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Downtime Cost Analysis of Offloading Operations due to Influence of Partially Standing Waves in Malaysian Waters and Development of Graphical User Interface

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Abstract A cost related study for the offloading operations is an integral part of monetary risks assessment. The partially standing waves which occur between the gap of vessels are responsible for impacting the offloading operations in terms of downtime costs. This paper presents a downtime cost analysis of side-by-side offloading operations in Malaysian waters for regular waves addressing the influence of partially standing waves through a Graphical User Interface (GUI). The developed interface is explained and its work procedure is demonstrated in this paper. The downtime is studied for two sea-states, beam and heading seas for which the probability of occurrence was calculated from the location specific wave scatter distribution. The results of wave kinematics for partially standing waves influencing the offloading operation for side-by-side configuration are presented. The down-time cost analysis will help the oil operator companies to analyze the economic risks involved for field developments and anticipate the loss in revenue for down-time occurrences. Overall, an attempt to integrate the influence of gap between vessels with offloading operations and related cost is presented.

Keywords: downtime, cost, partially standing waves, side-by-side, GUI

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Nomenclature

- η_t - time varying wave elevation
- k - wave number
- d - water depth
- ω - wave frequency in rad/s
- H_i, H_r - incident and reflected wave heights
- ϕ - velocity potential
- u, w - horizontal and vertical velocity
- $\dot{u}_x, \dot{u}_z$ - convective horizontal acceleration
- $\dot{w}_x, \dot{w}_z$ - convective vertical acceleration

1 INTRODUCTION

Oil and gas industries are among those sectors where production is subjected to higher costs due to downtime [1]. Offloading operations are part of offshore oil production which are performed around the globe wherein an offloading shuttle tanker is stationed near the FPSO to facilitate the offloading of hydrocarbons from the FPSO into the shuttle tanker either in tandem or side-by-side configuration. However, side-by-side configuration tends to undergo complex hydrodynamic interactions and vessel-vessel interactions [2]. The feasibility of offloading operation is determined by the dynamic load acting on the side-by-side mooring system [3]. The waves are usually assessed as external load which influences the offloading operation [4]. Furthermore, the relative motion and the wave drift between the vessels have dominant impact on the transfer of hydrocarbon between vessels [5]. Finally, proper and deep rooted investigation of hydrodynamic interaction can avoid collisions of two adjacent vessels in close proximity [6]. This paper studies the downtime cost incurred as an outcome of the effects of partially standing waves on oil offloading operation in side-by-side configuration. The wave elevation of the partially standing wave represents the superimposing of the incident and reflected regular waves, from which the linear velocity potential is deduced. The percentage reflection of the incident waves depends upon the distance between the vessels. This study considers closely spaced vessel which accounts for 40% reflection of incident waves [7]. The offloading operation is studied in Malaysian waters and the probability of occurrence is obtained from wave scatter distribution extracted from real time location based hind-cast data of 50 years.

The operating expenditure (OPEX) in this study is just for illustration and does not reflect any specific operator. The actual downtime cost and the economic risk involved can be drawn to a more realistic value if the operating cost and actual downtime days are exactly known. This paper is broadly divided into two major parts. The first part focuses on the methodology, numerical formulation of partially standing waves and downtime cost with results on wave kinematics and downtime cost. The second major part deals with the development of Graphical User Interface (GUI), its work flow and illustration on its working. These two major parts comprises the present paper, which is organized into eight sections. In addition to the current section which introduces the research study, the second section presents the literature background. The third section explains the methodology of study and deals with wave scatter distribution obtained from real-time metocean data. The partially standing waves and its equations of wave kinematics are derived from the wave elevation given in [8]. The third section also explains the methodology of down-time cost analysis followed by details of shuttle tankers and wave conditions for which down-time cost was performed. The fourth section of the paper presents the results and discusses on the findings of downtime cost in Malaysian waters. The fifth section focuses on the development of graphical user interface. The block diagram which explains the flow of user interface and its features has been presented. The sixth section illustrates the working of graphical user interface and discusses the output from the user interface. The conclusion of present study is presented in seventh section. The future works for LNG carriers under consideration are discussed in the eighth section.

2 Background

Based on extensive reviews, real life operations and simulations, the dynamically positioned vessel served feasible within operational limits. The research article [9] presented a probabilistic model for estimating downtime. It used connected Markov chains to generate binary workability sequences for each procedure using real metocean circumstances. Also, the delay in some activities due to weather conditions was accompanied by extra economic expenses. The authors in [10] presented a methodology based on static calculation of dynamically positioned for determining the downtime of offloading operations. The mathematical modeling consisted of static analysis where mean forces were calculated. The dynamic effects were not taken into consideration. For three generations of dynamically positioned tankers, the offloading downtime was decreased and number of disconnections were reduced due to incrementing the angle which defines the feasibility zone. However, there was no significant reduction in downtime by increasing the dynamically positioned power. The research paper discussed the downtime faced due to unplanned shutdown of a subsea production system [11]. An integrated work flow was proposed to counter act the downtime problem. An economical related key findings of certain considered parameters to reduce the operational cost and yet target higher recovery through simulation has been carried out to evaluate the effect of parameters on oil recovery [12]. A case study was presented in [13] where operational costs were minimized by facilities improvement and low cost alternatives. The successful implementation of keeping both OPEX and CAPEX less with safety and integrity in the plan was the breakthrough for redevelopment of field. Operability and downtime due to metocean parameters was studied and a numerical wave model was employed for determining the significant wave height at each port of consideration [14]. The validation of the numerical results was performed with the wave measurements by oceanic buoys. Their work signified the occurrence of severe environments which affects the berth operability and port operations. Overall, levels of metocean parameters were defined to set as guiding limiting operational conditions. Also, the downtime due to significant wave height was more as opposed to other metocean parameters like winds and currents. The authors in [15] presented an approach to assess the operational risks and re-validating them through Process Hazard Analyses (PHAs) and other techniques. The authors have further suggested that operational risk assessment is crucial for prevention of loss. A stochastic approach was used to determine the total uptime of a system over its life time through development of bounds [16].

A numerical and experimental study has been presented on wave induced motions on side-by-side take off of shuttle tanker in head seas to examine the limit of the system operability, relative motions and mooring loads [17]. A numerical study on the side-by-side offloading operations of Floating, production, storage and offloading vessels (FPSO) under the effects of motion responses, drift forces and partially standing waves was conducted [7, 18]. The availability of weather data can determine the feasibility of offloading for constrained conditions [19]. The authors in [20] concluded the prediction of connection systems load were of prime importance for side-by-side offloading operations. The authors evaluated a specific Oil Loading Terminal (OLT) in Brazilian location and numerical simulations were carried out to understand the effectiveness of offloading flexible lines between FPSO and calm buoys [21]. The cost analysis was also carried out. This study also suggested the use of the offloading method as a technical feasible solution. However, it was advised that it should be experimentally and field tested. The impact of certain variables on the side-by-side offloading operations were carried out for an FLNG in [22]. This paper discussed an improved methodology using ANN to evaluate the impact on offloading operations. The improved methodology would facilitate decision making with respect to offloading operations. The feasibility of operability operation was identified from offloading window. However, lesser time domain simulations are required for ANN. The authors in [23] have laid emphasis on studying the factors which influence the offloading operations. The global motions, accelerations and mooring loads and their influence on safe offloading operation were presented. A review on the various risk and reliability methods specific to offshore wind industry was presented in [24]. The risk assessment of side-by-side offloading configuration has been studied under different environment conditions within operating sectors [25]. The researchers proposed detailed time domain simulations to evaluate reliable offloading criteria. The impact on downtime cost of offloading operations due to vessel response in six degrees of freedom and mooring cable forces was studied in Malaysian waters by authors in [26, ?]. Additionally, the authors simulated the failure of mooring cable and assessed the downtime cost due to it. A statistical comparison between measured metocean data to hindcast data through regression analysis between environmental loads in Malaysian waters was presented in [27]. The application of hindcast was useful in determining the probability distribution of environmental loads which uses computer application to predict the future occurrences of events based on their past occurrences.

The side-by-side offloading operation throughout the world was presented and alternative offloading possibilities were discussed for locations where higher uptime is required in [28]. The offloading availability was defined followed by operational phases of transfer were briefly discussed. The proposed methodology calculated the offloading availability using site specific environmental conditions. The offloading availability included evaluation of environmental forces on hull, hydrodynamic interactions and mean headings. The limiting criteria termed as downtime criteria were presented for offloading operations. The offloading criteria was evaluated based on three factors namely, significant wave height, peak period and direction of heading which affect the mooring loads and relative motions, which are compared to limiting value. The offloading availability was carried out for several locations. The authors mentioned the use of time domain tools to assess specific criteria for offloading operations [29]. The past study focused on extending the operating limits to minimise the downtime through numerical tool and model testing. The different criteria to assess the offloading operation which impact the design of the offloading system were discussed. The criteria are identified with respect to forces in the connections, distance between vessels and relative heading. The developed methodology was concluded practical. The safety factors were summarized as guideline for design. The work by [30] discussed the importance on selection of offloading system as they affect the performance of marine operations. The economic performance of a vessel was affected by weather downtime. The work presented tools which are available for numerical simulations. Eventually, the authors focused on the combination of numerical tools with experience for safe offloading operations. The work presented safe offloading assessment under limiting environmental conditions with more attention towards risk of collision. The downtime condition considered was extreme environmental conditions, failure of engine, gear and tugs. For each downtime simulation, the risk of collision was observed. Furthermore, Quantitative Risk Assessment was studied under which possible scenarios were found where possibility of collision could occur. Every scenario was assigned a probability of occurrence based on environmental statistical data. The safety of offshore offloading operation in terms of probability of collision was presented. An artificial neural network to reduce relative horizontal distance and hawser tension was developed for sever environmental conditions [31]. The simulation was performed through controlled algorithm which provided the operating rate and total cost. Also, the effect of wave height on the production downtime was studied via simulation. It was concluded that with the developed algorithm, the station keeping was possible for increased wave height limit and reduced hawser tension. A new method to determine the storage capacity for side-by-side offloading operation has been proposed by researchers in [32]. The proposed methodology was based on model testing for past 10 years environmental data. Navigation simulation was used to determine the offloading criteria. Furthermore, cost analysis was performed for the FLNG to determine the inventory and production costs. Finally cost benefit analysis using Net Present Value (NPV) methods allowed to decide the suitability of FLNG storage capacity. The downtime analysis was based on the availability of offloading window. The researchers have considered linear time domain simulations to understand the hydrodynamic interaction for close vessels. An optimum tank capacity was calculated considering the investment and downtime due to weather. A graphical user interface was developed by authors to assess downtime cost of offloading operations due to dynamic stability of offloading shuttle tanker in Malaysian waters [33].

It is concluded from past works that there is no much work done in down-time cost estimation. A research gap exists to connect motion responses to cost. Also, authors have developed researches related to vessel interaction and fluid behaviour. However, there is no much literature available to link the vessel behaviour and wave interaction to economical performance of FPSO and shuttle tanker. Thus, this paper will focus on one particular study co-relating the partially standing waves kinematics to OPEX.

3 Methodology

3.1 Partially Standing Waves

A partially standing wave is made up of an encountering wave with a certain incident wave height H_i. These incident waves then propagate forward and hit the adjacent vessel and thereby part of the wave is reflected back with reflected wave height H_r. This reflected wave would then superimpose with the next incident wave to form a partially standing wave as shown in Fig. 1. The FPSO and shuttle tanker are positioned in a side-by-side configuration to facilitate the offloading operation but side-by-side configuration is more critical as it involves two vessels in close proximity but separated by a gap. The gap between the FPSO and shuttle tanker may be regarded as narrow water column wherein partially standing waves originate due to superposition of incident and reflected waves. The authors in [7] studied the influence of partially standing waves for adjacent vessels in close proximity through mathematical modeling. It was shown that wave kinematic interactions are more susceptible for wave with lower time period but with a greater percentage of reflected wave height. Furthermore, the wave kinematics of partially standing waves are derived from the velocity potential with the assumption that wave elevation of the superimposed incident and reflected wave heights have zero spatial and temporal mean [7]. Equation (1) represents

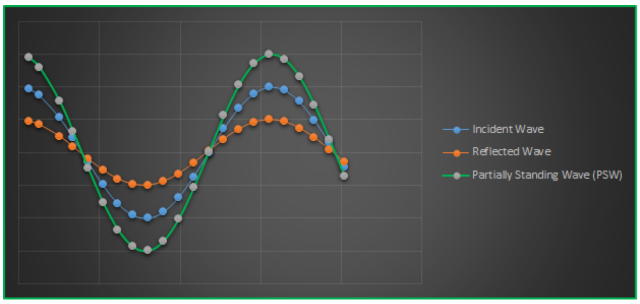


Fig. 1: Partially standing wave

the wave elevation of partially standing waves with certain incident (H_i) and reflected (H_r) wave heights [7].

$$\eta_t = \frac{H_i}{2}\cos(kx-\omega t) + \frac{H_r}{2}\cos(kx+\omega t+\varepsilon) \tag{1}$$

The linear dynamic free surface boundary condition relates the instantaneous displacement of free surface to the time rate of change of velocity potential [8] as given by Eq. (2). Equations (3) and (4) represent the velocity potential deduced thereafter.

$$\phi = g\int \eta(t) \tag{2}$$

$$\phi_{z=0} = \frac{g}{2\omega}[H_r\sin(kx+\omega t+\varepsilon) - H_i\sin(kx-\omega t)] \tag{3}$$

$$\phi_{z<0} = \frac{g}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r\sin(kx+\omega t+\varepsilon) - H_i\sin(kx-\omega t)] \tag{4}$$

The wave kinematics are derived from using the following relationships [7]. 'u' and 'w' are the velocities in horizontal and vertical directions, respectively. The dot over the velocity represents the convective accelerations.

$$u = \frac{\partial\phi}{\partial x}, w = \frac{\partial\phi}{\partial z}, \dot{u}_x = \frac{\partial u}{\partial x}, \dot{u}_z = \frac{\partial u}{\partial z}, \dot{w}_x = \frac{\partial w}{\partial x}, \dot{w}_z = \frac{\partial w}{\partial z} \tag{5}$$

The equation of wave kinematics for partially standing waves are given by Eqs.(6) to (11).

$$u = \frac{-gk}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r\cos(kx+\omega t+\varepsilon) - H_i\cos(kx-\omega t)] \tag{6}$$

$$w = \frac{-gk}{2\omega}\frac{\sinh(k(d+z))}{\cosh(kd)}[H_r\sin(kx+\omega t+\varepsilon) - H_i\sin(kx-\omega t)] \tag{7}$$

$$\dot{u}_x = -\frac{gk^2}{2\omega}\frac{\cosh(k(d+z))}{\cos(kd)}[H_i\sin(kx-\omega t) - H_r\sin(kx+\omega t+\varepsilon)] \tag{8}$$

$$\dot{u}_z = -\frac{gk^2}{2\omega}\frac{\sinh(k(d+z))}{\cos(kd)}[H_r\cos(kx+\omega t+\varepsilon) - H_i\cos(kx-\omega t)] \tag{9}$$

$$\dot{w}_x = -\frac{gk^2}{2\omega}\frac{\sinh(k(d+z))}{\cos(kd)}[H_r\cos(kx+\omega t+\varepsilon) - H_i\cos(kx-\omega t)] \tag{10}$$

$$\dot{w}_z = -\frac{gk^2}{2\omega}\frac{\cosh(k(d+z))}{\cos(kd)}[H_r\sin(kx+\omega t+\varepsilon) - H_i\sin(kx-\omega t)] \tag{11}$$

Eqs. (6) and (7), respectively displays the horizontal velocity and vertical velocity. The convective accelerations of horizontal and vertical velocities are displayed by Eqs. (8) to

Table 1: Criteria wave conditions for offloading operation in different sea states

Sea State	Criteria for safe offloading
Beam seas	H_s = 1 m and T_p = 6 s
Head seas	H_s = 2 m and T_p = 6 s

(11), respectively. The wave kinematics of partially standing waves are associated with encountering waves having certain incident wave height (H_s) and time period (T_p). The influence of wave kinematics for closely spaced vessels are studied under different real time weather conditions.

3.2 Down-time cost analysis

This study focuses on the feasibility of offloading operation which depends upon two parameters, i.e. encountering wave conditions and the sea state. These parameters influence the wave kinematics of the partially standing waves occurring between the gap of vessels and impact the offloading operations resulting in downtime. In case of extreme weather condition, where in the offloading operations can not be performed is regarded as a downtime condition and the downtime condition ceases the further transfer of oil, causing loss in revenue of production. This loss of revenue in production is termed as downtime cost. The wave criteria for safe offloading in Malaysian waters in different sea states were obtained by offshore industry experts as shown in Table 1. An offloading downtime condition would occur if the values of wave kinematics exceeds the limiting value under safe offloading criteria. This study has been divided into two major parts, the first part presents the study on the downtime cost of two shuttle tankers in three different location in Malaysian waters under the influence of partially standing waves. The second part illustrates the working of developed GUI.

3.3 Real Time Metocean Data and Downtime Cost

3.3.1 SEAFINE hindcast data

SEAFINE is a Joint Industry Project (JIP) administered by Oceanweather, Inc. (OWI) [34]. Metocean hindcasts carried out with fine mesh nested grids covering the offshore and coastal resource development areas of interest to the participants of SEAFINE. All measured datasets within the domain and time period of the update hindcast were assembled from participants as provided under the JIP Independent Proprietary Information (IPI) provision and used to validate the wave model [34] and [35]. Validation against satellite altimeter measured wave height was carried out using OWIs standard TIMESCAT statistical software package [35]. Offshore designs and operations are best undertaken by utilizing the measured metocean data. The integrity of the metocean data is of prime importance due to multitude of reasons. Thus, mitigating the fallacies of measured metocean data, hindcast in the form of SEAFINE which is a feasible solution was considered in this research. It is reasonable to say that SEAFINE hindcast is good as a numerical approximation wherein the deficiency and weakness of the measured and SEAFINE hindcast are recognized. Therefore, hindcasting was carried out by comparing the simulating results of the SEAFINE hindcast with the historical real event data from the considered locations to confirm the capability.

To achieve higher reliability, SEAFINE has to be corrected so as to present the same results as actual conditions of wave in the regions [34]. The corrected SEAFINE will be statistically identical as the measured metocean data and therefore will be a feasible solution in replacing the inconsistence measured in metocean data. The statistical properties and time series of regional actual wave and SEAFINE model were analyzed and improved by incorporating correction factors to regions under study. The SEAFINE hindcast wave data were obtained from PETRONAS oil company along with the correction factors for the regional location as shown in Table 2. The obtained SEAFINE wave data is considered reliable and trustworthy for application. Since the variance in correction factors are not much between the monsoons for every location, the corrected wave scatter distribution was attributed to represent the maximum downtime cost. Therefore, the correction factor considered in the present study for location 'A' was for NEM (1.2), IM (1.02) for location 'B' , and SWM (0.99) for location 'C', respectively. Hence this would allow to cover all monsoons for the research.

3.3.2 Wave scatter distribution and downtime cost

Based on the 50 years hindcast wave data for three locations of interest in Malaysia, the wave scatter distributions were produced. The locations were renamed to locations 'A', 'B' and 'C' to protect the privacy of the metocean data. Consequently, the marginal probability of wave height and time period as well as the joint probability of wave height and time period were known. The wave scatter distribution for location 'A' is shown in Table 3. The wave scatter distribution for location 'B' and 'C' were derived in the similar manner from the real-time metocean data but are not displayed in this paper. The wave scatter distribution would yield the probability of occurrence of a incident wave with certain time period and having known the probability, the downtime cost can be calculated for that specific location. The downtime days are the duration when cease of transfer of oil takes place between the stationed FPSO and adjacent

Table 2: SEAFINE hindcast correction factors for significant wave height

Location	North East Monsoon (NEM)	South West Monsoon (SWM)	Inter Monsoon (IM)
'A'	1.20	1.15	1.16
'B'	1.05	1.02	1.02
'C'	0.97	0.99	0.99

shuttle tanker, which then leads to loss of production and surmounts higher until the offloading operation is restored back. The downtime cost can be calculated from Eq. (12) [36].

$$z = a \times b \times c \times d \qquad (12)$$

where, 'z' is the downtime cost, 'a' is the probability of the occurrence of waves, 'b' is the downtime days, 'c' is the operating cost per barrel of oil and 'd' is the production of oil in barrels per day.

3.4 Details of offloading shuttle tankers and wave conditions

The influence of wave kinematics of partially standing waves on offloading operation were studied for two sea states (head seas and beam seas) for which the encountering wave conditions exceeded the safe offloading criteria previously shown in Table 1. The values of wave kinematics for partially standing waves were then calculated for both, safe offloading criteria and encountering wave condition. The downtime cost analysis was performed for two similar shuttle tankers ('S1-B' and 'S1-H') operating in two different scenarios of sea-state. The production capacity refers to the total storage capacity of FPSO (in barrels). The offloading capacity may be less than the total storage capacity of FPSO. The offloading capacity of shuttle tanker is measured in percentage of total storage capacity of FPSO. The study on downtime cost due to influence of partially standing waves was presented with respect to four offloading capacities of shuttle tanker, i.e. 70, 80, 90 and 100%. The procedure of determining the downtime cost remains the same for all four offloading capacities. The details of encountering wave conditions are shown in Table 4.

4 Results and Discussion

The results pertaining to input values from Table 4 are presented and discussed. This discussion is further subdivided into two parts, wave kinematics results and downtime cost analysis

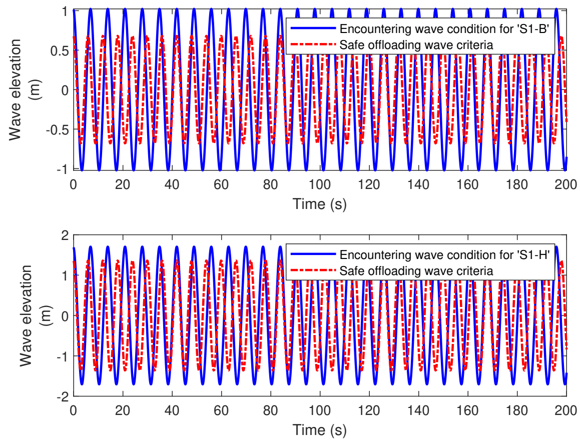


Fig. 2: Wave elevation of partially standing wave affecting shuttle tankers

4.1 Wave kinematics results

The wave kinematics peak values for partially standing waves for shuttle tanker 'S1-B' and 'S1-H' are presented in Table 5. These wave kinematics values were generic with respect to the encountering wave conditions and remains the same for different percentage offloading capacity of shuttle tankers. It was observed that the values of wave kinematics parameters under encountering wave conditions were higher than the safe offloading criteria. For the shuttle tanker 'S1-B', the wave elevation for partially standing wave was around 50% more than safe criteria for offloading operations while the horizontal velocity exceeded the safe criteria by 55%. The vertical velocity was also almost twice the safe criteria for offloading operations. However, for shuttle tanker 'S1-H', the increase in the wave elevation from the safe offloading criteria was 24.5%. There was marginal increase in the horizontal velocity while vertical velocity exceeded the safe offloading criteria by nearly 11%. The percentage increase in wave kinematic parameters for beam sea-state were higher as compared to the heading seas. Though the wave kinematics in heading sea exceeded the safe offloading limits, but the amount of excursion was at lower extent.

The wave kinematics of partially standing waves affecting the offloading operations of shuttle tankers 'S1-B' and 'S1-H' are shown in Figs 2 to 5. Also, the vertical accel-

Table 3: Wave scatter distribution for location 'A'

H_s / T_p	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	TOTAL
0-0.5	32	14,392	116,895	3466	473	218	58	19	7	**135,560**
0.5-1	0	3,774	139,830	57,466	2,986	880	333	122	14	**205,405**
1-1.5	0	9	7,848	56,116	1,662	104	67	7	0	**65,813**
1.5-2	0	0	143	37,178	6,972	4	0	0	0	**44,297**
2-2.5	0	0	0	8,521	16,113	7	0	0	0	**24,641**
2.5-3	0	0	0	372	10,553	0	0	0	0	**10,925**
3-3.5	0	0	0	9	3,299	18	0	0	0	**3,326**
3.5-4	0	0	0	1	726	120	0	0	0	**847**
4-4.5	0	0	0	0	52	30	0	0	0	**82**
TOTAL	**32**	**18,175**	**264,716**	**163,129**	**42,836**	**1,381**	**458**	**148**	**21**	**490,896**

Table 4: Wave conditions for downtime cost analysis

Shuttle tanker	Wave condition	Sea state	Water depth (m)	Storage capacity of FPSO (barrels of oil)
'S1-B'	H_s = 1.5 m and T_p = 7.0 s	beam seas	100	318,000
'S1-H'	H_s = 2.5 m and T_p = 7.0 s	head seas	100	318,000

Table 5: Comparision between peak wave kinematics and safe offloading criteria

Shuttle tanker 'S1-B'		
Wave kinematic parameter	**Encountering wave condition**	**Safe offloading criteria**
Wave elevation (m)	0.99	0.66
Horizontal velocity (m/s)	0.45	0.35
Vertical velocity (m/s)	0.88	0.7
Vertical acceleration (m/s^2)	0.91	0.72
Shuttle tanker 'S1-H'		
Wave kinematic parameter	**Encountering wave condition**	**Safe offloading criteria**
Wave elevation (m)	1.661	1.344
Horizontal velocity (m/s)	0.71	0.66
Vertical velocity (m/s)	1.52	1.37
Vertical acceleration (m/s^2)	1.41	1.43

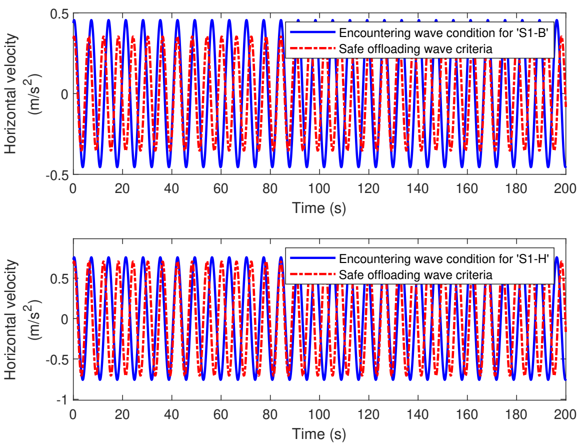


Fig. 3: Horizontal velocity of partially standing wave affecting shuttle tankers

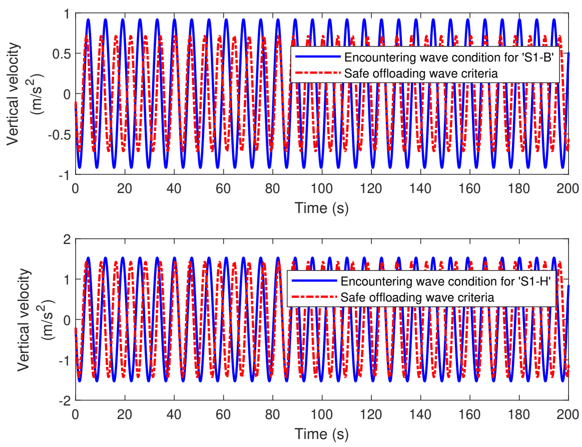


Fig. 4: Vertical velocity of partially standing wave affecting shuttle tankers

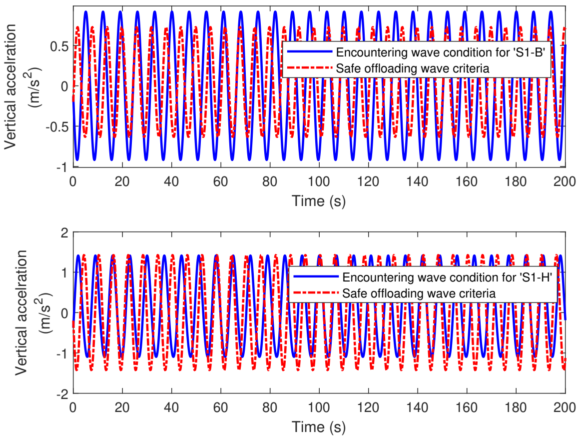


Fig. 5: Vertical acceleration of partially standing wave affecting shuttle tankers

erations are more significant than the horizontal accelerations and therefore, only vertical accelerations are displayed. Generally, the higher wave velocities and wave accelerations are related to higher wave forces on the vessels and thereby greater response of vessels. Also, the time period of the encountering wave greatly influences the response of the vessels due to the fact that it affects the number of transitions for the same wave height. The wave with a lower time period usually have greater transitions of peak value which affects the response of value. Thereby, wave with a greater wave height and lower time period is more critical for offloading operations. Between the shuttle tankers, it was observed that the wave kinematics in beam sea were more significant as compared to head sea.

4.2 Downtime cost analysis results

It was observed that the wave kinematics parameters exceeded the safe offloading criteria and condition of downtime occurs. From the wave scatter diagram, the percentage annual joint probability of occurrence of a wave with a certain encounter wave height and time period was calculated. Table 6 displays the joint probability of wave height and time period for the three different locations in Malaysian waters. The down-time cost was calculated for the two shuttle tankers in the three different location for downtime periods of 1, 2 and 3 days. The OPEX considered in the three locations was US$ 35.

Figures 6 and 7 display the down-time cost of both shuttle tankers calculated for three different locations in Malaysian waters. It can be clearly seen that greater the number of days, higher was the downtime cost involved but it also depends on the probability occurrence of wave conditions which was location specific and the operating cost per barrel of oil per day. It was comparatively observed that the downtime cost was highest for location ‘A’ due to its higher probability of occurrence. For ‘S1-B’ in location ‘A’ and for 70% offloading capacity, the downtime cost varied between US$ 1.48 million per day to US$ 4.44 million per three days. Meanwhile for 80% offloading capacity, the impact on downtime cost was between US$ 1.692 million per day to US$ 5.07 million per three days. For 90% offloading capacity, it varied nearly between US$ 2 million per day to US$ 6 million per three days. The downtime cost per day for maximum offloading capacity was US$ 2.115 million. For ‘S1-B’ in location ‘B’, the maximum downtime cost observed was US$ 1.693 million per three days for 100% offloading capacity. For ‘S1-B’ in location ‘C’ and for 70% offloading capacity, the downtime cost varied between US$ 1 million per day to US$ 3.296 million per three days. Meanwhile for 80% offloading capacity, the impact on downtime cost was between US$ 1.255 million per day to US$ 3.766 million per three days. For 90% offloading capacity, it varied nearly between US$ 1.412 million per day to US$ 4.237 million per three days. The downtime cost per day for maximum offloading capacity was US$ 1.569 million.

Table 6: Probability occurrences for different locations

S1-B			
Particulars	**Location ‘A’**	**Location ‘B’**	**Location ‘C’**
Probability occurrence	19 %	5.07 %	14.1 %
OPEX (US$/barrel of oil)	35	35	35
Downtime day	1, 2, 3	1, 2, 3	1, 2, 3
S1-H			
Particulars	**Location A**	**Location B**	**Location C**
Probability occurrence	1.81 %	1.35 %	0.183 %
OPEX (US$/barrel of oil)	35	35	35
Downtime day	1, 2, 3	1, 2, 3	1, 2, 3

The downtime cost for ‘S1-H’ was significantly lesser. The maximum downtime cost was observed in location ‘A’. The downtime cost per day in location ‘A’, ’B’ and ‘C’ was less than half a million US$ for all range of offloading capacities. The encountering wave height for shuttle tanker ‘S1-B’ was 1.5 m, which is 0.5 m more than the safe offloading criteria. Thereby considering all the three locations, overall it was clearly observed that an unpredictable increase in wave height by 0.5 m can significantly impact the offloading operation in beam seas for which the downtime cost incurred is as high as US$ 6.3 million for three days for maximum offloading capacity and US$ 4.44 million for three days for minimum offloading capacity. Table 7 presents the peak value of downtime cost incurred due to influence of partially standing waves for different percentage offloading capacities under highest considered downtime day.

The percentage contribution to downtime cost of offloading operations due to influence of partially standing waves is shown in Fig. 8. The offloading shuttle tanker in location ‘A’

Table 7: Peak values of downtime cost for different percentage offloading capacities under highest considered downtime day

Downtime cost in million US$ due to influence of partially standing waves												
Location	**‘A’**				**‘B’**				**‘C’**			
Offloading Capacity (%)	**70**	**80**	**90**	**100**	**70**	**80**	**90**	**100**	**70**	**80**	**90**	**100**
‘S1-B’	4.44	5.07	5.71	6.34	1.185	1.354	1.524	1.693	3.296	3.766	4.237	4.708
‘S1-H’	0.423	0.483	0.543	0.604	0.315	0.361	0.406	0.451	0.043	0.048	0.055	0.061

under beam sea state contributed 46% of the total downtime cost incurred due to influence of partially standing waves. The downtime cost under beam sea state in location ‘C’ contributed to 36% of the total downtime cost due to influence of partially standing waves while it was 12% in location ‘B’. The contribution to downtime cost under head sea state was very less.

5 Development of GUI Based Numerical Tool: *“DowntimePSW 1.1”*

The graphical user interface (GUI) named *”DowntimePSW 1.1”* was developed as a tool for evaluating the downtime cost based on the effects of partially standing waves. The flowchart for the GUI is given in Fig. 9. The GUI has two major modules, first module accepts the inputs from the user and post downtime analysis, the second module displays the results and plots. The input module is divided into three panel sections named as *“Offloading Sea Conditions”*, *“Production Details”* and *“Probability Distribution”*. The first panel section requires the user to provide the sea type, water depth, wave height and time period. The numerical secant method which uses the dispersion relation is used to calculate the other wave parameters from the inputs given. The sea-state is further subdivided into head seas and beam seas drop down list for which the offloading criteria was previously established. The offloading conditions were limited to three water depths of 50, 100 and 250 m. The offloading operational criteria has been obtained from offshore operator experts, and the offloading operational wave conditions criteria were $H_s = 2$ m and $T_p = 6$ s for head seas, while $H_s = 1$ m and $T = 6$ s for beam seas. Fig. 11 presents the proposed graphical user interface with input values from Table 8.

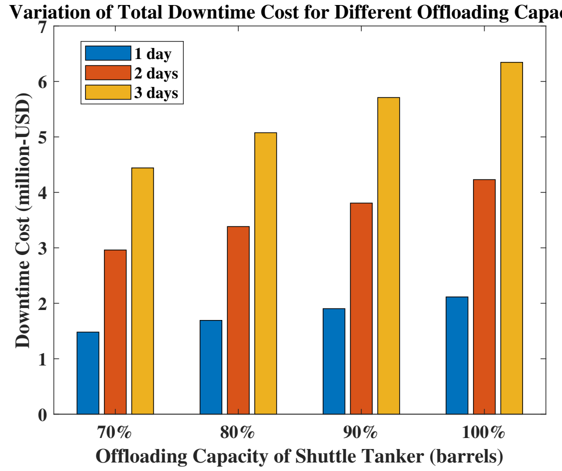
The second panel section requires the user to input the production details like operational expenditure (OPEX), production (in barrels per day), downtime days and distance between the vessels. The distance between the vessel is bifurcated into two types, closely spaced and distantly spaced. This spacing would account for the percentage of reflected wave height. In this research, closely spaced vessels account for 40% of reflected wave height, while distantly spaced vessel accounts for 10% of reflected wave height. The last panel section of the input module deals with the probability of occurrence. This category allows the user to choose from the location drop-down menu and pertaining to the selected location, the wave scatter diagram could be seen from the *“Wave Scatter”* button. The wave scatter diagram would display the joint occurrence of the desired wave height and time period. The probability of occurrence can be obtained from the number of occurrences and total occurrences, respectively. Finally, with the click of *“Proceed”* button, the output module is displayed and the successful downtime cost analysis is completed. However, an error would be displayed if inputs are not given or kept zero as shown in Fig.12.

The output module has two panel sections named as *“Downtime Analysis”* and *“Plots”*. The Downtime Panel section would give final result of downtime cost incurred per day which is based on the user input of downtime days. Additionally, downtime chart can be obtained from the *“Downtime Chart”* button. This downtime chart is a bar chart which represents the downtime cost incurred depending on the selected percentage offloading capacity of the shuttle tanker for downtime period of 1, 2 and 3 days. Furthermore, the Total Downtime Cost Chart which can be seen by clicking on *“Total Downtime Cost Chart”* button represents the bar chart for downtime cost for all different percentage offloading capacity of shuttle tanker and all range of downtime days. The *Plots* section of the output module displays the wave kinematic plots of the partially standing waves. However, the plots include the wave kinematics due to both existing wave as well as the offloading criteria for the different sea state. Last but not least, The *“About”* button gives the preliminary information on the graphical user interface. Additionally, the *“i”* button acknowledges the collaborative research units involved in the development of the interface.

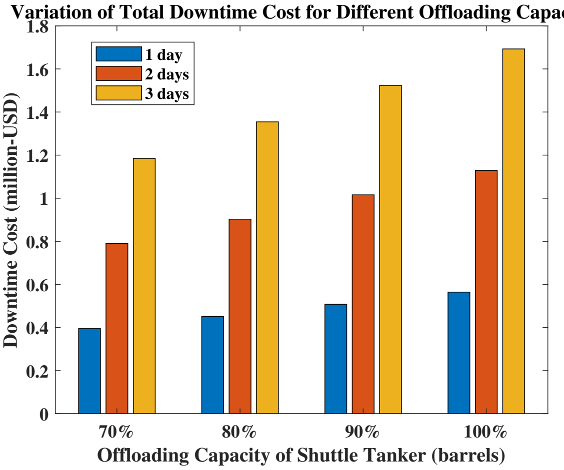
5.1 Illustration on working of GUI: *”DowntimePSW 1.1”*

The input for illustrationof this GUI is shown in Table 8. The OPEX was considered as US$ 35 and the region of interest was location ‘A’.

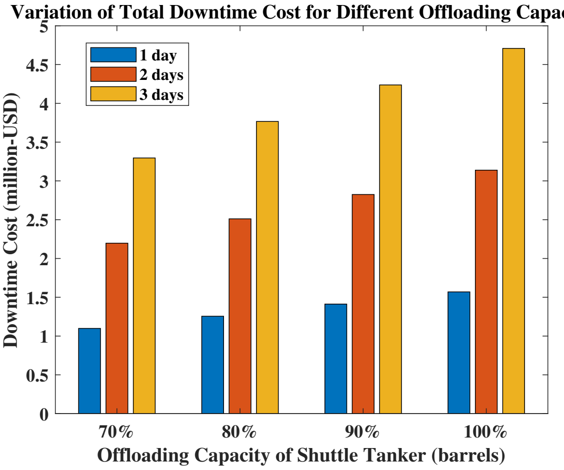
This GUI would serve as novel platform for various field operators and researchers to estimate the likely possible downtime cost for offloading operations affected by wave kinematics of partially standing waves under certain operating wave conditions in side-by-side offloading configuration. An attempt to connect motion responses to cost has been made through this GUI by considering real time metocean data



(a) Location ‘A’

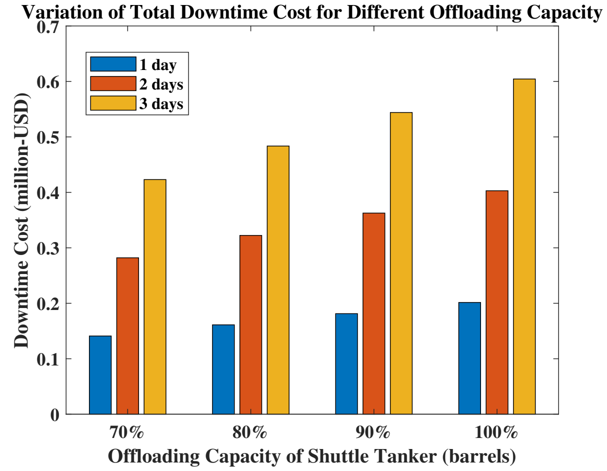


(b) Location ‘B’

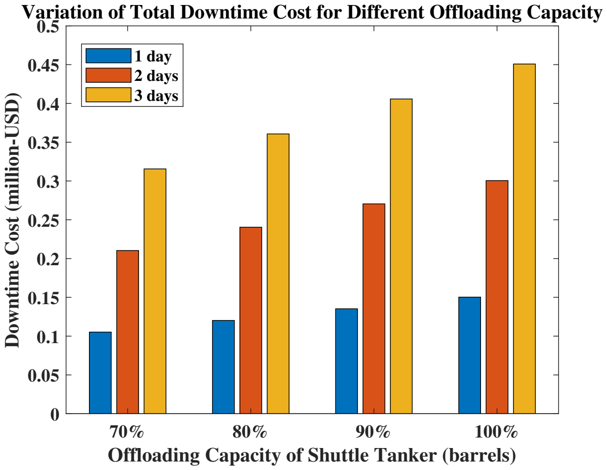


(c) Location ‘C’

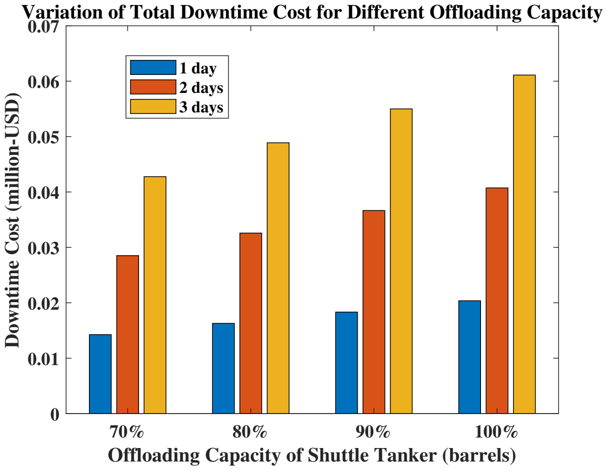
Fig. 6: Downtime cost of offloading operations for shuttle tanker ‘S1-B’



(a) Location ‘A’



(b) Location ‘B’



(c) Location ‘C’

Fig. 7: Downtime cost of offloading operations for shuttle tanker ‘S1-H’

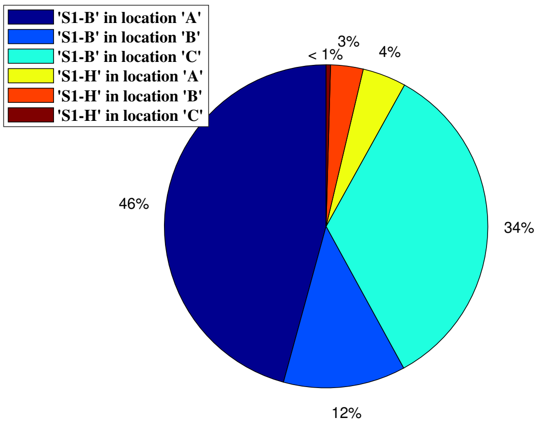


Fig. 8: Percentage contribution of downtime cost of offloading operations due to influence of partially standing waves

Table 8: Sample of Input for GUI Illustration: *"DowntimePSW 1.1"*

Input: offloading sea conditions	
Sea type	Beam seas
Water depth	100 m
Wave height	2.0 m
Time period	8.0 s
Input: production details	
Production in barrels	318,000
Operating expediture (Opex per barrel)	35 US$
Downtime days	1 day
Distance between vessels	Closely spaced
Input: Probability of occurrence	
Region	Location 'A'
Number of occurrences	45,699
Total occurrences	490,896

from which wave scatter diagrams has been derived. This GUI platform is versatile with regards to the fluctuating operating expenditure and varying capacity of shuttle tanker as well as water depth. The equations of wave kinematics of partially standing waves takes into account the spacing of vessels to deliver a near approximation between the incident and reflected waves. Finally, the downtime charts and wave kinematics plots relative to the safe offloading wave criteria are displayed which helps the end user to understand the downtime condition.

6 Illustration on working of GUI

The results pertaining to input values from Table 8 are discussed but the discussion is further subdivided into two parts, namely "wave kinematics results" and "downtime cost analysis results".

Table 9: Peak wave kinematics for location 'A' obtained from GUI *"DowntimePSW 1.1"*

Wave kinematic parameter	Encountering wave condition	Safe offloading criteria
Wave elevation (m)	1.09	0.543
Horizontal velocity (m/s)	0.42	0.21
Vertical velocity (m/s)	0.5	0.25
Horizontal acceleration (m/s^2)	0.33	0.16
Vertical acceleration (m/s^2)	0.39	0.19

6.1 GUI Example: wave kinematics results

The encountering wave conditions for illustration in Malaysian water is given in Table 8 and the downtime charts were presented. The distance between the vessels was selected as closely spaced vessels for both locations. The sea state for offloading operation in Malaysian water was a beam sea state for which offloading downtime criteria was as H_s is 1 m and T_p is 6 s but the encountering wave conditions were higher than that. It was seen that allowable peak wave elevation between the vessels for offloading criteria in beam seas was 0.543 m but due to encountering wave conditions, the wave elevation exceeded by twice the peak safe offloading criteria value as shown in Fig.13. Also, the maximum horizontal velocity and vertical velocity were increased nearly by twice the velocity for safe offloading criteria as shown in Figs.14(a) and 14(b). Based on the wave conditions entered in GUI, Table 9 displays the criteria and operational value of wave kinematics of partially standing waves. The horizontal and vertical acceleration for the encountering wave condition was 48% higher than the safe offloading criteria value. However, it was noted that wave height largely affected the wave kinematics and vertical components of wave kinematics were comparatively at a higher rate of change, respectively.

6.2 GUI Example: downtime cost analysis results

The downtime cost chart has been presented in Fig. 17. The percentage annual joint probability of occurrence of a wave with wave height 2 m and time period 8 s was 6.25. The downtime cost to be faced by operators in beam sea was around US$ 2 million for 3 days. With the click of *"Down Time Cost per Day"* button, the message box window opens up and displays the total down-time cost incurred for the selected downtime days as shown in Fig. 16. The GUI additionally facilitates to present the downtime cost pertaining to different percentage offloading capacity of shuttle tanker. Fig. 17(b) represents the total downtime cost with respect to the different percentage offloading capacity for three different downtime days. Since, the offloading of the oil may not be 100% of the storage capacity of FPSO, thereby comparative downtime cost have been presented for different percentage of offloading. The downtime cost varied between

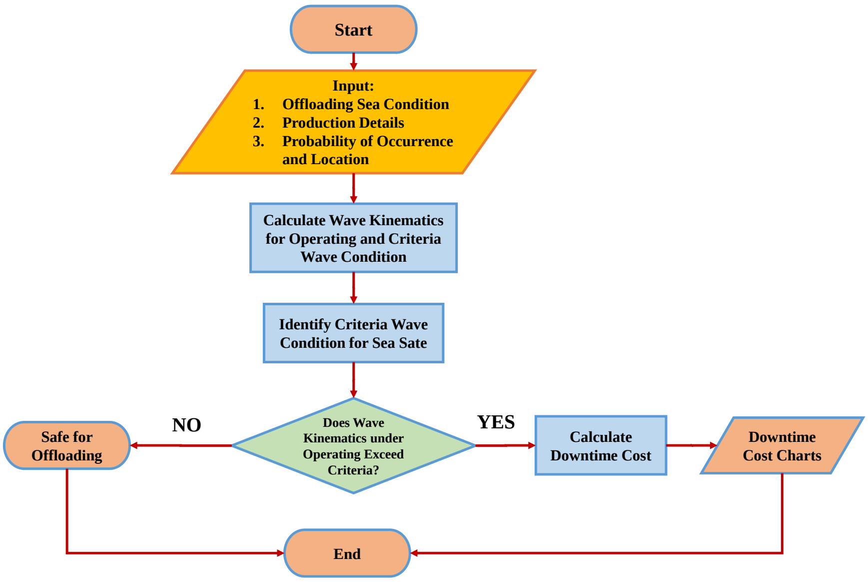


Fig. 9: Flowchart for *"DowntimePSW 1.1"*

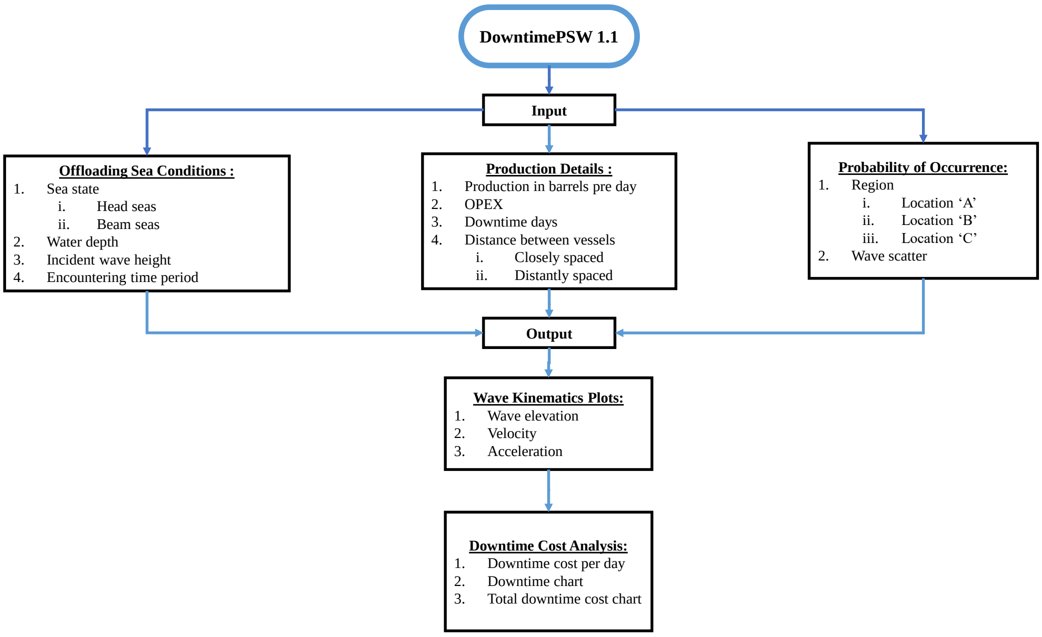


Fig. 10: Block diagram for *"DowntimePSW 1.1"*

US$ 1.5 million for 70% offloading capacity to US$ 2 million for 100% offloading capacity for 3 downtime days.

7 Conclusion

The present work focused on operability of offloading operations through permissible weather window or criteria. The influence of offloading operations due to partially standing waves in two sea states as well as comparison between peak wave kinematics under criteria and operational condition has been presented and discussed. Finally, the downtime cost charts for the three different locations comparatively provides the most affected location and corresponding loss in revenue for different offloading capacity of shuttle tanker and range of downtime days. The developed GUI is a mean of providing numerical tool for potential field operators in Malaysian waters to estimate the probable downtime cost of offloading operations. This numerical tools facilitate to im-

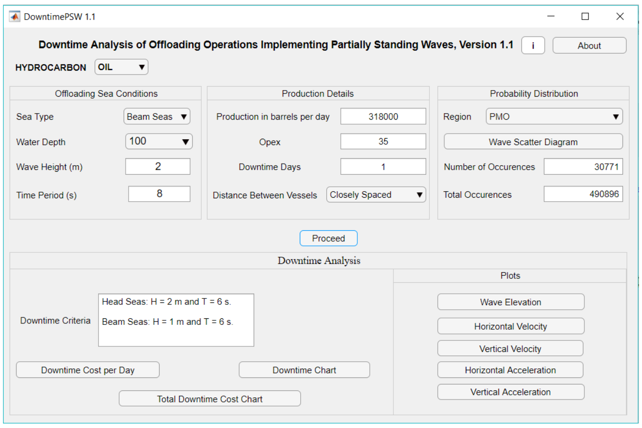


Fig. 11: GUI (*"DowntimePSW 1.1"*) window

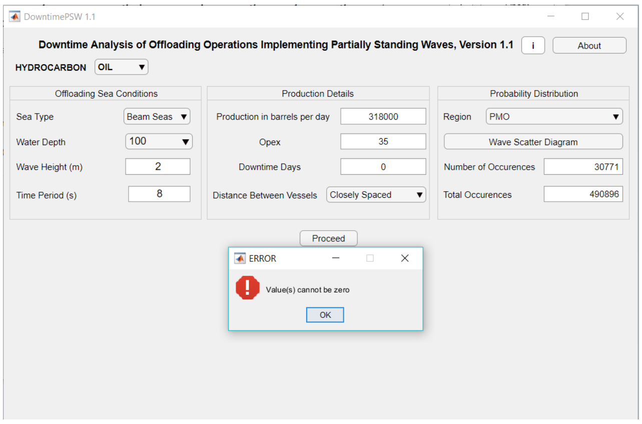


Fig. 12: Error message for incorrect inputs in *"DowntimePSW 1.1"*

plement real time wave scatter data and successfully bridges vessel response to operating costs, thereby providing the operator far sight of the possible loss in global production, respectively. It is found to be more critical for beam sea state and an unpredictable increase in wave height by 0.5 m can significantly impact the downtime cost per day. In line with this, the time period of the partially standing wave affects the motion response and a wave with a greater wave height, higher percentage of reflected wave height and lower time period is more likely to cause downtime as it generally relates to higher response for vessels. The offloading shuttle tanker in location ‘A’ under beam sea state contributed 46% of the total downtime cost incurred due to influence of partially standing waves. The downtime cost under beam sea state in location ‘C’ contributed to 36% of the total downtime cost due to influence of partially standing waves while it was 12% in location ‘B’. The contribution to downtime cost under head sea state was very less. Overall, it was seen that gap between vessels plays a significant role in influencing downtime costs. The kinematics of partially standing waves is directly proportional to the prevailing wave condi-

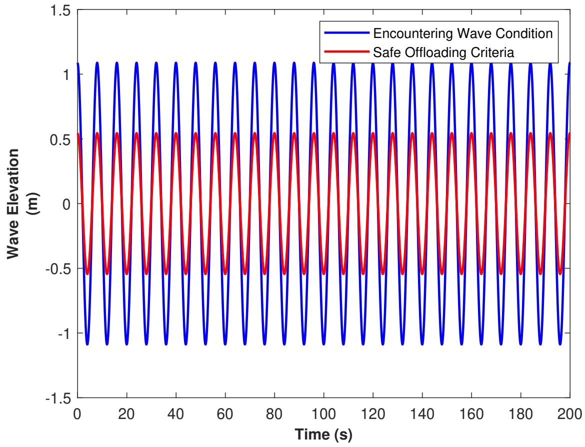
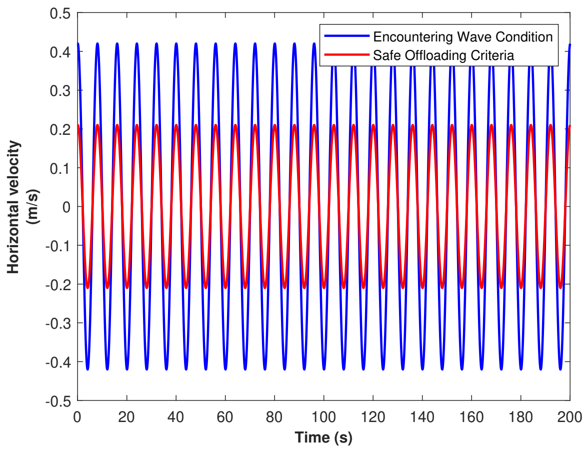
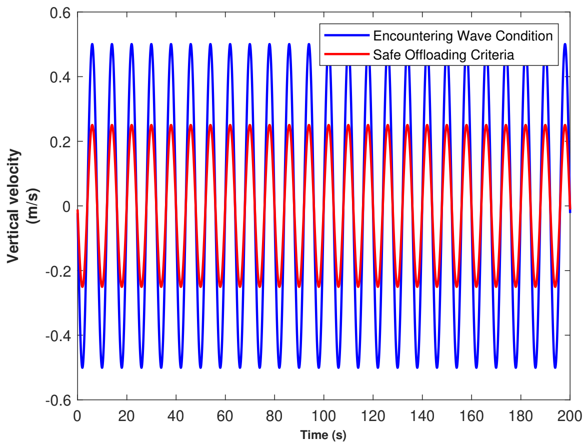


Fig. 13: Wave elevation for location ‘A’ from GUI *"DowntimePSW 1.1"*

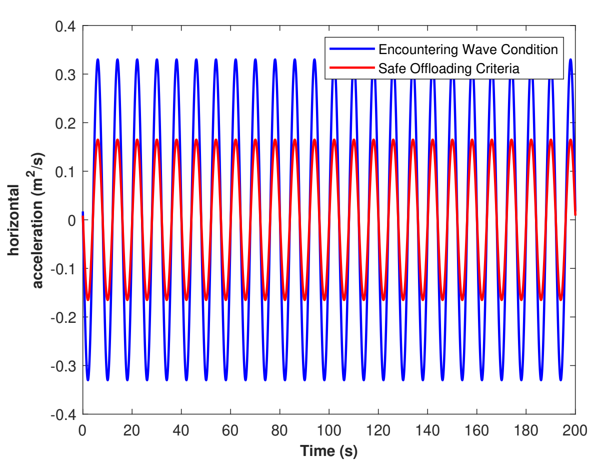


(a) Horizontal velocity

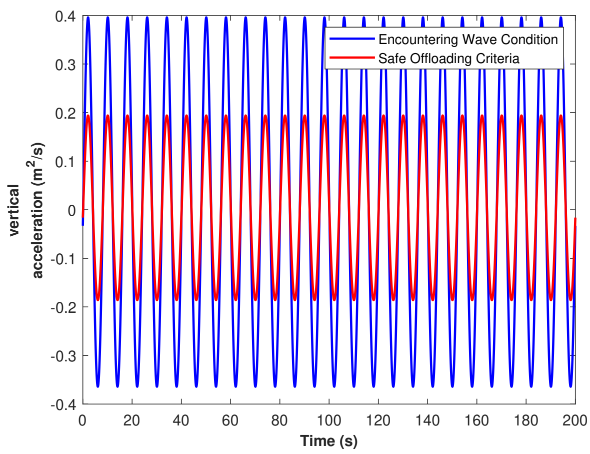


(b) Vertical velocity

Fig. 14: Wave velocity for location ‘A’ from GUI *"DowntimePSW 1.1"*



(a) Horizontal acceleration



(b) Vertical acceleration

Fig. 15: Wave acceleration for location ‘A’ from GUI *”DowntimePSW 1.1”*

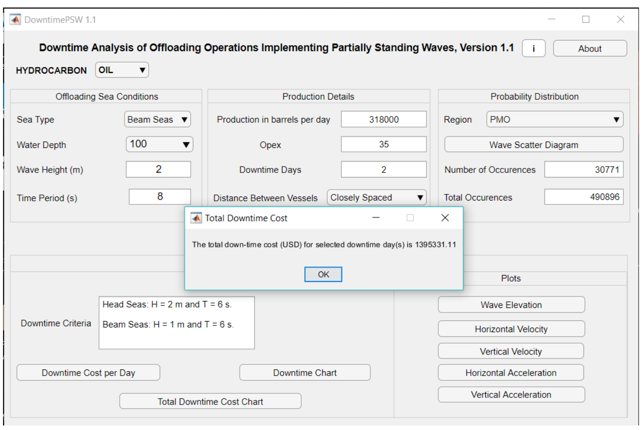
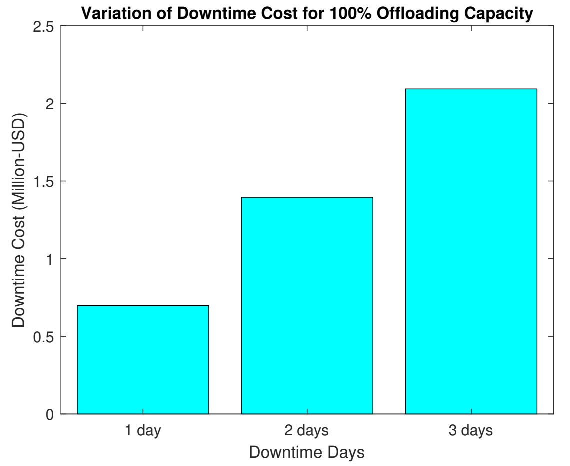
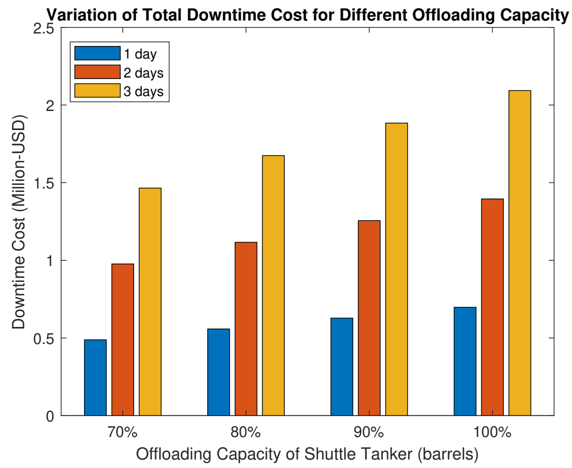


Fig. 16: Total downtime message window in GUI *”DowntimePSW 1.1”*



(a) Downtime cost chart



(b) Total downtime cost chart

Fig. 17: Downtime cost charts for location ‘A’ from GUI *“DowntimePR 1.0”*

tion and kinematics attributed to these waves causes higher wave forces and response of vessels, respectively. Thus, risk assessment under non-operable or extreme wave conditions is notable.

8 Future works

The GUI will be extended for studying the downtime cost analysis of offloading operations for oil in irregular waves and LNG in both regular and irregular waves in Malaysian waters.

Conflict of Interest

The graphical user interface, *DowntimePSW 1.1* has been copyrighted under ***INSTITUTE OF TECHNOLOGY PETRONAS***

SDN BHD (LY2018006548). The authors declare that there is no conflict of interest regarding publication of this article.

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