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NUMERICAL SIMULATION OF THE MOORING PROCEDURES OF THE BGL-1 PIPELINE LAUNCHING BARGE

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ABSTRACT

The objective of this paper is to present the application of a computational tool intended to help the crew of the BGL-1 pipeline launching barge to develop safe mooring procedures. This tool is able to calculate the deformed catenary configuration of all mooring lines, regarding the subsea layout and the local environmental conditions, and taking into account one or more buoys attached to the mooring lines in order to avoid interference and accidents with subsea obstacles.

One of the main characteristics of this computational tool is the fact that it is able to incorporate the correct definition of the seabed from bathymetric curves, and to automatically consider the position of the subsea obstacles, and possible interferences between the mooring lines and the obstacles. This is performed through a specialized interface with the SGO (Obstacles Management System) database system. This system, developed by Petrobras, contains frequently updated information about the bathymetry and position of subsea obstacles, gathered by a special vessel equipped with a ROV (Remote Operated Vehicle).

Case studies will be presented, in order to illustrate the application of the system to the design of actual mooring procedures.

INTRODUCTION: THE BGL-1 BARGE

The BGL-1 (Figure 1) is a pipeline launching barge owned by Petrobras. It performs installation operations by moving forward using its own mooring lines. This involves the definition of a complex mooring procedure, as a sequence of operations that determine the mooring line positions and induce the laybarge movement as it lays the pipeline [1]. Basically, tug boats drop anchors at some predefined positions; then the barge winches release the stern mooring cables, and collect the mooring cables located at the bow.



Figure 1: The BGL-1 Pipeline Launching Barge

Definition of Mooring Procedures

Most of the times the laybarge operates at locations where the sea bottom is congested with other pipelines, Christmas trees, manifolds, or fiber optics. Therefore, for safety reasons, the definition of the mooring procedure (leading to the motion of the barge) must take into account not only the desired pipeline route, but also possible interferences between the mooring lines and subsea obstacles.

In order to avoid interference and accidents with such obstacles, the definition of the mooring procedure includes the placement of buoys attached to the cables, with the purpose of lifting the mooring lines and increasing the distance between cables and subsea obstacles. The definition of the mooring procedure should also provide information about the amount and length of buoys' cables, pendants, and all related material such as shackles, swivels, cables, etc.

The need of Computational Tools for Numerical Simulation

This task of defining the sequence of operations that will comprise the mooring procedure is performed by the technicians of the BGL crew, previously, at the office. It is

obvious that the BGL-1 crew needs to exert extreme care when designing such mooring procedures, in order to avoid accidents.

Moreover, during the actual barge operation generally some changes are required. These changes occur due to unexpected changing weather conditions, winch maintenance, rupture of cables, exchange of support vessels, etc.

Therefore, while operating the barge and monitoring the tension of all cables, the operational supervisor must take decisions “on-the-fly”, without much time to think of what changes should be done to the mooring procedures when an unexpected event occurs. This is the main motivation for providing to the BGL crew an efficient and user-friendly computational tool that allows quick onboard simulations of possible mooring procedure changes.

Traditionally, the BGL-1 crew had been employing the CATCOM software. It is a DOS-based software for catenary calculations that allows the insertion of buoys and the definition of subsea interferences, as shown in Figure 2:

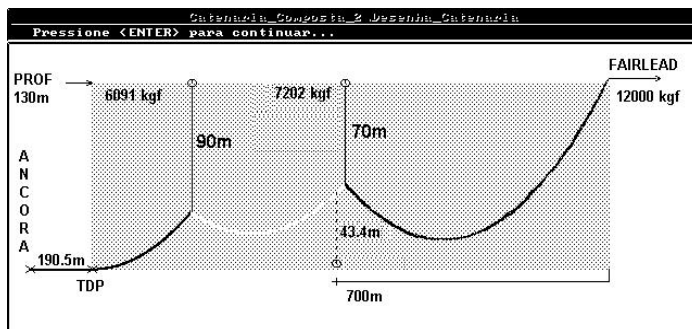


Figure 2: CATCOM

The CATCOM software, however, presents several drawbacks and restrictions:

- It requires the sequential input of the data that characterize one line, and does not keep any line information. If the user wants to change only one input data, he has to restart and input all data, all over again. This restriction makes the software extremely “non-operational” and cumbersome.
- It is a 2D software, allowing the calculation of only one line at a time. Since the BGL-1 has 10 mooring lines, this again makes the process too time consuming for the user.
- The software does not regard either the environmental conditions or the seabed (that is always considered as an horizontal plane). Thus, any interface with the SGO is not possible.
- It does not provide enough data about mooring lines types, materials, anchors, etc.

These drawbacks have, therefore, motivated the replacement of the CATCOM software by a more modern, efficient and user-friendly computational tool for the numerical simulation of the mooring procedures of the BGL-1 barge.

NUMERICAL SIMULATION TOOL: SITUA/PROSIM

As mentioned before, in order to help the barge crew to develop safe mooring procedures, the computational tool should be able to calculate the motions of the barge due to the operations performed with its mooring lines, leading to changes in their catenary configuration (including placement of buoys,

and variation of the onboard/released cable lengths); should consider general seabottom data and interferences with subsea obstacles; and, ideally, should take into account the local environmental conditions and perform dynamic analyses of the barge.

In order to meet these requirements, Petrobras considered the use of the SITUA/Prosim system, with a series of adaptations and enhancements intended to specialize its use for simulation of the BGL-1 mooring procedures. This system is based in the Prosim numerical solver [2], developed in cooperation by Petrobras and LAMCSO (Laboratory of Computational Methods and Offshore Systems, at the Civil Eng. Dept. of COPPE/UFRJ, Federal Univ. of Rio de Janeiro).

Numerical Finite Element Solver: Prosim

The Prosim numerical solver comprises a time-domain nonlinear dynamic analysis program, which has been employed by Petrobras since 1998 in several design activities related to floating production systems. The coupled formulation of the Prosim program incorporates, in the same computational code and data structure, a hydrodynamic model to represent the hull and a finite element model to represent the structural-hydrodynamic behavior of the lines.

This coupled formulation allows the simultaneous determination of the motions of the hull, and the structural response of the lines. Moreover, the results will be more accurate since all dynamic and nonlinear interaction effects between the hull and the lines are implicitly and automatically considered. Details of the mathematical models and the numerical solution strategies for coupled analysis implemented in the Prosim program may be found in [2].

The original Prosim code was oriented towards the analysis and design of floating systems, considering their installed and operational situations. Later, the SITUA/Prosim system was developed by adapting / specializing the code for the analysis of installation and damage situations (hence its name, from the Portuguese *SITUAções de instalação e Avaria*).

Graphical Interface for Pre-Processing and Model Generation; Catenary Solver

Another important aspect was that, much as the Catcom code, the original Prosim code also worked on a DOS environment, reading input data contained in an ASCII file that should be manually prepared by the user. As a result of recent developments, the SITUA/Prosim system now incorporates a graphical interface, designed to work as a pre-processor and model generator for the Prosim finite-element based numerical analysis modules, and to provide facilities for statistical and graphical post-processing and visualization of results.

The model generation procedures of the SITUA interface incorporate an analytical catenary solver, able to represent complex configurations such as lines with multiple segments and different materials, connected to other lines or to platforms, and with flotation elements such as buoys or segments with distributed floaters. This solver has been validated with the results of the monitoring of field operations, as has been described in a previous work [3].

As mentioned in [3], the next step in the development of the SITUA/Prosim systems regarded several aspects related to enhanced modeling facilities specifically devised for the

simulation of the BGL-1 mooring procedures (including for instance the accurate seabed representation in terms of bathymetry and obstacles). The development of such facilities is concluded, as will be described in the following sections.

ENHANCED MODELING FACILITIES

Seabed Representation: Bathymetry and Obstacles

One of the more important requirements for the efficient use of a computational system in the analysis of mooring procedures is the correct representation of the seabed. This allows the barge operator a safe and accurate simulation of operations in cluttered seabottoms.

Interface with Sea bottom and Obstacles Database (SGO)

A source of information that is already available at Petrobras is the SGO (an acronym for Obstacles Management System, in Portuguese) [4]. This is a database system, developed in C language, that contains frequently updated information about the bathymetry and position of subsea obstacles. The information is gathered by a special vessel - RSV Sagueiro, equipped with a ROV (Remote Operated Vehicle). An example of a screen of the SGO system can be seen in Figure 3.

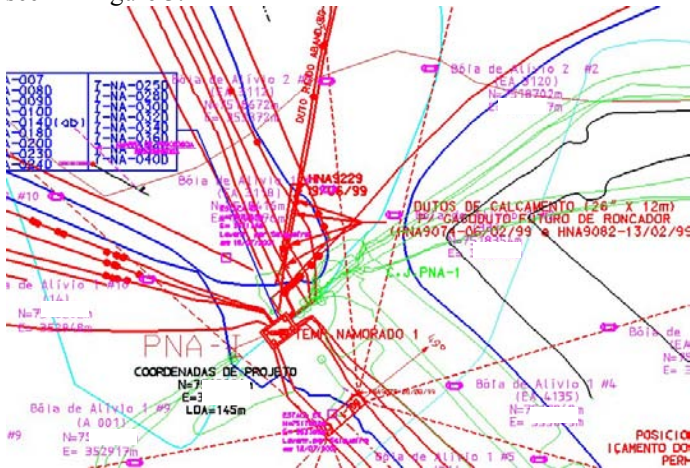


Figure 3: Typical SGO Screen

Therefore, one of the first tasks performed for the adaptation of the SITUA/Prosim system for the analysis of mooring procedures was to implement an interface with the SGO system, that is, the software is now able to read the SGO seabed data and simulate the pipeline launching operation considering the actual bathymetric information and obstacle characteristics and positions. The SGO files can be input either in the native DGN format, or in the popular DXF format (Drawing Exchange Format).

Figure 4 illustrate the screen that manages the input of the SGO file containing the definition of bathymetry and obstacles. The selected sea bottom region can be precisely defined in terms of its UTM world coordinates, which is subsequently related to the global coordinate axis considered in the definition of the model of the barge and its mooring system for the analysis.

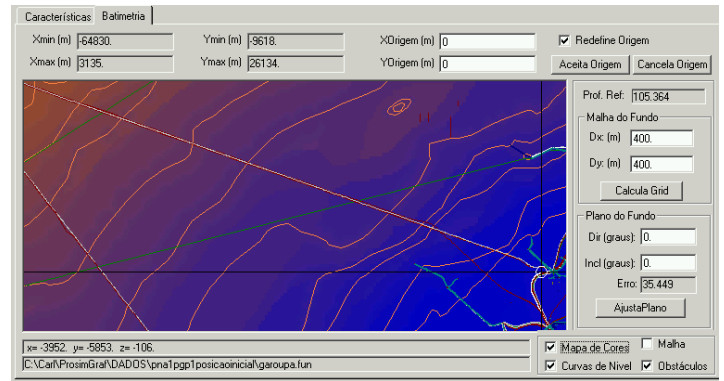


Figure 4 – Interface with Bathymetry and Obstacles Database

Models for Representation of Seabottom-Lines Interaction

The adequate representation of the interaction of the lines with the seabottom is a very important aspect in the analysis of mooring lines in regions with irregular topographies, in order to obtain an accurate evaluation of relevant results such as effective loads on the anchors and line tensions.

The bathymetric data define the seabottom as a generic surface in terms of bathymetric contour lines. From this generic surface, different alternatives are available to define the model for representation of the seabottom-lines interaction, to be considered: **a)** in the analytical catenary solver modules of the SITUA interface; **b)** in the pre-processor and finite element mesh generation modules of the interface, and finally **c)** in the finite element numerical solver of the Prosim program.

The available alternatives are the following:

- Automatically adjusting one global inclined seabottom plane, by a least squares procedure that minimizes the vertical distances between points of the bathymetric contour lines and the projections of these points on the adjusted plane. The results are the azimuth and declination angles that define the plane. The user has also the option of manually defining these values.
- Automatically adjusting several inclined seabottom planes, one for each mooring line of the system individually, by the same least squares procedure.
- Automatically generate a bathymetric grid, with density specified by the user. This grid can be used by all modules of the SITUA/Prosim system to interpolate the vertical position of each segment/element of all lines.

Visualization / Manual Definition of Seabed Obstacles

Eventually, the BGL operator may be aware of any actual obstacle that is not included in the SGO database. In this case, he can use the facilities incorporated in the system to manually define such obstacles. Both types of obstacles (those input from SGO, or manually defined) can be visualized in two or three-dimensional views.

To each obstacle is assigned a name and code (either manually, or input from the SGO database) that fully describes its type and function. The representation of the obstacles may be schematically organized in three classes: **1) Point**, for obstacles with relatively small height and extension, defined in

terms of its x,y coordinates and a characteristic dimension; this type of obstacle is represented as a hemisphere. **2) Cylinder**, for obstacles with a considerable height but small horizontal extension, and **3) Line**, for long obstacles such as pipelines, defined in terms of a series of x,y points. In all classes, the depth (or z -coordinate) of each obstacle is automatically defined by the system, by interpolating with the x,y coordinates in the bathymetric curves that were input from the SGO file.

Figure 5 illustrates the screen that manages the manual definition and visualization of obstacles (including those input from the SGO database). From this screen the user can also generate a report of the interferences of any obstacle against all lines of the mooring system, employing the facilities of interference management that will be described in the following section. Figure 6 presents a 3D view of a model of the BGL positioned over a seabed defined by the SGO database.

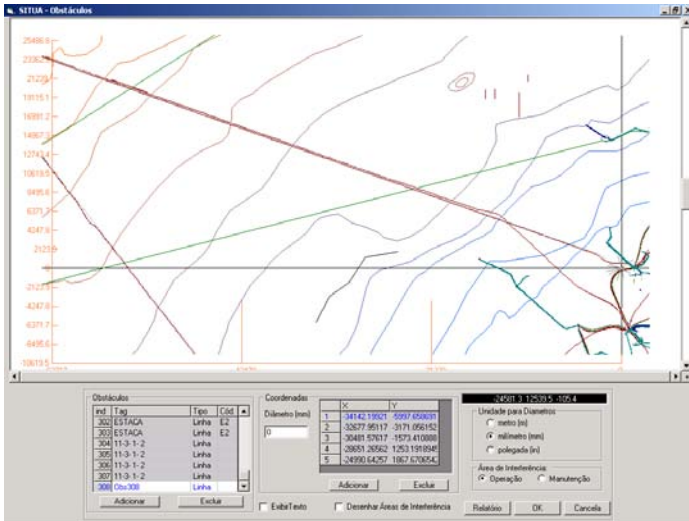


Figure 5 – Definition of Seabed Obstacles

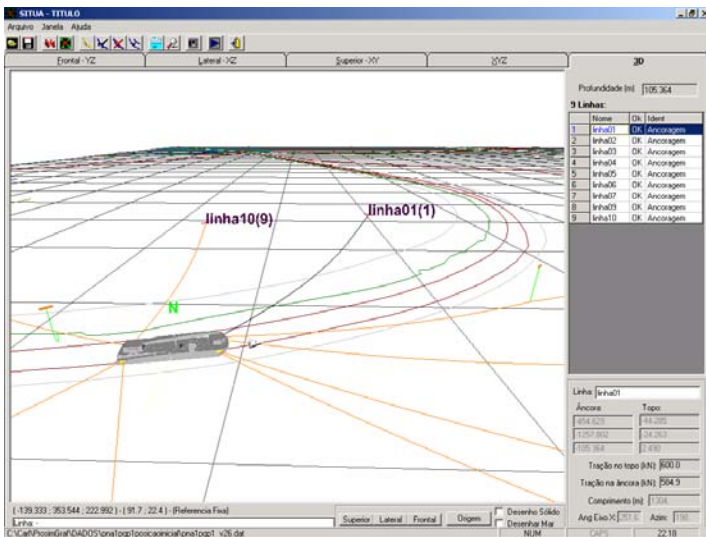


Figure 6 – BGL Barge over Seabed with Obstacles

Analytical Solver for Complex Catenary Configurations

As mentioned before, the SITUA interface incorporate an analytical catenary solver, able to represent complex configurations such as lines with multiple segments and

different materials, connected to other lines or to platforms, and with flotation elements such as buoys or segments with distributed floaters.

This solver is based on an iterative implementation of the catenary equations defining each representative segment of the line. The formulation considers the extensibility of the material, which is very important for general lines, and essential for lines that incorporates polyester segments (although this is not the case for the lines of the BGL-1 barge).

The graphic interface allows a very simple and intuitive definition of the model of the line. The user needs only to specify the number, length and type of segments that comprise the line. A database with several material types is incorporated in the system. The user may also specify a value for one of the parameters that define the catenary: the anchor position, the horizontal force, the top angle (more usual for risers), and, as an enhanced modeling facility, the total axial tension at the top.

Finally, another enhanced facility for the definition of lines for actual operations of the BGL barge consists in the definition of two of the aforementioned catenary parameters, in a “variable-length” procedure. The system then automatically adjusts the laid length of the top segment of the mooring line to comply with the given parameters.

Validation of the Complex Catenary Solver

A validation of the catenary solver incorporated in the SITUA interface had been presented in a previous work [3]. The validation consisted in monitoring the behavior of several mooring line parameters, observed in an onboard real case operation. The operation was then simulated by the SITUA/Prosim system, and the results obtained were compared with the monitored data, and also with the Catcom program.

During the monitored operation, the BGL-1 barge was operating at Campos Basin on a waterdepth of 165m. The mission was lifting cargo to the PNA-1 fixed platform. Therefore, unlike usual pipeline launching operations, the barge was in a stationary position. However, the seabed near PNA-1 is one the most crowded in Campos Basin, with gas pipelines, fiber optics and wells, rigid and flexible oil pipelines with diameters varying from 0.254 m (10 in.) to 0.406 (16 in). This fact posed severe requirements for the mooring layout, and two buoys for each line were needed to avoid the obstacles.

The behavior of all nine lines of the resulting mooring system was then simulated by the SITUA/Prosim analytical catenary modules. For each line the following parameters were calculated: top angle, TDP distance, position of buoys, azimuths and horizontal projection. The values of the two last parameters were compared with the values measured by a DGPS on board. The other results were compared with those obtained by the CATCOM software, which has been employed for a long time and had already been validated.

Detailed results of this validation were presented in [3]. A good agreement was observed between the results of several mooring line parameters, and, as a conclusion, the SITUA/Prosim was considered capable of accurately simulating the BGL-1 quasi-static mooring procedures.

Barge Motion Module

During a pipeline launching procedure, the barge continuously moves along a predefined route. The planning of such procedure consists in the definition and charting of a series of points on this route, specifying the positioning of the anchors, the lines, the buoys and the hull of the barge.

In order to help the barge operators to define the sequence of mooring operations that leads to the barge motion, the SITUA/Prosim system now incorporates an equilibrium-mobilization module. Initially, this module calculates the neutral equilibrium position of the barge and all lines, for a model generated using all data that defines the physical and geometric characteristics of the hull and its mooring lines.

Next, this module can simulate the mooring operations (releasing and collecting cables, or by relocating anchors) that lead to the motion of the barge. The user can then specify a target position, and the system will then employ an iterative algorithm to simulate the operations of releasing/collecting cables (at each iteration recalculating the equilibrium position of all lines and the global equilibrium of the array of lines with the barge), until one of the two following situations occur:

1. The target has been reached and a new equilibrium configuration is attained (and in this case the system reports the operations that were necessary to reach the desired position), or
2. The system detects that the target cannot be reached, either because the tension on one or more lines has exceeded maximum predefined values, or an interference with subsea obstacles has been detected (via the interference management module that will be described in the following section). The alternative then is to relocate anchors using tug boats.

The numerical simulation of these operations requires constant recalculations of the configurations of the mooring lines, considering also the possible interference with obstacles, and the presence of buoys, as will be described in the following sections.

Interference Management Module

The SITUA/Prosim system incorporates an interference management module that can be employed during the simulation of the mooring operations of the BGL. This module encompasses interference criteria established by Petrobras technicians, as specified in [1].

The interference criteria are based in an “exclusion area” around segments of each mooring line laying on the seabottom, and a vertical distance below suspended segments of the lines. An interference situation is then characterized when an obstacle is positioned in this area, with risks of collision and damage to the line and/or the obstacle (a manifold, another pipeline, etc.)

Regarding the suspended sections of the lines, the criteria originally mentioned in [1] defined interferences only in the plane of the catenary configuration of the line. This was adequate for use with the original Catcom software, which performed only 2D calculations of one mooring line individually. However, in order to enhance the safety of the operations, and since the SITUA/Prosim software is able to incorporate all mooring lines and the hull of the barge in the

same three-dimensional model, those criteria have been enhanced by considering an “exclusion volume” defined as a lateral distance measured from the catenary plane.

The characterization of an interference situation may then be visually detected, in 2D and 3D views with snapshots of the barge, the mooring lines and the obstacles. Figures 7 and 8 presents 3D views where the exclusion region around one line is graphically displayed, showing a possible interference situation with a previously installed pipeline.

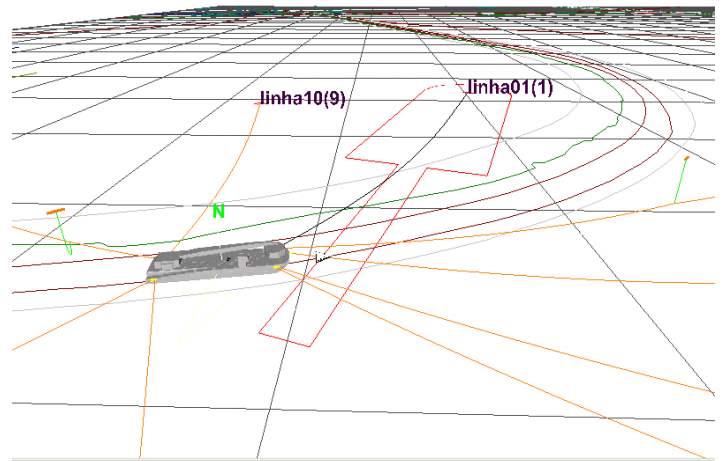


Figure 7 – 3D view of Exclusion Region with Interference.

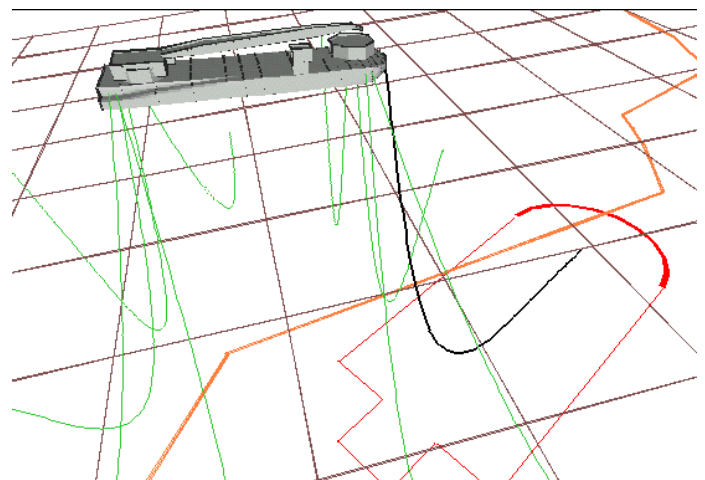


Figure 8 – 3D view of Exclusion Region with Interference.

A more detailed visualization of possible interferences, that include the definition of the types of obstacles and distances from the line, is presented in 2D views such as the depicted in Figure 9. In these views the interferences are indicated by red arrows, with the corresponding distances, and a tag defining the obstacle.

Finally, a detailed printed report can be generated with a full description of the possible interferences for all lines.

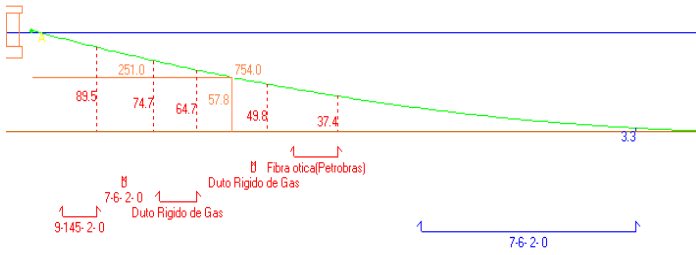


Figure 9 – 2D view detailing interferences.

Buoy Definition

Once the possible interferences are identified, the BGL operator can take some measures to avoid them, including the placement of buoys in given positions along the line. This way, the catenary configuration can be altered in order to meet the interference criteria and allow the operation to proceed. Figure 10 shows a configuration of a mooring line with two buoys, to keep the line suspended well over a pipeline.

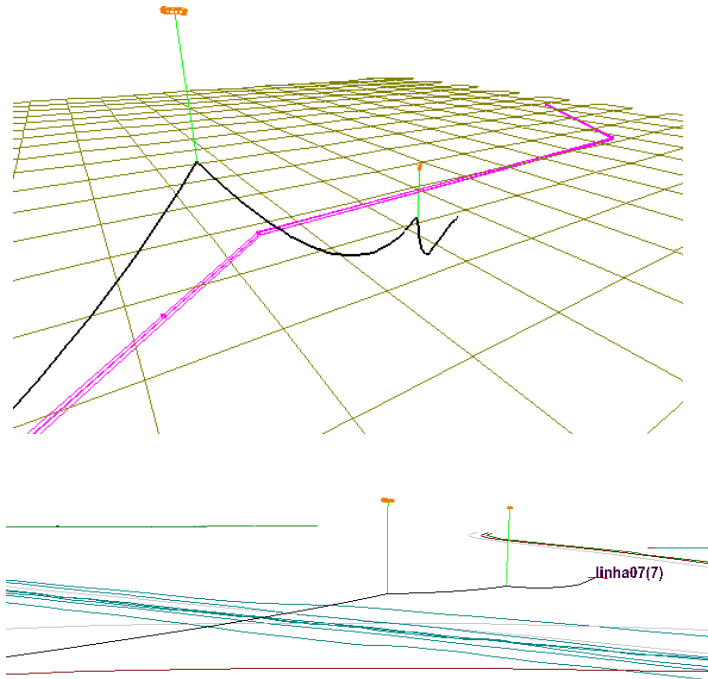


Figure 10 – 3D Views of Mooring Lines with Buoys

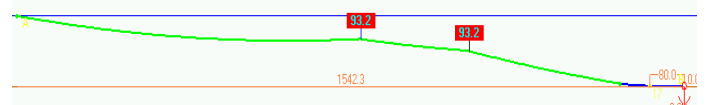
The BGL operators have standard cylindrical buoys for their operations. The inclusion of buoys in the model of the lines for analysis by the SITUA catenary solver involves the specification of their maximum nominal buoyancy value, its height and diameter, its spatial orientation (horizontal or vertical), and the position of the buoy in the line, measured from the anchor.

The catenary solver is able to deal with any given number of buoys placed along the line, and even to adequately consider the actual characteristics of the pendant that connects the buoy to the mooring line. Usually the pendant is comprised by two different segments (e.g. chain and wire cable), each with its particular data (length, weight, stiffness).

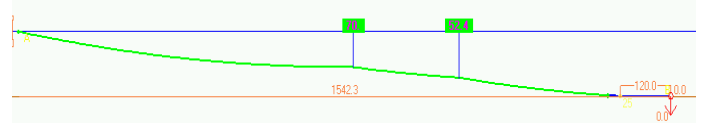
Amongst the results provided by the catenary solver, those specifically related to the buoys include its effective buoyancy, the tension it exerts on the mooring line, and its position in terms of depth and distance to the water surface.

One requirement for the BGL operators is that the buoy should be visible at the water surface. This configuration can be attained by adjusting the length of the pendant. Therefore, one important facility provided by the SITUA interface is the ability of quickly redefining pendant lengths and recalculating the catenary configuration, until the buoy reaches the surface.

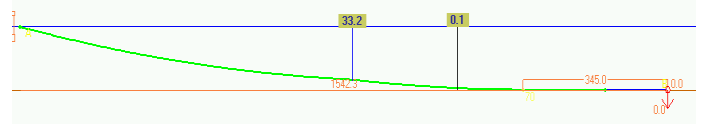
Of course an additional criterion, in terms of the effective buoyancy, is required for the placement of buoys on the water surface. Pendants with excessive length may lead to slack and ineffective floating buoys. Therefore, the SITUA interface provides a visual indication of the buoy positioning and effective buoyancy. Buoys with effective buoyancy values higher than a user-specified maximum percentage of the nominal buoyancy (usually 90-95%) can be considered as submerged, and will be displayed in red:



Buoys with effective buoyancy values between 50% and the maximum percentage of the nominal buoyancy are considered to be floating in the surface and still effective. These buoys will be displayed in green:



Finally, buoys with effective buoyancy values less than 50% of the nominal buoyancy may be considered as slack and not effective. These buoys will be displayed in yellow:



APPLICATION

This section illustrates the application of the SITUA/Prosim system in the simulation and planning of actual mooring procedures for a pipeline laying operation in Campos Basin. The pipeline was designed to connect the fixed platforms PNA-1 and PGP-1.

Simulations were performed for the planning of the whole operation, in which the BGL should cover a total distance of about 9 kilometers. The results presented here correspond only to one section of the route, where the barge is displaced between two points A and B separated by approximately 500 meters.

Figures 11 and 12 represent the model of the hull of the barge. The first of Figure 12 depicts spheres indicating the position of some of the fairleads of the mooring lines. The BGL-1 has eleven fairleads, but in usual operations only ten mooring lines are connected. The fairlead coordinates are indicated in Table 1; the x axis is measured from stern to bow, with origin at midsection.

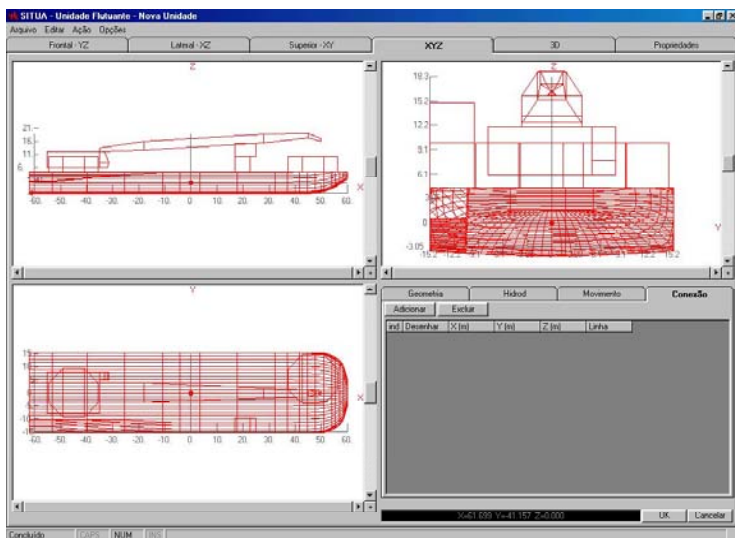


Figure 11 – 2D Views of Hull Model

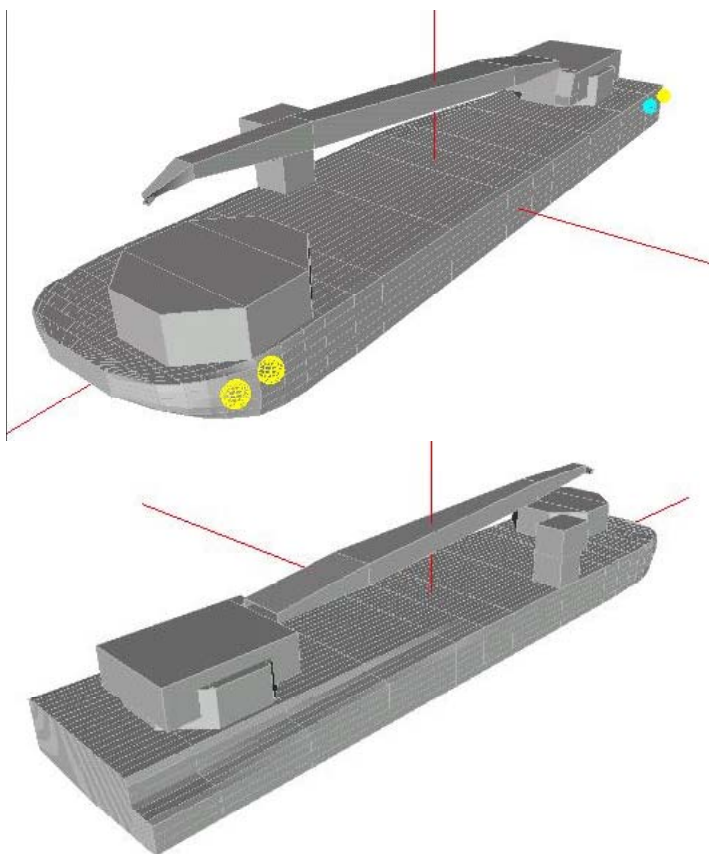


Figure 12 – 3D Solid View of Hull Model

Table 1 – Position of Fairleads

Fairlead	X	Y	Z
1	47.825	16.204	2.49
2	50.575	16.204	2.49
3	62.407	4.32	3
4	50.56	-15.953	2.49
5	47.892	-15.953	2.49

6	-54.095	-16.355	4.1
7	-56.845	-16.355	4.1
8 BB	-59.361	15.803	3
8 BE	-59.644	-16.719	4.925
9	-56.845	16.189	2.49
10	-54.095	16.189	2.49

All mooring lines are composed by two segments, with characteristics presented in Table 2. The length value for segment 2 presented in this table corresponds to the total length available on the winch drum; the released length varies during the mooring operations.

Table 2 – Characteristics of Mooring Line Segments

Segment	Length (m)	Material
1 (anchor)	150	R3S Stud Chain 3"
2	1780 (max)	EEIPS Steel Wirerope 2.5"

Initially, all lines were modeled for the original position of the barge at point A, defined by the UTM world coordinates specified in Table 3. The anchor positions are specified in Table 4, also in UTM coordinates, along with the corresponding fairlead tensions.

Table 3 – UTM World Coordinates of Point A

E	N
352435	7525040

Table 4– Point A: Coordinates of Anchors, Tensions at Fairleads

Line	E	N	Tension (kN)
1	351970	7523750	600
2	351030	7524338	500
3	350730	7524720	600
4	350840	7525300	550
5	351030	7525530	450
6	352000	7526430	490
7	353700	7526020	650
9	353420	7524480	600
10	352669	7523970	600

The catenary solver then provided the results defining the equilibrium configuration of the mooring system. A preliminary survey of the results of the interference management module then identified several possible interferences with obstacles.

Once these interferences were identified, the facilities of the SITUA interface regarding the definition of buoys were employed. Figure 13 illustrate one preliminary configuration of a line with two buoys; in this case the pendant lengths are excessive and the buoys are slack. It can be observed that the pendants are even forming a catenary and pulling down the mooring line catenary, instead of suspending it.

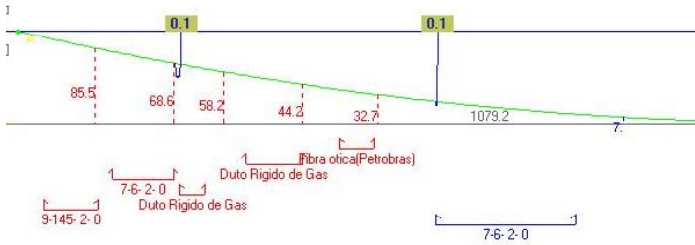


Figure 13 –Buoys and Interferences

As the result of some quick studies with the interference management module and the definition of buoys, all interferences were successfully avoided by placing two buoys on most of the lines, as specified in Table 5, with the exception of lines 3,4 and 5 that did not require any buoy. This table indicates, for each buoy, its position in the line measured from the anchor, and the length of the pendant.

Table 5 – Buoys

Line	B1		B2	
	S (m)	Pendant (m)	S (m)	Pendant (m)
1	450	90	750	70
2	450	90	750	70
3	---	---	---	---
4	---	---	---	---
5	---	---	---	---
6	450	90	750	70
7	350	85	800	85
9	450	90	750	70
10	450	90	750	70

Again, the catenary solver provided the results defining the final equilibrium configuration of the mooring system with buoys at point A, as presented in Table 6 and illustrated in Figures 14 and 15.

It should be recalled that the released length shown in Table 6 is also a result of the calculations using the “variable-length” procedure described before, since for each line two parameters that define the catenary are input: the position of the anchors, and the tension at the top of the line.

Table 6 – Configuration of Lines for Point A

Line	Azimuth (degrees)	TDP (m)	Length (m)	Buoy 1 (m)	Buoy 2 (m)
1	198.4	250.04	1186	37.708	15.484
2	243.5	280.03	1368.6	33.67	15.407
3	259.5	730.49	1526.2	---	---
4	279.3	664.2	1417.7	---	---
5	289.6	629.98	1294.9	---	---
6	340.4	280.01	1299.8	34.129	15.418
7	51.8	145	1391.9	26.602	18.227
9	120.9	150	932.8	68.607	25.063
10	170.5	150	932.5	68.655	25.092

In Figure 14 the barge is seen at the center of the picture; the mooring lines are represented in green, with the respective names in blue letters. All remaining objects are obstacles imported from the SGO database.

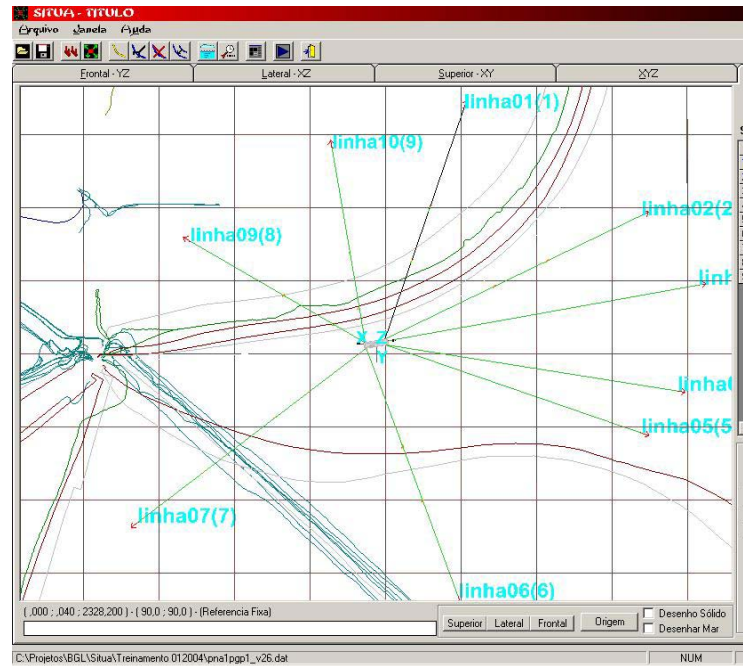


Figure 14 – Barge and Mooring System at point A, Top View

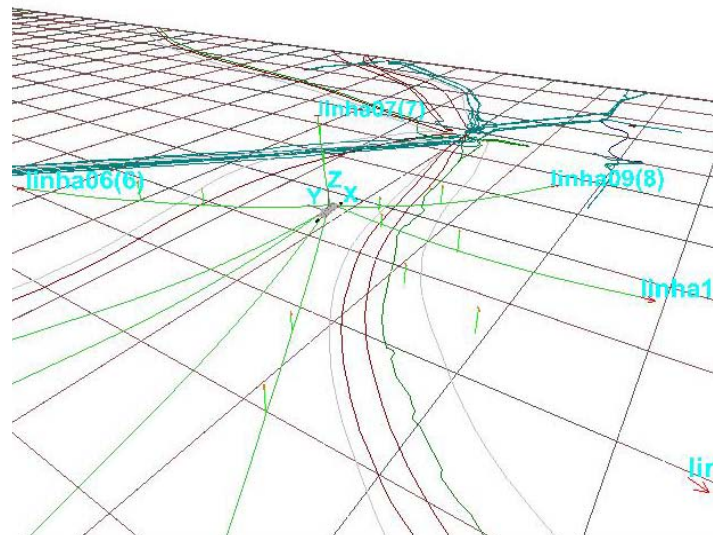


Figure 15 – Barge and Mooring System at point A, 3D View

Finally, the barge motion module of the SITUA/Prosim system was employed to simulate the mooring operations need to move the barge from the original position A to a new position B, defined by the UTM world coordinates specified in Table 7.

Table 7 – UTM World Coordinates of Point B

E	N
352510	7525120

All that was needed is to input these coordinates, and the lines were automatically adjusted (stern lines released, bow lines collected). The catenary solver provided the results defining the final equilibrium configuration of the mooring

system at point B, as presented in Table 8 in terms of the new cable lengths, and positioning of buoys in relation to the fairleads. Again, a check of possible interferences with obstacles was also automatically performed.

In this case, there was no need of relocating anchors, and, although the barge was moved due to the variation of the length of the mooring lines, the anchor coordinates remained the same presented in Table 4 for point A.

Table 8 – Configuration of Lines for Point B

Line	Azimuth (degrees)	Length (m)	Buoy 1 (m)	Buoy 2 (m)
1	200.2	1285.2	34.404	15.42
2	242.2	1471.3	35.801	13.688
3	257.4	1615.7	---	---
4	276.1	1481.4	---	---
5	285.7	1342.1	---	---
6	336.4	1253.4	34.495	15.425
7	52.5	1283.8	36.892	19.199
9	126.7	915	71.833	27.023
10	174.9	1002.3	56.642	18.009

FINAL REMARKS

The computational system described in this work is currently being employed by the BGL-1 crew in the simulation and planning of actual mooring procedures for pipeline laying operations in Campos Basin.

The system has been shown to be able to calculate the motions of the barge due to the operations performed with its mooring lines (including placement of buoys, and variation of the onboard/released cable lengths), taking into account general seabottom data and interferences with subsea obstacles. Moreover, it can perform the converse calculations – that is, for a given motion of the barge, it is able to determine which operations should be performed to reach that motion.

These aspects are important for both of the main uses of the SITUA/Prosim by the BGL-1 crew: **a)** Firstly, at the office, to plan and design the sequence of operations that will comprise the mooring procedure; **b)** Then, onboard at the barge, to quickly account for unexpected situations requiring changes in the mooring procedure.

Therefore, it meets the requirements for a modern, efficient and user-friendly computational tool for the numerical simulation of the mooring procedures of the BGL-1 barge. The next steps in the development of this system are presented in the text that follows.

Future Developments

Coupled Dynamic Analysis

The SITUA/Prosim system was originally oriented towards the coupled analysis and design of semi-submersible platforms, and other floating systems based on framed members such as TLPs and SPAR buoys. The hydrodynamic model of the hull is based in an extended Morison formulation. This formulation allows the representation of wave diffraction and radiation effects that occur in large-diameter cylindrical members, such as the columns of SS platforms for instance. Slow and mean drift forces, as well as frequency-dependent radiation damping,

are incorporated through the use of coefficients generated by a diffraction code such as Wamit [5].

Presently, a new hydrodynamic model that incorporates all diffraction and radiation effects in ship hulls is being implemented, with the cooperation of researchers from the University of São Paulo [6]. With the conclusion of the implementation and validation of this model, the SITUA/Prosim system will be able to perform full coupled time-domain dynamic analyses of the BGL-1 barge and its mooring lines modeled by finite elements.

Analysis of Pipeline Behavior during Laying Operations

The Prosim finite-element numerical solver already includes a 3D frame element that can account for all material and geometrically nonlinear effects that arise in the pipeline behavior during the laying operation. Therefore, all that is needed to include the representation of the pipeline in a coupled model with the barge and its mooring lines, for quasi-static and/or dynamic analyses, are a few adaptations in the SITUA interface.

Such adaptations may include, for instance: **a)** Generation of initial finite-element meshes for the S-laying operation of the pipeline; **b)** Inclusion of generalized scalar elements to represent the variable contact between the pipeline and the barge stinger; **c)** Generation of finite-element models for other types of laying operations that may eventually be considered for the BGL-1, including *J-lay* and reeling methods.

Traditional analysis methods for pipeline laying consider an uncoupled model where the motions of the barge are previously determined, without taking into account the influence of the pipeline, and are then prescribed at the top of the pipeline. Therefore, the application of such coupled model (barge + mooring lines + pipeline) for dynamic analyses will be a step further over current methods for the numerical simulation of pipeline laying operations.

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