EVALUATION OF A TOP TENSIONED RISER MODEL FOR EXPERIMENTS

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Abstract. *In this paper, a small scale modelling of a top tensioned riser for experimental analysis in a wave basin is featured. It basically means to define dimensions of a riser model in reduced size keeping similarity with the prototype. A small scale experimental analysis proposes to study the behavior of a riser under controlled loads for a given geometry and material properties, and to guarantee the reproduction of all interested phenomena involving on a riser in real scale. Among all parameters that influence the dynamic behavior of a riser, special attention is paid to bending and axial stiffness established to the riser model and geometric parameters that influence directly the hydrodynamic forces. Then the main purpose of the present study is to describe the theoretical fundamentals involved in the scale reduction for the riser model design. Finally, to illustrate the results, a case study for riser experiment in laboratory is shown and compared with numerical simulation results.*

Keywords*: Production Riser, Hydrodynamics, Offshore Wave Basin*

1. Introduction

The Top Tensioned Riser (TTR) is a vertical rigid pipe that connects a subsea wellhead to surface facilities for hydrocarbons production, or injection of water or gas into the reservoir. Sometimes, the riser is part of oil/gas export system that connects the floating production platform (TLP´s, SPAR buoys, etc) with pipeline that exports the hydrocarbons to the onshore. In the connection between riser and platform, the riser is free to move and to oscillate horizontally. The two perpendicular directions of riser displacements and motions are denominated as in-line and transverse directions. In this paper, the in line direction coincides with the direction of environmental loads and the transverse direction is the perpendicular direction to the in-line one. Figure 1 shows a scheme for a typical vertical TTR system.

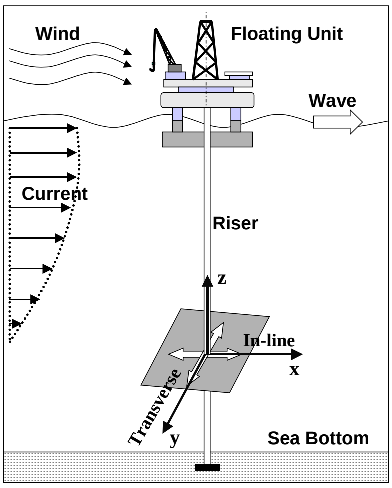

Figure 1   A scheme for a typical vertical Top Tensioned Riser system.

In a deepwater scenario, a riser can be considered as a slender pipe under the effects of floating platform motions at its upper end due to waves, currents and winds acting on the floating platform, and direct action of currents and waves along the its length.

In this present study, similarity analysis is carried out and main parameters for a wave basin experiment, riser model definitions and construction are discussed. Finally, a case study is presented compared with numerical simulations based on quasi-3D approach (Kubota et al, 2004, Martins et al, 2001).

2. Similarity between Real Prototype and Experimental Model

A riser model (small scale test body), to test in laboratory, must be designed to provide useful experimental data for the estimation of involved forces, momentum, and dynamic loads that can be used for the riser design in real scale (prototype). The use of experimental data for the prototype design is possible only if the test is complied with some requirements that ensure the similarity between model and prototype.

A first requirement is the geometric similarity between model and prototype. Geometric similarity requires that the model and the prototype have the same shape and the proportional geometric dimensions; this geometric proportionality must correspond to a constant scale factor (λ).

Next, model and prototype should follow a kinetic similarity. Kinematic similarity requires that the model and prototype have the same length-scale ratio and the same time-scale ratio. The result is that the velocity-scale ratio will be the same for both. The motions of two systems are kinematically similar if homologous particles lie at homologous points at homologous times.

Finally, dynamic similarity exists when the model and the prototype have the same length scale ratio, time-scale ratio, and force-scale (or mass-scale) ratio. Again geometric similarity is a first requirement; without it, proceed no further. Then dynamic similarity exists, simultaneous with kinematic similarity, if the model and prototype force and pressure coefficients are identical. The perfect dynamic similarity is more of a dream than a reality because true equivalence of Reynolds and Froude numbers can be achieved only by dramatic changes in fluid properties, whereas in fact most model testing is simply done with water or air, the cheapest fluids available. In order to establish the necessary conditions for complete dynamic similarity, all forces acting in a structure should be considered in the analysis. Then, in the case of a riser analysis, nonlinear effects due viscous forces, pressure forces, superficial tension, and others must not be neglected. If model size and geometry for experiment are being considered, experimental conditions should be carefully designed in order to correlate all important forces and other phenomena in the experiment with the model and the real prototype according to the scaling factor. When dynamic similarity is present, experimental data measured in the model structure can be quantitatively related to conditions of the prototype structure.

The Buckingham Pi Theorem may be applied for obtaining the governing dimensionless numbers for the structure and the flow pattern. From this analysis, it can be concluded that to obtain similarity between model and prototype, dimensionless parameters such as Reynolds Number (Re), Keulegan-Carpenter Number (KC), Froude Number (Fr) should be the same.

3. Dimensionless Analysis and Scale Reduction

The dimensionless parameters for scale reduction of a vertical top tensioned riser can be obtained from the Equation of lateral motion behavior of the riser (Ferrari, 1999), given in matrix form by:

$$[M]\{\ddot{x}\}+[B]\{\dot{x}\}+[K]\{x\}=\{F\} \tag{1}$$

where, $x, \dot{x}, \ddot{x}$ is riser displacement, velocity and acceleration, M is total riser mass, B is riser structure damping, K is riser stiffness that is a function of the riser top tension (T_{Top}), the bending stiffness (EI) and the riser axial stiffness (EA). Finally, F is the external hydrodynamic force described by Morison's Equation (2),

$$F_x = C_M \frac{\rho\pi D^2}{4}\dot{u} + C_D \frac{\rho D}{2}|V_r|(U_c + u - \dot{x}) - C_A \frac{\rho\pi D^2}{4}\ddot{x} \tag{2}$$

where, C_M, C_D, C_A are respectively drag, mass and added mass coefficient, ρ is fluid density, D is riser diameter, U_c is the current velocity, $\dot{u}$ is the water particle acceleration, u is the water particle velocity and the relative velocity V_r is given by $|V_r| = \sqrt{(U_c + u - \dot{x})^2 + \dot{y}^2}$.

Then, riser lateral motion can be represented by the following Equation (3)

$$x = f(\rho, u, D, \dot{u}, \ddot{x}, m, B, \dot{x}, L, \mu, U_c, H, T, EI, EA, T_{Top}, g) \tag{3}$$

where, m is riser mass per length, L is riser length, μ is fluid viscosity, H is wave height, T is wave period and g is gravity acceleration.

By selecting the fundamental parameter as being ρ, u, D, and following the Buckingham Pi theorem, the dimensionless parameters can be obtained as follows:

$$\frac{x}{D} = f\left(\frac{EI}{\rho u^2 D^4}, \frac{\dot{u}D}{u^2}, \frac{\ddot{x}D}{u^2}, \frac{m}{\rho D^3}, \frac{B}{\rho u D^2}, \frac{\dot{x}}{u}, \frac{L}{D}, \frac{\mu}{\rho u D}, \frac{U_c}{u}, \frac{H}{D}, \frac{uT}{D}, \frac{EA}{\rho u^2 D^2}, \frac{T_{Top}}{\rho u^2 D^2}, \frac{gD}{u^2}\right) \tag{4}$$

where, $\left(\frac{\rho u D}{\mu}\right)$, $\left(\frac{u^2}{gD}\right)$ and $\left(\frac{uT}{D}\right)$ are respectively, the Reynolds Number (Re), Froude Number (Fr) and Keulegan-Carpenter Number (KC).

Dimensionless parameters shown in the Equation (4) should be the same for real riser prototype and riser model in order to obtain complete similarity. These parameters allow us to determine the scale factor between real prototype and reduced riser model, following equations (5).

For bending stiffness, the constant for scale reduction is obtained as follows:

$$\left.\frac{EI}{\rho u^2 D^4}\right|_{prototype} = \left.\frac{EI}{\rho u^2 D^4}\right|_{model} \Rightarrow \qquad EI_{model} = \frac{EI_{prototype}}{\lambda^5} \tag{5}$$

The scale reduction factor for mass, elasticity and axial stiffness etc. can be obtained from the same procedure.

It is not rare to happen that a dynamic similarity between model and prototype is not achieved, in defining the model itself and determining experimental conditions. In this case, incomplete similarity is commonly adopted. The remaining non- similarities, due to this fact, should be solved separately.

4. Model Testing for Deep and Ultra-Deep Water Riser

A traditional procedure to evaluate the riser response under environmental loads is the extrapolation of results obtained from the use of riser model in a wave basin under controlled load conditions. Usually, the design of riser model for moderate water depth is unproblematic. The scale reduction factor can be obtained from dimensional analysis and experimental tests can be carried out in a typical wave basin (depth about 5m). However, for deep and ultra-deep water risers, the modeling requires wave basin depth that is not usually available, and the model diameter will be very small, in general, to represent correctly all involved effects such as viscous effects and riser structural properties. Table 1 shows prototype dimensions and corresponding required model dimensions for several scale factors for an ultra deep-water production riser.

Table 1 Riser properties for several different scale factors

Scale	L (m)	D (m)	Din[(1)] (m)	m (kg/m)	EI (N.m²)	EA (N)
full scale	3000	2,731E-01	2,318E-01	1,284E+02	2,725E+07	3,399E+09
1/25	120	0,010922	0,009272	0,2054072	2,7905244	217521,08
1/50	60	5,461E-03	4,636E-03	5,135E-02	8,720E-02	2,719E+04
1/100	30	2,731E-03	2,318E-03	1,284E-02	2,725E-03	3,399E+03
1/200	15	1,365E-03	1,159E-03	3,209E-03	8,516E-05	4,248E+02
1/400	7,5	6,826E-04	5,795E-04	8,024E-04	2,661E-06	5,311E+01
1/600	5	4,551E-04	3,863E-04	3,566E-04	3,505E-07	1,574E+01

[(1)] Din is the internal diameter of the riser.

From Table 1, a feasible scale relationship for modeling this riser is around 1/600. However, the model dimensions are not suitable to be built and tested. The design of small scale model is a hard task and it is necessary more than the use of scale factor to design a representative model. In order to solve this problem, three alternatives are presented to realize experimental: keeping all dimensions except the diameter, using only a truncated part of the riser for the test, or using only a component of the riser.

The first alternative is to perform the experiment with dimensions obtained from the scaling and modify only the model diameter. Once maintaining scale relationship of bending stiffness and mass distribution in the model, the static and dynamic behavior of riser model should be similar to the prototype, except in the magnitude of displacements and forces, which means that global behavior of the riser can be observed and the obtained information from the experiment can be qualitatively used. The quantitative use of information will depend on correlations obtained from the new diameter effects on the other parameters. Further, data from the experiment will be useful for validation procedure of numerical codes for riser problem.

The second one is the use of truncated model (Baarholm et. al, 2005). The main idea of this procedure is the use of larger dimension model compared with the first one. The model must be appropriately truncated in the length in order to make it possible to assemble it into the model basin. The truncated part of the model and its boundaries should be represented by a set of devices that allow the simulation of the cut part of model. The truncated model can better represent the viscous effects than the complete model in length, for deep and ultra-deep water scenario. In this manner, effects could be minimized due to differences in the Re number between model and prototype.

Finally, the third alternative is to use a piece or element of the riser. In this case, the forces acting on this elementary riser model is deeply investigated, and the results are extended into all riser length. A numerical model could be developed to perform necessary simulations for all riser system. In terms of riser model and experiment, it could be the simplest procedure to be carried out, however the understanding of overall riser behavior is done by computational model.

There is no best solution for riser model design; all the methods here discussed present uncertainties in the results. The most appropriated model will depend on the desired information expected from experiments in a model basin, and facilities available to perform the tests.

5. A Case Study

From initial evaluation for the scale factor, defining the desired information and observing unfeasible dimensions for a riser model due to experiment facility restrictions, fine adjustment of the experiment model scale is necessary.

Considering the prototype dimensions as described in Table 1, the limitation due to wave tank depth (5.0m) and the objective of the study regarding the riser global behavior, the scale factor is defined as 1/600.

Table 2 shows comparisons among different prototype dimensions, ideal model scale reductions and the modified ones. External diameter limit for the riser in experiment, around 5.0mm (Maeda et al, 2005), is observed. Small diameter of the riser model complicate the instrumentation and data acquisition, particularly for transverse direction due to small amplitude of displacements in this direction and limitations of actual measurement devices.

Table 2 Comparison between riser properties for prototype, ideal and modified scale

Item	Prototype	1/600 (ideal)	1/600 (modified)
L (m)	3,000E+03	5,000E+00	5,000E+00
Dext (m)	2,731E-01	4,551E-04	5,500E-02
Dint (m)	2,318E-01	-	-
mris (kg/m)	0,000E+00	3,566E-04	3,566E-04
EI (Nm²)	2,725E+07	3,505E-07	3,505E-07
EA (N)	3,399E+09	1,574E+01	1,574E+01

Another important parameter in the riser model design is the flow velocity that includes velocities due to waves and current. The scaling of these parameters is carried out following Froude's law, which related effects are usually dominant close to the free surface. Consequently, different Re number for model and prototype is expected, as shown in Table 3.

Table 3 Reynolds Number for different diameters and flow velocities

Item	Prototype	Model (ideal)	Model (modified)
V1 (m/s)	2	8,16E-02	8,16E-02
V2 (m/s)	1	4,08E-02	4,08E-02
V3 (m/s)	0,5	2,04E-02	2,04E-02
V4 (m/s)	0,1	4,08E-03	4,08E-03
Re (V1)	5,54E+05	3,67E+01	4,49E+02
Re (V2)	2,77E+05	1,84E+01	2,25E+02
Re (V3)	1,38E+05	9,19E+00	1,12E+02
Re (V4)	2,77E+04	1,84E+00	2,25E+01

Figure 2 shows the relation between Reynolds Number and the dimensionless length of the riser for different flow velocities.

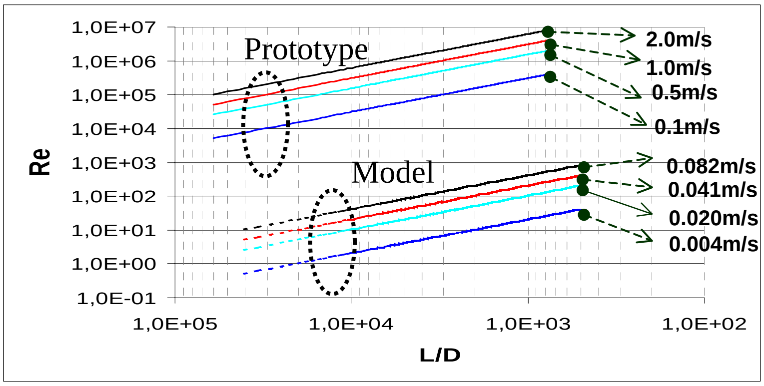

Figure 2 Relation of Re number and dimensionless riser length for full and small scale (1/600)

If Re number there was similarity between model and prototype, the curves in the Figure 2, for a specific velocity, should be coincident when it is represented by a scaled dimensionless parameter.

Figure 3 shows the relation between dimensionless stiffness parameter $EI/\rho u^2 D^4$ and the riser diameter.

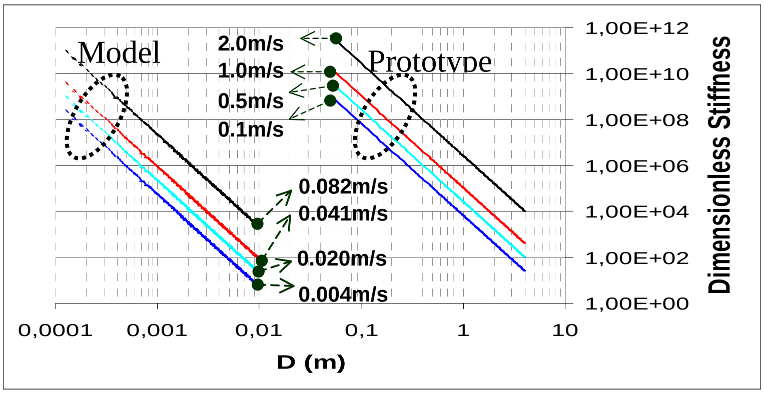

Figure 3 Relation between Diameter and Dimensionless stiffness for full and small scale (1/600)

The bending stiffness parameter must be the same for both, model and prototype, to maintain necessary similarity. In fact, the fluid properties external to the riser (ρ and u) do not influence directly on riser bending stiffness, however, the dimensionless stiffness parameter must be the same for prototype and model in order to obtain complete similarity. If the curves in Figure 3 were exactly scaled by a dimensionless parameter (for example L/D) instead of the diameter, the curves for prototype and model should be almost coincident. This tendency occurs due to the fact that water density parameter is not usually scaled. If the water density was scaled, the curves for model and prototype would be coincident, however the use of another fluid different from the water, is not adequate, in general.

Figure 4 shows the relationship between dimensionless riser length and KC number.

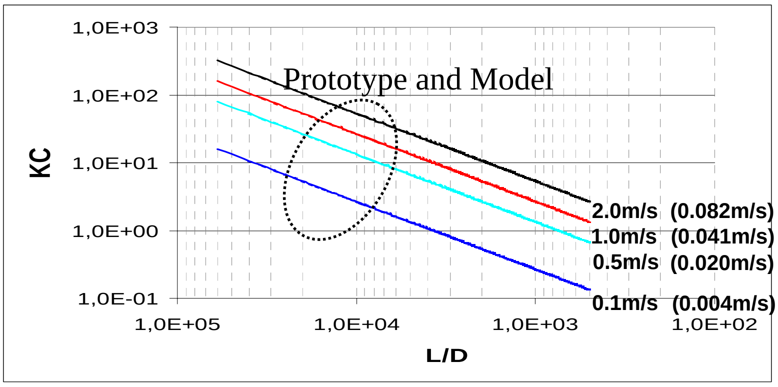

Figure 4 Relation between L/D and KC number for full and small scale (1/600)

KC number indicates the importance of drag force effect. The Figure 4 shows the coincidence in the KC number for model and prototype. This tendency is observed because the parameters used in the KC number are exactly scaled. If the model is completely similar to the prototype, all dimensionless parameter curves will have the same tendency of KC number.

Table 4 shows main properties of the riser prototype and the model for ideal and modified cases. The modified prototype dimensions are calculated from the modified model ones. Comparing data for prototype in this Table, with ideal and modified cases, it is observed that there is only difference in the riser diameter but the other properties are maintained equal. This means that if the model is built following data described in the Table 4, riser model structural behavior should appropriately represent prototype behavior. However, magnitudes in the behavior, for example, riser displacements and hydrodynamic forces in the riser, should be similar to that acts on 3,3m diameter riser. This diameter is obtained from the scaling of modified model diameter to prototype dimension.

Table 4 Properties of model and prototype for ideal and modified cases

	Ideal		Modified	
Item	Prototipo	Model	Prototype	Model
L (m)	3000	5	3000	5
Dext (m)	0,27305	4,551E-04	3,3	5,500E-02
mris (kg/m)	1,284E+02	3,566E-04	1,284E+02	3,566E-04
EI (Nm²)	2,725E+07	3,505E-07	2,725E+07	3,505E-07
Re(2,0m/s)	5,535E+05	3,674E+01	6,765E+06	4,491E+02
Re(1,0m/s)	2,768E+05	1,837E+01	3,383E+06	2,245E+02
Re(0,5m/s)	1,384E+05	9,186E+00	1,691E+06	1,123E+02
Re(0,1m/s)	2,768E+04	1,837E+00	3,383E+05	2,245E+01

The use of dimensionless parameters is very useful to design model experiments. If effect of dimensional parameters are considered independently, for example, only effect of D, L, u and μ, it would be necessary to use several models and fluids with different dimensions and properties, which means that a huge amount of experiments should be carried out. The use of dimensionless parameters in the analysis allows the reduction of necessary experiments and models.

Usually, complete similarity is not obtained in the design of a riser model, mainly for the case of deep-water riser, due to unsuitable dimensions required by the model and experimental facility requirements. Sometimes, to accomplish scale reduction requirement, unfeasible modifications are needed in the experimental facility or model, such as changes in the fluid properties of water in the wave tank and high-speed water current velocities. Then, the parameters involved in the scale reduction should be carefully analyzed and approximations are required for riser model design according to desired information from the experiment and following non-dimensional parameters.

In the present case study, the main objective is to measure lateral displacements of the riser for in-line and transverse directions. Then, the bending stiffness (EI) and the axial stiffness (EA) are important structural parameters to be followed up. Similarities of those parameters between model and prototype are important to estimate the fatigue life of riser from the experiment. However, the dimensioning of riser model material to keep the similarity of EI and EA, simultaneously, between model and prototype is a hard task. On the other hand, for the present study, it is desirable to have similarity in Re and KC numbers between prototype and model in order to reproduce properly the hydrodynamic forces in the riser model. The KC number can be obtained as observed in the Figure 4, however Re number cannot be reproduced in the experiment because the flow velocity scaled with water needs to follow Froude's number which leads to unfeasible high current flow velocities. Even with different Re number for model and prototype, it is possible to be obtaining similarity on hydrodynamic load, if Re is in the range between $250<Re<2x10^5$ (laminar flow) in both, model and prototype. In this range of Re number, the drag coefficient (C_D) is almost constant around 1.0 (Fox, 1999), which means that the drag coefficient can be considered same for the model as to the prototype and forces will be proportional to u, ρ, D.

6. Application of the Experiment

An example of application of scaling for riser model and experiment is available in Suzuki and Maeda (2000) and JIRP (2001). They performed experimental tests with a model of vertical TTR in a wave tank. The dimensions of model and prototype are in the Table 5.

Composite solid model with Teflon coated brass is used in the experiments. Geometric similarity is obtained in this experiment from the outer diameter and length relationship between model and prototype. Then, hydrodynamic phenomena are represented in the experiments, conveniently. The riser model scale in the experiment is 1/50.

Table 5   Comparison between prototype and model parameters

Properties	Real Scale	Model (1/50)	
		Teflon	Brass core
Outer Diameter (m)	0.25	0.0050	0.0017
Inner Diameter (m)	0.21106	0.0018	-
Modulus of Elasticity (N/m2)	2.1x1011	0.4x109	1.006x106
Density of Material (kg/m3)	7860	2170	8600
Water Depth (m)	100	2.0	
Riser Length (m)	120	2.4	
Top Tension (N)	5.0x105	3.092	
T_{Top}/mL (N/kg)	21.15	21.15	
EI/mL^3 (N/kg)	0.058	0.0502	
$\rho A/m$	0.2554	0.2555	
$\rho DL/m$	156.08	156.17	
Mass per Length (kg/m)	197.01	0.08244	

For the case study here presented, the riser length of 120m, riser diameter of 0.25m and scale reduction of 1/50 allowed to have model dimensions to be representative for the needed riser structural and hydrodynamics representation. In other words, material properties such as EI, EA and mass per length, and geometric dimensions could be obtained with available materials to represent the prototype behavior in a small scale riser model.

The wave basin dimensions used in the experiment are: 2.0 m deep with 30 m wide and 50 m long. Wave generators are disposed in the short side of the basin and in the opposite side, passive wave absorber is installed.

The riser model is tensioned at the top by constant weights and horizontal forced oscillation device is installed for the experiments. Two sets of underwater cameras are used to measure riser displacements. Both ends of the riser, top and bottom respectively, are free to rotate.

Comparisons between numerical simulations and experimental results are shown in Figure 5 in terms of the maximum and minimum displacement envelope.

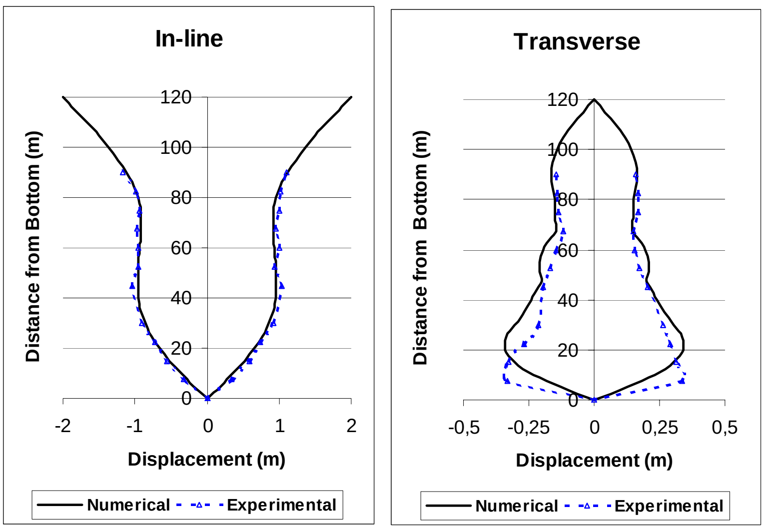

Figure 5   Comparison between numerical and experimental data for forced oscillation case

In general, there is good agreement between numeric calculation and experimental results. This fact was already expected due the good adjustment of dimensionless parameters and the relatively small reduction scale factor, allowing the design of appropriated model.

Differences between calculations and simulations can be observed from the results. It could be taken into consideration hydrodynamics drag and inertia coefficients in the calculations, and accuracy of measurements in the riser model. These topics are subject to further analysis.

7. Conclusions

If deepwater scenario is considered for vertical Top Tensioned Risers, the reproduction of all dimensionless parameters from prototype to small scale riser model for laboratory experiment with complete similarity is a very difficulty task.

Guiding riser model design following dimensionless parameters is very suitable. These parameters are used to determine correlation between full scale prototype and small scale model. Varying dimensionless parameters in the analysis avoids unnecessary variation of each dimension parameter themselves (L, D, μ, ρ, etc), independently, and reduces the need of construction of several models.

In the design process of an experiment, when feasible dimensions are not possible to be obtained from the direct prototype scaling, it is possible to design models by the use of appropriate experimental procedures fitted to the desired information to be obtained from the experiment. If the main objective is to verify the global behavior of a riser, in general, dimension of the riser diameter should be bigger than indicated by the model scale relationship, otherwise, truncated model or experiment with element of the riser could be more appropriate.

Wave tank size, particularly its depth, is very important for riser model experiments. Minimum water depth is required to obtain fundamental similarities between prototype and model, such as riser structural and hydrodynamic similarities.

In order to investigate global behavior of a riser in an experiment, the most important parameters are the outer diameter and length of the riser, due to the direct influence of those in the hydrodynamic loads, riser mass distribution, riser axial and bending stiffness, due the influence in the structural response.

Comparisons between experiment and numerical simulations have shown good results from measurements in the experiment. In general, good agreement could be observed for in-line riser displacements. Some differences observed for transverse direction motivate further improvements in the experimental technique as much as in the numerical simulation methods.

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