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Submarine Pipeline Shore Approach Design Analysis Procedures- RNEST

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Abstract

This paper describes the analysis procedures applied to the structural design of the submarine outflow pipeline shore approach for the RNEST-Abreu e Lima Oil Refinery in the Suape maritime terminal in Ipojuca at the northeastern coast of Pernambuco. Submarine Pipeline structural model topology is described, as well as the sea environment loading modeling conditions, to obtain hydrodynamic forces through Morison's Equations under combined wave and current effects. Numerical analysis matrix considered distinct Linear, Stream Function and Solitary kinematic wave-current theories with tidal conditions. Detailed consideration of Wave breaking patterns and hydro-elastic effects is presented, since significantly impacts upon pipeline integrity and stability conditions. Numerical analysis procedures included static and dynamic steady state vibration evaluation methods with the application of the GTSTRUDL system consistent with metocean wave-current scatter patterns adopted. Numerical results were applied to the strength and fatigue assessments that allowed for a complete verification of submerged structures stress strength interaction conditions according to API(2014). Critical correlations with DNV(2010B) submarine pipeline stability conditions were made with the DNV(2014). A key aspect of the numerical evaluations consisted in the analytical application of the Wave Momentum Flux (WMF) parameter concept, introduced by the USACE, as a robust methodology to correlate wave structure loading interaction directed to the assessment of safety and integrity of coastal structures.

Keywords

Submarine pipeline outflow; shore approach; design & analysis.

Introduction / Background

The Petrobras Abreu e Lima (RNEST) is a newly built oil crude refinery unit which will have a process capacity of 230000 barrels per day. The refinery is fitted with advanced technologies that meet international guidelines with respect to environment, as well as reliability and operational performance, aiming at achieving optimum quality and security standards. As part of this program, the installation of a submarine process outflow pipeline linking both the RNEST with the SUAPE Petrochemical Complex effluent underground ducts to the Suape port terminal tie-in connection with the 2000 m submarine pipeline length with 6750 m total extension. The scope of structural consultancy evaluations focused on the submarine landfall shore approach, where sea wave-current loading conditions, soil-foundation-structure interactions and line stability are mostly severe, being exposed to intense integrity degradation, marine corrosion, soil erosion/scour, wear and slamming issues.

Basic Operational Design Data

Basic operational design parameters of the submarine outflow pipeline are concisely:

- Nominal Diameter: 560 mm (22") HDPE pressure class PN20 61.7 mm thickness
- Total submarine length: 2.0 km
- Water Depth variation: approx. 1.0 m to 30.0 m (average depth z = 14.0 m)
- Maximum Operational Internal Pressure: 14.7 kgf/cm^2
- Hydrostatic test Internal Pressure: 18.6 kgf/cm^2
- Maximum Design Temperature: 40 C
- Pipe Material Grades: Offshore Line pipe HDPE (PEAD ABNT NBR 15561)
- Carrier/sleeve pipe: API 5L-grade X60, D =660.4 mm, t = 22.4 mm, density = 7850 kgf/m^3
- Reinforced concrete coating: 125 mm thick with density 3040.0 kg/m^3

Figure 1 describes the Abreu e Lima (RNEST) submarine pipeline shore approach at Suape port terminal, while Figure 2 presents a general view of the shore approach section length.

Figure 1 – RNEST – Suape terminal – Submarine outflow pipeline.
(Fonte SIO-NOA-US *Navy* – Google Earth)

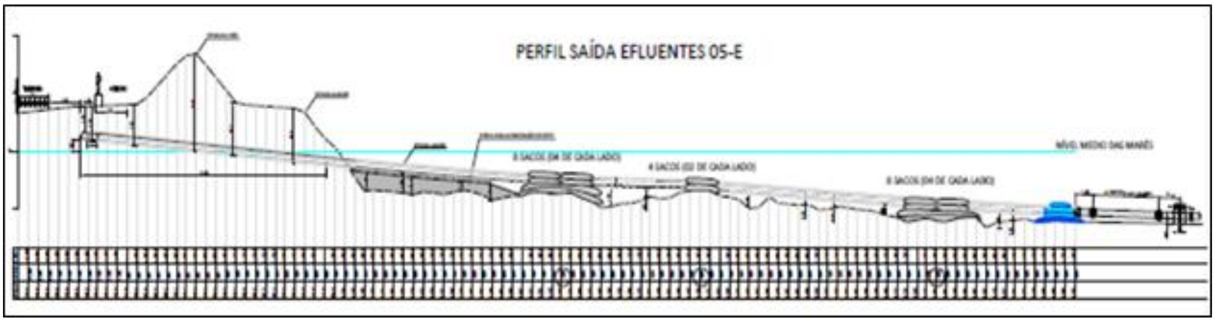

Figure 2 – RNEST – Shore Approach – Submarine outflow pipeline layout.

Geotechnical Conditions and Foundation-Structure Interaction Issues

The submarine soil strata are presented in Table 1. These geotechnical parameters are critical for the shore approach design as compared to the submarine pipeline design. The soil-foundation-structure interactions continuously affect the bearing and friction resistance capacities of the seabed soil strata. The imposed contact reactions, cause foundation subsidence, dynamic vibration impedance interaction effects, erosion scour, and soil liquefaction processes. Severe integrity issues to the shore approach pipeline related with large displacements and deformations and internal stresses that can reach the limit states of rupture, buckling and fracture as well as various damages mechanisms.

Table 1 – RNEST Suape Terminal Geological strata data.

Layer depth [m]	Soil strata
0.0 < d < 15.0	Biodedritic gravel + coral formation
15.0 < d < 17.0	Biodedritic sand + Carbonate concretions
17.0 < d < 18.0	Biodedritic gravel + coral formation

The seabed soil strata above, typical of Pernambuco seaside, only apparently provide adequate embedment strength capacity. Despite the high values of confined compressive strength, the bearing capacity is highly dependent upon the soil void pore hydrostatic pressure, as well as void porosity, granulometry. The underlying soil layers attain larger deformations levels, which can steer shear rupture, install soil instability and liquefaction mechanisms as highlighted in API(2014) and DNV(2010B). Carbonate and biodedritic strata also have higher relative pore void volume fraction, so that the material compressive bulk modulus tend to decrease with time. This is especially so with cyclic dynamic loading and under soil-structure contact pressures, and varying horizontal shear forces.
By inspection of the route shown in Figure 2, it is noted that the shore approach mechanical and geometrical boundary conditions varies continuously along its length. The initial 15.0 m long rigid rock breakwater riprap is followed by a 15.0 m submarine earthwork embedment, and successive extensions of raised bank berms followed by biodedritic sandstone and coral reefs embedment and free spans of varying lengths, as well as sand trench embedment.
The risks of attaining large foundation subsidence and high lateral displacements are high.
Albeit the coral reefs reveals higher soil roughness, which is a favorable effect for stability, the mechanical behavior under load of such type of geologic strata formation still require intensive research. Especially so near shore, since the normative specification and reliable project experience are mainly directed to deeper water submarine pipelines and umbilicals.
While the lateral displacement stability depends on the soil material particle size and density ´as well as internal friction parameters, these properties can vary significantly for biodedritic sandstones and coral reef layers during submarine pipeline operational lifecycle.
The shore approach exhibit a sufficiently rigid flexural stiffness characteristic behavior, compatible with a continuous beam bearing upon an elastic foundation, that make it pertinent to consider the generalized lateral stability analysis consistent with DNV(2010B).
Under these assumptions, the maximum lateral pipeline transversal admissible displacement is proportional to at most 0.5D. It is only consistent to consider that maximum foundation bearing subsidence displacements commensurate with this admissible displacement level.

Material Application and Sectional Construction Details

Applied pipeline structural steel material considered the Petrobras client basis of design recommendations, in line with DNV(2013) Section F. The adopted pipeline material is API-5L-Gr X60 with product specification level with higher impact toughness characteristics and metallurgical composition adequate to the sea environment. Table 2 concisely presents the mechanical strength parameters and Table 3 the material sharpy testing requirements. Recommended welding consumable material is AWS-E7018 with low hydrogen content.

Table 2 – Pipeline Structural Steel API-5L-X60 Mechanical properties.

Material Class	Grade	Thickness [mm]	f_y [N/mm²]	f_u [N/mm²]
API-5L-X60 PSL 2	B	22.2	241 to 448	414 to 758

Table 3 – Pipeline Structural Steel API-5L-X60 Sharpy testing requirements.

Base plate thickness	Testing temperature [ºC]	Impact Energy (Sharpy) [J]
T < 25 mm	$T_D + 10 = -10$	32
	-20	27

Concisely, the applied conductor pipe material is Polyethylene EPE (PE-100), with average tensile strength of 23.5 MPa and density of 950 kg/m^3.

Concrete Weight Coating (CWC) was specified according DNV(2006), DNV(2010B) and DNV(2013) with 40 MPa compression strength and density of 3000 kg/m^3. CWC 125 mm layer was determined both analytically and numerically through means of DNV STABLELINES System.

The CWC thickness strongly correlates with the shore approach bottom stability. However, the biodedritic gravel and coral formations embedments impose thickness limitations due to the high sensitivity to weight bearing and localized contact pressures. Other CWC design variables, distinct from conventional submarine pipeline, constitute a higher variance in wave and current induced hydrodynamic forces, the impulsive wave breakers energy dissipations, abrasion and wear out due to flow turbulence. The API(2015) practice additionally recommends that increased thicknesses should be taken into account due to sunlight and thermal degradation effects to obtain and better corrosion and wear-out protection.

Larger outflow pipeline diameter, and CWC thickness, would also stir-up higher drag and inertial hydrodynamic forces by increasing the added non-structural fluid-dynamic mass and volumes, which strongly correlates with pipeline stability and integrity strength.

Though previous Petrobras reports prescribed smaller 90 mm CWC layer, a thickness larger than 150 mm would bring constructive issues, such as the need to adopt 3 internal reinforcement meshes. The steel welded mesh, with 100x100x6.3mm, is CA 60 Q138 with galvanized corrosion protection according ASTM A-641: Zinc Coated (Galvanized) Carbon Steel Wire.

Alternatively, the application of stainless steel reinforcement rebar mesh layer BS 6744 provide for additional long time corrosion protection as well as fracture control performance.

The general sectional structural elements of the shore approach pipeline are shown in Figure 3 below. The 28 mm annulus gap between the 560 mm (22”) diameter HDPE flow pipe and the 660.4 mm API 5L-grade X60 carrier/sleeve pipe, is filled with epoxy based concrete.

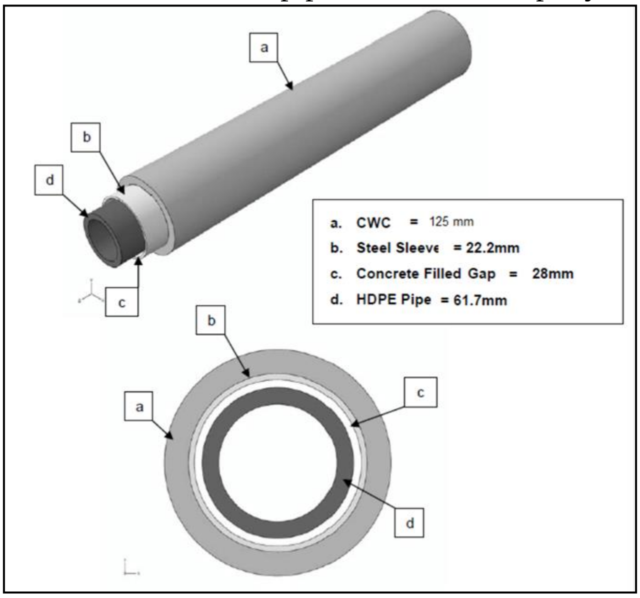

Figure 3 – RNEST – Shore Approach – Pipeline Section Construction Details

Environmental Conditions

Meteorological-Oceanographic conditions were considered according Petrobras specification ET-4100.01-6611-941-PPC-001 referenced for Suape Port. In a concise fashion, the following wave incidence scatter with significant wave height H_s and periods T_p:

– Significant wave height Hs: 0.5 m < H_s < 4.0 m;
– Significant wave period Tp: 3 s < T_p < 19 s.

Table 4 present a summary of representative wave incidence direction, H_s and T_p data and current velocities for distinct return periods.

Table 4 – SUAPE Region – Wave Incidence Scatter data

Wave Dir [deg]	Current Dir [deg]	$H_{s,\,1yr}$ [m]	$H_{s,\,10yrs}$ [m]	$H_{s,\,100yrs}$ [m]	T_p [s]	$U_{c,\,1yr}$ [m/s]	$U_{c,\,10yrs}$ [m/s]	$U_{c,\,100yrs}$ [m/s]
0.0	0.0	1.5	1.9	2.2	12.0	0.6	0.6	0.7
30.0	30.0	1.6	1.9	2.1	11.8	0.5	0.5	0.6
60.0	60.0	1.6	1.9	2.1	11.8	0.5	0.5	0.6
90.0	90.0	2.5	3.2	3.7	8.3	0.3	0.4	0.4
120.0	120.0	3.0	3.9	4.5	9.5	0.5	0.5	0.6
150.0	150.0	3.0	3.9	4.5	9.5	0.5	0.5	0.6
180.0	180.0	3.0	3.6	4.2	12.5	0.6	0.8	0.9
210.0	210.0	1.5	1.9	2.2	12.0	0.6	0.6	0.7
240.0	240.0	1.5	1.9	2.2	12.0	0.6	0.6	0.7
270.0	270.0	1.5	1.9	2.2	12.0	0.6	0.6	0.7
300.0	300.0	1.5	1.9	2.2	12.0	0.6	0.6	0.7
330.0	330.0	1.5	1.9	2.2	12.0	0.6	0.6	0.7

A statistical correlation study between the available data for T_r =1 and T_r =10 years allowed it to make an inference on the directional scatter for distinct return periods T_r = 2 and 20, 30, 50 and 100 years respectively. This was accomplished to acquire a complete and consistent set of wave data for static and fatigue strength analysis as well as stability purposes.
Tidal variations occurring at the Suape typically modify the sea wave and current hydrodynamic boundary conditions near shore. This occur for lower water depths ranging from 1.5 m to 6.0 m, in presence of an irregular coral reef bottom surface and declivity variation, which significantly affect the wave kinematic and wave breaking conditions. Table 5 presents the local characteristic tidal amplitudes consistent with Brazilian navy DHN data.

Table 5 – SUAPE Region – Tidal variation – Relative to MWSL

Tidal variations	m
Astronomic maximum + Meteorologic maximum tide	3.46
Astronomic maximum tide	2.76
Sigize average high tide	2.26
Average tidal level	1.25
Sigize average low tide	0.23
Astronomic minimum tide	-0.25
Astronomic minimum + Meteorologic minimum tide	-0.84

The observed incidence wave distribution could be proportionately grouped as 25% low tide, 50% average sigize tide, and 25% low tide, which can occur 341 times a year, while the extreme astronomic + meteorological tidal variations can occur 24 times a year.
The Petrobras Met-oceanographic report originally did not considered detailed local current measurements, so that it was necessary to take into account the current velocities pattern from other site Guamaré RN as a stochastic distribution reference. The local current flow is considered geostrophic, so that it is mostly aligned parallel with the shoreline. Rip curl and Ebb current, normal to the shore, was associated with tidal variation currents for simplicity.

Sea Bottom Wave Breaking and Wave Shore Run-up Effects

Near Shore Sea environment conditions were mainly assessed according DNV(2010a) and API(2014) while analytical concepts refer to CHAKRABARTI(1990) and others. The determination of wave and current hydrodynamic forces in shallow waters near shore are affected by the bottom declivity and irregular surface, as well as wave breaking conditions that induce high non-linearity in wave kinematics parameters.
Along the shore approach submarine pipeline the average depth is Z = -3.72 m below MWSL. Thus the average wave breaking height H_b = 0.78Z, which is a limit critical stability parameter for gravitational waves. It is pertinent to note that the near shore bottom operates on the incident waves as a filtering and energy dissipation system. Bottom conditions are described by the non-dimensional parameter β according DNV(2010a) section 3.4.6.3 that correlates wave breaking height H_b with wave period T, and gravity g and mean bottom declivity m. For local conditions, m varies between 0.065 < m < 0.082, with the equation:

$$\beta = {}^{H_b}/_{(gT^2m)} \tag{1}$$

Assessing the characteristic wave breaking behavior is essential to determine the hydrodynamic forces upon near shore and shallow water submarine structures. Taking into account the wave scattering table data and the given bottom conditions: $\beta < 0.1$. It can be shown that *Wave Surge* effects predominate in the wave breaking processes, while other effects such as *Spilling* and *Plunging* are not significant in this case. Bottom declivity also causes the Wave shore Run-up effect, which increases the wave potential energy and wave height, see HUGHES(2005). The Wave Shore Run-up also affects the WMF parameter $M_{fw.}$

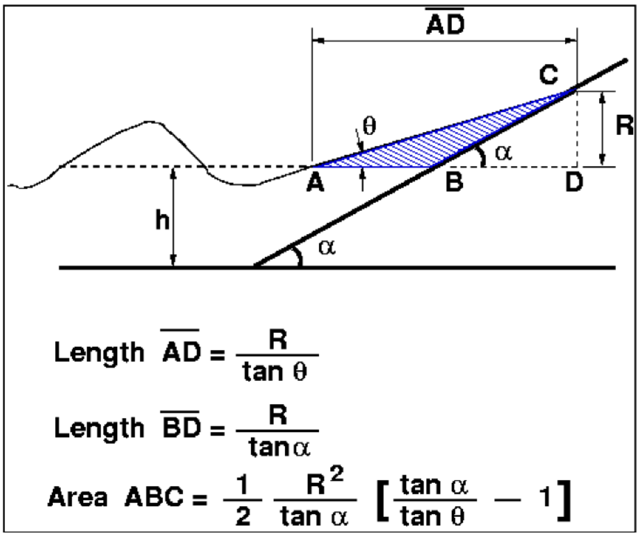

Figure 4 – RNEST – Shore Approach – Wave Shore Run-up effect and Bottom declivity

Analytic Wave Kinematics Models

Due to the near shore shallow water conditions, determining the applicable wave kinematics model require evaluation of the wave parameters: reduced depth (d/gT2) and the reduced wave height (H/gT2), as shown in API(2014). The wave incidence data reveal that the latter reduced parameters fall consistently in the shallow water transition regime, with kinematic effects described by the Stream Function 5^{th} order, and Soliton waves characteristic of breaking waves. As a function of the tidal variation, three analytic wave models were chosen:

– Linear Wave /Airy Model : for MWSL and High tides and higher depths;
– Stream Function Model: For Neutral MWSL Sigize and Ebb tides and average depths;
– Solitary wave model: For Ebb and Minimum extreme tides and Shallow depths.

Comparison between the Stream, Airy and Solitary analytic acceleration pressures and profiles are presented in Figure 5 below, with wave equations according DNV(2010a). Numerical evaluation developed with GTSTRUDL Sea Environment Loading System. In shallow waters, the Solitary and Stream Function waves have a stronger non-harmonic correlation with the wave group velocity (celerity) and horizontal speed hydrodynamic pressures, while the corresponding vertical acceleration pattern and pressures are typically impulsive, in contrast with the harmonic horizontal-vertical pressure of the Linear Waves.

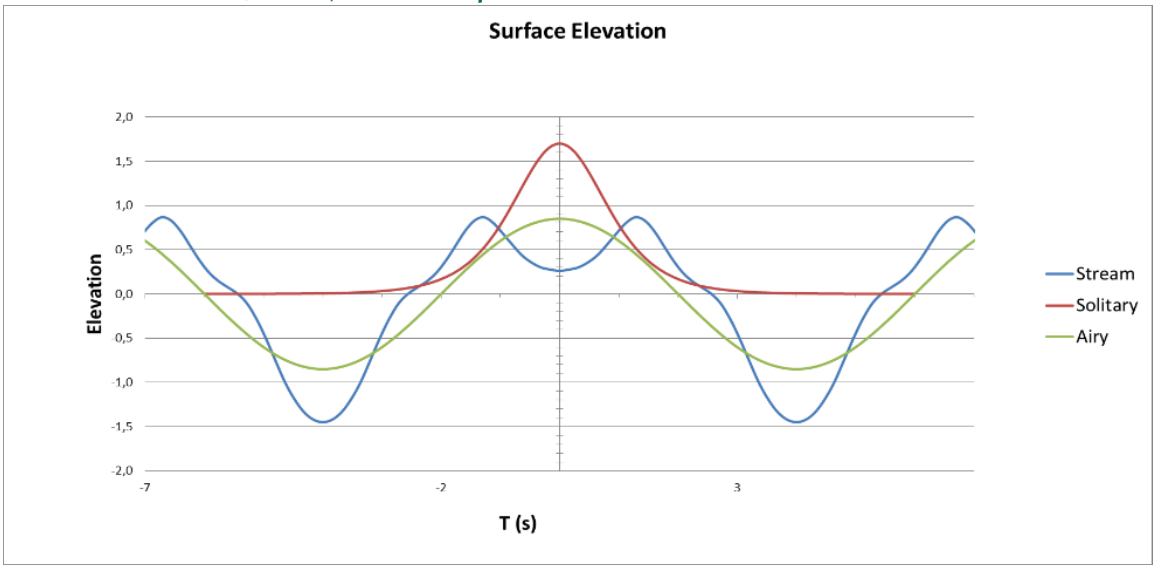

Figure 5 –RNEST – Shore Approach – Kinematic wave model results comparison

The wave breaking forces are thus controlled by horizontal impulsive pressure drag, see CHAKRABARTI(1990). The pipeline drag coefficient C_d, for Solitary breaking waves, are typically between $2.0 < C_d < 5.0$, and taken as $C_d = 3.0$ in this work, considering Re flow numbers.

Wave Momentum Flux (WMF) Concept

In coastal and near shore marine structures, the maximum hydrodynamic forces are strongly correlated with the Wave Momentum Flux parameter M_{fw}, see HUGHES(2005). The WMF is an integral function of the time rate of wave energy per unit area normal to the direction of propagation of the wave. The WMF has been recently introduced as a simple and robust physical parameter indicator to assess wave loading interaction process upon coastal structures. The WMF parameter is represented by dimensions of hydrodynamic force per unit wave crest width, and it can be defined for both periodic and non-periodic waves. In this paper the WMF parameter is introduced as a relevant analytical indicator of the hydrodynamic wave loading conditions, allowing correlations with structural strength limit indicator determined according to API(2014), namely the Base shear, indicating its potential application of structural risk conditions of near shore structures. Equation 2 below describes de WMF integral formulation.

$$M = S_{xx} = \frac{1}{L}\int_0^L \int_{-h}^{n_x} (p_d + \rho_w u^2)\, dzdx \qquad (2)$$

Where:
x = horizontal direction perpendicular to wave crests;
z = vertical direction, positive upwards with z = 0 at still-water level (swl);
t = time;
p_d = instantaneous wave dynamic pressure at a specified position;
ρ = water density;
u = instantaneous horizontal water velocity at the same specified position.

The Solitary wave type the WMF parameter, normalized by $\rho g h^2$, can be promptly determined for the set of the breaking waves heights. Where H/h is the relative wave height to average depth, as presented in Figure 6 below. Considering the average water depths of 3.0 m and incident wave heights ranging from 0.5 m to 2.5 m the corresponding WMF M_{Fh} for solitary waves parameters typically varies between $0.025 < M_{Fh} < 9.15$ kN/m per unit of wave crest length. Since WMF has units of force per unit crest width, it is a physical descriptor of wave forces acting on coastal structures. Figure 6 represents the normalized WMF parameter curve for solitary type waves for both lower (yellow) and higher (magenta) tidal variations.

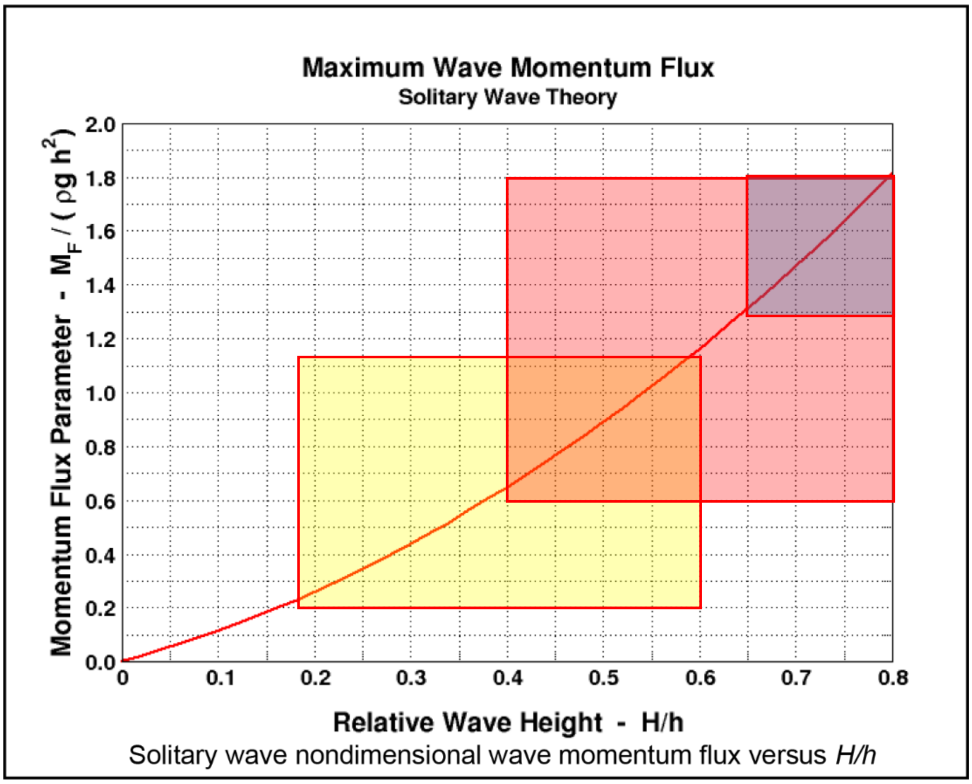

Figure 6 – RNEST – Shore Approach – Solitary Normalized WMF x H/h

Hydrodynamic Forces and Structural Response Behavior

Pursuant the waves incidence scatter data, a corresponding set of wave forces was determined according DNV(2006) and API(2014), to perform both statics and dynamic structural analysis procedures. However, to evaluate sea wave forces upon structural systems, two models are often considered: i) Response Models (RM); ii) Force Models (FM).
Model specification is based on the flow regimes, hydro-elastic interactions, and line slenderness (L/D) with L a free-span length and D the hydrodynamic diameter, as given by DNV(2006) section 1.8.
An amplitude response model is valid when the vibration of the free span is dominated by vortex induced resonance phenomena, which occur mainly for flexible pipelines and umbilical lines and slender free-span lengths with L/D>100. A force model is valid when the free-span response is dominated by rigid flexural stiffness with hydrodynamic loads given by Morison’s equation, such as wave drag, inertial loads, and impulsive loads, usually with

L/D<100. In shallow waters, due to turbulence effects and wave instability, the VIV frequencies loose coherence with structural vibrations, so that the force model prevails, particularly for rigid structural elements with L/D<30 as in the considered shore approach case. In addition, the lower Eigen frequencies are comparatively higher than incident wave frequencies. The resulting dynamic structural behavior is therefore consistently multimodal.
Wave-current action forces are presented in Figure 7 below according API(2014) was determined with GTSTRUDL system resources. The combined structural loading case matrix, considered the set of wave and current statistics of incidence scatter for two sets of static (for strength and stability design) and dynamic numerical analysis cases (for vibration and fatigue design), each with 90 wave current incidences for 1, 10 and 100 years return periods combined with 5 cases of tidal variation conditions.

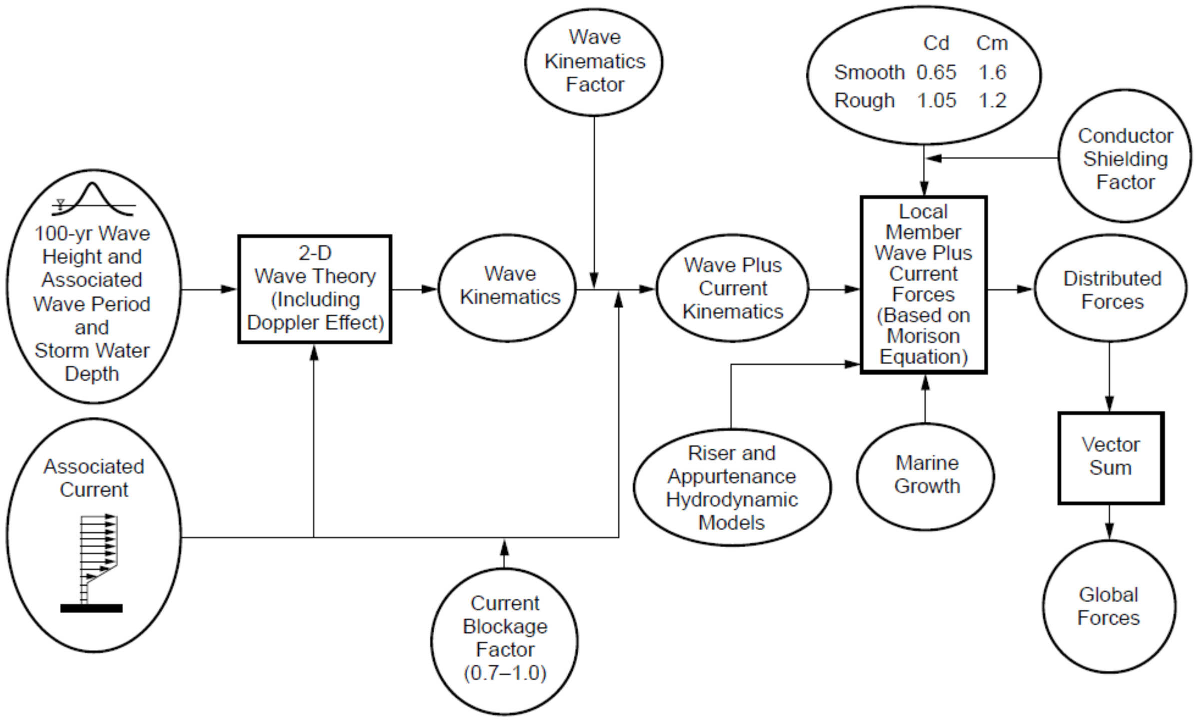

Figure 7 – RNEST – Shore Approach – Procedure for Calculation of Wave Forces

Structural Model Description

Structural topology and boundary conditions of the numerical discrete model developed with the GTSTRUDL system, and applying Timoshenko shear consistent beam elements, is concisely described in Figures 8 and Figures 9 below. A 20 m rock dump embedment length near shore is followed by 4 lengths of free-spans respectively with, 5.0 m, 10.0 m, 20.0 m and 8.0 m length and bearing upon intermediate lengths of hydraulic cyclopic concrete filled bag berm embedment which lay in the seabed coralline soil strata. Soil structure interaction conditions adopted Winkler type spring with variable linear displacement at the vertical direction, typically ranging between 200 kN/cm to 100 kN/cm depending on the local soil geotechnical conditions, and horizontal direction springs typically at 15% of those values.

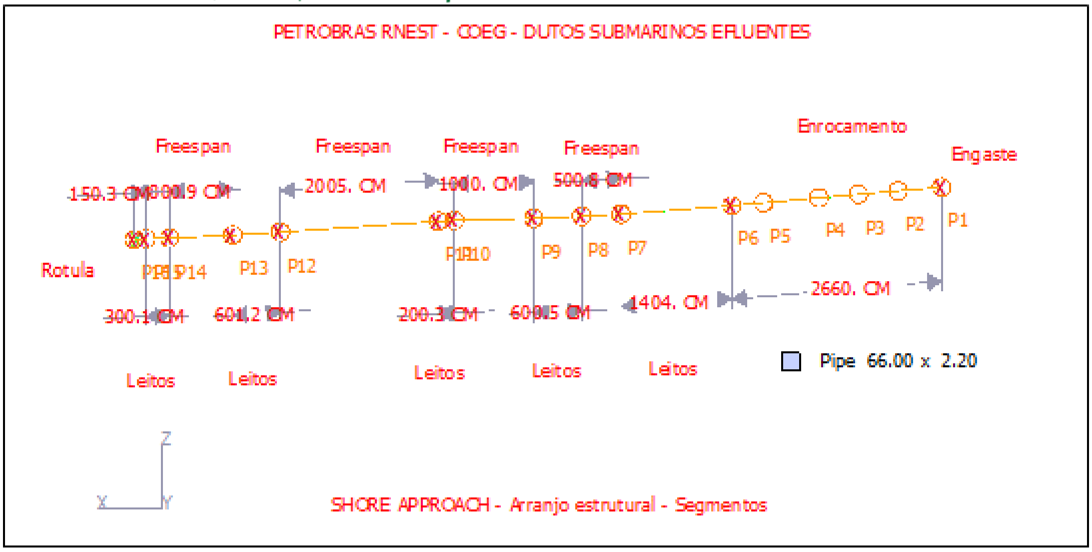

Figure 8 – RNEST – Shore Approach – Structural topology

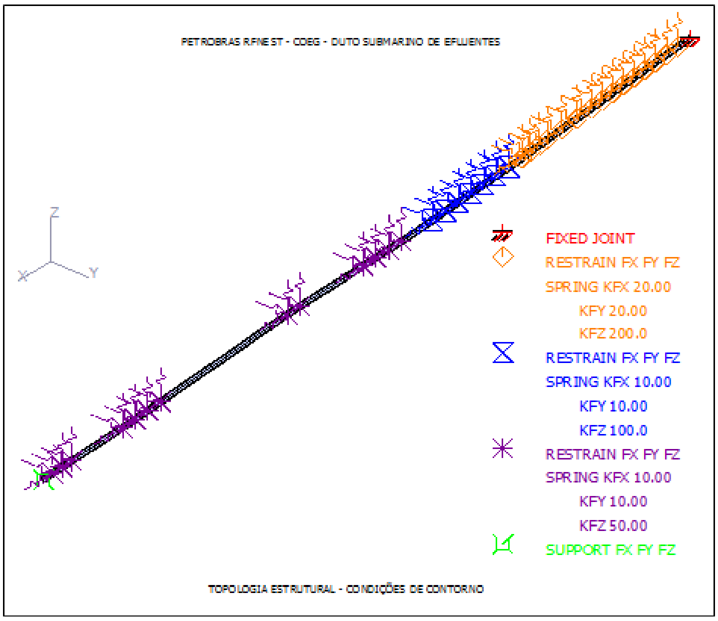

Figure 9 – RNEST – Shore Approach – Structural boundary conditions

Static Analysis Results and API(2014) Structural Strength Assessments

Static stiffness analysis solutions were obtained for a set of combined loading matrix cases with 5 permanent load and buoyancy loadings that were combined with a set of 90 wave independent loading cases. Results allowed to complete normative code check verifications as well as to verify lateral displacement response and localized support reaction upon the bearing points. The FEM solutions allowed to establish correlations with lateral displacement and on bottom stability conditions consistent with DNV(2010B). Maximum lateral and vertical displacements vary between 15 cm to 30 cm in the free-spans. Average horizontal plane displacements were lower than 10 cm, while vertical direction maximum subsidence found were lower than 10.0 cm, with no upward displacement observed. Vertical support reaction R_z were between 100.0 kN < R_z < 750.0 kN with no uplift, while horizontal reactions H_x and H_y were between 10.0 kN and 300.0 kN depending on the incident wave height and direction. These results greatly allowed evaluating general requirements of DNV(2010B) and to assess expected levels of lateral displacements and vertical foundation subsidence. Combined loading and hydrostatic stress-strength code check according API(2014) revealed the stress levels were moderate for all cases compared to member strength interaction rates including hydrostatic collapse verification IR, typically IR < 0.40.

Natural Vibration Analysis and Interpretation

Natural vibration analysis procedures were followed with the application of GTSTRUDL system high performance Lanczos Eigen solver. In addition to the consistent determination of structural mass distribution, the hydrodynamic added masses, together with the permanent structural added masses, as well as adhered marine growth masses as required to accomplish submerged structural eigenvalue analysis. The analysis selected the first 30 modes of natural vibration Eigen modes, representative of up to 99% of the mass vibration energy in the horizontal lateral direction and 88% in vertical direction.
The obtained set of eigenvalues results reflect essential boundary conditions consistent with the assumptions of equilibrium analysis, required by dynamic steady state modal superposition analysis problem. In addition, the careful observation of the natural vibration modes and patterns provided in depth understanding of the lateral stability analysis with DNV STABLELINES system. It is noted that the natural frequency ranges are distinctly different from the incident waves, i.e. confirming that the low amplification dynamic response behavior predominate, as indicated in DNV(2010B) and highlighted above. The vortex shedding frequencies however range between 0.52Hz< f_{vs} <0.77 Hz and coincides with eigenvalues corresponding to natural vibration frequencies of modes 3 to 5. It is inferred that the fluid-structure interaction regime exhibits weak vorticity in the expected range of hydrodynamic of Reynolds and Strouhal numbers, which effect is strongly attenuated due to existing dissipative factors such as foundation damping, turbulence and others. Obtained natural vibration periods are generally lower than 3.1 seconds while the first eigenvalue frequencies are higher than 0.33 Hz.

Dynamic Steady State Analysis Procedures

A set of steady state dynamics analysis procedure resolution was followed to determine the response of the shore approach structure to dynamic harmonic wave loadings as linear combinations of the Eigen modes (Modal Superposition). The incident wave and current load is considered is determined according API(2014) through means of GTSTRUDL system procedures on a discrete incremental basis (step wave loading) for each wave passage cycle. Wave-current interaction effects are consistently determined taking into account fluid flow velocity fields. Morison equation wave drag and inertial components are determined and combined for each wave passage step, obtaining the time history of the wave passage forces together with base shear and overturning moments. Modal Damping conditions were considered in a very simple fashion, adopting a uniform damping ratio of 0.25% for all active modes. It could be shown however that existing damping conditions are higher. Albeit this a conservative lower damping ratio value was adopted taking into account the characteristics of the soil foundation strata. Obtained dynamic internal stresses were applied to determine fatigue damage conditions, while the dynamic response displacement also provided comparative reference to the lateral and stability analysis according DNV(2010B). In a concise manner, the obtained horizontal base shear results H_{BS} for each wave passage typically varied between: 0.15 kN/m < H_{BS} < 10.0 kN/m in average, per unit pipeline length depending on the wave incidence direction, current direction and tidal conditions. It is to highlight that the above results compare in magnitude very effectively with the corresponding WMF per unit wave crest: 0.025 < M_{Fh} < 9.15 kN/m.

Lateral Stability Check according DNV(2010B)

The on-bottom lateral displacement and stability of the submarine shore approach pipeline was assessed through means of the DNV STABLELINES system consistently applying DNV(2010B) requirements. This system however was originally developed to verify stability conditions for submarine pipelines flowlines and umbilicals installed in deeper waters, and not particularly aimed at verifying shallow water shore approach pipelines. That is the reason why the complementary FEM numerical correlation analysis developed with GTSTRUDL system was deemed important. With regard to the sea state representation, the available Pierson-Moskowitz omnidirectional wave energy spectrum could not be directly applied in this case due to its applicability for depths greater than 100 m, and the fact that the local bathymetric conditions impose a wave height filter causing the waves to break. The DNV STABLELINES system offered a relatively limited number of discrete wave-current data that could be modeled to represent sea states. In contrast, the available meteorological oceanic data in Porto de Suape did not offered a complete set of directional information for all wave-current conditions tidal variations, and return periods, so that a statistical inference analysis was required to assure that a representative set of wave-current scatter data was applied. Verification were carried out for two distinct configuration: lightweight installation and operational conditions respectively. For conciseness, only the operational case will be discussed. The numerical results obtained with DNV STABLELINES system indicates that existing submerged carrier pipe and concrete outer cover shell weights converge to the required weight under the considered sea bottom soil conditions and incident wave-current hydrodynamic effects. Resulting soil support displacements subsidence are in the order of 10 cm while maximum lateral displacements are lower than 25 cm. The adopted carrier steel pipe thickness t = 22.0 mm and together with the proposed reinforced concrete cover layer of 125 mm are adequate to guarantee the required minimum submerged weight of Ws = 15.35 kN/m in order to maintain lateral displacement stability as required by DNV(2010B). In addition, the obtained results also reflect the observed FEM analysis results obtained through means of GTSTRUDL system.

Conclusion and Discussions

The shore line has an extremely complex interface of sea, soil, atmosphere and biological that interact dynamically. Past experience has evidenced that the sea shore environment, in shore shallow waters, requires that the submarine shore approach design is developed with special care to consider these factors in detail Yong Bai(2014)

Design analysis procedures required to develop the submarine outflow pipeline shore approach for the RNEST-Refinery in the Suape terminal was described, with focus on consulting aspects of the assignment. A careful discussion of the geotechnical and environmental controlling conditions was advanced with a view to assure the pipeline integrity and stability conditions and determine optimum permanent weight taking into account both pipeline lateral behavior and stability as well as soil strength and deformation.

Detailed hydrodynamic and wave kinematic investigations were developed consistent with shallow water wave breaking incidence statistics and tidal variations. Intensive numerical static and dynamic analysis procedures were developed with the GTSTRUDL system resources. The FEM analysis solutions were applied to code check verifications according API(2014) and were fundamental to stablish detailed numerical assessments of the structural behavior and structural response for combined operational and environmental conditions. An in-depth analysis introduced the application of the Wave Momentum Flux (WMF) concept as a robust integrity indicator of the incident wave breaking forces upon coastal structures. In particular, it is evidenced that the WMF parameter can be applied as a complementary Base Shear Force integrity indicator, adequate for coastal and submarine near shore structures, providing for obtaining better structural safety and reliability assessments and also as an additional analytic verification of FEM numerical model Base Shear results.

The numerical evaluation of the WMF values for the considered case, revealed a fine correlation with the numerically obtained FEM results and correlate with on-bottom lateral displacement and stability results assessed with the DNV STABLELINES system applying DNV(2010B) requirements. Another important analytical and consulting engineering observation is that, although the application of specialized lateral line stability system is essential for determining on-bottom stability requirements, the application of intensive numerical FEM correlation is also deemed fundamental to characterize structural behavior and performance evaluations, as well as to determine structural strength and stability conditions of the submarine pipeline shore approach.

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