Applicability of dynamic behaviour studies on Ocensa's offshore pipeline over liquefied seabed

Alejandro Marín, CEng, MSc, MSc.
Ocensa, Carrera 11 No 84-09 piso 10
Bogotá D.C, Colombia

ABSTRACT

Oleoducto Central-Ocensa (central oil pipeline), located in Colombia, South-America, has 12.5km of subsea pipeline approximately in the Gulf of Morrosquillo-Caribbean Sea. Crude oil from eastern plains of Colombia, is transported throughout this 42" pipeline, which is stored at the maritime terminal of Coveñas, before being loaded to tankers for exportation. Applicability of a simplified pipe-soil interaction model on determining pipeline's dynamic behaviour, once seabed support is lost due to seabed liquefaction, is evaluated. Pipeline's loss of support length is function of metocean features such as wave height, length, period, seabed depth, among others. Once the simplified pipe-soil interaction model is applied, calculation of pipeline's dynamic behaviour in terms of wall stress, for typical Gulf of Morrosquillo's metocean environment may be possible; as of this, critical conditions for pipeline's operation are identified, and seabed geotechnical maintenance plans are defined, based on rational methods, in order to minimise harm potential over pipeline's integrity due to seabed loss of support.

INTRODUCTION

Due to oil & gas offshore production, seabed pipeline's deployment is necessary for hydrocarbons transportation, trough shallow and water depths greater than 1000 meters. In the same way, transportation lines and additional facilities such as Tanker Loading Units (TLU) must be installed, for transfer, connection and loading activities in order to guarantee crude oil exportation to tankers. Therefore, it is mandatory the undertaking of rigorous and exhaustive analysis of seabed behaviour, in order to develop accurate integrity and maintenance plans based on metocean features (*i.e.* wave height, length, period, seabed depth, tidal and wave current), and factors as geohazards associated to metocean conditions, like landslides on the continental slopes and stress states' variations within the seabed, leading to liquefaction.

Evidence of large seabed liquefaction areas are reported in Christian *et al.* (1997), where identification of large zones exceeding 100m of submarine slope failures, due to seabed liquefaction were exposed close to the Fraser River Delta, as well as those reported within the Yellow River Delta by Jia *et al*. (2014). Therefore, large scale seabed failures due to earthquakes and wave induced stresses causing seabed liquefaction, are a reality, which must be addressed to guarantee subsea pipelines' integrity.
It has been also identified, that influence of wave induced pressure over seabed is greater in shallow water than in deeper water. This, increases seabed liquefaction potential as consequence of pore water pressure raising. However, influence of grain-size on seabed liquefaction, among other parameters, must be addressed; aforementioned potential decreases once seabed fine grain-size content

increases (*i.e.* silts and clays), regardless a high wave induced pressure over the latter.

Even though it is necessary to embrace comprehensive methods on describing seabed liquefaction, and even more, interaction between liquefied soil and pipeline dynamic behaviour, there is still deficiencies to allow pipelines operators to stablish criteria for decision making based on its quantification. Nevertheless, experimental studies as those conducted by Teh *et al*. (2003) have demonstrated that for subsea pipelines design, current design methods and approaches fulfil sufficiently stability requirements for a non-liquefied seabed, but are not adequate once the seabed experiences liquefaction. This, due to absence of liquefied seabed characterisation and a subsequent deficiency on pipe-liquefied soil interaction prediction.

Moreover, Wang *et al.* (2004) developed a numerical approach based on Biot's consolidation theory where interaction between soil skeleton and inter-granular water is regarded, but neglecting acceleration components for simplification. Similar developments based on Biot´s consolidation theory such as the undertaken by Zienkiewicz (1981), Ulker (2009) and Ulker (2012) have related fully dynamic, partially dynamic and quasi-static formulations to account the seabed response to a wave-induced pressure, as a function of metocean and seabed parameters variation.

Linear wave theory has been applied to associate seabed liquefaction onset, and its transient behaviour, to wave induced pressure over the seabed. Gao *et al.* (2011) established the seabed response in terms of vertical stress, horizontal stress, shear stress and pore water pressure entirely as function of the harmonic wave-load [(2πx / L) – (2πt / T)] and its repercussion at any depth by means of classic Boussinesq principle.

Although liquefaction potential decreases as fine grain-size content increases, regardless a high wave induced pressure over the seabed, once an almost saturated porous media *(i.e.* S≈1) is assumed, wave induced stress over soil may develop an instantaneously reduction of the mean effective stress (Ulker, 2012). Consequently, instantaneous liquefaction may occur even though a low soil permeability is given (*i.e.* dense sands or high fine grain-size content soils).

Additionally, according to Ulker (2009), cyclic wave induced pressure over seabed develop downward (*i.e.* suction or negative pore water pressure) and upward pore water flow. This, leads to wave induced liquefaction once seepage force, governed by upward flow, overtakes the submerged unit weight of soil (Figure 1).

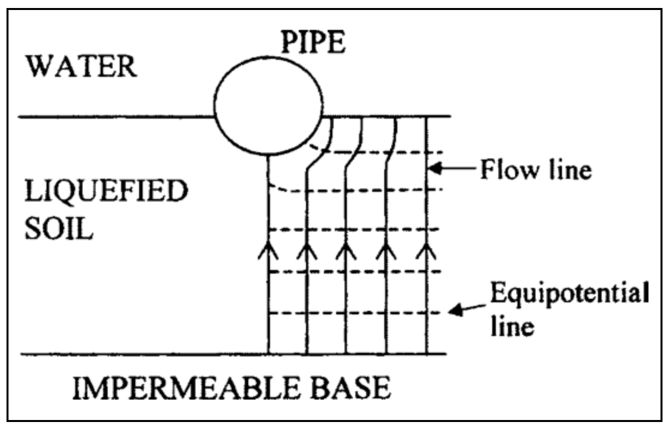

Figure 1. Upward pore water flow during seabed liquefaction, after Teh *et al.* (2006).

According to experimental studies conducted by Teh *et al.* (2003), heavy pipelines (*i.e.* large diameter) instability phases, once seabed liquefaction takes place, can be described as plotted in Figure 2.

Regarding this scenario, for time t_1, the hydrodynamic wave induced pressure is not sufficient to move the heavy pipeline, but is large enough to liquefy the seabed (*i.e.* the pipeline is stable); for times t_2 and t_3 the pipeline starts to move and therefore sinking into the liquefied soil mass, up to a final position for time t_4.

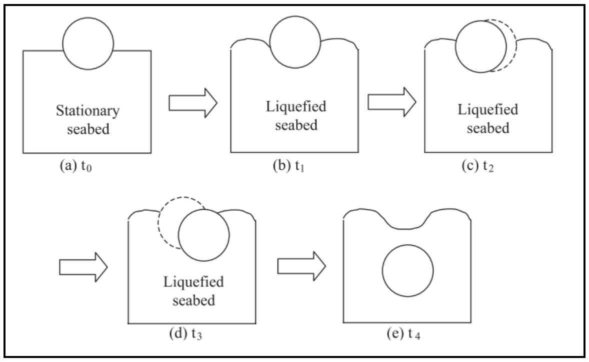

Figure 2. Instability phases throughout time for a heavy pipeline over liquefied seabed, after Teh *et al.* (2003).

Furthermore, according to Teh *et al.* (2006), both positive pore pressure and negative pore pressure may take place under cyclic loading around a submarine structure (*e.g.* a pipeline). Also, the author claims both sinking velocity and depth are greater for a heavier pipe, whilst a lighter pipe (*i.e.* small diameter pipelines) tends to float once soil liquefies. In order to describe abovementioned behaviours, Teh *et al.* (2006) stated three different modes governing the extent of pipeline sinking once seabed experiments liquefaction, related to seabed bearing capacity lost associated to depletion of vertical effective stress (*i.e.* $\sigma'_v = 0$):

- Mode I: For a slow sinking light pipe, the gradient of the increasing pore pressure acts as buoyancy force stopping the downward advance of it;

- Mode II: Pipe stops sinking, due to the increase or recover of soil bearing capacity, once excess of pore water pressure starts dissipating or when the pressure gradient is not sufficient;

- Mode III: For a fast sinking heavy pipe, it will continue to sink if whether the sinking velocity is greater than the excess of pore pressure dissipation rate or the pressure gradient is not enough to act as a buoyant force. Once it reaches a stable stratum, it may stop sinking.

As of this, once pipelines' behaviour in terms of wall stress and strain is desired to be estimated, regarding its sinking degree within the liquefied seabed, it is necessary to define the magnitude of upward pore water flow, once liquefaction takes place. This process is shown schematically in Figure 3.

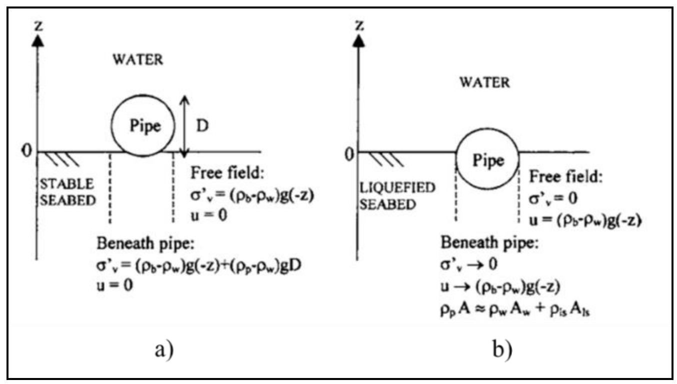

Figure 3. Excess of pore water pressure (u) and vertical effective stress (σ'_v) under a) non-liquefied seabed and b) liquefied seabed, after Teh *et al.* (2006).

METHODOLOGY

Since seabed stress field, related to wave motion, which induces liquefaction varies according to simple harmonic motion, seabed dynamic response will be consequently governed by this motion. Thus, seabed dynamic response in terms of stresses and displacements due to liquefaction, is calculated regarding a coupled soil skeleton-pore water flow model. For practical purposes, liquefied seabed length is equal to the wave length (L) that induces harmonic pressure over it, according to seabed dynamic response approaches conducted by Wang *et al.* (2004), Ulker *et al.* (2009) and Ulker (2009; 2012).

Modelling scenarios conducted by Marín (2015), exhibit pipelines' dynamic behaviour where seabed dynamic response, regarding coupled soil skeleton-pore water flow, was accounted. In the study, different pipe diameters and seabed depths were adopted, analysing 10", 16", 24", 36" pipe diameters, and 25m, 50m, 75m and 100m seabed depths, respectively. Figure 4 shows normalised vertical stress variation within seabed, for a 25m seabed depth and T=5s wave period scenario.

After Marín (2015), light pipelines (*i.e.* 10" and 16") behaviour was found to be sensitive to seabed dynamic response once liquefaction takes place, according to Mode I stated after Teh *et al.* (2006). Conversely, heavier pipelines (*i.e.* 24" and 36") behaviour was found to be governed by their own weight, aligned to Mode III after Teh *et al.* (2006).

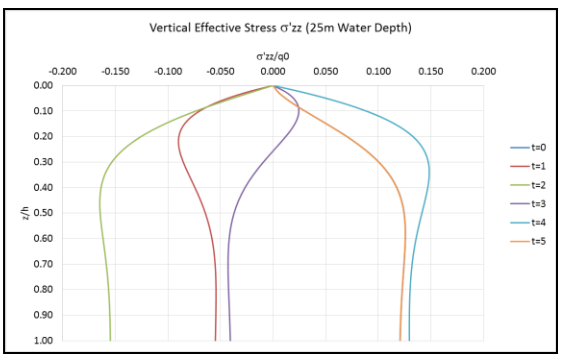

Figure 4. Normalised vertical stress variation within seabed thickness, for T=5s wave period, 25m seabed depth scenario, after Marín (2015).

The above mentioned is shown in Figure 5, where the influenced dynamic behaviour for a 10" pipeline, once seabed dynamic response is accounted (in terms of pore water pressure, vertical, horizontal and shear stress variation, plotted as the red curve), is evident if compared to pipeline dynamic behaviour regarding the assumption of an incompressible fluid-like seabed response (*i.e.* blue curve). On the other hand, in Figure 6 is shown how for a 36" pipe, its dynamic behaviour is not influenced by the liquefied seabed dynamic response, reflected on similar curve paths (*i.e.* blue and purple curves).

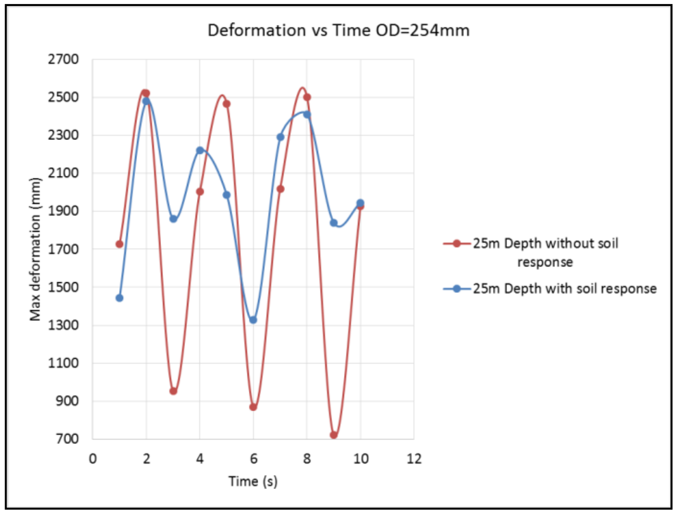

Figure 5. Light pipeline (10") dynamic behaviour variation, as function of seabed dynamic response, after Marín (2015).

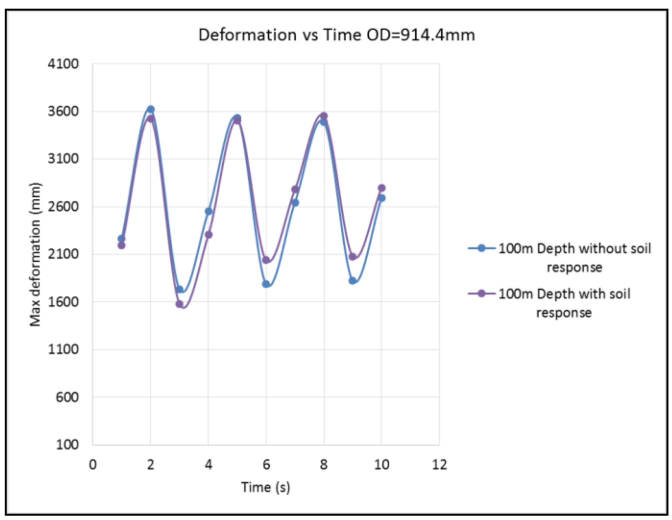

Figure 6. Heavy pipeline (36") dynamic behaviour variation, as function of seabed dynamic response, after Marín (2015).

According to previously mentioned, Ocensa's 42" offshore pipeline is not expected to exhibit changes on its dynamic behaviour once seabed dynamic response is accounted. Hence, it may be assumed

an incompressible or fluidised-like seabed response, when pipeline dynamic behaviour is desired to be calculated.
However, is relevant to account that models completed by Marín (2015) included low D/t ratios, between 21 and 30, which means significant thickness if compared to its diameter. This, leads large diameter pipelines' dynamic behaviour to be aligned to Mode III after Teh *et al.* (2006). Nevertheless, Ocensa's 42" offshore pipeline D/t ratio is 84, which means reduced thickness compared to its diameter. As of this, it may be suggested a potential for this pipeline, to exhibit a dynamic behaviour influenced by seabed dynamic response, due to a low mass percentage in relation to its size.

Accordingly, models regardless seabed dynamic response (*i.e.* liquefied soil assumed as an incompressible fluid) and regarding the latter, were conducted. This, in order to validate if whether a large diameter pipeline-low D/t ratio, as Ocensa 42", follows Teh *et al.* (2006) and Marín (2015) suggested dynamic response, or reveals different behaviour based on its high D/t ratio.

ANALYSIS AND RESULTS

Adopted mechanical and operational parameters for modelling are shown in Table 1.

Table 1. Pipeline properties adopted for modelling.

Properties	Value
Steel grade	API 5L X60
Outer diameter	42"
Wall thickness	12.7 mm
Operation pressure	1.0 MPa

Accounting relative steady slope throughout Ocensa 42" alignment of 12.5km, mean water depth of 29m for seabed dynamic response and pipeline dynamic behaviour calculations, induced by harmonic wave pressure, was adopted.

For pipeline dynamic behaviour estimation, where seabed dynamic response using coupled model, is not accounted, assumptions done by Foda and Hunt (1993) were embraced. Hence, once seabed is liquefied, its bearing capacity and shear strength reduce to zero. What is more, seabed behaviour may be described as an incompressible liquid, adopting a similar harmonic motion described by wave over it. In terms of metocean environment and based on linear wave theory, abovementioned harmonic motion transmitted to seabed, as a pressure or stresses' field *q* (*p* in equation below), is described by means of:

$$p(x,t) = \frac{\rho_w g H}{2\cosh(kd)} e^{i(kx-\omega t)}$$

Where *k* corresponds to wave number, ω to angular frequency and *x* to wave length, varying through time *t*¸ equal to assumed wave period *T*.
Complementary, values representing hydrodynamic variables corresponds to real storm for Gulf of Morrosquillo's returning period of 100 years, as follows:

Table 2. Hydrodynamic parameters for returning period of 100 years.

Parameter	Value
Wave height	4.94m
Wave length	100m
Wave period	11 s
Angular frequency	0.571 s^{-1}
Wave number	0.034 m^{-1}

For seabed dynamic response estimation, under wave induced cyclic loads in terms of soil skeleton stresses and displacements, once liquefaction takes place, originally methodology proposed by Biot

(1962) and further developed by Zienkiewicz (1981) and Ulker *et al.* (2009), was utilised.

This methodology states a coupled model with equations relating soil particles' strain and displacement, to pore water flow induced by wave cyclic load. Aforementioned equations are solved to obtain seabed dynamic response, in terms of vertical stresses, horizontal stresses, shear stresses and pore water pressure, applied as contact pressures in soil-pipeline interaction Finite Element Model (FEM). For seabed dynamic response calculation, a linear system with simultaneous equations set are derived, where non-dimensional matrix is required to be solved, leading to equations shown as follows, whose solving procedures can be consulted in aforementioned references.

$$\begin{bmatrix} \beta\Pi_2 - m^2\kappa & im\kappa\frac{\partial}{\partial\bar{z}} & \left(\frac{\beta\Pi_2}{n} + \frac{i}{\Pi_{1x}} - m^2\kappa\right) & im\kappa\frac{\partial}{\partial\bar{z}} \\ im\kappa\frac{\partial}{\partial\bar{z}} & \left(\beta\Pi_2 + \kappa\frac{\partial^2}{\partial\bar{z}^2}\right) & im\kappa\frac{\partial}{\partial\bar{z}} & \left(\frac{\beta\Pi_2}{n} + \frac{i}{\Pi_{1z}} + \kappa\frac{\partial^2}{\partial\bar{z}^2}\right) \\ \left(\Pi_2 - m^2 + \kappa_2\frac{\partial^2}{\partial\bar{z}^2}\right) & im(\kappa + \kappa_1 + \kappa_2)\frac{\partial}{\partial\bar{z}} & (\beta\Pi_2 - m^2\kappa) & im\kappa\frac{\partial}{\partial\bar{z}} \\ im(\kappa + \kappa_1 + \kappa_2)\frac{\partial}{\partial\bar{z}} & \left(\Pi_2 - m^2\kappa_2 + \frac{\partial^2}{\partial\bar{z}^2}\right) & im\kappa\frac{\partial}{\partial\bar{z}} & \left(\beta\Pi_2 + \kappa\frac{\partial^2}{\partial\bar{z}^2}\right) \end{bmatrix} \begin{Bmatrix} U_z \\ \bar{W}_x \\ \bar{W}_z \end{Bmatrix} = 0$$

$$\sigma'_{zz} = \left[\sum_{j=1}^{6}\left(ik\lambda + b_jK\frac{\eta_j}{h}\right)a_je^{\eta_j\frac{z}{h}}\right]e^{i(kx-\omega t)}$$

$$\sigma'_{xx} = \left[\sum_{j=1}^{6}\left(ikK + b_j\lambda\frac{\eta_j}{h}\right)a_je^{\eta_j\frac{z}{h}}\right]e^{i(kx-\omega t)}$$

$$\tau'_{xz} = \left[\sum_{j=1}^{6}\left(ikb_j + \frac{\eta_j}{h}\right)a_je^{\eta_j\frac{z}{h}}\right]e^{i(kx-\omega t)}$$

$$p = -\frac{K_f}{n}\left\{\sum_{j=1}^{6}\left[ik\left(1 + c_j\right) + \frac{\eta_j}{h} * \left(b_j + d_j\right)\right] a_je^{\eta_j\frac{z}{h}}\right\}e^{i(kx-\omega t)}$$

According to stated conditions, modelling scenarios were undertaken as:

- Pipeline dynamic behaviour assuming liquefied soil as an incompressible fluid, with equal harmonic motion as overlaying wave;
- Pipeline dynamic behaviour accounting seabed dynamic response, in terms of stresses and pore pressure, by means of soil skeleton-pore water flow coupled model.

As previously mentioned, pipeline liquefied soil (or span) length corresponds to calculated wave length for returning period of 100 years, which exerts cyclic pressure over seabed, along 100 meters. Also, dynamic soil-pipeline interaction models were calculated for times (t) varying between 0 and 11 seconds, which corresponds to adopted wave period for same returning period of 100 years.

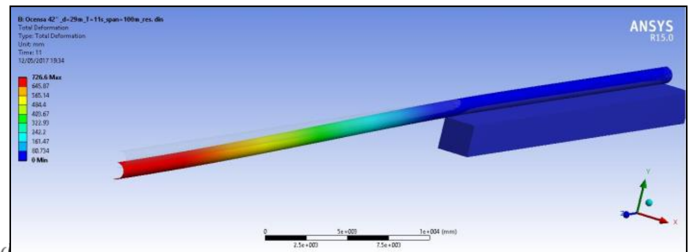

Figure 7. Graphic output from liquefied soil-pipeline Finite Element Model, for Ocensa 42", for maximum deformation.

Typical graphic output of liquefied seabed-pipeline by means of Finite Element Model, undertaken for Ocensa 42", for maximum deformation is shown in figure 7. For the analysis, symmetry principles in Z axis (*i.e.* parallel to pipeline alignment) and in X axis (*i.e.* pipeline and seabed cross section), in order to minimise number of elements for model solids and its dimensions. The abovementioned allows the model to be analysed in less time and reduces errors related to model solution convergence.

After modelling, plots regarding pipeline's dynamic behaviour in terms of wall stresses and pipe´s deformation, associated to loss of support due to seabed liquefaction were obtained. Figure 8 shows harmonic wave induced pressure over seabed, for modelling assuming liquefied soil as an incompressible fluid, with equal harmonic motion as overlaying wave, whilst Figure 9 shows point of maximum stress location once seabed support is lost, corresponding to pipeline´s bottom. Finally, Figure 10 plots dynamic behaviour variation once liquefied soil is assumed as an incompressible fluid, and once seabed dynamic response is calculated by means of skeleton-pore water flow coupled model.

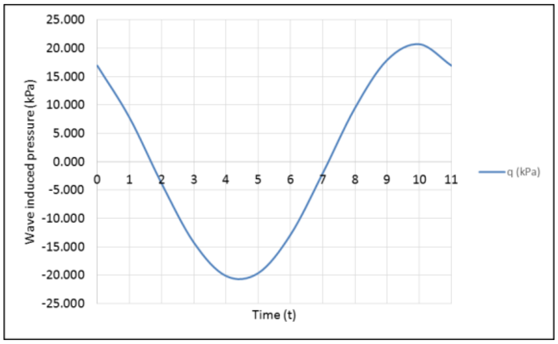

Figure 8. Harmonic wave induced pressure over seabed, for pipeline dynamic behaviour calculation assuming liquefied soil as an incompressible fluid.

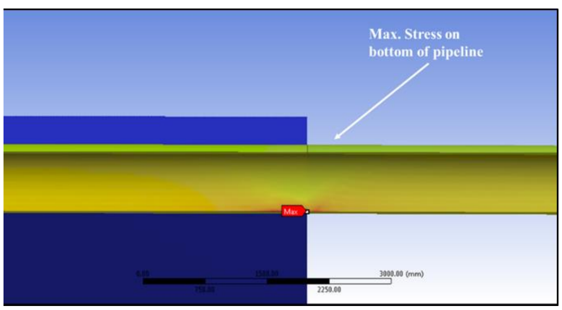

Figure 9. Maximum stress location once seabed support is lost.

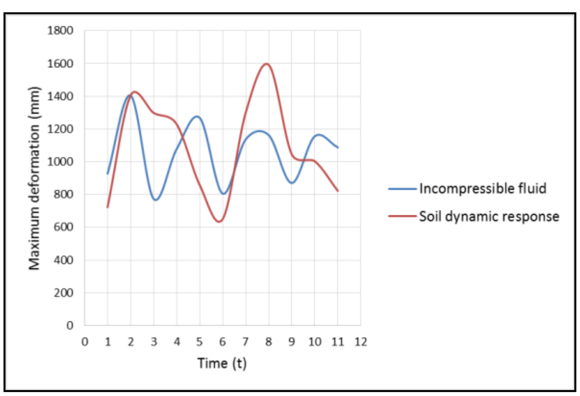

Figure 10. Difference between pipeline´s dynamic behaviour assuming seabed as an incompressible fluid (blue curve) and after calculating seabed dynamic response (red curve).

CONCLUSIONS

After modelling, differences between pipeline's dynamic behaviour assuming liquefied seabed as an incompressible fluid, and after calculating seabed response as contact pressures over the pipe, were recognised. Found results differs from conducted by Teh *et al.* (2006) and Marín (2015), where large diameter pipelines (*i.e.* heavy pipelines) show trends on their dynamic behaviour once seabed support is lost, governed by their own weight, inertial moment, angular frequency and oscillation amplitude, regardless dynamic seabed response.

Behaviour abovementioned is potentially influenced by D/t ratio, due to as previously stated, in spite of being a large diameter pipeline, associated mass is low regarding its reduced thickness value. This, since external hydrostatic pressure requirements for Ocensa´s 42" offshore pipeline are low related to its shallow water location.

Therefore, a potential of being influenced by liquefied seabed response under influence of wave cyclic loads, for the studied pipeline may be suggested. In this way, it is recommended to complete soil-pipeline interaction models once integrity and maintenance plans are undertaken.

Finally, it is also recommendable to complement soil-pipeline interaction models with Vortex Induced Vibration (VIV) analysis, addressing to identify potential pipeline damage associated to fatigue induced by cyclic stresses. To do so, periodic submarine inspections and regular bathymetry studies must be conducted, in order to determine and identify critical span lengths; additionally, constant metocean parameters variations and weather forecast monitoring must be rigorously done, since accuracy on obtaining these variables is vital to models' representativeness.

REFERENCES

- Christian, H., Woeller, D., Robertson, P.K. and Courtney, R.C. (1997) 'Site investigations to evaluate flow liquefaction slides at Sand Heads, Fraser River delta', Canadian Geotechnical Journal, 34(3), pp. 384-397.

- Foda, M. and Hunt, J. (1993) 'A nonlinear model for the fluidization of marine mud by waves', Journal of Geophysical Research, 98(C4), pp. 7039-7047.

- Jia, Y., Zhang, L., Zheng, J., Liu, X., Jeng, D.-S. and Shan, H. (2014) 'Effects of wave-induced seabed liquefaction on sediment re-suspension in the Yellow River Delta', Ocean Engineering, 89, pp. 146-156.

- Marín, A. (2015) “Dynamic behaviour of shallow water pipelines due to seabed liquefaction”, Thesis for MSc in Pipeline Engineering Degree, Newcastle University.

- Ulker, M. (2009) 'Dynamics of saturated porous media: Wave induced response and instability of seabed' Rahman, M. and Guddati, M. ProQuest, UMI Dissertations Publishing.

- Ulker, M.B.C. (2012) 'Pore Pressure, Stress Distributions, and Instantaneous Liquefaction of Two-Layer Soil under Waves', J. Water. Port Coast. Ocean Eng.-ASCE, 138(6), pp. 435-450.

- Ulker, M.B.C. and Rahman, M.S. (2009) 'Response of saturated and nearly saturated porous media: Different formulations and their applicability', International Journal for Numerical and Analytical Methods in Geomechanics, 33(5), pp. 633-664.

- Ulker, M.B.C., Rahman, M.S. and Jeng, D.S. (2009) 'Wave-induced response of seabed: Various formulations and their applicability', Applied Ocean Research, 31(1), pp. 12-24.

- Teh, T., Palmer, A., Bolton, M.D. and Damgaard, J. (2006) 'Stability of Submarine Pipelines on Liquefied Seabeds', Journal of Waterway, Port, Coastal and Ocean Engineering, 132(4), pp. 244-251.

- Teh, T.C., Palmer, A. and Damgaard, J. (2003) 'Experimental study of marine pipelines on unstable and liquefied seabed', Coast. Eng., 50(1), pp. 1-17.

- Wang, J., Zhang, B. and Nogami, T. (2004) 'Wave-induced seabed response analysis by radial point interpolation meshless method', Ocean Eng., 31(1), pp. 21-42.

- Zienkiewicz, O., Chang CT, Bettess P. 18 (1981) 'Drained, undrained, consolidating and dynamic behaviour assumptions in soils: Zienkiewicz, O C; Chang, C T; Bettess, P Geotechnique, V30, N4, Dec 1980, P385–395' Chang CT, B.P., pp. 48-48.

Alejandro Marín

Ingeniero Civil de la Universidad Nacional de Colombia, MSc en Ingeniería-Geotecnia de la Universidad Nacional de Colombia con Distinción Meritoria , MSc Pipeline Engineering de la Universidad de Newcastle con Grado de Primera Clase, con experiencia en el sector Oil & Gas en trazado, diseño, operación, mantenimiento e integridad de líneas de transporte de hidrocarburos. Realización de trabajos de investigación en estabilidad de taludes, geotecnia aplicada, integridad estructural de ductos, gestión del riesgo e interacción suelo-tubería.

Amplio conocimiento en análisis y gestión del riesgo en los componentes geotécnicos y mecánicos, así como en integridad y gestión de activos en el área del transporte de hidrocarburos. Habilidades en cuanto a evaluaciones de ingeniería asociadas a "fitness for service", en miras de optimizar la inversión de capital de operación en la gestión de integridad de ductos.

1. Nombre del autor: Alejandro Marín Tamayo
2. Teléfono:
    a. Residencia: 4576062
    b. Oficina: 3250200
    c. Celular: 3002831277
3. Dirección del autor:
    a. Residencia: Carrera 5 No. 74-75
    b. Oficina: Carrera 11 No. 84-09
    c. Email: Alejandro.marin@ocensa.com.co
    d. Ciudad: Bogotá D.C
    e. País: Colombia