Stress analysis of freestanding risers subjected to waves and current loadings - Numerical modelling

A M Al-Yacouby1*, Hakim Arifin1, M S Liew1 and Zahari Razak2

1Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
2Kuala Lumpur City Centre, 50088 Kuala Lumpur, Malaysia
*Corresponding author email: ahmad.alyacouby@utp.edu.my

Abstract. Free Standing Risers are vertical steel pipes tensioned by a near surface buoyancy can. These risers are subjected to different types of loads that lead to fatigue damages. Therefore, this study aims to predict the stresses of freestanding risers subjected to hydrodynamic loads. The methods applied consists of numerical analysis and computer simulation. In this paper, the wave and current loads acting on the risers have been determined using Morison equation, then the stress analysis was conducted using ANSYS software. The important parameters investigated are the pipe diameter D, the wall thickness, t, the wave height, Hmax, the wave period, Tass, the tensile strength, fy and the water current, v. The outcome of the study shows that wave height, wave period, pipe diameter and the wall thickness are affecting the maximum stress on the risers.

Keywords. Stress Analysis, Freestanding Risers, Waves loads, Current.

1. Introduction
Production risers have been used worldwide for transportation of oil and gas. The modern history of oil and gas started since the 18th century when oil refinery and oil-works were commercially formed for the first time. Since then, transportation of oil and gas become crucial issue to dealing with. In the U.S., 70% of crude oil and petroleum products are transported by pipeline and riser. Riser is important in subsea oil/gas production systems that acts as oil and gas conductor pipe between an offshore platform or vessel and a well at seabed [1]. Just like the pipeline, riser is a vertical pipe system connecting a floater at the water surface and the wellheads at the seabed [2]. In deep water, freestanding risers are subjected to many loads that lead to fatigue. Fatigue is associated with many factors [3]. VIV is considered as a critical among all factors that affect the stress of riser significantly [4]. This paper will discuss about the effect of pipe diameter, D, wall thickness of riser, t, wave height, Hmax and wave period, Tass on riser stress.

Production risers are fabricated variously; there are risers that can be sat on site, and pre-installed risers that can be connected to the pipe on the seabed by a subsea tie-in arrangement [5]. The famous four of them includes Top Tensioned Risers, Flexible Riser, Steel Catenary Risers and Free-Standing Hybrid Risers. Free Standing Hybrid Riser (FSHR) is comprised of vertical steel risers and Flexible Jumpers (FJ). They are jointly connected to a submerged Buoyancy Can (BC) [6]. The original philosophy for this system, developed by Cameron Iron Works in early 1983, was to design a system, for small or marginal fields, that could drain a reservoir and then be moved on to a second or even a
third location [7]. Nowadays, freestanding hybrid riser, FSHR have been commonly deployed in offshore oil field such as Gulf of Mexico, offshore Brazil and offshore Indonesia [8].

A number of studies related to stress assessment of tubular steel has been conducted in the past decades with the aim to develop a simplified yet accurate empirical formulation. At present, the most simplified empirical formulation for stress assessment of tubular steel often considers axial, hoop and shear stress as these are the most significant controlling factor on the ultimate stress of tubular steel structure. In order to improvise the accuracy of existing empirical formulations, the effect of different parameters on stress such as pipe diameter, \( D \), wall thickness, \( t \), wave height, \( H_{\text{max}} \) and wave period, \( T_{\text{ass}} \) are to be considered. However, the developed empirical formulation tends to become more complex as more parameters are considered and consequently leads to human errors during application or calculation.

2. Theoretical background

2.1. Morison’s equation

Hou [9] once conducted a stress analysis on Buoyancy Can of FHSR to predict fatigue damage. Upper area of the riser is very sensitive due to the currents and wave velocities. Thus, axial stress is significant at this portion as the moment is higher. At lower assembly, it is considered as fix. Stress at the bottom region is higher because of its connectivity. In many cases, stress analysis of tubular structure addressed hoop stress, axial stress and shear stresses. The combination of the three fundamental stresses is well known as Von Mises stress. In certain case i.e. riser structure shear stress is insignificant. K. Wang et al. [10] considered only combination of axial and bending/hoop stress given by \( \sigma = \sigma_a + \sigma_M \). Based on PTS 20.214 shear stress is excluded [11]. The Maximum Von Mises stress in a riser is calculated using equation (1).

\[
2\sigma_v^2 = 2\sigma_h^2 + 2\sigma_l^2 - \sigma_h\sigma_l + 3\sigma_s^2
\]  

where \( \sigma_v = \) Von Mises, \( \sigma_h = \) Hoop stress (due to pressure) \( \sigma_l = \) Longitudinal stress (due to pressure, thermal expansion, bending) \( \sigma_s = \) Shear stress

Basically, the shear stress is neglected for riser because riser is in vertical position. However, shear stress is considered in the API [12]. All stresses are calculated according to Von Mises stress failure criterion as following equation (2).

\[
2\sigma_v^2 = (\sigma_l - \sigma_h)^2 + (\sigma_h - \sigma_s)^2 + (\sigma_s - \sigma_l)^2
\]  

2.2. Computer simulation

Evaluation of the hydrodynamic stresses on fluid-structure interaction simulation is a great challenge, because the grid around the particle is usually not fine enough to properly resolve the velocity gradients. Software simulation is relevant for stress analysis as it solves all the complex formulation. Most well-known Navier-Stokes equation always been used for ages to model the incompressible flows of fluid motion [13].

\[
\frac{\partial u}{\partial t} + \nabla \cdot (u \otimes u) = -\nabla p + \frac{1}{Re} \nabla^2 u + f
\]

where \( u \) is the non-dimensional velocity \( p \) is the non-dimensional pressure \( t \) is non-dimensional time
3. Methodology

3.1. Hydrodynamic forces

Table 1 presents the parameters used to estimate the hydrodynamic forces using Morison Equation. Riser diameter was as 0.244 m with 0 m corrosion allowance. Thus, total wall thickness is equal to thickness of the main pipe. Mass and drag coefficient and current velocities are in accordance with PTS [11].

| Parameters                                | Values |
|-------------------------------------------|--------|
| Inertia force per unit length, $f_t$ (kNm$^{-1}$) |        |
| Drag force per unit length, $f_b$ (kNm$^{-1}$)  |        |
| Seawater density, $\rho$ (kNm$^{-3}$)        | 1025   |
| Mass coefficient, $C_m$                    | 1.6    |
| Drag coefficient, $C_d$                    | 0.65   |
| Wave velocity, (ms$^{-1}$), $U$             |        |
| Current velocity, (ms$^{-1}$), $u_c$        |        |
| Wave acceleration, (ms$^{-2}$), $\ddot{u}$  |        |
| Riser diameter, D (m)                      | 0.244  |

3.2. Software simulation

Software simulation was conducted to assess the stresses of riser subjected to hydrodynamic forces. There are few steps to complete the simulation:

1. Input the Engineering Data.
2. Riser Modelling.
3. Quality of Meshing.
4. Input the Parameter.
5. Solve the Simulation.

A riser was designed 75 m long standing vertically, with the tension on the top provided by the buoyancy can at the top and fixed by the lower connector at the bottom. The coordinate system is selected as: x direction coincides with riser axis, y is the current direction, and z is the crossflow direction. For actual case, the maximum deflection occurs in the middle of the riser. However, in this simulation, the maximum riser deflection occurs at top portion of the riser as the buoyancy can was not included. Physical properties of the riser are shown in the table 2.

The riser was set straight and vertically standing in the still water. The simulation was performed under current velocities of 1.8 m/s and 1.43 m/s at 1.0 L m and 0.5 L m from the seabed respectively based on PTS [11]. The riser was fixed at the bottom of the riser and total forces of hydrodynamic forces, gravitational acceleration, and ocean current were applied along the riser body. The stress and deflection were observed for different case and riser.

Figure 1 shows the texture of meshing on riser model that had been applied hydrodynamic loads. Sensitivity of meshing is important for assurance of measurement quality. The finest size of meshing, the more accurate the result will be. The smallest size of meshing that computer capable was applied until it reached the limit. Hydrodynamic loads were applied in many directions. Figure 2 shows the direction of applied loads along the riser.
Table 2. Physical properties of riser.

| Parameter                             | Values       |
|---------------------------------------|--------------|
| Riser outer diameter, D (m)           | 0.244        |
| Riser inner diameter, Di (m)          | 0.178        |
| Internal Corrosion Allowance (mm)     | 3            |
| Material Grade (API 5L)               | X-70         |
| Material Yield Stress (MPa)           | 483          |
| Ultimate Tensile Strength (MPa)       | 565          |
| Young Modulus (MPa)                   | 206843       |
| Poission Ratio                        | 0            |
| Steel Density (kg/m^3)                | 7850         |

Figure 1. Meshing of 3D model.

Figure 2. Applied forces direction.

Simulations were performed for several times until ultimate precision achieved. The steps are repeated for a few times using different parameter as shown in table 3. Each parameter is denoted as case 1, case 2 case 3 and case 4.
Table 3. Manipulated parameter.

| Case 1 | Case 2 | Case 3 | Case 4 |
|--------|--------|--------|--------|
| Do (m) | t (m)  | H\(_{\text{max}}\) (m) | T\(_{\text{ass}}\) (m) |
| Riser 1 | 0.244 | 0.033 | 11.65 | 9.64 |
| Riser 2 | 0.2684 | 0.0363 | 12.815 | 10.604 |
| Riser 3 | 0.2806 | 0.03795 | 13.3975 | 11.086 |
| Riser 4 | 0.2928 | 0.0396 | 13.98 | 11.568 |
| Riser 5 | 0.3172 | 0.0429 | 15.145 | 12.532 |
| Riser 6 | 0.366 | 0.0495 | 17.475 | 14.46 |

4. Results and Discussion

4.1. The effect of wave heights on total hydrodynamic forces

Figure 3 shows the effects of wave heights on total hydrodynamic forces respectively. The value of the initial H\(_{\text{max}}\) was increased by 10%, 15%, 20%, 30% and 50%. The graph shows that increasing the wave height has resulted in higher drag and inertia forces. For instance, the wave height with 50% increment has resulted the highest hydrodynamic force with maximum increment of 53.32% as the value of the force increased from its initial value of 46750 kN to 71677 kN. We can also observe that the effect of wave heights on the drag forces is higher than the effects on the inertia forces.

![Figure 3](image)

4.2. The effect of wave periods on hydrodynamic forces

Figure 4 shows the effects of wave periods on drag, inertia and the total hydrodynamics forces respectively. Based on the graphs above the effect of drag forces is greater than inertia forces. The value of the initial wave period was increased by 10%, 15%, 20%, 30% and 50%. The graphs show that increasing the wave period has resulted in higher drag and inertia forces. For instance, the wave height with 50% increment has resulted the highest hydrodynamic force with maximum increment of 32.8% as the value of the force increased from its initial value of 46750 kN to 62082.4 kN. We can also observe that the effect of wave periods on the drag forces is higher than inertia forces.

4.3. The effect of wave heights on hydrodynamic forces

Figure 5 shows the effects of wave heights on drag, inertia and the total hydrodynamics forces respectively. The value of the initial H\(_{\text{max}}\) was increased by 10%, 15%, 20%, 30% and 50%. The graph shows that increasing the wave height has resulted in higher drag and inertia forces. For instance, the wave height with 50% increment has resulted the highest hydrodynamic force with maximum increment of 74.83% as the value of the force increased from its initial value of 46750 kN to 81732 kN. We can
also observe that the effect of wave heights on the drag forces is higher than the effects on the inertia forces.

![Figure 4. Inertia forces of different wave period for D = 0.224 m, t = 0.033 m, H = 11.65 m & f_y = 483 MPa.](image)

![Figure 5. Total forces of different wave height for D = 0.224 m, t = 0.033 m, T = 9.64 s & f_y = 483 MPa.](image)

4.4. The effect of pipe diameter, D on stress

Figure 6 shows the effects of pipe diameter on riser stresses. The value of the initial diameter was increased by 10%, 15%, 20%, 30% and 50%. The graph shows that increasing the diameter has resulted in stresses. For instance, the diameter with 50% increment has resulted the lowest stress with maximum increment of 33.83% as the value of the stress increased from its initial value of 194498 MPa to 128695 MPa. We can also observe that the riser stresses inversely change with the diameter size.

![Figure 6. Stresses of riser of different pipe diameter for t = 0.033 m, H = 11.65 m, T = 9.64 s & f_y = 483 MPa.](image)
4.5. The effect of wall thickness, \( t \) on stress

Figure 7 shows the effects of wall thickness on riser stresses. The value of the initial diameter was increased by 10\%, 15\%, 20\%, 30\% and 50\%. The graph shows that increasing the diameter has resulted in stresses. For instance, the diameter with 50\% increment has resulted the lowest stress with maximum increment of 88.50\% as the value of the stress increased from its initial value of 194498 MPa to 366637 MPa. We can observe that the riser stresses decrease when thickness increase. Thus, the change in thickness affect the stress significantly among the others.

![Figure 7. Stresses of riser of different wall thickness for D = 0.244 m, H = 11.65 m, T = 9.64 s & f_y = 483 MPa.](image)

4.6. The effect of wave height, \( H_{\text{max}} \) on stresses

Figure 8 shows the effects of wave height on riser stresses. The value of the initial diameter was increased by 10\%, 15\%, 20\%, 30\% and 50\%. The graph shows that increasing the diameter has resulted in stresses. For instance, the diameter with 50\% increment has resulted the lowest stress with maximum increment of 74.66\% as the value of the stress increased from its initial value of 194498 MPa to 339709 MPa. We can also observe that the riser stresses increase when wave height increases.

![Figure 8. Stresses of riser of different wave height for D = 0.244 m, t = 0.033 m T = 9.64 s & f_y = 483 MPa.](image)

4.7. The effect of wave period, \( T_{\text{ass}} \) on stresses

Figure 9 shows the effects of wave periods on riser stresses. The value of the initial diameter was increased by 10\%, 15\%, 20\%, 30\% and 50\%. The graph shows that increasing the diameter has resulted in stresses. For instance, the diameter with 50\% increment has resulted the lowest stress with maximum increment of 32.72\% as the value of the stress increased from its initial value of 194498 MPa to 258146 MPa. We can also observe that the riser stresses increase when wave period increases.
Figure 9. Stresses of riser of different wave periods for \( D = 0.244 \text{ m}, \ t = 0.033 \text{ m}, H = 11.65 \text{ m} \) & \( f_y = 483 \text{ MPa} \).

4.8. The effect of current on stresses
Figure 10 shows the graphs of the effect of current velocity, \( v \) on stress. The value of the initial diameter was increased by 10\%, 15\%, 20\%, 30\% and 50\%. The graph shows that increasing the diameter has resulted in stresses. For instance, the diameter with 50\% increment has resulted the lowest stress with maximum increment of 15.36\% as the value of the stress increased from its initial value of 194498 MPa to 224381 MPa. We can also observe that the riser stresses increase when wave period increases.

Figure 10. Stresses of riser of different velocities for \( D = 0.244 \text{ m}, \ t = 0.033 \text{ m}, H = 11.65 \text{ m} \) & \( T = 9.64 \text{ s} \).

5. Conclusion
In this paper, the stress analysis of freestanding risers subjected to waves and current loadings has been investigated using numerical modelling. Upon completion of numerical analysis, stress analysis was conducted. The hydrodynamic forces are calculated and assessed. The riser stresses are assessed by simulation using ANSYS software. The important parameters involved are the pipe diameter, the wall thickness, the wave height, the wave period and the water current. The analysis results show that the stresses are linearly proportional to water depth. The wave periods have more significant effect on the stress as compared to wave height. Generally, the pipe diameter, wall thickness, wave heights and wave periods have significant impact on the riser’s stresses.

6. References
[1] Chakrabarti, S.K. and R.E. Frampton 1982 Review of riser analysis techniques Applied Ocean Research 4(2) 73-90.
[2] Veritas, D.J.D.N. 2010 DNV-RP-F204 Riser Fatigue.
[3] Veritas, D.N.J.D. 2010 R.P.D.-R.-C., Fatigue design of offshore steel structures.
[4] Kim, D.K., Incecik, A., Choi, H.S., Wong, E.W.C., Yu, S.Y. and Park, K.S. 2018 A simplified method to predict fatigue damage of offshore riser subjected to vortex-induced vibration by adopting current index concept Ocean Eng. 157 401-11.

[5] Fishe, E. and P. Hoolley 1995 Development and deployment of a freestanding production riser in the gulf of Mexico Offshore Technology Conference.

[6] Kim, K.-S., Choi, H.-S. and Kim, K.S. 2018 Preliminary optimal configuration on free standing hybrid riser Int. J. Naval Architecture Ocean Eng. 10(3) 250-8.

[7] Tellier, E. and Thethi, R. 2009 The evolution of free standing risers ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers.

[8] Bai, Y. and Bai, Q. 2005 Subsea Pipelines and Risers, Elsevier Ltd.

[9] Hou, T. 2014 Numerical Simulation of Free Standing Hybrid Risers, Texas A&M University.

[10] Wang, K., Xue, H., Tang, W. and Guo, J. 2013 Fatigue analysis of steel catenary riser at the touchdown point based on linear hysteretic riser-soil interaction model Ocean Eng. 68 102-11.

[11] PTS 20.214 2008 Pipeline and Riser Engineering, PETRONAS CARIGALI Sdn. Bhd. (PCSB).

[12] API, R. 1993 16Q, Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser System, Washington, D.

[13] Armfield, S. and Street, R. 2002 An analysis and comparison of the time accuracy of fractional-step methods for the Navier–Stokes equations on staggered grids Int. J. Numer. Methods Fluids 38(3) 255–82.

Acknowledgments
The authors would like to acknowledge the financial support provided by Universiti Teknologi PETRONAS (UTP) through YUTP grant (015LC0-095).