# A COMPARISON BETWEEN TWO SIMPLE MODELS OF A SLUG FLOW IN A LONG FLEXIBLE MARINE RISER

*A. Pollio*[1] *& M. Mossa*[2]

(1) Department of Water Engineering and Chemistry, Technical University of Bari, Via E. Orabona 4, 70125 Bari, Italy, a.pollio@poliba.it
(2) Department of Environmental Engineering and Sustainable Development, Technical University of Bari, Via E. Orabona 4, 70125 Bari, Italy, m.mossa@poliba.it

SUMMARY

*Slug flows are extremely interesting multiphase regime phenomena which frequently occur in flexible marine risers used by the petroleum industry in offshore environments and have both a liquid and gaseous phase. Generally, the gaseous phase is pumped in together with the liquid phase to facilitate the suction of the latter. Literature and experimental observations show a wide range of multiphase regimes which are the result of numerous parameters such as liquid and gaseous discharge, the pipe diameter and its inclination.*
*This work describes two simple models of the slug flow regime by means of an equivalent monophase flow with a non-constant density. In the first model, the slug wavelength is supposed to be independent of the riser inclination, while in the second one a simple linear relationship between the slug wavelength and the pipe inclination was imposed. The global equation of the motion of the riser (written in a two-dimensional domain) was solved using a Matlab code in the time domain to investigate the dynamic stresses which the riser undergoes. In particular, the axial tensile force, the bending moment, the viscous structural damping, the wave-induced forces and the riser-seabed interaction are all modelled here.*

## 1 INTRODUCTION

Recently, the oil industry has shown interest in extracting coal oil from oilfields located at deep ocean levels. To achieve this goal, flexible marine risers, which are specifically-designed flexible pipes, must be used in the extraction operation. The risers allow for the transfer of crude oil from the seabed, where there is a pumping station, up to the free water surface where other structures (modified oil tanks or oil platforms) are located in order to store the crude oil before treatment. Because of the extreme depths involved (generally from several hundred up to thousands of meters), the risers are subjected to numerous forces that induce high stress levels in the pipe material. Therefore, an appropriate pipe design is essential to render them more resistant and to avoid possible breaks and subsequent dispersal of oil and gas which could be transported towards sensitive areas near coastal environments.

In this study, in order to investigate the riser behaviour in the time domain, the lumped mass approach (*Ghadimi*, 1988) is used to represent the riser and all the forces acting on it. Specifically, the riser is divided into a given number of segments and nodes and at each node a lumped mass representing the segment mass is associated. All the forces acting on the pipe are applied at the various nodes by means of the free body diagram of each lumped mass. In particular, in this study the modelled forces are the submerged weight of the riser, the Morison's forces in the presence of regular monochromatic waves, the slug flow forces and the seabed-riser interaction. The inner stresses of the pipe are added to these: the axial tensile force, the tangential structural damping modelled by a viscous model and the shear force, useful in investigating the bending moment distribution of the riser.

In this work, the authors present some results from the time domain simulations for two riser configurations (either in the absence or presence of the seabed) for which both its ends are pinned as a free hanging configuration. In order to obtain these results, the non-linear equation of the motion was solved by using the ODE 113 algorithm implemented in MATLAB.

The results are presented in order to highlight the impact of the inner hydraulic regime due to the slug flow on the internal stresses of the riser. Several considerations could be taken into account by the designers of risers in planning a suitable riser resistance, thus avoiding possible breaks.

## 2 STATE OF THE ART

Multiphase flow regimes are a very complex area of study. If the objective is to model the slug flow pattern, it must be described in a specific way as it is an intermittent and unsteady phenomenon. Generally, the equations describing this non-steady motion are highly complex and as a result some simplifications may be useful to describe simple models, an approach adopted in this study. The time domain analysis is the most accurate method available to study the behaviour of a flexible marine riser. This is because only this type of analysis is capable of describing all the non-linearities in structural geometry, loading and material behaviour in a suitable way.

*Gardner & Kotch* (1976) used a finite element analysis in conjunction with the Newmark method to provide a time domain technique for the analysis of vertical risers in waves. They supposed that the effects of structural damping in comparison with fluid damping are slight and that it is more important to stabilize the problem numerically.

It should be noted that in the code used in our study, the introduction of structural damping allowed the authors to filter the output of the various quantities involved in the system in order to obtain the same results as the commercial code Orcaflex. The difference in our approach is that the coarse code (that is, without structural damping) does not create numerical difficulties but takes into account the higher frequency content; as a result, the outputs are noised.

*Cowan & Andris* (1977) also used the Newmark method for a time domain analysis of a pipe laying system. In the time domain analysis they considered the dynamic variations of the system parameters as perturbations of their mean static values.

*Patel & Jesudasen* (1987) considered vertical free hanging risers subjected to vessel motion and wave loading using the Newmark method. *Patel & Sarohia* (1984) used frequency and time domain procedures for vertical risers. The time domain solutions employed the Newmark method.

A clear presentation of the derivation of the equation of the motion of a riser by using a lumped mass approach may be found in *Ghadimi* (1988) who implemented the Newmark technique to solve the problem. In his work, he used the tangent stiffness matrix and also a model for the bed force by a hyperbolic tangent function.

The most interesting research on the internal flow effect in a riser by considering the actual features of the phenomenon was carried out by *Patel & Seyed* (1989). In their work, the authors derived the equation by following the finite element approach and the slug flow was modelled by considering a fluid with a periodic density.

More literature about the study of the equation of the motion for flexible marine risers may be found in *Patel* (1995) in which all the time and frequency techniques are clearly described together with all their advantages and disadvantages. The good quality of the code presented in this work with regard to the comparison between its results and those obtained from the commercial code Orcaflex is discussed in *Pollio et al.* (2006).

## 3 SHORT DESCRIPTION OF THE PRESENT MODEL

As previously said the riser is compounded by a set of nodes connected to each other by massless elements. Considering each node as isolated, the free body diagram allows for the forces acting on it. Essentially, these forces are of two types: the forces spreading throughout the pipe wall, that is, the shear force $\boldsymbol{Q}_i$, the structural damping $\boldsymbol{F}^C_i$ and the axial force $\boldsymbol{T}_i$, and the other forces, due to external causes (submerged weight $\boldsymbol{W}_i$, Morison's forces due to the drag and the inertia $\boldsymbol{F}^D_i + \boldsymbol{F}^I_i$) and the internal force (slug effect $\boldsymbol{F}^S_i$).

The equation of motion of each element of the riser (in which the slug force does not appear), written for both nodes, can be assembled in the following vectorial equation (4×1) related to the j-th element:

$$[\mathbf{M}]_j \ddot{\mathbf{S}}_j = T_j \boldsymbol{\upsilon}_j + \mathbf{W}_j + \mathbf{F}^D_j + \mathbf{F}^I_j + \mathbf{F}^C_j + \mathbf{Q}_j \tag{1}$$

where *[M]* is the mass matrix, $\boldsymbol{S}$ the displacement vector of the nodes, $T$ the module of the axial tension, $\boldsymbol{\upsilon}$ the unit vector of the element. For detailed information about the meaning of the various quantities see *Marano et al.* (2006), *Pollio et al.* (2006), *Pollio et al.* (2007). The structural damping force $\boldsymbol{F}^C_i$ considers the relative velocity between the nodes $i$ and $i+1$ along the direction of the element $j$ (see *Pollio et al.*, 2006). The seabed acts only on those riser nodes actually lying on it. In this study, two components of the force deriving from the contact between the seabed and the riser were considered: the first, $R_s$, is due to the elastic behaviour of the seabed which affects the nodes lying on it while the second, $F_s$, is the result of friction and acts along the seabed surface (*Liu & Bergdahl*, 1997). The normal reaction $R_s$ is written as function of the relative displacement between the seabed (which has the depth $d$) and the node depth $y$ and also depends on the seabed stiffness $e=E_sA_s/d \propto W$ (represented by the stiffness factor $e$ which here is considered proportional to the submerged weight of the pipe) where $E_s$ is Young's module of the soil and $A_s$ is the contact area between the pipe and the seabed.

The biphasic flow is considered as a monophase fluid flow with variable density as a function of time and the riser's node location. At the generic section $s$ the fluid density is modelled in the following way (see also *Patel et al.*, 1989):

$$\rho(s,t) = \rho_m + \rho_f \cos(k\,s - \omega t) \tag{2}$$

where $\rho_m$ is the mean density of the fluid, $\rho_f$ its amplitude, $\omega$ the circular frequency of the slug flow regime, $t$ the time at which the density is evaluated, $s$ the curvilinear abscissa of the node and $k=2\pi/L_s$ the slug wave number in which $L_s$ is the slug wavelength. In the second case, a relationship between slug wavelength $Ls$ and the pipe inclination $\theta$ can be written as:

$$L_s(\theta) = \frac{\theta - \theta_{\max}}{\theta_{\min} - \theta_{\max}}\left(L_{s\_\max} - L_{s\_\min}\right) + L_{s\_\min} \tag{3}$$

in which (*Fabre & Line,* 1992) $L_{s\_min}$=8 $D_i$ at $\theta_{min}$=0 and $L_{s\_max}$=30 $D_i$ at $\theta_{max}$=$\pi$/2.

## 4 RESULTS

In the present work a series of simulations were carried out in order to appreciate differences in the pipe behaviour with the aforementioned two slug flow models.

In order to highlight only these aspects, a number of parameters were considered constant in each simulation, which had a real time of 400s, and the output was recorded every 0.1s. Table 1 shows the main quantities and the values which characterised the input parameters.

| | | |
|---|---|---|
| Cable length | [m] | 1400 |
| Number of elements | [-] | 80 |
| Horizontal span | [m] | 1200 |
| Vertical span | [m] | 550 |
| Axial rigidity EA | [N] | $5{\cdot}10^8$ |
| Moment of inertia EJ | [kN·m$^2$] | 120.8 |
| Inner diameter | [m] | 0.305 |
| Outer diameter | [m] | 0.396 |
| Critical damping factor | [-] | 0.2 |
| mass per unit length | [kg/m] | 165 |
| Drag coefficient | [-] | 1 |
| Normal added mass coefficient | [-] | 1 |
| Seawater density | [kg/m$^3$] | 1024 |

**Table 1.** Main constant quantities used for the simulations.

The code was validated in the absence of a seabed and slug force as presented in a previous paper by the authors (*Pollio et al.*, 2006).

The top node of the riser was set at 5m under the mean seawater surface. The system underwent a simple sinusoidal wave motion with a wave height of 6m and a period of 10s. The seabed was flat and its depth corresponded to the depth of the bottom node in order to keep the riser lying on it at its lower parts (Figure 1-b). The riser initially had an elastic catenary configuration. Table 2 shows the main parameters of the two sets of simulations for both the slug flow models presented here. For the simulations *Ti*, the riser was subjected to all forces except seabed reaction, which was considered only for the tests *TBi*. In the case of constant slug density along the riser, only the slug wavelength varies and a constant mean velocity of 6m/s was used as a typical value proposed by *Patel & Seyed* (1989). In the case of the slug density variable with pipe inclination, the slug wavelength assumed the expression presented in the previous section and also in this case the mean travelling velocity of the fluid was set at 6m/s.

| Simulation name | Slug wavelength [m] | Slug frequency [Hz] | Slug period [s] |
|---|---|---|---|
| T1,TB1 | 2.44 | 2.46 | 0.41 |
| T2,TB2 | 5.12 | 1.17 | 0.85 |
| T3,TB3 | 7.80 | 0.77 | 1.30 |
| T4,TB4 | 10.5 | 0.57 | 1.75 |
| T5,TB5 | Slug flow with frequency from 0.57 Hz to 2.46 Hz depending on pipe inclination | | |
| T6,TB6 | Fluid with constant density | | |
| T7,TB7 | No inner fluid | | |

**Table 2.** Tests carried out.

The density of the equivalent liquid of the biphasic slug regime was based on a liquid density of 900kg/m$^3$ and a gaseous density of 500kg/m$^3$. The two geometrical configurations are sketched in Figure 1.

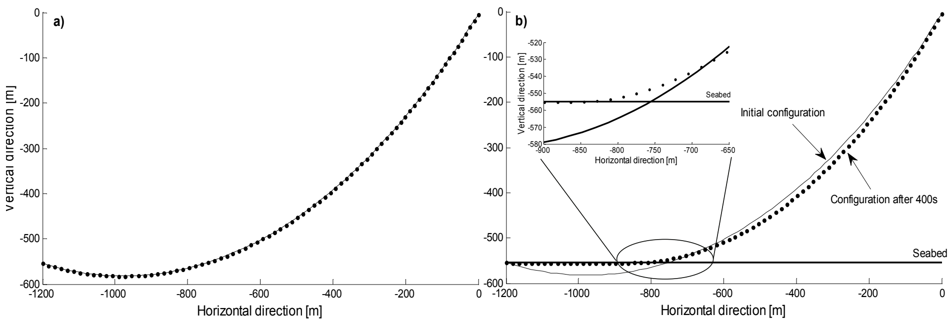


**Figure 1.** Examples of the geometric configurations of the riser in absence of bed (*T1*, a) and in presence of bed (*TB5*, b). (continuous line: initial riser geometry; dotted line: configuration after 400s).

Figure 2 shows the top effective tension temporal behaviour for all the *Ti* tests.

It is possible to note that the presence of a slug flow with density as a function of the inclination (*T5*) affects the axial tensile force in the same way as the effects of the slug flow with constant slug wavelengths (*T1*-*T4*) in the same range of frequencies. In the absence of inner fluid, the tension values are very low in comparison with their former ones (*T7*). Figure 2-b shows a close-up over the last 50s of the simulations. It is possible to see that for the tests *T1*-*T4* and *T5* the riser is subjected to more complex tension variations due to the intrinsic frequency of the liquid slugs passing through the riser. In all cases the tension behaviour seems to have a good general regularity. The greater distortion of the axial tension due to the presence of a slug flow with a varying frequency along the entire pipe length (*T5*) is clearly visible.

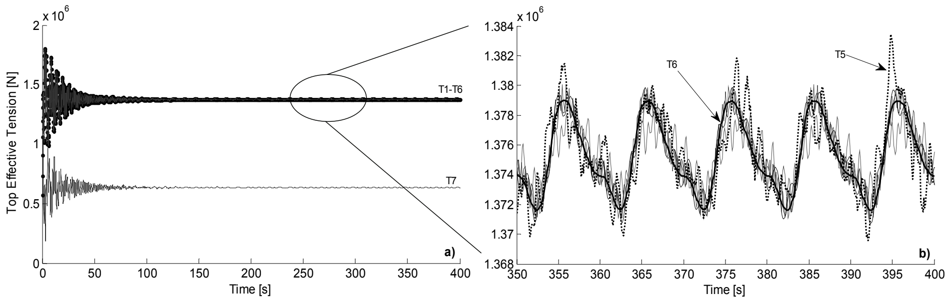


**Figure 2.** Top effective tension temporal behaviour for all the *Ti* tests with a close-up of the last 50s (continuous line, *T6*; dotted line, *T5*).

Similar results are obtained for the bottom effective tension, which is the tension evaluated at the bottom end node, but they are not reported here for the sake of brevity.

It is interesting to note from Figure 3-a and Figure 3-b that the mean effective tension and the mean bending moment distributions obtained in test *T5* have a general behaviour practically identical to that obtained from the other tests.

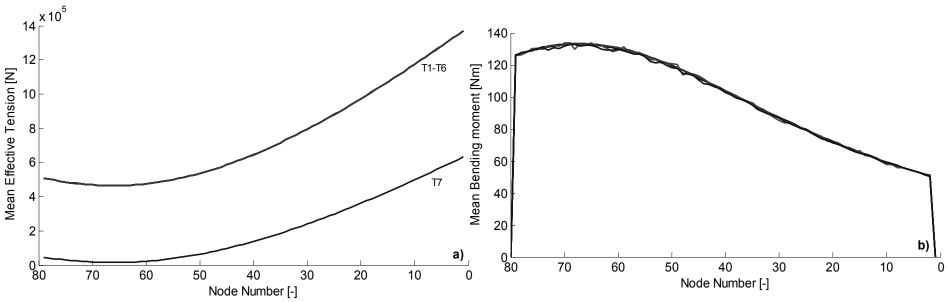


**Figure 3.** Mean effective tension (a) and mean bending distributions (b) along the riser for the *Ti* tests.

The differences between the maximum and the minimum effective tension and bending moment obtained along the riser are reported in Figure 4. Test *T5* presents the higher variations of tension between its minimum and maximum values. This does not happen with the same magnitude in the other tests (Figure 4-a), while test *T3* has the highest variation of the bending moment along the riser (Figure 4-b). Such peculiar behaviour may be due to the possible resonant effect at the frequency of almost 0.77Hz that mainly affects the moment values, even though the study of the natural frequency of the riser is not presented here.

The results obtained from the simulations with seabed presence show that the axial tension is less than that obtained in the absence of the bed at both the pipe extremities. Also in this case, the top effective tension for test *TB7* (no presence of inner fluid, and pipe subjected only to wave motion) is less than that of the others which present a value of almost $12 \cdot 10^5$N (graph not reported here for sake of brevity, see Figure 2 for a comparison).

For the bottom end node, the effective tension values follow the same behaviour of those depicted for the top end node.

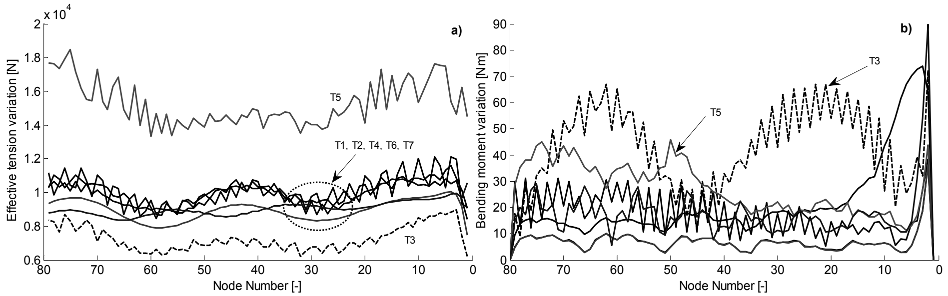


**Figure 4.** Variations of the effective tension (a) and the bending moment (b) along the riser for the *Ti* tests.

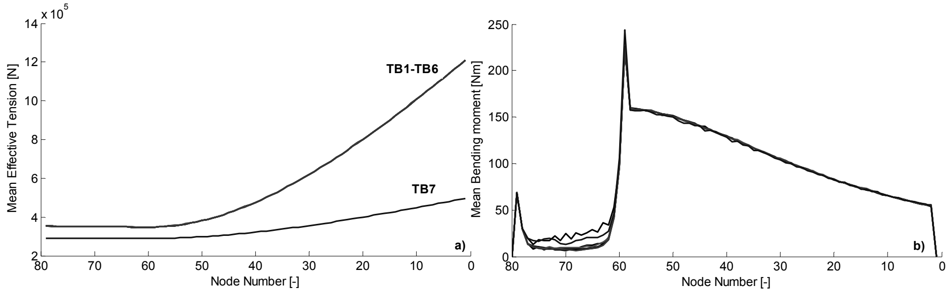


**Figure 5.** Mean effective tension (a) and mean bending distributions (b) along the riser for the *TBi* tests.

Figure 5 presents the mean effective tension and moment distribution along the riser lying on the seabed. Figure 5-b highlights the presence of the touchdown region at which the bending moment values increase suddenly due to the riser detachment from the seabed.

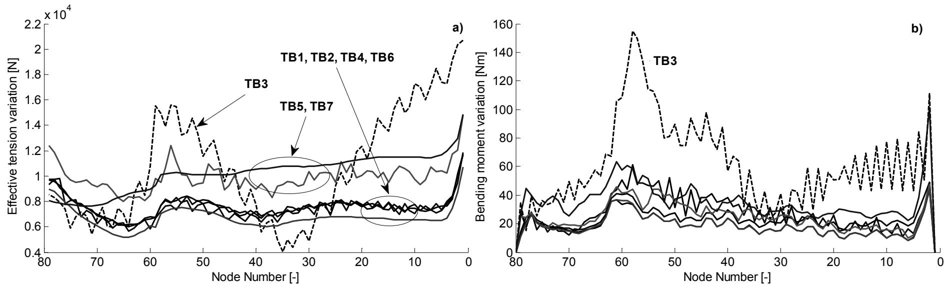


**Figure 6.** Variations of the effective tension (a) and the bending moment (b) along the riser for the *TBi* tests.

In the presence of the seabed, too, the variations for the effective tension and the moments along the pipe are plotted (Figure 6-a and Figure 6-b respectively). In this case, the differences are lower than those obtained for the tests *Ti* (see Figure 4); this may well be an important aspect that must be considered in designing this kind of pipe when a seabed-cable interaction is present.

## 5 CONCLUSIONS

Some interesting results obtained from the simulations can be summarised as follows:

- a slug flow with variable frequency allows for irregular inner stress behaviour over time, while the tension and moment variations seems to be more regular when a steady flow and slug flow with constant frequency occur.
- In the presence of the seabed there are fewer differences between the maximum and minimum values of the axial tension along the riser with respect to those obtained in the absence of the seabed for all the tests. The opposite phenomenon happens to the variation between the maximum and the minimum values of the bending moments.
- The presence of a slug flow with variable frequency either with seabed-riser interaction or without it has a greater effect on these differences and the riser itself undergoes higher stress with a greater probability that it will reach failure point.

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