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Estimation of Wave Load on Offshore Structures

Igbomgbo Parabosi Ogilizibe*, Okoli Engr and OE Ozeagu
Department of Engineering, University of Port-Harcourt, Port-Harcourt, Nigeria
***Corresponding author:** Igbomgbo Parabosi Ogilizibe, Department of Engineering, University of Port-Harcourt, Port- Harcourt, Nigeria, E-mail: exponentparabosi@gmail.com

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Abstract

In this study, a program that is capable of estimating environmental wave loads on offshore steel structures was developed using jquery, CSS and HTML for its front end and javascript for its back end. It carries out the analysis by incorporating existing wave load standards and codes (API, DNV and ASCE). The program was then tested to estimate wave loads on three different case studies. Case one was a 400 mm diameter steel jacket that is located in 30 m water depth with a wave height of 4 m and period of 11 sec, and the wave load result obtained from the analysis was 372 N. Case two was on a steel jacket of 3 m wave height with a period of 6 s in water depth of 12 m and the result obtained for the wave load was 1077 N. Case three was on a breaking wave with flood elevation of 7 m acting on a steel pipe jacket of diameter 1000 mm and the result of the result obtained for the wave load was 108 N. The result shows that the wave kinematics and diameter of the steel pipes is directly proportional to the wave load of a nonbreaking wave. While the flood elevation and diameter of the steel pipes is directly proportional to the wave load of a breaking wave. With this program the downtime in estimating wave load was greatly reduced by 98.7%.

Keywords: Oil; Gas; Pregnancy; Kinematics; Vertical transmission; Velocity

Introduction

The growing demand for oil and gas to satisfy the growing energy demands of the world has necessitated further search and exploration in deep and ultra deep waters for these products. The challenges encountered in the exploration and exploitation of oil and gas in ultra-deep waters is one of the main drivers for the development and improvement of the technologies and systems adopted in the study of environmental factors affecting the marine structures in various deep waters in the world [1]. Offshore platforms are one of the most important structures in exploration and production of oil and natural gas in deep waters. Offshore platforms are huge steel or concrete structures which provide facilities for exploring and exploiting oil and gas from the earth's crust. Offshore structures are designed for installation in the open sea, lakes, gulfs, etc., many kilometers from shorelines. These structures may be made of steel, reinforced concrete or a combination of both [2].

Offshore structures have the added complication of being placed in an ocean environment where hydrodynamic interaction effects are huge in addition to the usual conditions and situations met by land based structures, hence, dynamic response become major considerations in their design [3].

The calculation of the wave loads on vertical tubular members is always of major concern to engineers. The analysis of wave effects on offshore structures, such as wave loads and corresponding responses, are of great importance to ocean engineers in the design, and for the operational safety of offshore structures, especially recently when such studies are motivated by the need to build solid marine structures in connection with oil and natural gas productions [4].

This study is directed at producing a program capable of calculating environmental loads due to waves on offshore steel jacket structures [5].

Materials and Methods

The following steps were adopted to develop the program that estimates the wave load at a particular location on a structural object using the following steps:

For non-breaking wave steps 1-7 are used for its analysis while step 8 applies to breaking wave:

- Selecting appropriate wave theory to be used in estimating the wave kinematics in case of non-breaking wave.
- Using the appropriate wave theory to estimate the wave particle horizontal and vertical velocity and acceleration at seventy-two different directions at an interval of 5 degrees
- Find the vector resultant of the wave kinematics.
- Select the maximum resultant of the wave kinematics.
- Use the specified wave kinematics factor to modify the water particle velocities and accelerations.
- Select the drag and inertia coefficients.
- Use Morison Equation to calculate the force exerted by the wave at a particular location on the object.
- Breaking wave is analysed using ASCE 7 standards as given in section 5.3.3.4.1.

Non-breaking wave

The procedure use in estimating the wave kinematics used in the analysis of the non- breaking wave is as follows [6].

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Particle kinematics of linear wave theory

The equations used to estimate the kinematics of linear wave theory was gotten from figure II-1-9 of EM 1110-2-1100 (Part 11).

Horizontal and vertical velocity equations for shallow water are as follows respectively:

$$u = \frac{H}{2}\sqrt{\frac{g}{d}}\cos\theta \quad (3.1)$$

$$w = \frac{H\pi}{T} * \left(1 + \frac{z}{d}\right) \sin\theta \quad (3.2)$$

Horizontal and vertical acceleration equations for shallow water are as follows respectively

$$a_x = \frac{H\pi}{T}\sqrt{\frac{g}{d}}\sin\theta \quad (3.3)$$

$$a_z = -2H * \left(\frac{\pi}{T}\right)^2 * \left(1 + \frac{z}{d}\right)\cos\theta \quad (3.4)$$

Horizontal and vertical velocity equations for transitional water are as follows respectively

$$u = \frac{H}{2} * \frac{gT}{L} * \frac{\cosh\left[\frac{2\pi(z+d)}{L}\right]}{\cosh\left(\frac{2\pi d}{L}\right)}\cos\theta \quad (3.5)$$

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{L}\right) \quad (3.5a)$$

$$w = \frac{H}{2} * \frac{gT}{L} * \frac{\sinh[2\pi(z+d)/L]}{\cosh(\frac{2\pi d}{L})}\sin\theta \quad (3.6)$$

Horizontal and vertical acceleration equations for transitional water are

$$a_x = \frac{g\pi H}{L} * \frac{\cosh[2\pi(z+d)/L]}{\cosh(\frac{2\pi d}{L})}\sin\theta \quad (3.7)$$

$$a_z = -\frac{g\pi H}{L} * \frac{\cosh\left[\frac{2\pi(z+d)}{L}\right]}{\cosh\left(\frac{2\pi d}{L}\right)}\cos\theta \quad (3.8)$$

Horizontal and vertical velocity equations for deep water

$$u = \frac{H\pi}{T} * e^{\left(\frac{2\pi z}{L}\right)}\cos\theta \quad (3.9)$$

$$L = \frac{gT^2}{2\pi} \quad (3.9a)$$

$$w = \frac{H\pi}{T} * e^{\left(\frac{2\pi z}{L}\right)}\sin\theta \quad (3.10)$$

Horizontal and vertical acceleration for deep water

$$a_x = 2H * \left(\frac{\pi}{T}\right)^2 * e^{\left(\frac{2\pi z}{L}\right)}\sin\theta \quad (3.11)$$

$$a_z = -2H * \left(\frac{\pi}{T}\right)^2 * e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$$

Particle kinematics of stoke wave theory

The expressions used for estimating the particle kinematics of stoke wave theory are as developed by Deo and the expressions are as follows:

The expression for horizontal and vertical velocities are given by:

$$u(x,t) = \frac{w}{k}\sum_{n=1}^{5} G_n \frac{\cosh(nky)}{\sinh(nkd)}\cos[(n(kx - wt)] \quad (3.13)$$

$$w(x,t) = \frac{w}{k}\sum_{n=1}^{5} G_n \frac{\cosh(nky)}{\sinh(nkd)}\sin[(n(kx - wt)] \quad (3.14)$$

where

$$G_3 = 3(a^3 + a^5 G_{35}) \quad (3.14a)$$

$$G_4 = (a^4 G_{44}) \quad (3.14b)$$

$$G_5 = 5(a^5 G_{55}) \quad (3.14c)$$

$$G_{33} = A_{33}\sinh(3kd) \quad (3.14d)$$

$$G_{35} = A_{35}\sinh(5kd) \quad (3.14e)$$

$$G_{44} = A_{44}\sinh(4kd) \quad (3.14f)$$

$$G_{55} = A_{55}\sinh(5kd) \quad (3.14g)$$

$$A_{33} = \frac{(13 - 4c^2)}{64s^7} \quad (3.14h)$$

$$A_{35} = \frac{(512c^{12} - 4224c^{10} - 6800c^4 - 12808c^6 + 16704c^6 - 12808c^6 - 17)}{4096s^{13}(6c^2 - 1)} \quad (3.14i)$$

$$A_{44} = \frac{(80c^6 - 816c^4 + 1338c^2 - 197)}{1536s^{10}(6c^2 - 1)} \quad (3.14j)$$

$$A_{55} = \frac{-(2880c^{10} - 72480c^8 + 324000c^6 - 432000c^4 + 163470c^2 - 16245)}{61440s^{11}(6c^2 - 1)(8c^4 - 11c^2 + 3)} \quad (3.14k)$$

$$s = \sinh(kd) \quad (3.14l)$$

$$c = \cosh(kd) \quad (3.14m)$$

$$k = \left(\frac{2 * (a + a^3 B_{33} + a^5(B_{35} + B_{55})}{H}\right) \quad (3.14n)$$

$$B_{22} = \frac{(2c^2 + 1)}{4s^3}c \quad (3.14o)$$

$$B_{24} = \frac{c(272c^8 - 504c^6 - 192c^4 + 322c^2 + 21)}{384s^9} \quad (3.14p)$$

$$B_{33} = \frac{3(8c^6 + 1)}{64s^6} \quad (3.14q)$$

$$B_{35} = \frac{(88128c^{14} - 208224c^{12} + 70848c^{10} + 54000c^8 - 21816c^6 + 6264c^4 - 52c^2 - 81)}{12288s^{12}(6c^2 - 1)} \quad (3.14r)$$

$$B_{44} = \frac{c(768c^{10} - 448c^8 - 48c^6 + 48c^4 + 106c^2 - 21)}{384s^{10}(6c^2 - 1)} \quad (3.14s)$$

$$B_{55} = \frac{(192000c^{16} - 262720c^{14} + 83680c^{12} + 20160c^{10} - 7280c^8)}{61440s^{11}(6c^2 - 1)(8c^4 - 11c^2 + 3)} + \frac{(7160c^6 - 1800c^4 - 1050c^2 + 225)}{12288s^{11}(6c^2 - 1)(8c^4 - 11c^2 + 3)} \quad (3.14t)$$

The expression for horizontal and vertical acceleration equations are given by:

$$a_x(x,t) = \frac{kc_s^2}{2}\sum_{n=1}^{5} R_n \sin n(kx - wt) \quad (3.15)$$

$$a_z(x,t) = \frac{-kc_s^2}{2}\sum_{n=1}^{5} S_n \cos n(kx - wt) \quad (3.16)$$

Wave speed c_s is given by the following equation

$$c_s = [\tfrac{g}{k}(1 + a^2 C_1 + a^4 C_2)\tanh kd]^{\frac{1}{2}} \quad (3.16a)$$

$$C_1 = \frac{(8c^4 - 8c^2 + 9)}{8s^4} \quad (3.16b)$$

$$C_2 = \frac{3840c^{12} - 4096c^{10} + 2592c^8 + 1008c^6 + 5944c^4 - 1830c^2 + 147)}{512s^{10}(6c^2 - 1)} \quad (3.16c)$$

$$R_1 = 2U_1 - U_1U_2 - V_1V_2 - U_2U_3 - V_2V_3 \quad (3.16d)$$

$$R_2 = 4U_2 - U_1^2 + V_1^2 - 2U_1U_3 - 2V_1V_3 \quad (3.16e)$$

$$R_3 = 6U_3 - 3U_1U_2 + 3V_1V_2 - 3U_1U_4 - 3V_1V_2 \quad (3.16f)$$

$$R_4 - 8U_4 - 2U_2^2 + 3V_1V_2 - 3U_1U_4 - 3V_1V_2 \quad (3.16g)$$

$$R_5 = 10U_5 - 5U_1U_4 - 5U_1U_3 + 5V_1V_4 + 5V_2V_3 \quad (3.16h)$$

$$S_1 = 2V_1 - 3U_1V_2 - 3U_2V_1 - 5U_2V_3 - 5U_3V_2 \quad (3.16i)$$

$$S_2 = 4V_2 - 4U_1V_3 - 4U_3V_1 \quad (3.16j)$$

$$S_3 = 6V_3 - U_1V_2 - U_2V_1 - 5U_4V_1 - 5U_4V_1 \quad (3.16k)$$

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Particle kinematics of cnoidal wave

Yuichi, develop the following formulas used for the determining the kinematics of cnoidal wave. The expressions for horizontal and vertical velocities are given by:

$$S_4 = 8V_4 - 2U_1V_3 - 2U_3V_1 + 4U_2V_2 \quad (3.16l)$$

$$S_5 = 10V_5 - 3U_1V_4 - 3U_4V_1 - U_2V_3 - U_3V_2 \quad (3.16m)$$

$$U_n = G_n \frac{\cosh(nky)}{\sinh(nkd)} \quad (3.16n)$$

$$V_n = G_n \frac{\sinh(nky)}{\sinh(nkd)} \quad (3.16o)$$

$$v = A_1 \operatorname{sech}^2\left(\frac{2K}{L}X\right) + A_2 \operatorname{sech}\left(\frac{2K}{L}X\right) - A_3 \quad (3.17)$$

$$A_1 = \left(1 + \frac{1}{2} * \frac{1}{k} * \frac{H}{d}\right)\frac{H}{d}\left[1 - \frac{5}{4}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} - \frac{3}{2}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} * \left\{2 * \frac{z}{d} + \left(\frac{z}{d}\right)^2\right\}\right] \quad (3.17a)$$

$$A_2 = \left(1 + \frac{3}{2} * \frac{1}{k} * \frac{H}{d}\right)\left(\frac{H}{d}\right)^2 \left[\frac{5}{4} + \frac{9}{4} * \left\{2 * \frac{z}{d} + \left(\frac{z}{d}\right)^2\right\}\right] \quad (3.17b)$$

$$A_3 = \left(1 + \frac{1}{2} * \frac{1}{k} * \frac{H}{d}\right)\frac{H}{d} * \frac{1}{k}\left[1 - \left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d}\left(\frac{1}{k} - \frac{1}{4}\right)\right] \quad (3.17c)$$

$$w = \left(1 + \frac{1}{k} * \frac{H}{d}\right)\left(1 + \frac{z}{d}\right)\sqrt{3} * \left(\frac{H}{d}\right)^{\frac{3}{2}} \operatorname{sech}^2\left(\frac{2k}{L} * X\right) \tanh\left(\frac{2K}{L} * X\right) * [1 - \frac{7}{8}\left(1 + \frac{1}{K} * \frac{H}{d}\right) * \frac{H}{d} - \frac{1}{2}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} - \frac{1}{2}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} * \left\{2 * \frac{z}{d} + \left(\frac{z}{d}\right)^2\right\} - \frac{1}{2}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} * \operatorname{sech}^2\left(\frac{2K}{L} * X\right)\{1 - 6\frac{z}{d} - 3\left(\frac{z}{d}\right)^2\}] \quad (3.18)$$

The expression for horizontal and vertical accelerations are given by

$$a_x = A_1\left(\tanh^{-1}(sihn)\right)^2\left(\frac{2K}{L}X\right) + A_2\left(\tanh^{-1}(sihn)\right)^2\left(\frac{2K}{L}X\right) - A_3 \quad (3.19)$$

$$a_y = \left(1 + \frac{1}{k} * \frac{H}{d}\right)\left(1 + \frac{z}{d}\right)\sqrt{3} * \left(\frac{H}{d}\right)^{\frac{3}{2}} \left(tanh^{-1}(sihn)\right)^2 \frac{2k}{L} * X) \tanh\left(\frac{2K}{L} * X\right) * [1 - \frac{7}{8}\left(1 + \frac{1}{K} * \frac{H}{d}\right) * \frac{H}{d} - \frac{1}{2}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} - \frac{1}{2}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} * \left\{2 * \frac{z}{d} + \left(\frac{z}{d}\right)^2\right\} - \frac{1}{2}\left(1 + \frac{1}{k} * \frac{H}{d}\right) * \frac{H}{d} * \left(\tanh^{-1}(sihn)\right)^2\left(\frac{2K}{L} * X\right)\{1 - 6\frac{z}{d} - 3\left(\frac{z}{d}\right)^2\}] \quad (3.20)$$

Where:

- is wave parameter (m)
- a is horizontal acceleration (m/s) az is vertical acceleration (m/s)
- u is horizontal velocity (m/s) w is vertical velocity (m/s) H is wave height (m)
- g is acceleration due to gravity (m/s) d is water depth (m)
- k is wave number
- T is wave period (s) t is time(s)
- z is water depth below mean sea level (m)

Wave kinematics factor

The wave kinematics gotten from the wave water particle velocities and accelerations are two dimensional and do not account for wave directional spreading and irregularity. Modification made by the wave kinematic factor to account for them. Wave kinematics factor ranges from 0.85-0.95 for tropical storms and 0.95-1.00 for extra-tropical storms [7].

Morrison equation

Morrison equation is used to estimate the wave force of a non-breaking wave at a particular location on the structure. The equation is given in Section 2.3.1b-10 of the API Recommended Practice.

$$F = F_D + F_I = C_D \frac{w}{2g} A|U|U| + C_M \frac{w}{g} V \frac{dU}{dt} \quad (3.21)$$

Where;

- F is hydrodynamic force per unit length acting normal to the object longitudinal axis FD is drag force per unit length.
- FI is inertia force per unit length CD is drag coefficient.
- w is weight density of water g is gravitational acceleration.

A is projected area normal to object axis per unit length. For pipes and circles this is the effective diameter of the object, including marine growth. For other section types, it is the dimension of the side of the rectangle that encloses the section (including marine growth, if any that is normal to the direction of the load [8].

V is displaced volume per unit length. For pipes and circles this is $\pi D^2/4$ where D is the effective diameter of the object, including marine growth. For other section types it is the product of the dimensions of two adjacent sides of the rectangle that encloses the section (including marine growth, if any) [9].

|U| is the absolute value of U. CM is inertia coefficient.

dU is component of the water particle acceleration acting normal to the axis of the object dt.

Breaking wave

Wave force of breaking wave is estimated based on ASCE 7 standards as given in section 5.3.3.4.1

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FD=0.5 × Yw × CD × D × H2

Where;

- FD is net wave force (kN)
- Yw is unit weight of water, in pounds per cubic ft. (kN/m), =62.4 pef (9.80 kN/m) for fresh water and 64.0 pef (l0.05 kN/m) for salt water
- CD is coefficient of drag for breaking waves, =l. 75 for round piles or columns, and= 2.25 for square piles or columns
- D is pile or column diameter, in ft (m) for circular sections, or for a square pile or column, 1.4 times the width of the pile or column in ft (m).
- HB is breaking wave height, in ft (m)

HB=0.507 × FE

Where;

FE is Flood Elevation Height.

Results and Discussion

In this program, javascript was used for the computation while jquery CSS and HTML were used for the frontend design. The program is used to estimate wave load on offshore structures taking steel jacket as a case study. The program was used to estimate wave loads of various cases (Figures 1-7) [10].

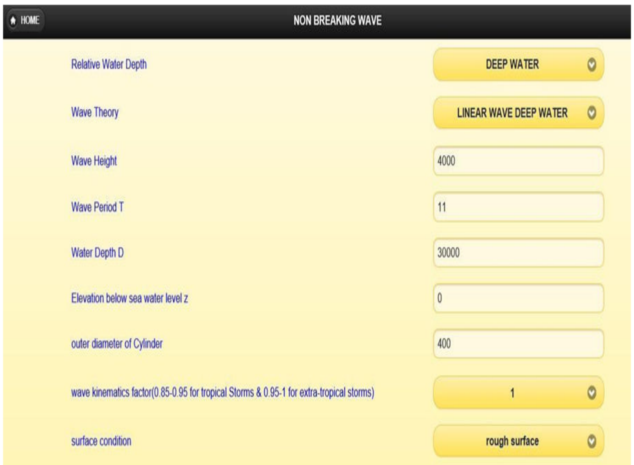

Figure 1: Inputs for case one.

Figure 2: Outputs for case one.

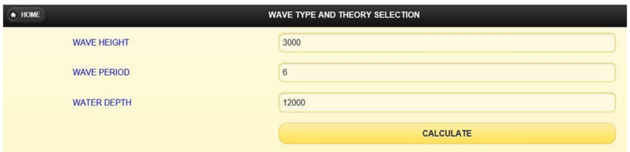

Figure 3: Inputs for wave type and theory selection case two.

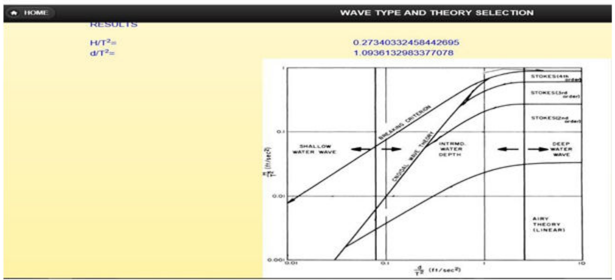

Figure 4: Outputs for wave type and theory selection case two.

Figure 5: Inputs for case two.

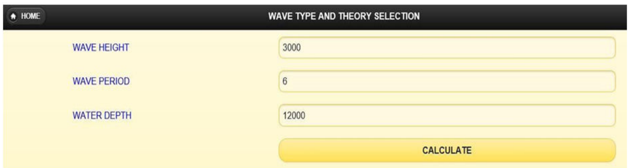

Figure 6: Output for case two.

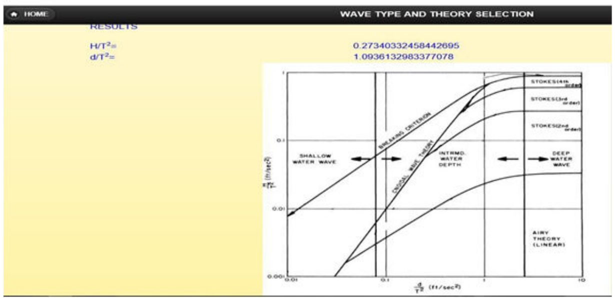

Figure 7: Inputs and output for case three.

Conclusion

The results obtained shows that the wave kinematics and diameter of the steel pipes is directly proportional to the wave load of a nonbreaking wave. While the flood elevation and diameter of the steel pipes is directly proportional to the wave load of a breaking wave. With this program the downtime in estimating wave load is reduced by 98.7% and the program can only be used to analyze waves with wave steepness less than one and depth/period ratio of ten.

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