stretchers on the snap loading of towlines in a static tow. This will be determined by carrying out a lot of different time domain simulations. This chapter describes the input that will be used in the simulation models.

4.1 Vessels

Three different vessels will be considered in the study – FPSO, VLCC and a tug.

There are two different configurations – 1) VLCC connected to a CALM buoy with the tug pulling back on the VLCC and 2) VLCC in tandem to a turret moored FPSO with the tug pulling back on the VLCC.

The main differences in the two scenarios is the distance of the tug from the rotation point (SPM or FPSO turret). The motions of the FPSO will not be c ritical in looking at the tug towline loads. Therefore, the same VLCC tanker model has been used for both the FPSO and the tanker (intermediate draft). The only difference will be in their wind areas, the FPSO has a much bigger topsides area. The table below gives some of the critical details of the three vessels, a more complete set of particulars in given in Table 1.

Table 4-1: Main particulars of the vessels

Particulars	Units	FPSO	VLCC	Tug
Length between perpendiculars	[m]	354.4	354.4	50
Beam	[m]	58	58	13.5
Draft	[m]	14.4	14.4	4.25
Mass	[tonnes]	245386	245386	2153
Area front	[m]	2500	2300	200
Area side	[m]	12300	6500	500

The wave forces, added mass and potential damping of the three vessels will be calculated using the frequency domain program Diffrac. This data will be stored in “hydrodynamic database” files. These files will then be used in the time domain software Anysim.

4.2 Mooring

4.2.1 Turret Mooring

The turret mooring system of the FPSO will be modelled with a surge and sway spring. These springs will be placed 20 m in front of the forward perpendicular of the FPSO (external turret). The spring stiffness will be 300 kN/m. This will give a natural period of approximately 190 s for surge and 210 s for sway motion of the FPSO.

4.2.2 SPM mooring

The CALM buoy will be modelled as a body with springs connected to it. The mass of the CALM buoy combined with the vertical pretension of the mooring is assumed to be 2500 tonnes and the surge and sway springs will again be taken as 300 kN/m. Assuming the added mass in surge and sway is equal to the dry mass, the surge and sway natural periods of the CALM buoy will be ~25 s. It should be noted that the CALM buoy will not have a hydrodynamic file, i.e. it will not be acted on by the environment. The motions of the CALM buoy will only be governed by the hawser loads on it and the surge/sway spring.

4.2.3 Hawsers

The hawser between the SPM and the VLCC and the hawser between the FPSO and the VLCC are both assumed to be 80 m long and made of 160 mm diameter Nylon rope. The properties of this line are given in the table below and the load elongation curve is given in Figure 4-1.

Table 4-2: Nylon hawser properties

Rope Diameter	160 mm
Mass in air	16.2 kg/m
Mass in water	1.56 kg/m
MBL (dry)	5925 kN
MBL (wet)	5435 kN

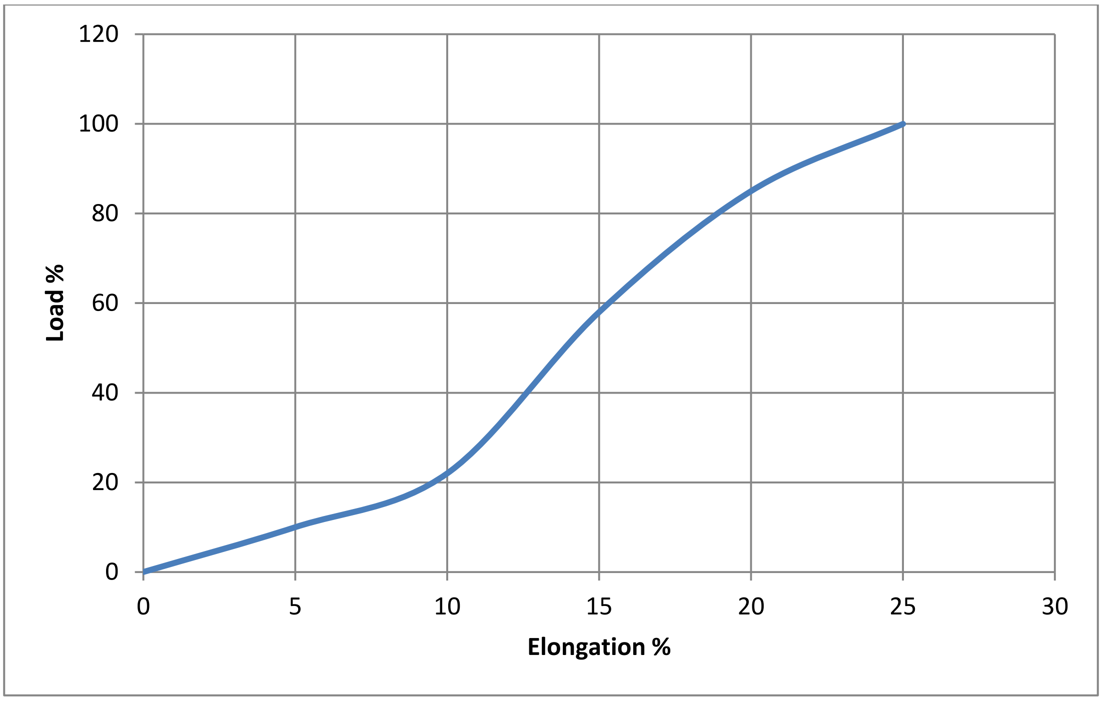


Figure 4-1: LEC curve of Nylon hawser

4.2.4 Tug Towline assembly

Four different tug towline assemblies will be used in the simulations:

- Steel wire towline
- Synthetic towline
- Steel wire towline with stretcher
- Synthetic towline with stretcher

The steel wire towline will be 56 mm in diameter. The mass in air is 13.1 kg/m (mass in water is 11.4 kg/m) and the MBL is 2190 kN. The stiffness (EA) of this line is 151549 kN.

The synthetic towline will also be 56 mm in diameter. The mass in air is 1.9 kg/m and MBL is 2237 kN. The figure below gives the load elongation curve.

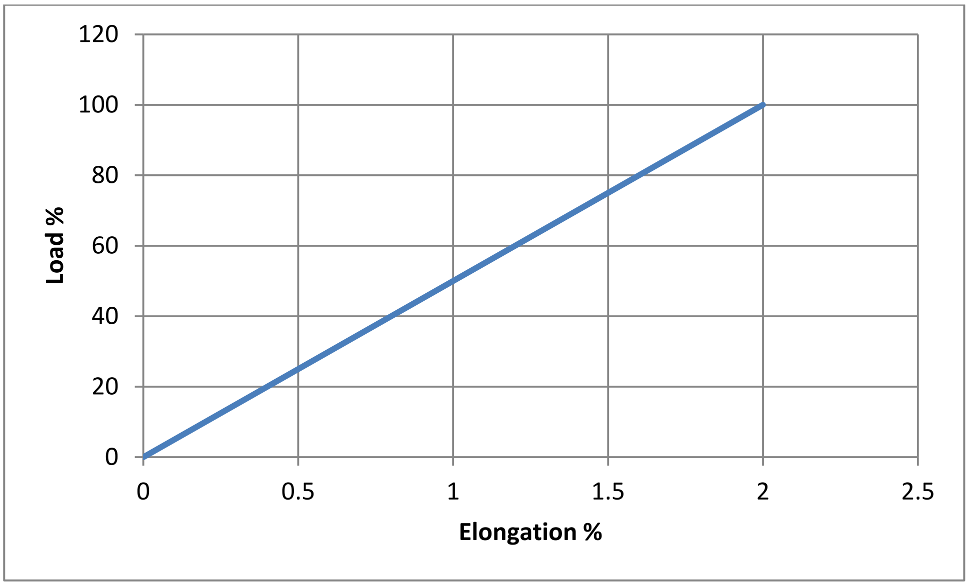


Figure 4-2: LEC curve of synthetic towline

Four different stretchers were proposed based on what is being used in the field in West Africa and Thailand. The stretcher used in Thailand is much weaker than the ones in West Africa because the weather is milder. Since the steel wire/ synthetic line part has a MBL of around 220 tons, only the stretchers from west Africa were considered in this study.

Table 4-3: Properties of the proposed stretchers

	Nigeria		Angola	Thailand
Diameter [mm]	96	96	80	80
Type	Grommet	single leg	grommet	single leg
Length [m]	20	15	25	20
MBL [t]	185	221	225	90
Material	Polypro	47% polyolefin,53% polyester	Nylon	polyprop or polyethylene

The load elongation curves (LEC) for the stretchers have been taken from OCIMF Meg 4 and manufacturers catalogue. The LEC for the polypropylene line is from the OCIMF document. The LEC for 47-53 mix line and the Nylon line are from manufacturers specifications. A grommet configuration will be 2 times as stiff as a single-leg rope. All the 3 stretchers will be modelled in the study.

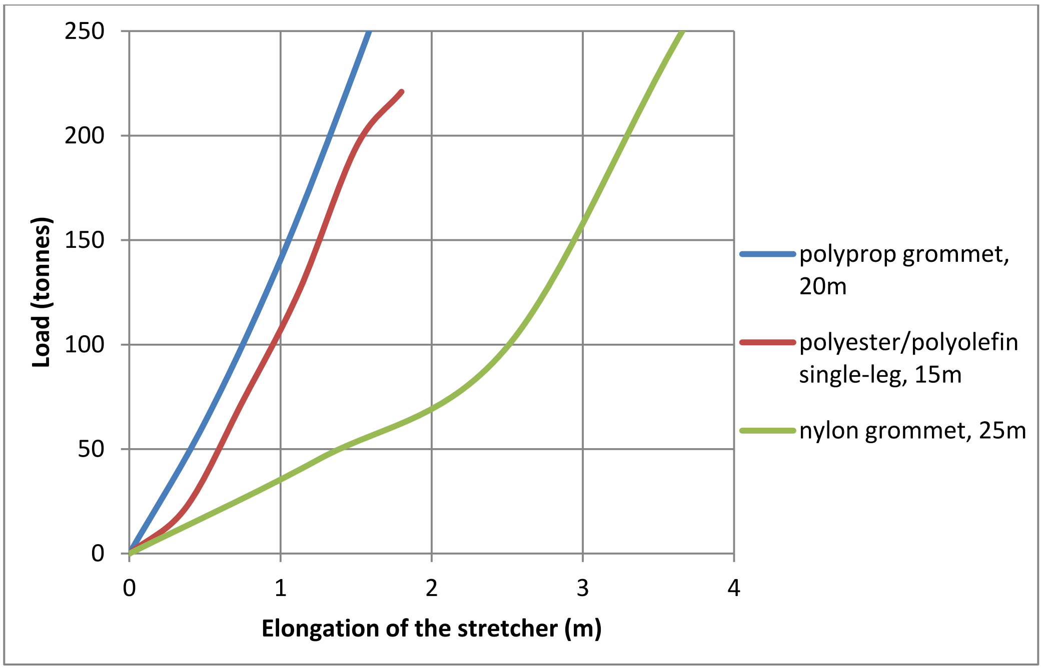


Figure 4-3: LEC curves for the 3 different stretchers

4.3 Current coefficients

The mean current loads are calculated with the following formulas:

$$F_x = \frac{1}{2}\rho v^2 T L_{pp} C_x$$

$$F_y = \frac{1}{2}\rho v^2 T L_{pp} C_y$$

$$M_z = \frac{1}{2}\rho v^2 T L_{pp}{}^2 C_N$$

in which:

F_x	Force in longitudinal direction	[kN]
F_y	Force in transverse direction	[kN]
M_z	Moment about vertical z-axis	[kNm]
ρ	Water density (specified as 1.025)	[tonne/m^3]
v	Current velocity	[m/s]
T	Draft	[m]
L_{pp}	Length between perpendiculars	[m]
C	Dimensionless current force coefficient	[-]

The OCIMF current coefficients for a cylindrical tanker in deep water are used for the FPSO and VLCC. OCIMF only gives the coefficients for ballast and loaded drafts. Since an intermediate draft has been used in this study, the average of the ballast and loaded is used. The current coefficients for the tug are from MARIN's database.
The current coefficients are given in Table 2 and Table 3 and are plotted in Figure 1 and Figure 2.

4.4 Wind coefficients

The wind loads are calculated with the following formulas:

$$F_x = \frac{1}{2}\rho v^2 A_f C_x$$

$$F_y = \frac{1}{2}\rho v^2 A_l C_y$$

$$M_z = \frac{1}{2}\rho v^2 A_l l_{pp} C_N$$

in which:

F_x	Force in longitudinal direction	[kN]
F_y	Force in transverse direction	[kN]
M_z	Moment about vertical z-axis	[kNm]
ρ	Air density (specified as 0.00125)	[tonne/m^3]
v	Wind velocity	[m/s]
A_f	Wind frontal area	[m^2]
A_l	Wind lateral area	[m^2]
L_{pp}	Length between perpendiculars	[m]
C	Dimensionless wind force coefficient	[-]

The wind coefficients for the FPSO are taken from MARIN's database. OCIMF wind coefficients are used for the VLCC. Again, the average of the loaded and ballast drafts is used. The tug wind coefficients are from MARIN's database.

The wind coefficients are given in Table 4 through Table 6 and are plotted in Figure 3 - Figure 5.

4.5 Decays and Damping

Any moored object in waves will show first order wave frequency motions, caused by first order wave loads, as well as low frequency (LF) motions, caused by second order wave drift forces. The damping of the first order motions consists mainly of potential damping, due t o radiated waves. The LF motions, on the other hand show such long periods that no waves are radiated. For this reason, the LF damping is of viscous origin only and needs to be included in the simulation model. In addition to the LF damping, roll damping is also of viscous origin.

Figure 6 shows the free floating roll decays of the FPSO, VLCC and the tug. A roll moment is applied on the vessels so that their initial heel angle is 5 deg. The moment is then removed and the vessel is allowed to decay back to its equilibrium position. The natural roll period of the FPSO and VLCC are 15.3 s and that of the tug is 12.4 s. Roll damping equal to 3% of the critical damping value has been applied to each vessel.

Surge and sway damping has been applied to the CALM buoy (equal to 4% of critical damping at a period of 25 s). Surge damping has also been applied to the FPSO, VLCC and Tug. For the FPSO and VLCC the damping value is equal to 2% of critical damping at a surge period of 185 s. For the tug, the surge damping is equal to 2% of the critical value at a period of 15 s. No additional sway damping has been applied to the vessels while a cross-flow damping model is applied to yaw.

Table 4-4: Applied damping on the various bodies

	Roll [kNms]	Surge [kNs/m]	Sway [kNs/m]
FPSO	3.44E+06	351	-
VLCC	3.44E+06	351	-
Tug	2.04E+03	37.9	-
CALM buoy	-	98	98

Figure 7 shows the surge decay of the whole SPM system in calmwater when the 15 t force is applied at the stern of the tug. The surge period of the whole system is ~334 s. In addition to this, a couple of different periods can also be seen in the first few hundred seconds. One is the period at which the Calm buoy oscillates (~22 s) and the other is the period of the tug (~15 s) associated with the tow-line spring. This period will be different for the different tow-lines. Figure 8 shows the yaw decay of the SPM system in the presence of a 1 kn current from 135 deg (bow quartering), with the tug pulling south at 15 t. The VLCC has a mean heading of 23 deg while the tug has a mean heading of 3 deg. The two vessels reach their mean orientations after about an hour.

Figure 9 shows the surge decay of the whole FPSO system in calmwater. The surge period is ~350 s. Again, a tug oscillation at a ~15 s period can also be distinguished. Figure 10 shows the yaw decay in a 1 kn current from 135 deg. The equilibrium headings of the FPSO, VLCC and Tug are 45 deg, 23 deg and 3 deg respectively. The FPSO heads into the current in this case.

Different towline configurations have been considered in this study that vary the materials (steel wire or synthetic line), stretcher and total length of the towlines. The towline acts as a spring that is connected to the tug and depending on the type of the towline the spring varies and hence the associated natural period in surge of the tug also varies.

Table 4-5 shows the natural periods in surge of the tug when it is connected to the VLCC with the different towlines that have been used in this study. These periods were calculated from simulations in calmwater where the VLCC was fixed and a 15 t force was applied at the stern of the tug.

Since steel wire is much heavier than synthetic line, there is a “catenary” effect that decreases the stiffness of the spring associated with a steel wire towline. The natural periods of the steel wire only lines (no stretcher) vary from 14.3 s to 42.9 s depending on the length (lower period means stiffer spring). Since the 400 m long line is heavier than the 150 m long line, the “catenary” effect is higher and results in a less stiff spring. Including a stretcher increases the natural periods further. The nylon stretcher has the biggest effect in this regard since it has the least stiffness. It should also be noted that the effect of the stretcher in modifying the towline-stiffness and hence the natural periods is most pronounced for the shorter lengths. When the towline is 400 m long, the stretcher does not modify it much.

The natural periods associated with the synthetic-only lines range from 11.4 to 19.7 s for the different lengths. Again, adding the Nylon stretcher has the greatest effect on decreasing the stiffness and increasing the surge periods.

Table 4-6 shows the natural periods when a 30 t tug force is applied. The natural periods with the synthetic lines and its various stretchers don’t change much from when the 15 t force is applied. However, the periods change a lot for the steel wires and it’s various stretchers. This is because the higher tug force decreases the “catenary” effect and hence increases the stiffness of the steel wire. The natural periods between the steel and synthetic lines are quite similar for the line lengths of 150 m, 200 m and 300 m.

Table 4-5: Surge natural periods (15 t Tug force) for different towline configurations

Steel Wire Line	Natural period in seconds for Stretcher Type			
Length [m]	None	Polyprop	47-53 mix	Nylon
150	14.3	16.0	17.0	20.9
200	19.5	20.8	21.6	24.8
300	32.2	32.8	34.0	35.4
400	42.9	43.4	43.7	45.0
Synthetic Line	Natural period in seconds for Stretcher Type			
Length [m]	None	Polyprop	47-53 mix	Nylon
150	11.4	13.5	14.6	18.9
200	13.2	15.1	16.1	20.1
300	16.6	18.1	18.9	22.5
400	19.7	21.0	21.7	24.9

Table 4-6: Surge natural periods (30 t Tug force) for different towline configurations

Steel Wire Line	Stretcher Type			
Length	None	Polyprop	47-53 mix	Nylon
150	10.4	12.8	14.0	18.5
200	12.7	14.7	15.7	19.9
300	17.3	18.9	19.7	23.2
400	22.5	23.9	24.4	28.3
Synthetic Line	Stretcher Type			
Length	None	Polyprop	47-53 mix	Nylon
150	11.3	13.3	14.4	18.8
200	13.0	14.8	15.8	19.8
300	16.0	17.5	18.3	21.9
400	18.5	19.8	20.6	23.8

5 ENVIRONMENTS AND SIMULATION MATRIX

The simulations will be carried out for the environments given in the table below. They have been based on the operational environmental list given by the participants but some adjustments have been made to the wave peak periods so that the wave heights and periods are in-line with the DNV ERN criteria.
The FPSO operates in higher waves than the SPM, so the simulations with SPM will only be done till wave heights of 2 m.

Table 5-1: Environmental matrix

FPSO	SPM	Location	Collinear wind and waves, current 45deg off from wind				Optional Swell crossed	
			V_w [kn]	H_s [m]	T_p [s]	V_c [kn]	H_s [m]	T_p [s]
x	x	Thailand	25	1	5	1	1.4	8
x	x	Nigeria	10	1.5	6	1	0.5	12
x	x	Nigeria	10	2.0	8	1	0.5	12
x	x	Brazil	25	2.0	8	1	0.5	12
x		Brazil	30	2.5	9	1	1	12
x		Angola	15	3.5	10	1	0.8	12

The wind and waves are considered to be collinear. The current will be a constant 1 knot in all the simulations and 45 deg off the wind/waves. The swells will be crossed with the waves, i.e. 90 deg off the wind/wave direction. Simulations will be done both with and without the swells. The waves will be modelled as JONSWAP spectra with a gamma of 3.3 and swells will be modelled as JONSWAP spectra of gamma 7.

This gives a total of 20 different environments (6 for the FPSO and 4 for the SPM, all cases done with and without swells).
The following test matrix will be evaluated:

- Towline assemblies with 4 different lengths: 150 m, 200 m, 300 m, 400 m (4)
- Simulations with and without stretchers, 3 different stretchers are considered (4)
- Simulations with steel wire and synthetic line (2)
- 20 different environments
- 2 tug forces at the stern

This results in a total of 4*4*2*20*2 = 1280 simulations.

The simulations will be done with the tug pulling at 15 tonnes and 30 tonnes at the stern of the VLCC such that the tug force is in the direction of the wind and waves, i.e., the tug tries to align the vessels into the wind and waves. All simulations will be done for a duration of three hours. A schematic of the operation is shown in Figure 5-1.

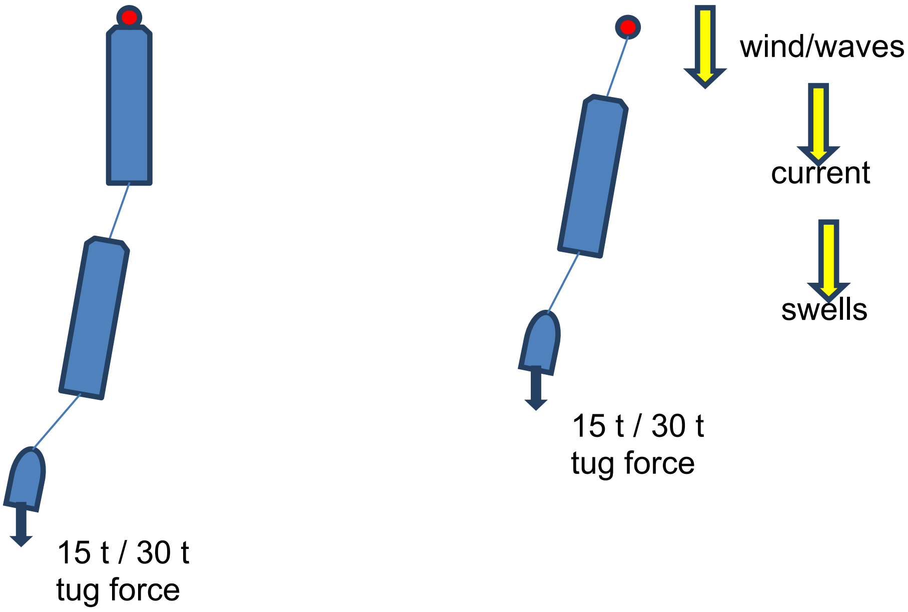


Figure 5-1: Schematic of the static tow operation with the FPSO and CALM buoy

6 RESULTS AND DISCUSSION

6.1 Review of Safetug JIP

MARIN carried out the SafeTug joint industry project (JIP) with a lot of industry partners in 2007 to study the operability of tugs in waves. A short review of that is given in this section.

Two main operations were studied in the JIP:

1) Escort: where the tug is following the ship at considerable speed (6-10 knots) to help it its maneuvering and braking.
2) Berthing: Assisting the ship at almost zero speed in either pull or push mode.

The berthing operations are a little more relevant for this current study although there are still some differences between that and static tow operations carried out offshore. The tow-lines used in berthing are quite short (50-80 m) since the tug will have to operate in both pull and push modes. The size of the tugs offshore are also a bit bigger than what is typically used in berthing operations.

During the start of the JIP, data was also collected from the participating tug captains about the tugs and equipment used in the field. The mean ASD tug length was 33.4 m with a mean bollard pull of 63 tons. The strength of the towline on the ASD tugs was commonly about 3-4 times the BP of the tug. The mean towline length for berthing was 50.5 m and the mean towline length for escorts was 75.5 m (note that this is significantly shorter than the towline lengths used for the static tow operations).

Data was also collected from the captains on the winches and towlines used in the tugs (based on answers from questionnaires). The mean brake holding capacity of the forward winch on ASD tugs was 152 tons (range from 80-250 tons). The mean brake holding capacity of the aft winch was 154 tones (range from 70 to 250 tons). The brake holding forces are commonly 2-2.5 times the tugs bollard pull. The data also said that more than half the winches had no load limiting devices. The tug captain is considered to have little influence on the reaction of the tugs to individual waves. The data collected on winches is given in Table 7.

The most common towlines used were made of synthetic line and galvanized steel wire. The most common stretchers were made of Nylon. The stretchers were only used with the steel wire. From the limited data available, no stretcher was used on the synthetic line.

The JIP studied an ASD tug and a Voith Schneider tractor tug since those are the most common tug designs used for berthing and escort operations. Model tests were carried out in different environments to study the tug motions, thruster performance in waves, towline dynamics, wave field around the LNGC and interactions between the tug and LNGC.

The tug used in the model tests had a length of 36 m and bollard pull of 80 tons. The towline used in the model test was an 80 mm diameter synthetic line with a 411 t MBL. Different lengths of the towlines ranging from 30 m to 80 m were used. Some of the tests had a 15 m long Nylon stretcher and some model tests also had a simplified render-recover winch. Peak loads of up to 6-8 times the bollard pull were observed for certain critical environments with the stiff towline. The peak loads could be decreased with the use of a stretcher. However, after a large load in a line with a stretcher, there is a forward surge of the tug (referred to as “catapulting” by the tug captains). This overshoot gives a slack line and when the line comes under tension again, there will be another peak load. Overall, this can make it a bit difficult to control the tug. Using the render- recover winch gives better control and also lower loads in these cases. However, these winches are not found in all tugs.

It was also noted that it is best to connect the towline to the winch at the bow of the ASD tug. It is sometimes not done in practise due to limitation on the bow winch or on the length of line on the bow winch. This current study does not model a winch. The towline has also been assumed to be connected to the bow of the tug with the 15 t force acting at the stern.

6.2 Results from Dynamic Simulations of the Static Tow, FPSO system

A total of 1280 simulations were done for the different configurations. As mentioned in Chapter 5, 2 different mooring line types, 3 different stretchers, 4 mooring line lengths and 2 tug forces were considered in the simulations. Since the stretchers and the mooring lines have different safety factors, Table 8 shows the safety factors used and the safe working loads of the different towlines based on OCIMF criteria for mooring lines. The safe working loads range from 123 t for a Steel wire line with no stretcher (SF of 1.82) to 74 t for a synthetic line with a polypropylene stretcher (SF of 2.5).

The maximum towline loads for the FPSO system are shown in Table 9 through Table 12. The values have been color coded – with green showing low loads, yellow showing loads near the SWL of the line and red showing loads around the MBL of the lines. The maximum loads increase with the wave heights.

For wave H_s less than 1.5 m, all the different line configurations will be fine. However, for waves greater than 1.5 m, the shorter line lengths of 150 and 200 m will need a stretcher. Without the stretcher, the safe working loads will be exceeded.

The results for a wave height of 2.5 m is also shown in the table below. The loads decrease with increasing length of the towline. For a given towline length, the maximum loads also decrease when using a stretcher with the lowest loads seen for the nylon stretcher which has the lowest stiffness.

The towline loads are also much higher with the 30 t tug, especially for the steel wire. This is because the increased tug force has a greater effect in changing the stiffness of the steel wire towline.

Table 6-1: Max towline loads (t) for H_s = 2.5 m, no swells

Line length [m]	Steel Wire Towline				Synthetic Line			
	Stretcher type (SWL)				Stretcher type (SWL)			
	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
	Tug Force = 15 t							
150	225	145	170	62	225	157	140	64
200	154	137	109	58	144	117	108	61
300	69	49	47	34	105	86	65	54
400	33	31	30	28	63	56	53	40
	Tug Force = 30 t							
150	265	192	220	80	232	202	163	75
200	234	227	140	75	197	149	144	67
300	148	114	105	71	135	84	79	69
400	84	69	64	52	76	75	70	58

The maximum towline loads can change quite a bit for different realizations of the same wave. So it is also instructive to look at the standard deviations of the towline loads which gives a sense of how distributed the data is from the mean values and will be almost the same for different wave seeds. For the tug force of 15 t, the standard deviations are always lower for the steel wire towline. This difference is very pronounced for the longer lines. When the tug force is increased to 30 t, the standard deviations of the line loads are very similar between the steel wire and synthetic lines.

Table 6-2: Std of Towline loads(t) for H_s = 2.5 m, no swells

Line length [m]	Steel Wire Towline				Synthetic Line			
	Stretcher type (SWL)				Stretcher type (SWL)			
	None (123 t	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
	Tug Force = 15 t							
150	29.5	22.7	20.1	10.0	31.4	26.1	23.8	10.9
200	21.5	16.5	12.4	6.9	26.7	21.9	19.1	8.9
300	5.7	4.7	4.4	3.4	18.1	14.4	11.4	7.1
400	2.6	2.5	2.4	2.2	10.1	8.3	7.6	5.6
	Tug Force = 30 t							
150	46.8	36.8	33.3	11.5	42.0	35.9	29.9	11.1
200	40.0	29.4	26.7	9.5	37.9	25.6	17.9	9.5
300	23.1	14.5	11.7	6.9	18.6	13.2	11.7	7.7
400	8.6	6.9	6.4	4.7	11.2	9.4	8.6	6.2

Figure 6-1 shows the comparison of standard deviation (std) and maximum values of the towline tensions for the steel wire and synthetic lines with a 15 t tug force (no distinction has been made between lines that have/don't have stretchers). The standard deviations of the line tensions with synthetic line are always higher compared to using the steel wire. This is because the synthetic lines are more stiff which was also seen Table 4-5 where the surge periods associated with the synthetic lines were smaller than the periods with the steel wire. The maximum loads with the synthetic lines are also generally slightly higher compared to the loads with the steel wire.

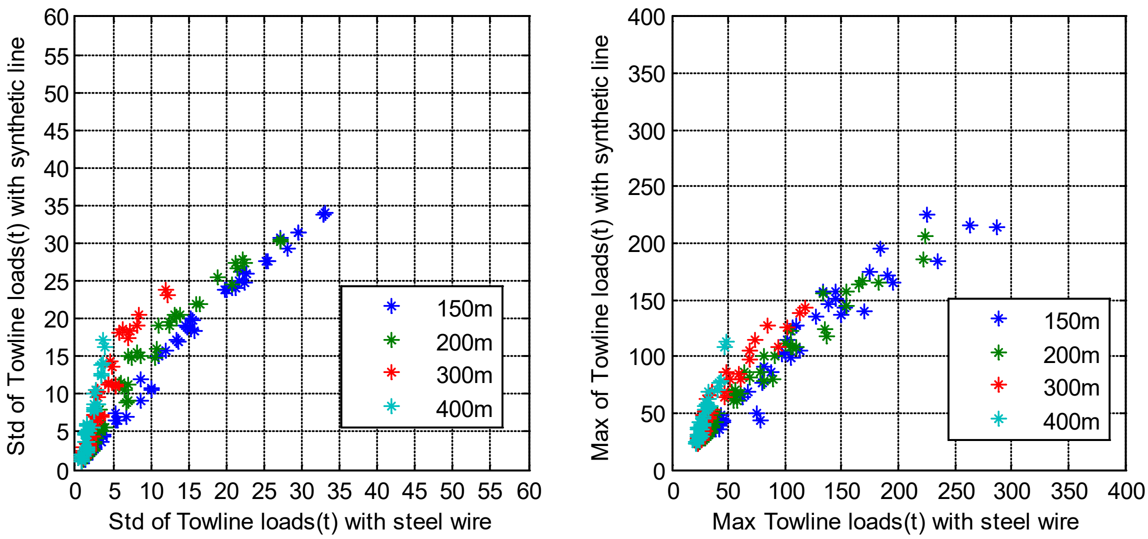


Figure 6-1: Comparison of std and max tensions for steel and synthetic towline, 15 t tug

Figure 6-2 shows the same figure with a 30 t tug. It can be seen here that, especially for line lengths of 150 m and 200 m, the standard deviations are higher for the steel wire towline. The maximum tensions are generally higher with the steel wire towline too. This is because the “catenary” effect of the steel wire has decreased with the higher tug force leading to higher stiffness and hence lower surge periods which are now closer to the wave peak periods and are excited more.

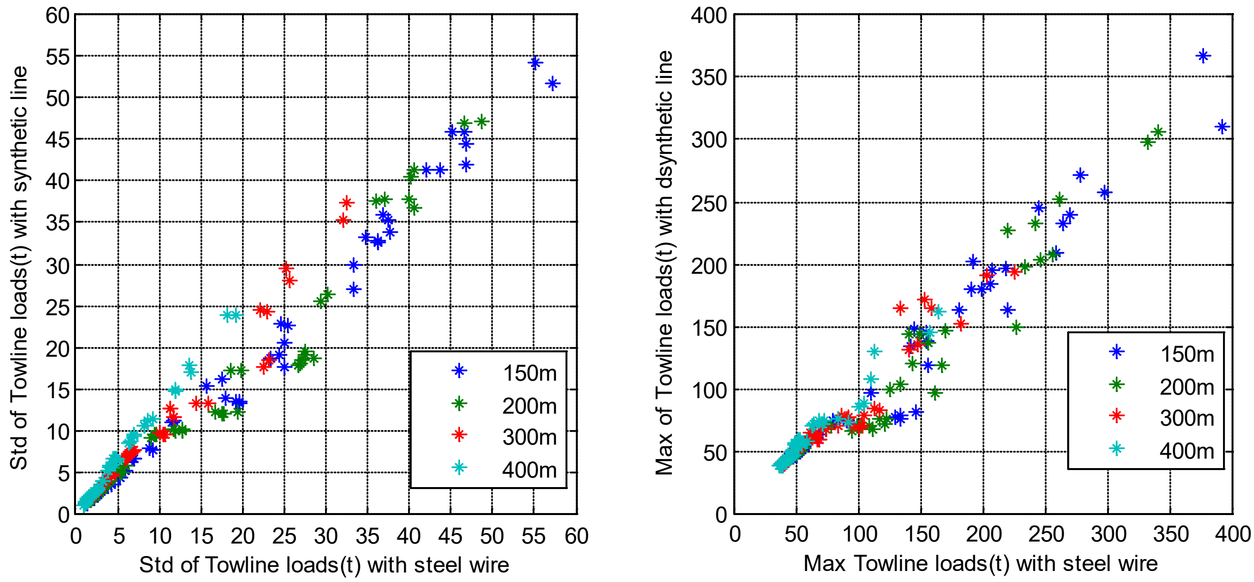


Figure 6-2: Comparison of std and max tensions for steel and synthetic towline,30 t tug

Figure 6-3 and Figure 6-4 shows the comparison between std and maximum towline tensions in the presence and absence of the swells from the beam of the vessel. It can be seen that the swells have some effect only when the waves are small (the swell height is 1.4 m when the wave is 1 m). For waves greater than 2 m, the swells don’t have much effect on the loads.

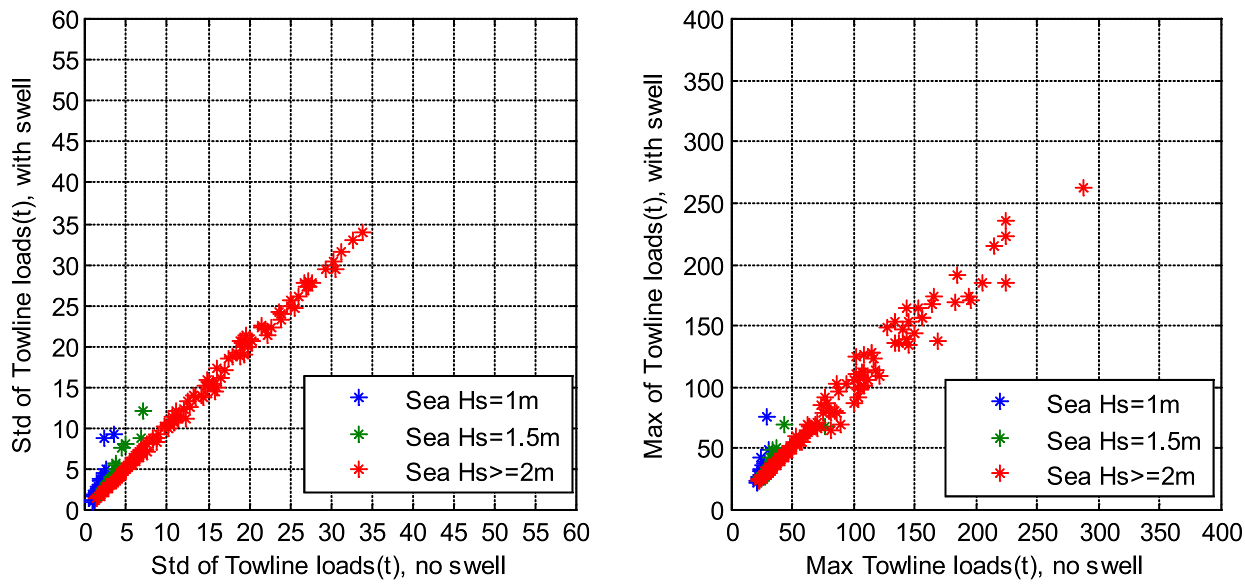


Figure 6-3: Comparison of std and max towline tensions with and without swell, 15 t tug

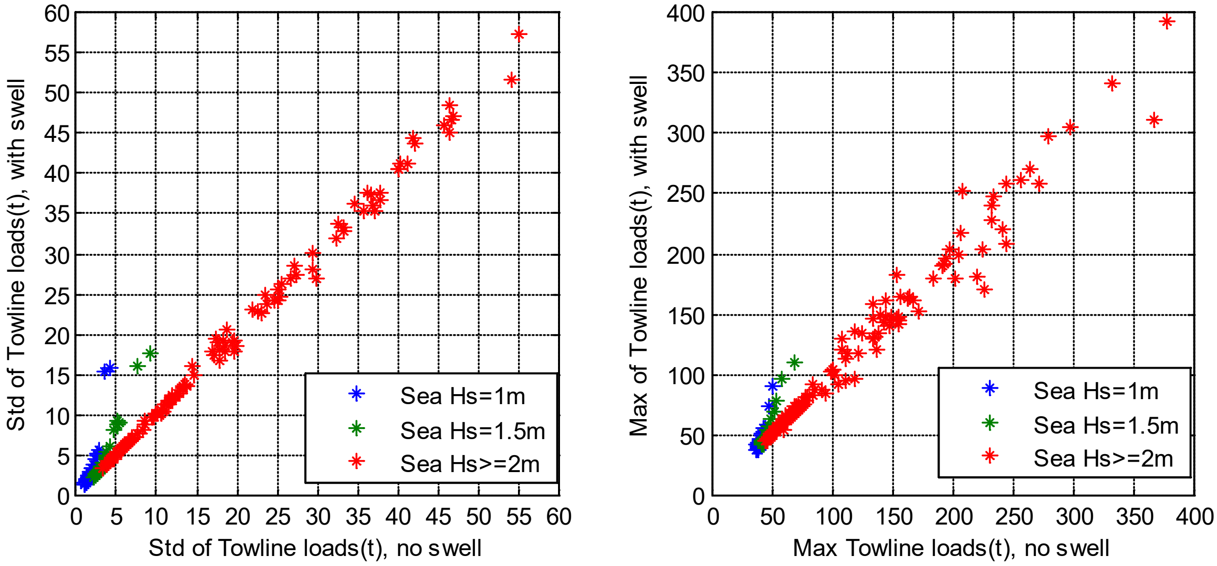


Figure 6-4: Comparison of std and max towline tensions with and without swell, 30 t tug

Figure 6-5 shows the effect of using a stretcher for a couple of different environments. On the first row, the wave height is only 1 m. The towline tensions are similar when using a 200 m long steel wire or a 175 m long wire plus a 25 m long nylon stretcher. Looking at the spectra of the line tensions, two different frequencies can be clearly distinguished: 1) The wave frequency (omega = 1.25 rad/s for T_p = 5 s) and 2) A lower frequency related to the towline stiffness. As was also seen in Table 4-5, the surge period of the tug for a 200 m steel wire was 19.5 s(0.32 rad/s) and for a 175 m wire+25 nylon stretcher was 24.8 s (0.25 rad/s).

The second row shows the towline tensions for a higher wave height of 2 m. Here, there is a lot of snap loading of the steel wire while the steel wire with nylon stretcher has significantly lower loads. The energy in the line load spectra for the steel wire only line is now spread over a wide range of frequencies and the peak at 0.32 rad/s has now shifted to 0.28 rad/s (22.4 s).

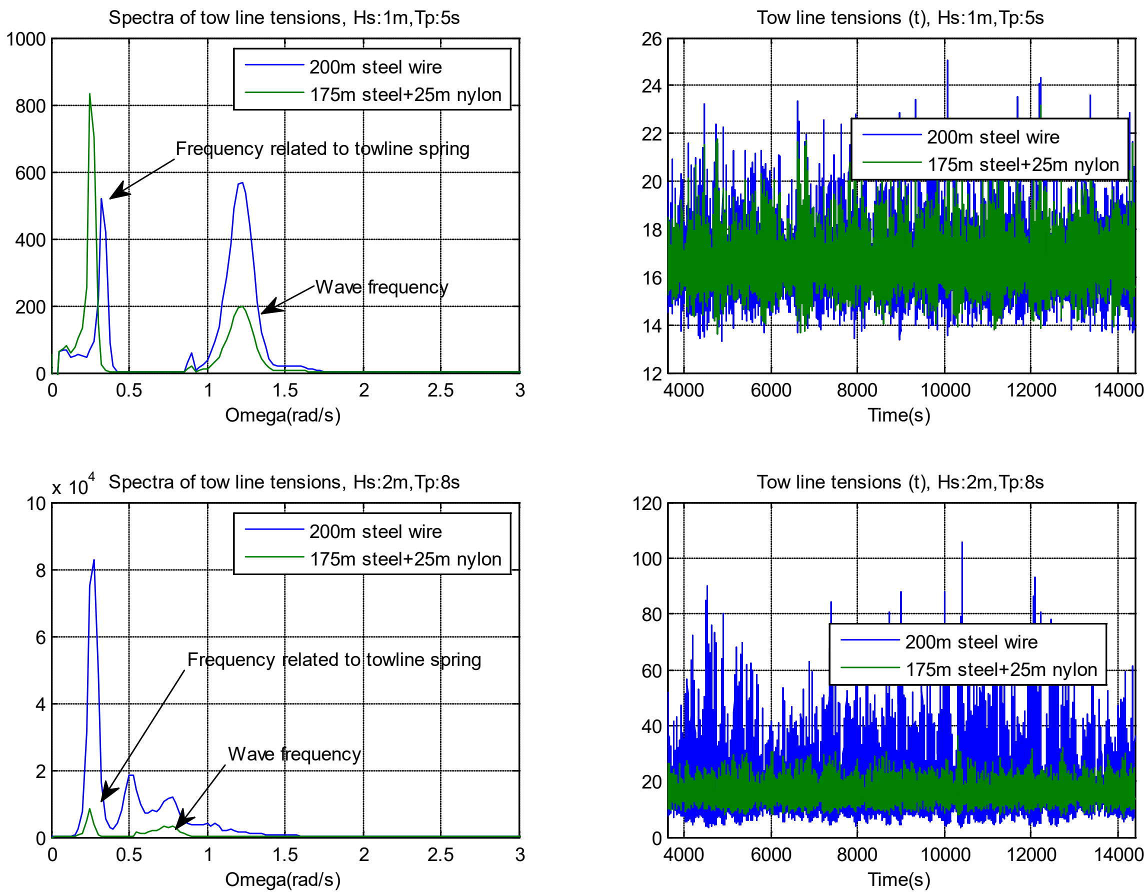


Figure 6-5: Comparison of towline tensions with and without stretchers, 15 t tug

6.3 Results from Dynamic Simulations of the Static Tow, SPM system

The maximum towline loads for the SPM system are shown in Table 13 through Table 16. The results for H_s = 2 m are s hown in the table below. In order to operate safely in 2 m waves, either longer towlines of 300/400 m or a shorter line with a stretcher needs to be used. This is true for both the 15 t and 30 t tug forces although the loads are higher with the 30 t tug.

Table 6-3: Maximum Towline loads(t) for H_s = 2 m, no swells

Line length [m]	Steel Wire Towline				Synthetic Line			
	Stretcher type (SWL)				Stretcher type (SWL)			
	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
	Tug Force = 15 t							
150	150	118	93	48	135	109	88	43
200	104	77	61	40	110	86	63	42
300	35	33	31	30	61	49	42	40
400	26	27	27	27	44	38	37	32
	Tug Force = 30 t							
150	209	144	122	61	176	93	83	59
200	164	118	103	57	94	72	70	57
300	81	63	62	53	69	59	56	53
400	58	52	50	44	57	52	51	47

The standard deviations are higher for the synthetic lines if a 15 t tug is used. However, with a 30 t tug, the standard deviations are higher for the shorter (150 m and 200 m) steel wire.

Table 6-4: Standard Deviation of Towline loads(t) for H_s = 2 m, no swells

Line length [m]	Steel Wire Towline				Synthetic Line			
	Stretcher type (SWL)				Stretcher type (SWL)			
	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
	Tug Force = 15 t							
150	22.2	16.6	13.6	5.7	25.0	19.9	16.7	6.4
200	12.2	8.4	6.7	4.1	19.7	15.3	9.6	5.6
300	2.9	2.7	2.7	2.3	9.9	6.9	6.2	4.4
400	1.7	1.6	1.6	1.5	5.8	5.1	4.8	3.7
	Tug Force = 30 t							
150	36.5	23.9	15.9	6.9	32.1	17.4	13.3	6.7
200	28.7	19.7	12.5	5.8	18.4	12.0	10.0	5.8
300	9.4	6.8	5.9	4.3	9.5	7.5	6.7	4.7
400	4.8	4.2	3.9	3.2	6.6	5.7	5.2	4.0

Figure 6-6 shows the comparison of standard deviation (std) and maximum values of the towline tensions for the steel wires and synthetic lines with a 15 t tug(no distinction has been made between lines that have/don't have stretchers). As seen before, the standard deviations of the line tensions with synthetic lines are always higher compared to using the steel wires. The maximum loads with the synthetic lines are also generally slightly higher compared to the loads with the steel wire.

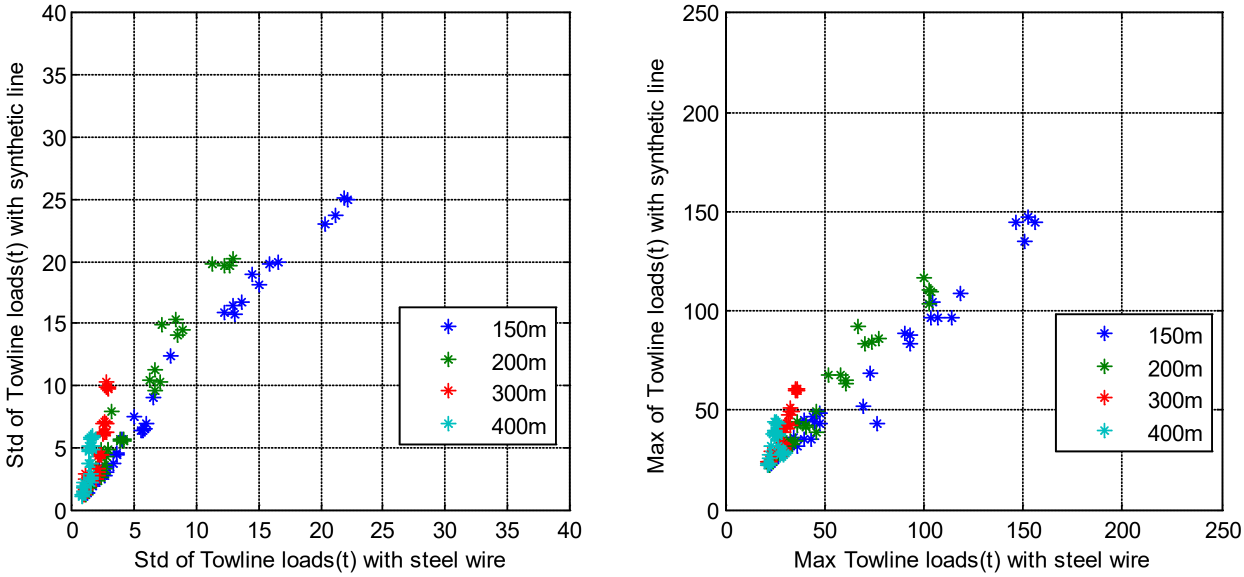


Figure 6-6: Comparison of std and max tensions for steel and synthetic towline, 15 t tug

The figure below shows the same data with the 30 t tug. The standard deviations are now higher for the shorter steel wire. The maximum loads are also generally higher for the steel wire.

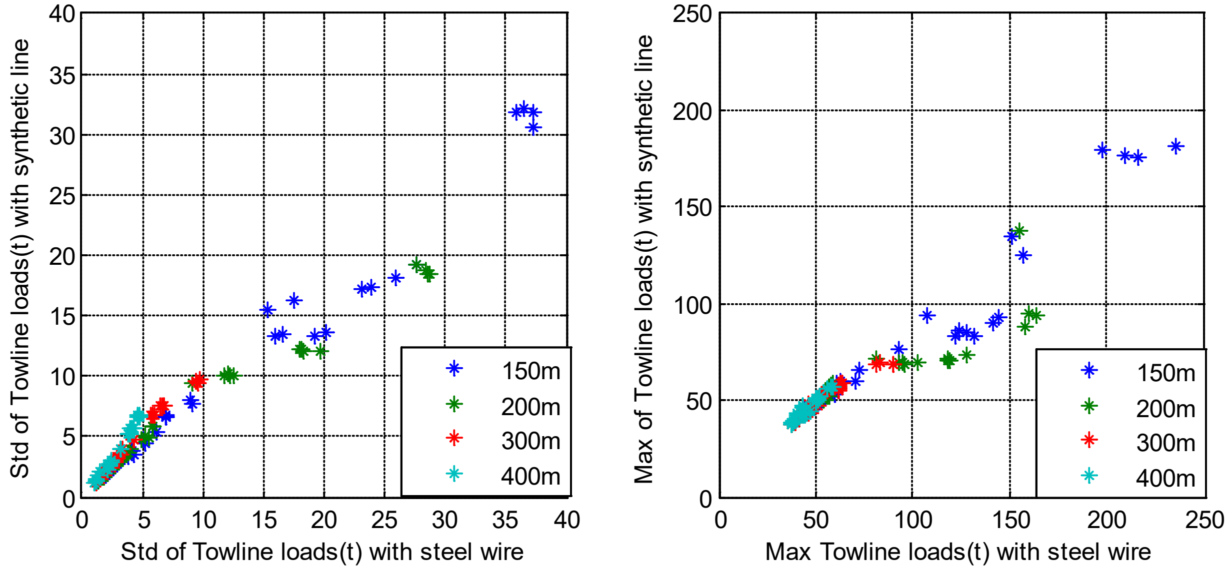


Figure 6-7: Comparison of std and max tensions for steel and synthetic towline, 30 t tug

Figure 6-8 and Figure 6-9 show the comparison between std and maximum towline tensions in the presence and absence of the swells from the beam of the vessel. The swells have some effect only when the waves are small (the swell height is 1.4 m when the wave is 1 m). For waves at 2 m (corresponding swell was only 0.5 m), the swells don't have much effect on the loads.

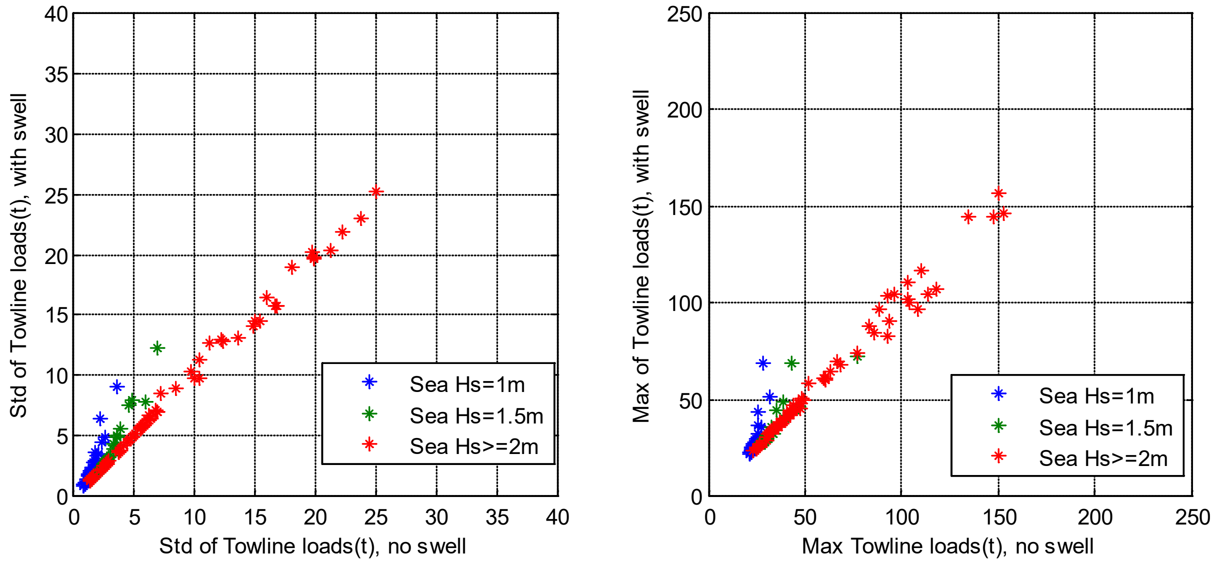


Figure 6-8: Comparison of std and max towline tensions with and without swells, 15 t tug

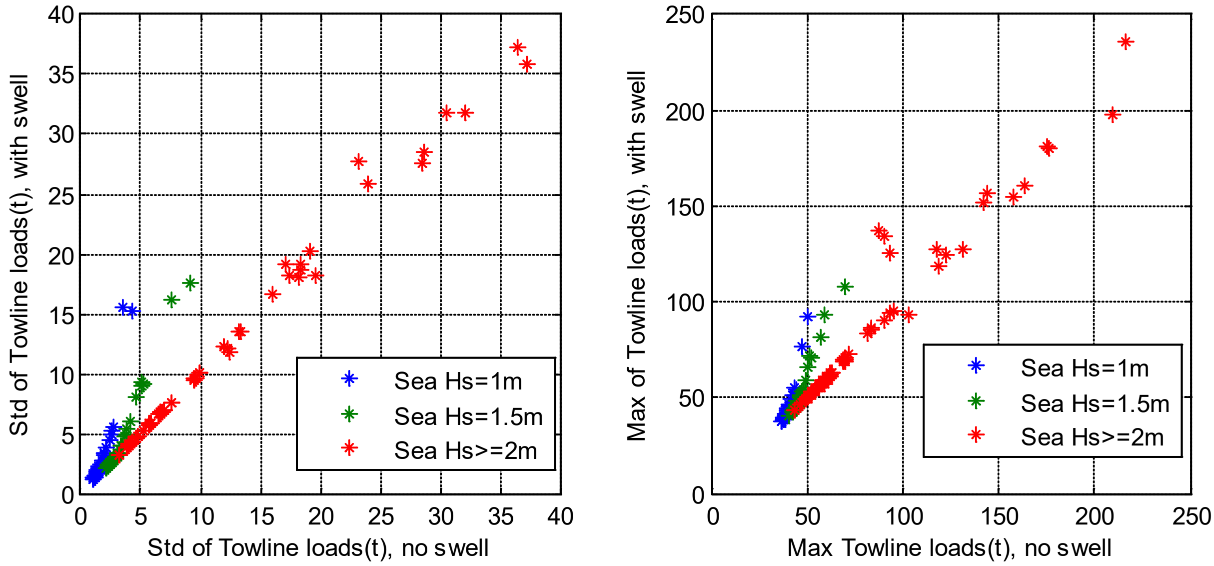


Figure 6-9: Comparison of std and max towline tensions with and without swells, 30 t tug

Figure 11 shows the comparison of the line loads for the SPM and FPSO systems. The results are quite similar in both cases.

Wageningen, July 2019
MARITIME RESEARCH INSTITUTE NETHERLANDS

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Manager Offshore

TABLES

TABLE 1 Main particulars – FPSO, VLCC and TUG

Designation	Symbol	Unit	FPSO	VLCC	Tug
Length between perpendiculars	L_{pp}	[m]	354.4	354.4	50
Breadth	B	[m]	58	58	13.5
Depth	D	[m]	27	27	
Draught mid	T	[m]	14.4	14.4	4.25
Displacement	Δ	[tonnes]	245386	245386	2153
Waterline area	A_{WL}	[m^2]	17702	17702	607
Longitudinal CoG	LCG	[m]	14.4	14.4	-0.5
Transverse CoG	TCG	[m]	0.0	0.0	0.0
Vertical CoG	KG	[m]	16	16	5.75
Transverse metacentric height	GM_T	[m]	9.85	9.85	0.74
Roll radius of gyration	k_{xx}	[m]	20.6	20.6	4.72
Pitch radius of gyration	k_{yy}	[m]	92.1	92.1	12.5
Yaw radius of gyration	k_{zz}	[m]	92.1	92.1	12.5
Frontal wind area	A_f	[m^2]	2500	2300	200
Lateral wind area	A_l	[m^2]	12300	6500	500

TABLE 2 FPSO and VLCC current coefficients

Dir	Cx	Cy	Cmz
0	0.048	0	0
10	0.048	0.065	-0.023
20	0.05	0.14	-0.041
30	0.047	0.235	-0.057
40	0.036	0.31	-0.067
50	0.024	0.39	-0.071
60	0.017	0.445	-0.065
70	0.014	0.5	-0.054
80	0.017	0.53	-0.038
90	0.021	0.545	-0.019
100	0.024	0.53	0.001
110	0.018	0.5	0.016
120	0.007	0.445	0.029
130	-0.011	0.39	0.038
140	-0.029	0.315	0.039
150	-0.04	0.24	0.032
160	-0.044	0.145	0.023
170	-0.045	0.075	0.012
180	-0.044	0	0
190	-0.045	-0.075	-0.012
200	-0.044	-0.145	-0.023
210	-0.04	-0.24	-0.032
220	-0.029	-0.315	-0.039
230	-0.011	-0.39	-0.038
240	0.007	-0.445	-0.029
250	0.018	-0.5	-0.016
260	0.024	-0.53	-0.001
270	0.021	-0.545	0.019
280	0.017	-0.53	0.038
290	0.014	-0.5	0.054
300	0.017	-0.445	0.065
310	0.024	-0.39	0.071
320	0.036	-0.31	0.067
330	0.047	-0.235	0.057
340	0.05	-0.14	0.041
350	0.048	-0.065	0.023
360	0.048	0	0

TABLE 3 TUG current coefficients

Dir	Cx	Cy	Cmz
0	0.12	0	0
15	0.1	0.3	-0.04
30	0.085	0.6	-0.08
45	0.06	0.9	-0.11
60	0.02	1	-0.1
75	-0.03	1.02	-0.06
90	-0.07	1.02	-0.025
105	-0.09	1.02	0.035
120	0.01	1.03	0.095
135	-0.015	0.8	0.085
150	-0.09	0.55	0.075
165	-0.11	0.18	0.05
180	-0.15	0	0
195	-0.11	-0.18	-0.05
210	-0.09	-0.55	-0.075
225	-0.015	-0.8	-0.085
240	0.01	-1.03	-0.095
255	-0.09	-1.02	-0.035
270	-0.07	-1.02	0.025
285	-0.03	-1.02	0.06
300	0.02	-1	0.1
315	0.06	-0.9	0.11
330	0.085	-0.6	0.08
345	0.1	-0.3	0.04
360	0.12	0	0

TABLE 4 FPSO wind coefficients

Dir	Cx	Cy	Cmz
0	1.311	0.006	0.003
10	1.422	0.128	-0.010
20	1.560	0.292	-0.028
30	1.560	0.468	-0.046
40	1.489	0.639	-0.053
50	1.302	0.788	-0.053
60	1.023	0.894	-0.044
70	0.669	0.970	-0.027
80	0.334	1.014	-0.007
90	0.038	1.036	0.012
100	-0.082	1.048	0.037
110	-0.456	1.020	0.052
120	-0.850	0.943	0.062
130	-1.189	0.829	0.067
140	-1.417	0.673	0.067
150	-1.482	0.489	0.057
160	-1.445	0.304	0.042
170	-1.274	0.133	0.022
180	-1.220	0.001	-0.001
190	-1.364	-0.135	-0.026
200	-1.510	-0.305	-0.048
210	-1.598	-0.490	-0.062
220	-1.429	-0.681	-0.070
230	-1.181	-0.840	-0.069
240	-0.768	-0.970	-0.063
250	-0.336	-1.049	-0.054
260	-0.150	-1.064	-0.030
270	0.098	-1.068	-0.013
280	0.385	-1.036	0.007
290	0.742	-0.991	0.027
300	1.108	-0.909	0.043
310	1.368	-0.796	0.053
320	1.518	-0.641	0.055
330	1.552	-0.461	0.048
340	1.523	-0.277	0.030
350	1.378	-0.120	0.013
360	1.313	0.005	0.003

TABLE 5 VLCC wind coefficients

Dir	Cx	Cy	Cmz
0	0.69	0	0
10	0.705	0.135	-0.057
20	0.675	0.295	-0.11
30	0.595	0.435	-0.148
40	0.48	0.56	-0.161
50	0.375	0.65	-0.161
60	0.275	0.73	-0.151
70	0.18	0.795	-0.133
80	0.1	0.835	-0.104
90	0.015	0.855	-0.077
100	-0.065	0.85	-0.048
110	-0.145	0.82	-0.026
120	-0.24	0.765	-0.012
130	-0.355	0.68	0
140	-0.48	0.55	0.006
150	-0.605	0.415	0.012
160	-0.73	0.255	0.011
170	-0.83	0.105	0.008
180	-0.915	0	0
190	-0.83	-0.105	-0.008
200	-0.73	-0.255	-0.011
210	-0.605	-0.415	-0.012
220	-0.48	-0.55	-0.006
230	-0.355	-0.68	0
240	-0.24	-0.765	0.012
250	-0.145	-0.82	0.026
260	-0.065	-0.85	0.048
270	0.015	-0.855	0.077
280	0.1	-0.835	0.104
290	0.18	-0.795	0.133
300	0.275	-0.73	0.151
310	0.375	-0.65	0.161
320	0.48	-0.56	0.161
330	0.595	-0.435	0.148
340	0.675	-0.295	0.11
350	0.705	-0.135	0.057
360	0.69	0	0

TABLE 6 TUG wind coefficients

Dir	Cx	Cy	Cmz
0	0.804	0	0
10	0.817	0.096	-0.012
20	0.773	0.322	-0.007
30	0.797	0.518	-0.006
40	0.721	0.666	-0.002
50	0.593	0.769	0.008
60	0.393	0.855	0.029
70	0.112	0.898	0.05
80	0.055	0.918	0.074
90	0.088	0.922	0.104
100	-0.131	0.942	0.129
110	-0.182	0.968	0.161
120	-0.244	0.946	0.173
130	-0.35	0.847	0.163
140	-0.435	0.749	0.159
150	-0.497	0.623	0.144
160	-0.512	0.42	0.112
170	-0.556	0.226	0.057
180	-0.534	0	0
190	-0.556	-0.226	-0.057
200	-0.512	-0.42	-0.112
210	-0.497	-0.623	-0.144
220	-0.435	-0.749	-0.159
230	-0.35	-0.847	-0.163
240	-0.244	-0.946	-0.173
250	-0.182	-0.968	-0.161
260	-0.131	-0.942	-0.129
270	0.088	-0.922	-0.104
280	0.055	-0.918	-0.074
290	0.112	-0.898	-0.05
300	0.393	-0.855	-0.029
310	0.593	-0.769	-0.008
320	0.721	-0.666	0.002
330	0.797	-0.518	0.006
340	0.773	-0.322	0.007
350	0.817	-0.096	0.012
360	0.804	0	0

TABLE 7 Winch information from safetug jip (data from questionnaires)

Forward winch of ASD tugs					
	Unit	Min	Max	Mean	No. of answers
Brake Holding	tonnes	80	250	151.7	15
Max. Pull	tonnes	5	137	46.3	12
Max. holding/rendering in tension	tonnes	2	137	64.8	5
Max speed	m/min	10	180	68.7	13
Load limiting device		Yes 4	No 5		
Aft winch of ASD tugs					
	Unit	Min	Max	Mean	No. of answers
Brake Holding	tonnes	70	250	154.1	11
Max. Pull	tonnes	10	137	53.6	10
Max. holding/rendering in tension	tonnes	15	137	83	4
Max speed	m/min	5	180	77.3	10
Load limiting device	- -	Yes 3	No 5	- -	- -

TABLE 8 SWL for the different towline configurations

Fitting	Material	SF = MBL/SWL
Mooring Lines	Steel	1.82
	Polyamide	2.22
	Other Synth	2
Tails for Wire mooring lines	Polyamide	2.5
	Other Synth	2.28
Tails for synthetic mooring lines	Polyamide	2.75
	Other Synth	2.5

Towline Type	MBL (t)	SWL (t)
Steel wire	224	123.1
Steel wire + Polyprop stretcher	224,185	81.1
Steel wire + 47/53 mix stretcher	224,221	96.9
Steel wire + Nylon stretcher	224,225	90.0
Synthetic line	224	112.0
Synthetic line + Polyprop stretcher	224,185	74.0
Synthetic line + 47/53 mix stretcher	224,221	88.4
Synthetic line + Nylon stretcher	224,225	81.8

TABLE 9 Max towline loads(t) for fpso system, 15 t tug

Environments with only Seas

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m V_w = 25 kn	150	29	25	25	23	31	27	25	23
	200	25	24	24	23	28	25	24	23
	300	22	22	22	22	25	24	23	23
	400	22	22	22	22	24	23	23	23
H_s = 1.5 m V_w = 10 kn	150	78	39	33	29	43	35	32	27
	200	35	34	34	29	37	33	32	28
	300	28	26	26	26	32	30	29	27
	400	26	25	25	24	30	28	29	26
H_s = 2 m V_w = 10 kn	150	127	112	80	44	135	104	76	42
	200	105	81	56	36	108	78	70	41
	300	31	30	29	27	62	51	46	36
	400	24	23	23	22	42	36	35	29
H_s = 2 m V_w = 25 kn	150	145	101	88	46	150	103	87	43
	200	106	89	53	38	122	80	69	42
	300	35	34	33	28	69	49	47	36
	400	28	27	26	24	46	39	36	31
H_s = 2.5 m V_w = 30 kn	150	225	145	170	62	225	157	140	64
	200	154	137	109	58	144	117	108	61
	300	69	49	47	34	105	86	65	54
	400	33	31	30	28	63	56	53	40
H_s = 3.5 m V_w = 15 kn	150	288	184	195	103	215	196	166	115
	200	224	183	133	82	206	165	156	100
	300	118	94	74	60	144	109	115	84
	400	47	42	40	33	108	76	70	54

TABLE 10 Max towline loads(t) for fpso system, 15 t tug

Environments with Seas + Swells

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m, V_w = 25 kn, H_{sw} = 1.4 m	150	76	43	32	25	49	36	32	25
	200	33	27	26	24	37	32	31	24
	300	23	23	23	23	30	28	26	23
	400	22	22	22	21	26	25	24	23
H_s = 1.5 m, V_w = 10 kn, H_{sw} = 0.5 m	150	67	44	39	28	69	48	42	29
	200	40	32	34	31	50	36	34	29
	300	29	27	27	26	34	31	30	27
	400	26	26	25	23	32	29	29	26
H_s = 2 m, V_w = 10 kn, H_{sw} = 0.5 m	150	149	106	81	43	136	99	92	45
	200	91	64	55	36	101	87	66	42
	300	33	29	28	27	65	52	49	35
	400	25	24	24	22	42	38	37	29
H_s = 2 m, V_w = 25 kn, H_{sw} = 0.5 m	150	153	106	97	46	143	125	102	42
	200	107	69	60	38	109	81	67	42
	300	36	33	33	28	68	50	45	37
	400	27	26	25	24	47	38	36	31
H_s = 2.5 m, V_w = 30 kn, H_{sw} = 1 m	150	235	134	138	63	185	157	147	64
	200	165	136	101	54	164	124	112	61
	300	70	51	46	35	98	79	68	54
	400	32	31	30	28	70	58	55	41
H_s = 3.5 m, V_w = 15 kn, H_{sw} = 0.8 m	150	240	191	174	110	215	171	174	128
	200	222	169	154	79	185	167	157	86
	300	113	102	85	60	139	126	128	80
	400	48	43	41	34	113	78	70	55

TABLE 11 Max towline loads(t) for fpso system, 30 t tug

Environments with only Seas

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m V_w = 25 kn	150	50	43	41	38	47	42	40	38
	200	44	41	39	38	43	40	39	38
	300	41	39	39	38	40	40	39	38
	400	39	39	38	37	39	38	38	38
H_s = 1.5 m V_w = 10 kn	150	69	52	48	42	59	50	47	42
	200	53	48	47	43	52	47	46	43
	300	46	44	43	42	46	44	43	42
	400	45	43	43	43	44	43	43	42
H_s = 2 m V_w = 10 kn	150	206	155	135	56	184	138	76	55
	200	156	109	112	57	137	71	68	56
	300	94	62	62	51	70	64	60	50
	400	54	49	47	46	55	55	49	45
H_s = 2 m V_w = 25 kn	150	207	156	134	56	195	119	79	57
	200	168	122	102	59	119	76	71	58
	300	101	65	68	50	68	61	58	51
	400	59	51	49	47	58	54	51	46
H_s = 2.5 m V_w = 30 kn	150	265	192	220	80	232	202	163	75
	200	234	227	140	75	197	149	144	67
	300	148	114	105	71	135	84	79	69
	400	84	69	64	52	76	75	70	58
H_s = 3.5 m V_w = 15 kn	150	377	279	245	154	368	272	245	145
	200	333	257	242	125	298	208	233	99
	300	225	153	135	92	194	171	164	76
	400	157	111	101	72	145	108	85	72

TABLE 12 Max towline loads(t) for fpso system, 30 t tug

Environments with Seas+Swells

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m V_w = 25 kn H_{sw} = 1.4 m	150	90	55	49	41	74	51	46	41
	200	56	46	44	39	52	45	43	39
	300	43	40	40	38	43	41	40	38
	400	40	39	39	37	41	39	39	38
H_s = 1.5 m V_w = 10 kn H_{sw} = 0.5 m	150	111	69	56	44	96	63	53	45
	200	78	52	49	44	70	50	48	43
	300	48	45	43	43	48	45	44	43
	400	47	44	43	42	47	44	44	42
H_s = 2 m V_w = 10 kn H_{sw} = 0.5 m	150	200	142	130	57	180	134	77	56
	200	144	121	95	57	120	71	66	56
	300	84	66	63	51	70	64	60	49
	400	52	49	48	45	56	56	51	45
H_s = 2 m V_w = 25 kn H_{sw} = 0.5 m	150	218	148	146	55	196	135	81	56
	200	162	118	100	59	96	75	71	58
	300	103	64	69	51	70	64	58	52
	400	53	52	50	48	59	54	51	46
H_s = 2.5 m V_w = 30 kn H_{sw} = 1 m	150	270	191	181	81	240	179	163	74
	200	247	170	149	75	203	147	144	70
	300	141	117	92	74	131	83	77	67
	400	92	73	65	53	73	74	71	59
H_s = 3.5 m V_w = 15 kn H_{sw} = 0.8 m	150	357	297	259	146	311	258	208	148
	200	341	261	220	135	306	252	227	103
	300	204	183	159	87	191	152	165	78
	400	164	113	104	71	161	130	88	71

TABLE 13 Max towline loads(t) for spm system, 15 t tug

Environments with only Seas

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m V_w = 25 kn	150	28	26	25	23	32	27	26	23
	200	26	24	24	22	28	25	25	23
	300	22	22	22	22	24	24	24	22
	400	22	22	21	21	23	23	23	22
H_s = 1.5 m V_w = 10 kn	150	77	40	33	30	43	36	33	31
	200	46	34	33	30	39	33	33	30
	300	30	29	29	29	33	30	29	28
	400	30	29	29	28	28	29	28	27
H_s = 2 m V_w = 10 kn	150	153	114	93	44	147	96	84	46
	200	103	67	52	36	103	93	68	42
	300	36	32	30	26	60	48	42	40
	400	25	25	25	23	44	39	37	32
H_s = 2 m V_w = 25 kn	150	150	118	93	48	135	109	88	43
	200	104	77	61	40	110	86	63	42
	300	35	33	31	30	61	49	42	40
	400	26	27	27	27	44	38	37	32

TABLE 14 Max towline loads(t) for spm system, 15 t tug

Environments with Seas + Swells

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m, V_w = 25 kn, H_{sw} = 1.4 m	150	69	43	36	25	52	35	32	27
	200	30	28	27	24	36	31	28	25
	300	23	23	24	23	29	27	27	24
	400	22	22	22	22	27	26	25	23
H_s = 1.5 m, V_w = 10 kn, H_{sw} = 0.5 m	150	73	40	35	31	69	45	36	31
	200	46	35	32	30	49	34	34	31
	300	29	29	29	28	33	31	30	28
	400	29	29	29	28	29	29	28	27
H_s = 2 m, V_w = 10 kn, H_{sw} = 0.5 m	150	147	105	90	47	145	104	88	48
	200	102	70	58	36	111	83	68	44
	300	36	33	31	27	61	51	43	40
	400	25	25	24	23	44	40	38	32
H_s = 2 m, V_w = 25 kn, H_{sw} = 0.5 m	150	156	107	103	45	145	96	97	44
	200	100	74	61	41	116	85	65	42
	300	36	34	32	29	60	49	42	41
	400	27	26	27	26	43	38	38	32

TABLE 15 Max towline loads(t) for spm system, 30 t tug

Environments with only Seas

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m V_w = 25 kn	150	50	44	41	38	47	43	41	38
	200	44	41	40	38	43	40	39	38
	300	40	39	38	38	40	39	38	37
	400	38	38	38	37	39	38	38	37
H_s = 1.5 m V_w = 10 kn	150	70	52	49	45	59	50	47	45
	200	57	48	48	45	52	47	46	44
	300	47	45	44	45	46	44	44	43
	400	46	44	44	41	44	43	43	42
H_s = 2 m V_w = 10 kn	150	216	142	132	63	175	90	83	59
	200	158	119	95	58	88	70	70	58
	300	90	62	62	52	69	58	55	52
	400	56	51	50	43	56	51	50	46
H_s = 2 m V_w = 25 kn	150	209	144	122	61	176	93	83	59
	200	164	118	103	57	94	72	70	57
	300	81	63	62	53	69	59	56	53
	400	58	52	50	44	57	52	51	47

TABLE 16 Max towline loads(t) for spm system, 30 t tug

Environments with Seas + Swells

		Steel Wire Towline				Synthetic Line			
		Stretcher type (SWL)				Stretcher type (SWL)			
Env	Line length [m]	None [123 t]	Polyprop [81 t]	47-53 [97 t]	Nylon [90 t]	None [112 t]	Polyprop [74 t]	47-53 [88 t]	Nylon [82 t]
H_s = 1 m V_w = 25 kn H_{sw} = 1.4 m	150	93	55	49	41	77	51	46	40
	200	54	46	44	40	51	44	43	39
	300	44	41	41	39	44	42	41	39
	400	39	39	38	37	40	39	39	38
H_s = 1.5 m V_w = 10 kn H_{sw} = 0.5 m	150	108	72	59	46	93	66	53	47
	200	82	54	50	45	71	50	48	45
	300	51	46	45	46	47	48	45	44
	400	48	45	45	40	45	43	43	43
H_s = 2 m V_w = 10 kn H_{sw} = 0.5 m	150	236	151	128	63	181	135	85	59
	200	155	119	95	59	137	70	69	58
	300	90	63	62	53	68	59	55	52
	400	55	51	50	43	56	50	49	46
H_s = 2 m V_w = 25 kn H_{sw} = 0.5 m	150	198	157	124	60	180	125	86	57
	200	160	128	93	57	94	73	70	57
	300	83	63	62	54	70	59	56	53
	400	59	52	50	44	57	52	51	47

FIGURES

FIGURE 1 FPSO and VLCC current coefficients

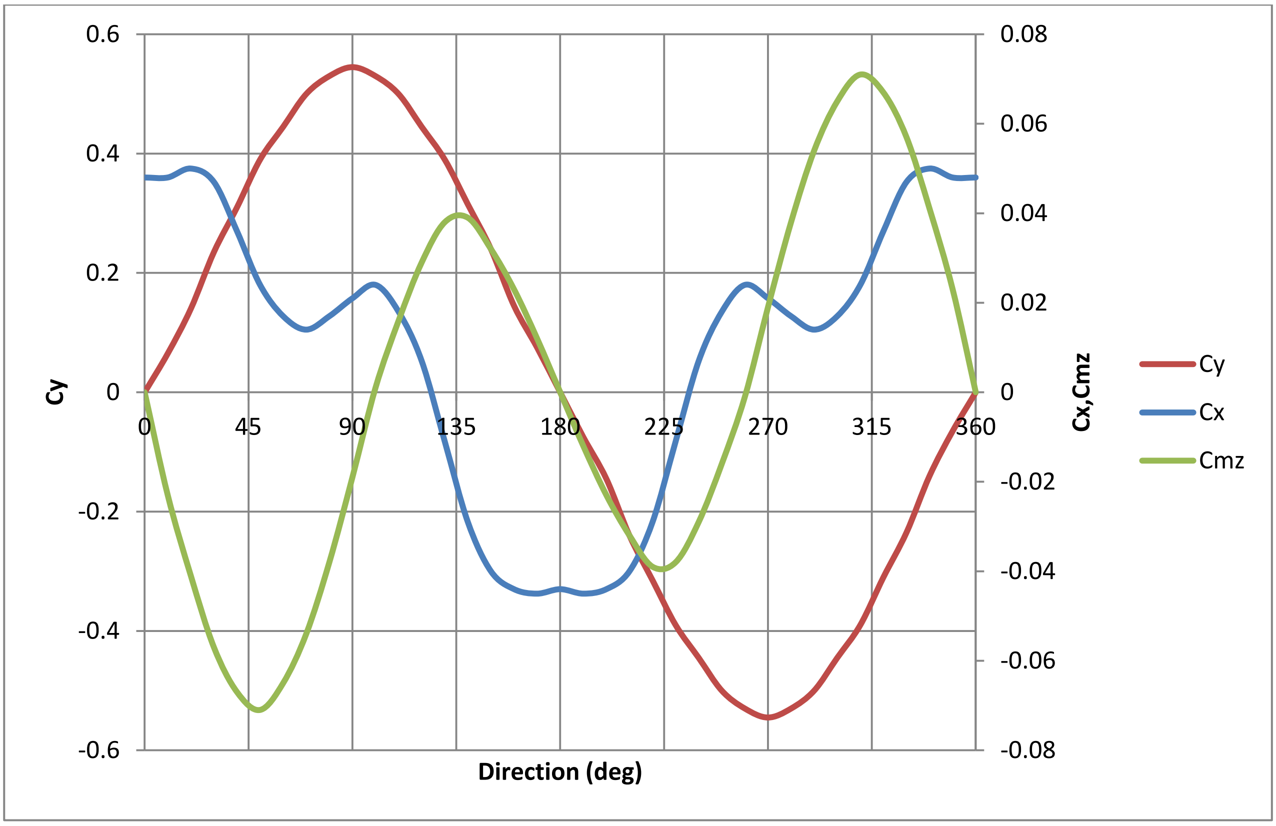


FIGURE 2 Tug current coefficients

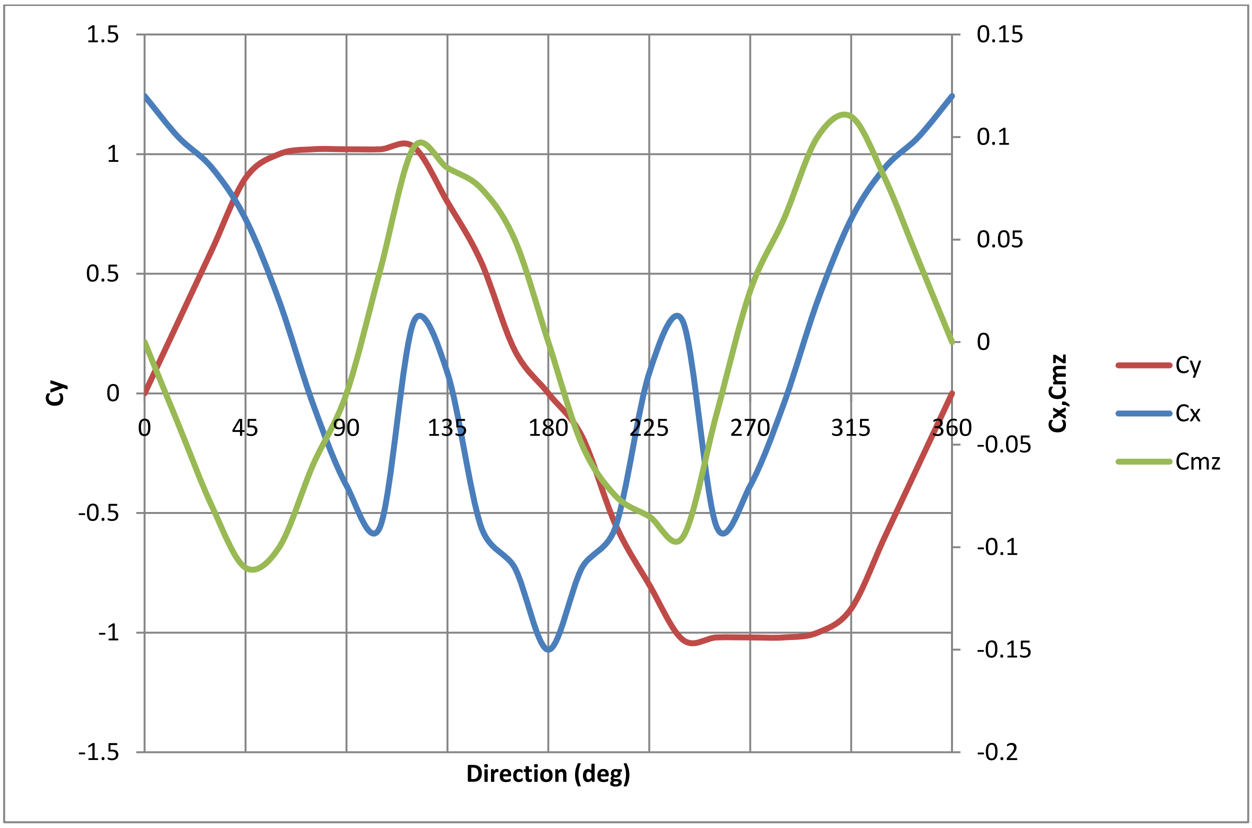


FIGURE 3 FPSO wind coefficients

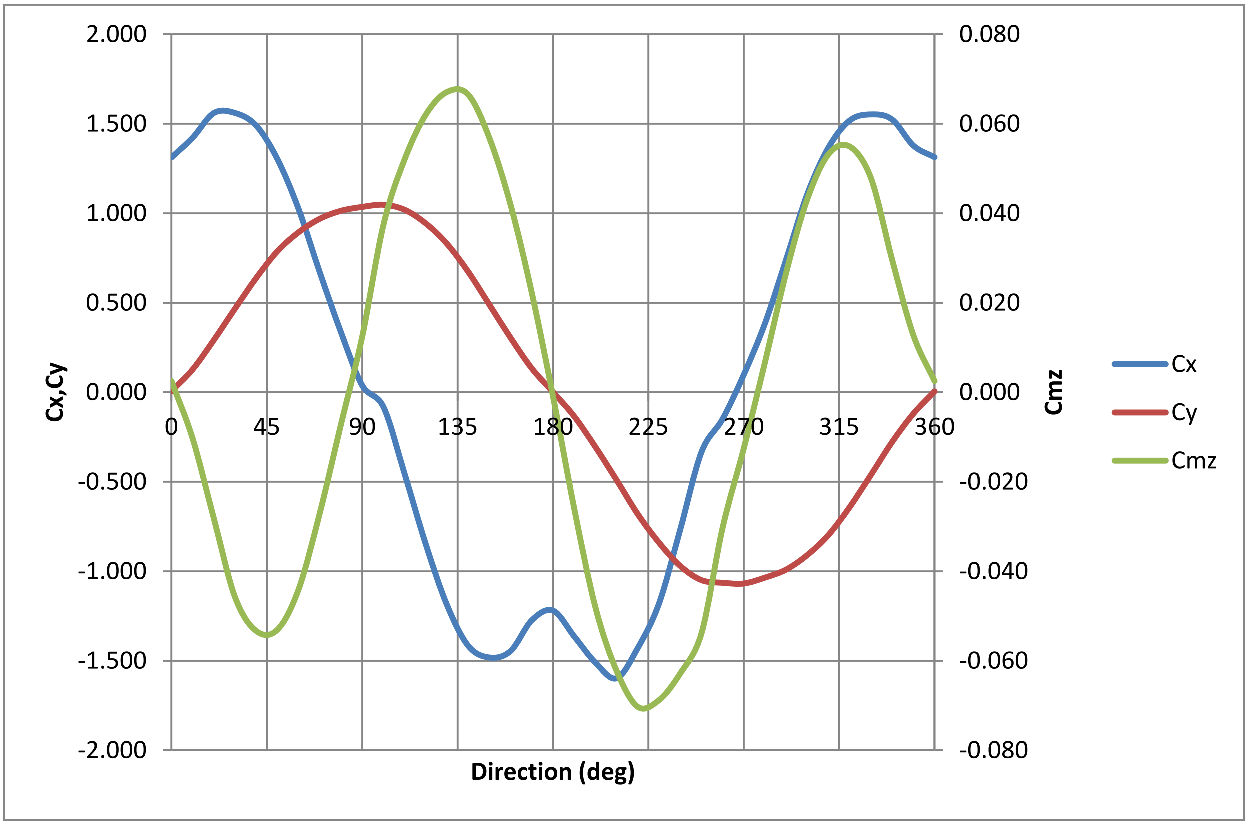


FIGURE 4 VLCC wind coefficients

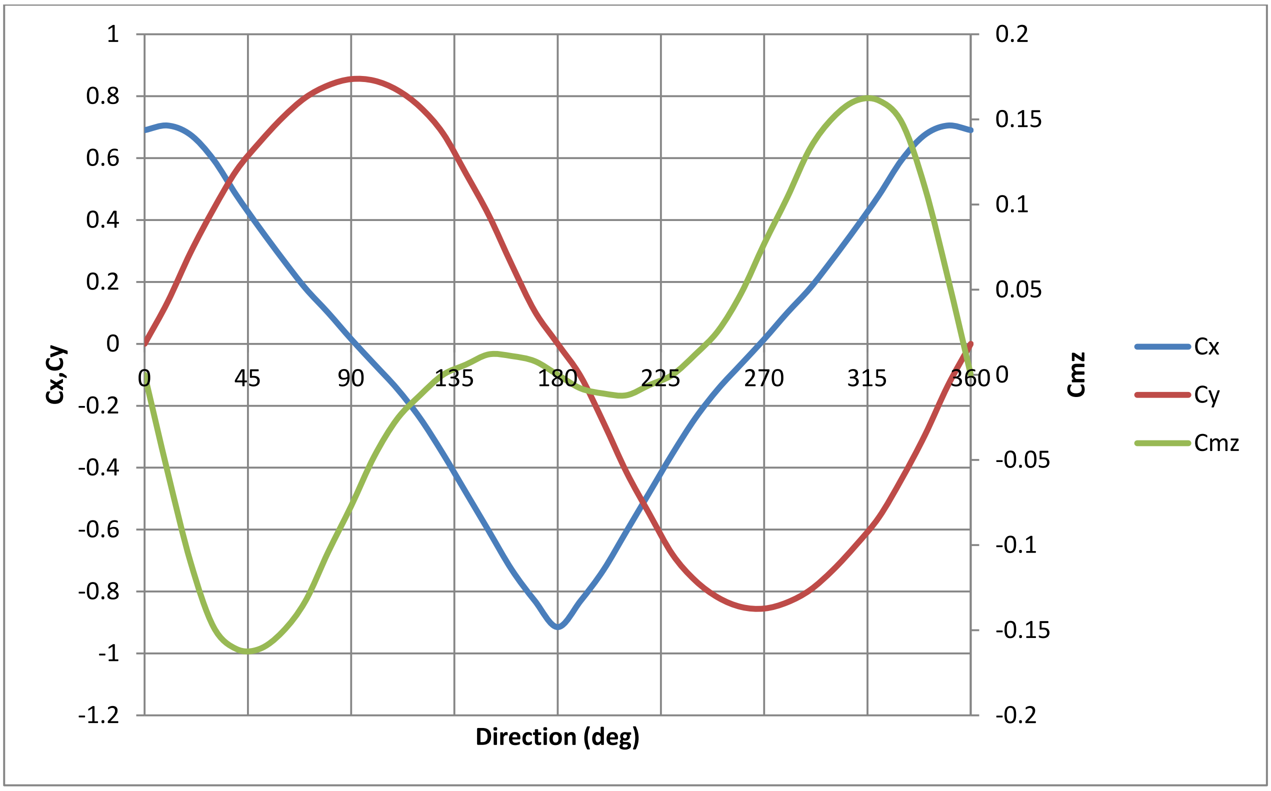


FIGURE 5 Tug wind coefficients

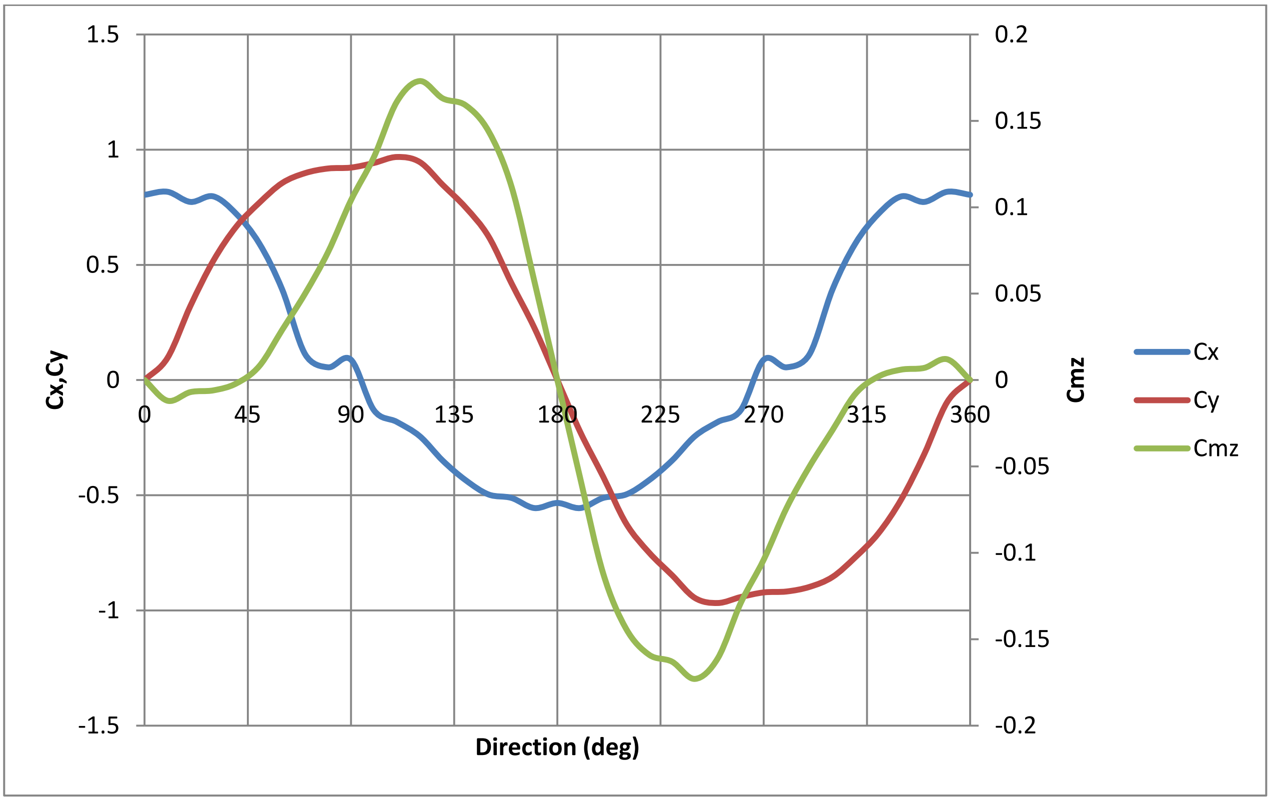


FIGURE 6 Roll decays

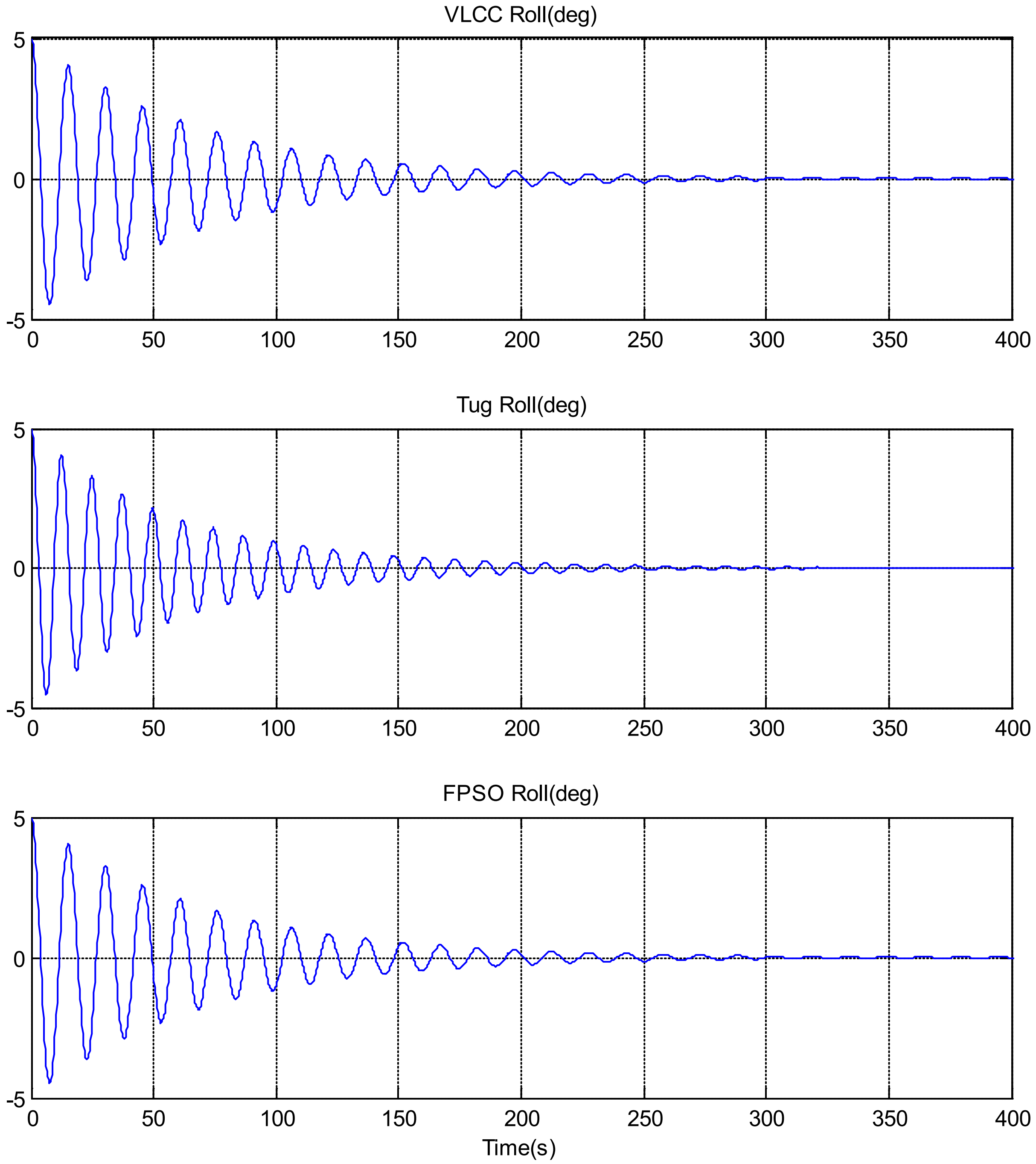
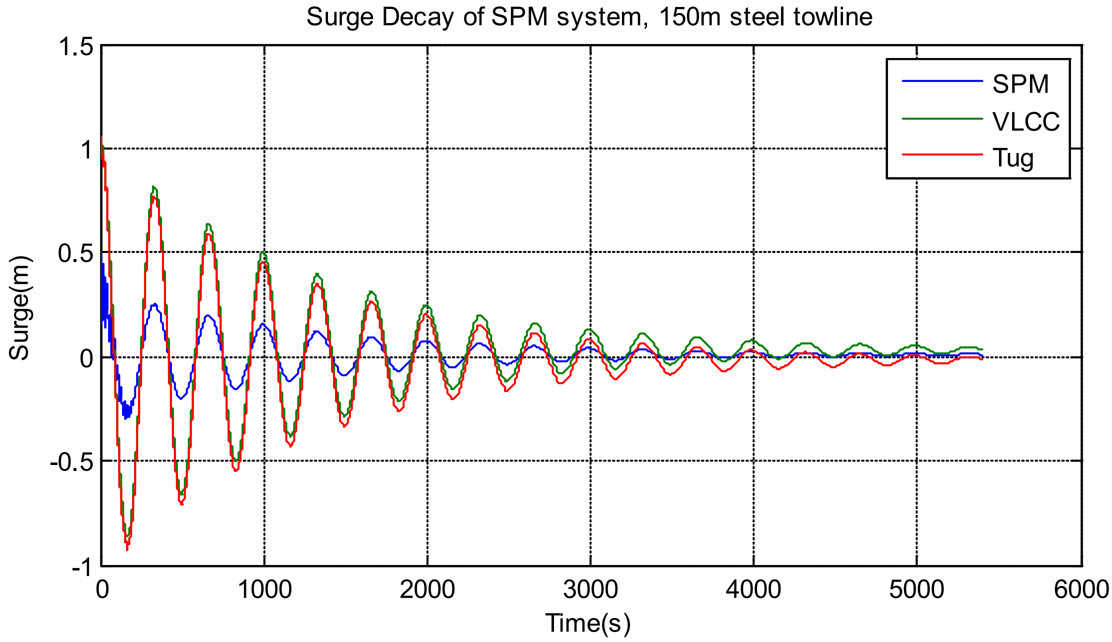


FIGURE 7 SPM system, surge decay in calmwater



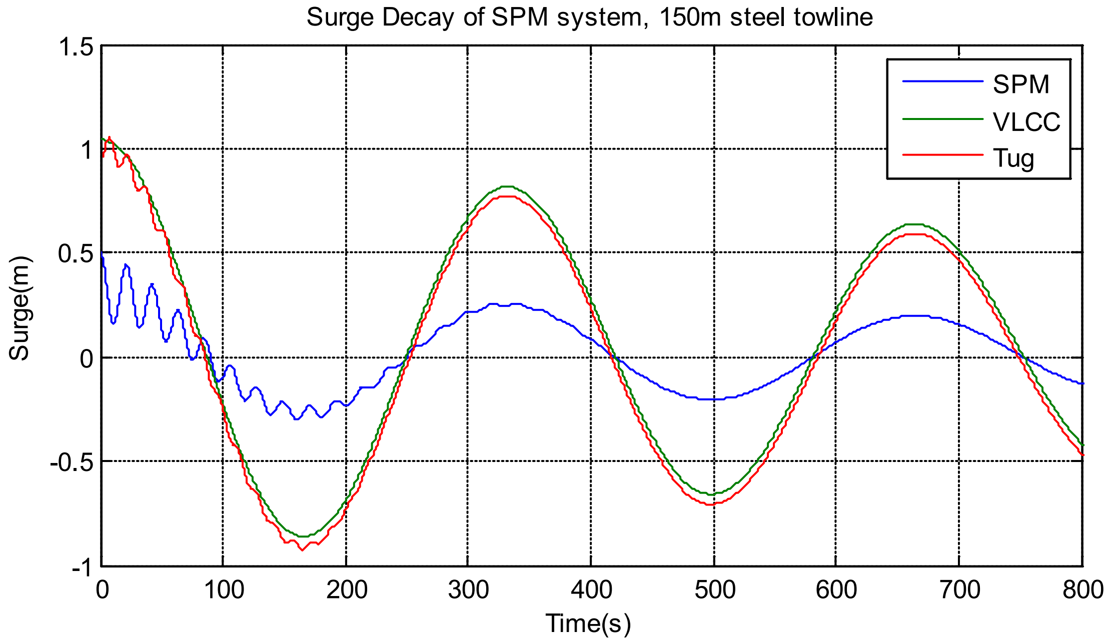


FIGURE 8 SPM system, yaw decay in current

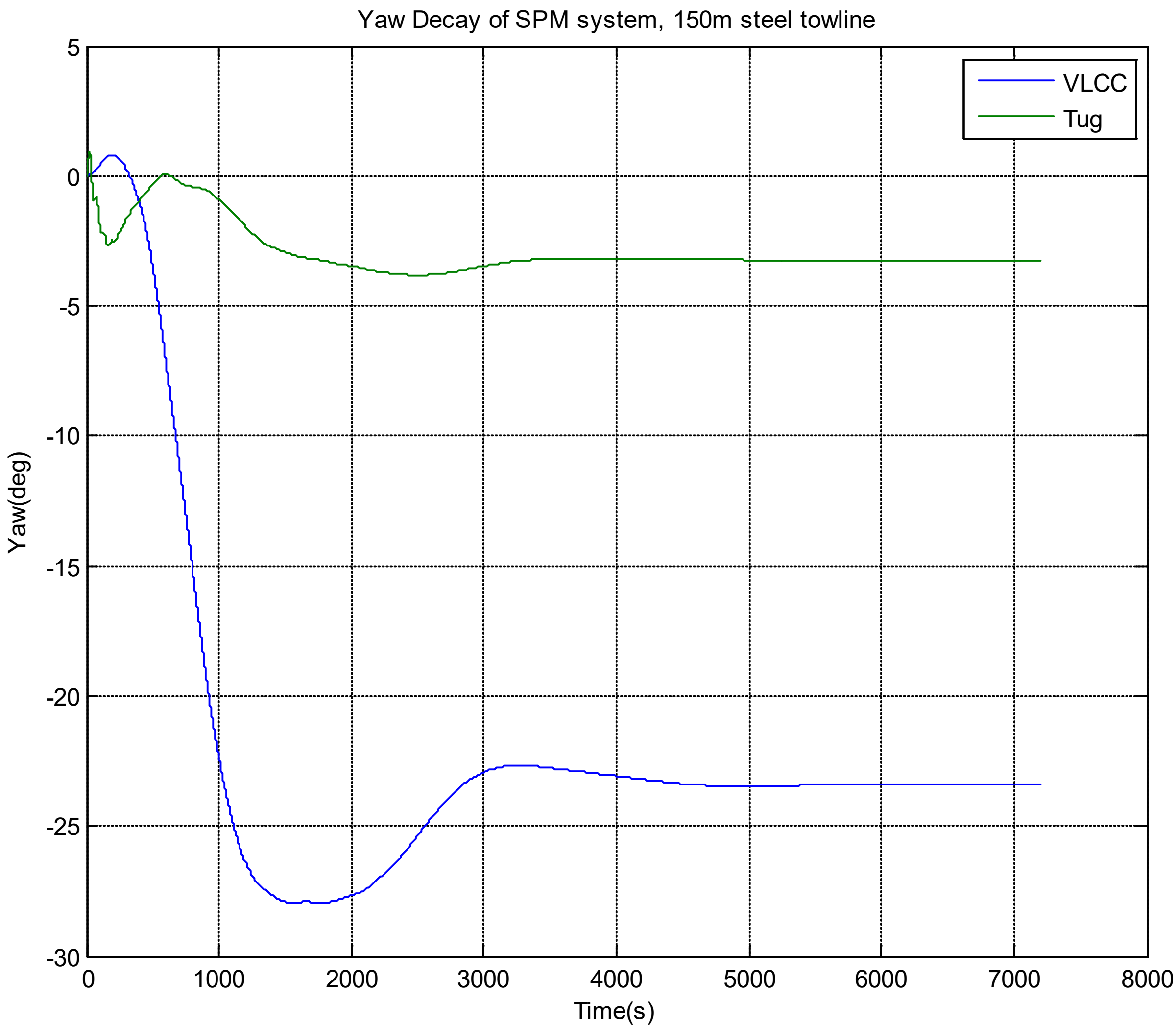
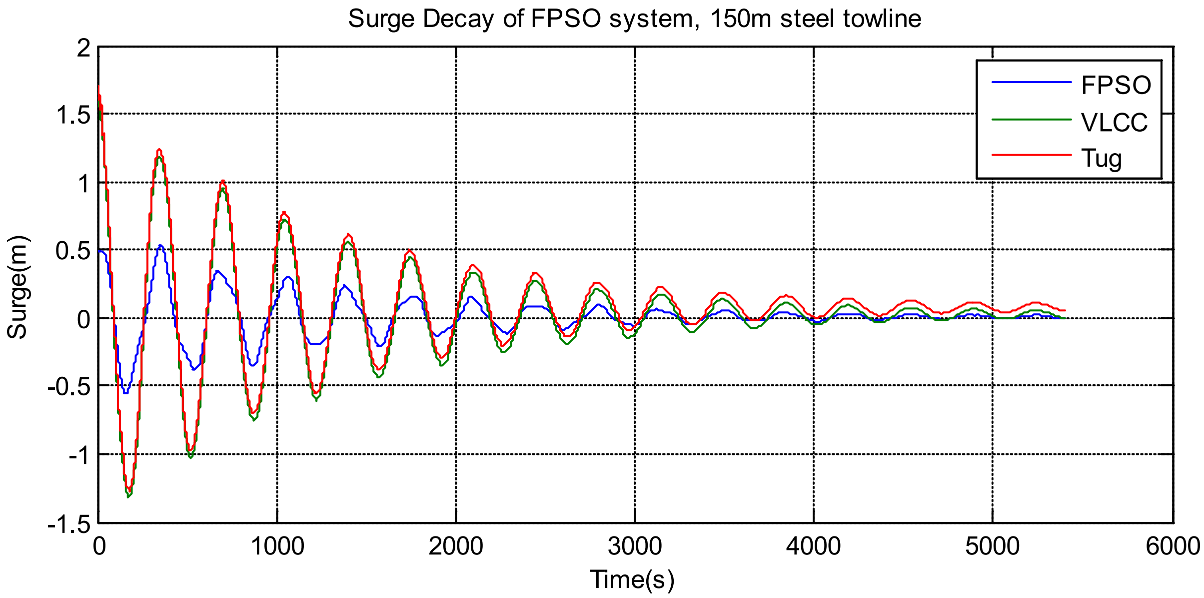


FIGURE 9 FPSO system, surge decay in calmwater



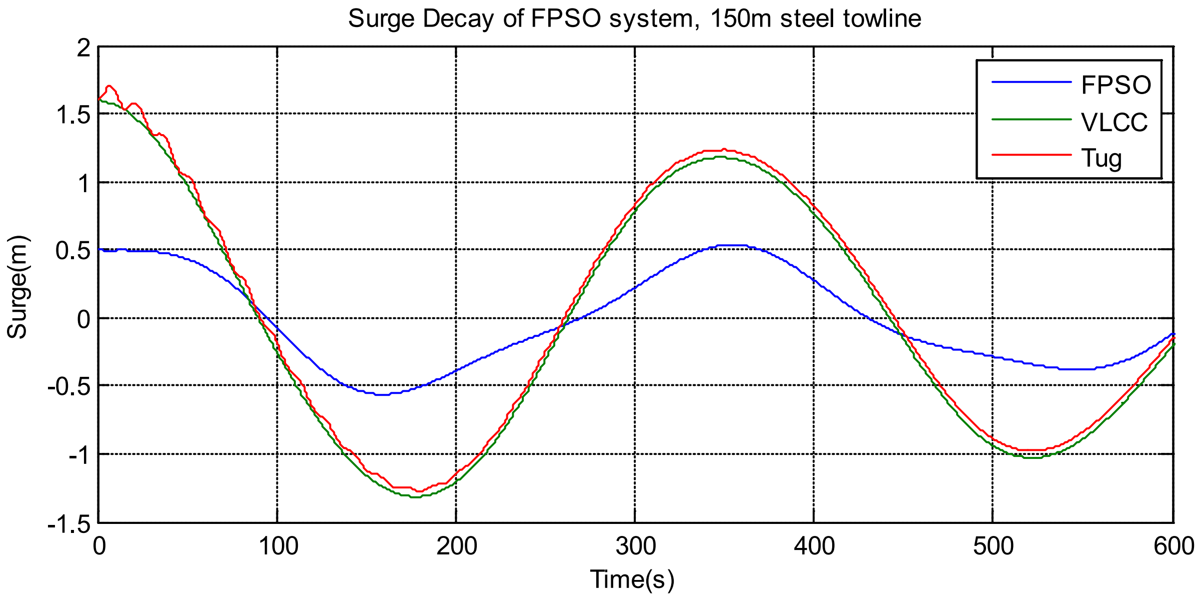


FIGURE 10 FPSO system, yaw decay in current

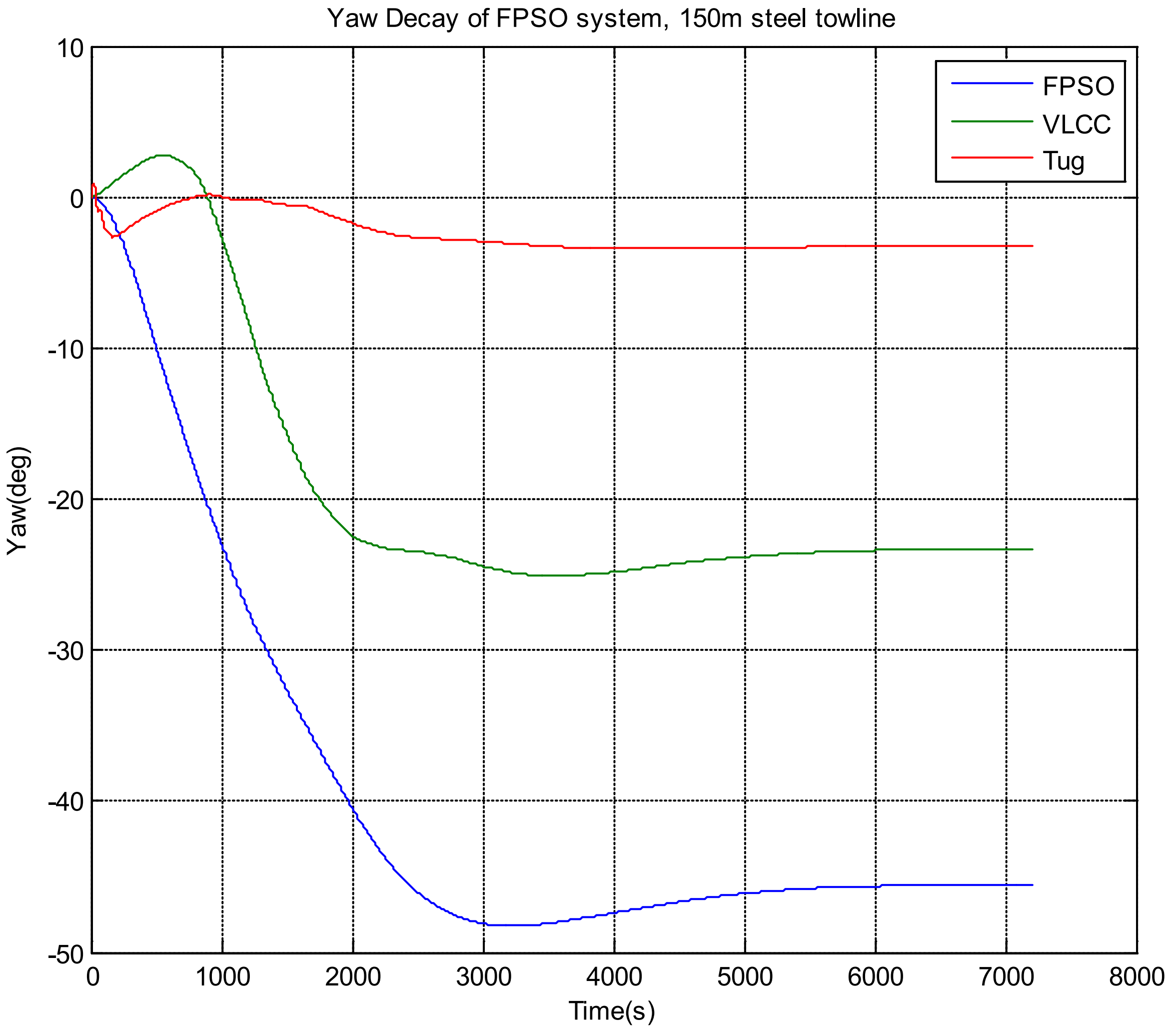
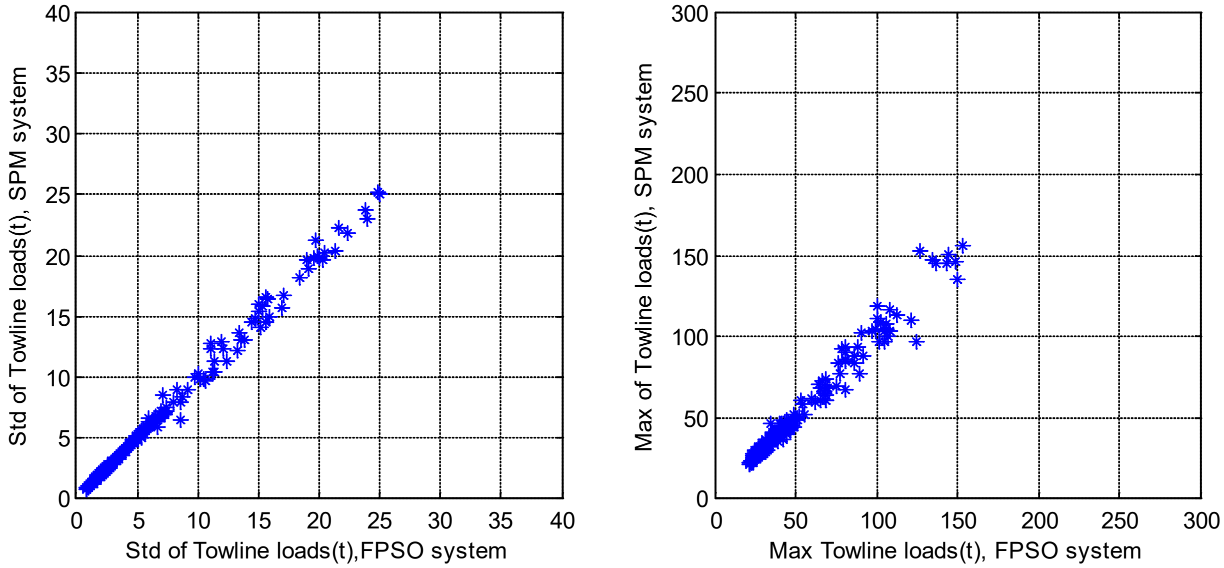
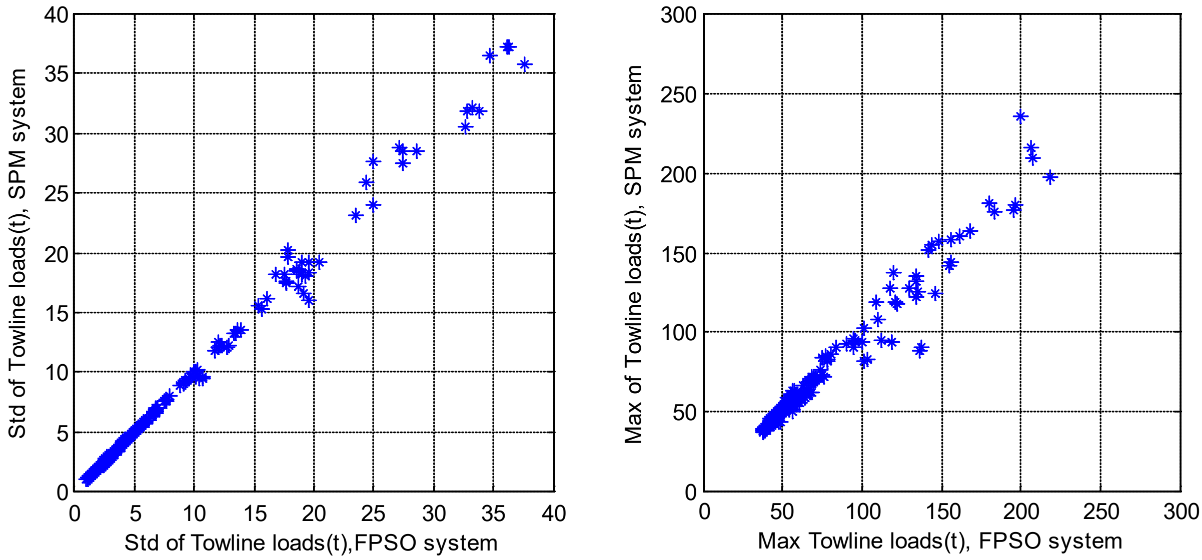


FIGURE 11 Comparison of loads between fpso and spm systems

Standard deviation and maximum loads with 15 t tug



Standard deviation and maximum loads with 30 t tug



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Appendix B: Torsion Effect Calculator

Torsion Effect Calculator
The following formula can be used to estimate the amount of twist that will be imparted into a typical 6 x 36 IWRC wire line when the load on the wire changes.

(**Note:** the formula does not work for other wire rope constructions).

Number of Turns = (1.6/D) x L x Δ%

Where:
D = wire line diameter (mm)
L = length of wire line (m)
Δ% = change in load expressed as a % of MBL
1.6 = constant

Example 1
44mm diameter wire x 20m x 15% MBL (around 20 tonnes) = (1.6/44) x 20 x 15 = 10.9, say 11 turns.

Example 2
76mm diameter wire x 10m x 5% MBL (around 20 tonnes) = (1.6/76) x 10 x 5 = 1.1, say 1 turn.

This example demonstrates the effect of changing length and diameter on the amount of rotations due to change of load and may be a useful method for selecting the pennant.

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