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Authors: Barbaro, Giuseppe, Foti, Giandomenico, and Sicilia, Carmelo Luca

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Evaluation of the Horizontal Wave Forces on Piles

Giuseppe Barbaro, Giandomenico Foti and Carmelo Luca Sicilia

Department of Civil, Energetics, Environmental and Materials Engineering, Mediterranea University, Reggio Calabria, Italy.

ABSTRACT: Reliability of offshore platforms is an important issue in the prevention of environmental disasters. In this paper, the variation of the horizontal force exerted on an offshore gravity platform is analyzed to achieve a deep comprehension of a storm scenario. Considering the wave motion as a potential motion, the quasi-determinism theory is applied to obtain the kinematic characteristics of a storm. The evolution of force against time is analyzed through the Morison's equation, diffraction theory, and a simplified method. Moreover, two case studies are examined, one in the Ortona region of the Italian coast and the other in the Gulf of Alaska, USA.

KEYWORDS: wave motion, wave forces, piles

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CORRESPONDENCE: giuseppe.barbaro@unirc.it

Introduction

The Morison's equation[1] is used to calculate the horizontal wave force acting on cylinders as a function of particle velocity and acceleration. This equation includes two coefficients: c_{in}, the inertia coefficient, and c_{dg}, the drag coefficient. There are many methods to obtain the coefficient values for random, wind-generated waves. They are based on wave by wave analysis, or on the time series analysis of a set of records, such as the method of moments developed by Pierson and Holmes[2] or the method proposed by Borgman.[3]

When using time series data, the random wave force is calculated through the Morison's equation using the measured particle velocity, the calculated particle velocity, or the theory of wind-generated waves from the measured directional wave spectrum as proposed by Boccotti et al,[4] Barbaro et al,[5,6] and Romolo and Arena.[7] Using one of the methods proposed by Borgman,[8] c_{in} and c_{dg} are estimated through the frequency spectrum. The Morison's equation is probably the most widely used equation in offshore engineering. That is why extensive laboratory work has been done to test the accuracy of this equation. In addition, some large projects have been undertaken to analyze the wave forces acting on cylinders in the field, including the work of Najafian et al and Wolfram and Naghipour.[9,10] Boccotti et al[11] carried out an experiment in the autumn of 2009 off the beach of Reggio Calabria, Italy, at the Natural Ocean Engineering Laboratory (NOEL).[12–15] During the experiment, the inline force acting on a rigid, smooth truncated cylinder was measured. Force on a horizontal cylinder has been analyzed by Romolo et al.[16,17]

According to Boccotti,[18] the force exerted on piles can be calculated using the diffraction theory. This theory is based on the concept that the force exerted on piles is greater than the force exerted on water of an equivalent mass, which is called Froude–Krylov force. This force is introduced by the unsteady pressure field generated by waves. The Froude–Krylov force and the diffraction force combine to make up the total non-viscous force acting on a body in regular or irregular waves. The difference is caused by a drop in the propagation speed of the pressure head at the cylinder.[18] For that reason, it is possible to estimate the forces on piles by multiplying the Froud–Krylov force for a diffraction coefficient, C_{do}, which represents the ratio between the two forces. Therefore, it is important that the coefficient evaluation is correct. All the particles' motion characteristics are determined with the quasi-determinism theory.[18] The directional spectrum necessary to apply the quasi-determinism theory is evaluated using the approaches of Boccotti et al,[4] Barbaro et al,[5,6] and Romolo and Arena.[7]

Nowadays, with any PC, it is easy to obtain the total maximum force on a cylinder. The analytical solution carries a significant advantage for synthesis, particularly in the planning stage. In many cases, the analytical solution allows one to see, simply and clearly, the effect of the variation of the parameters including sections of the girder, depth of the seafloor, and characteristics of the waves. In that regard, it could be useful to apply a simplified model such as the one proposed by Barbaro.[19–22]

This model starts from the Morison's equation and provides a quick and simple estimation of the horizontal force acting on a vertical cylinder. It is valid for regular waves.

The design wave has been estimated by applying the equivalent triangular storm (ETS) model.[18] According to this model, a real storm is approximated by a storm shaped as a triangle, in which the height of the triangle is equal to the maximum significant wave height in the actual storm. Furthermore, the base of the triangle, which is equal to the duration of the equivalent triangular storm, is such that the maximum expected wave height of the triangular storm is equal to the maximum expected wave height of the actual storm (see Fig. 1).

In the ETS model, the height of the triangle is immediately obtained, while the base is obtained through an iterative process. The process consists of the calculation of the maximum expected wave height for different values of the base until the calculated value is close to the real value. The equivalence between this triangular storm and the actual storm is complete because they have the same maximum significant wave height and the same probability that the maximum wave height exceeds any fixed threshold. To define the wave climate in a particular location, it is necessary to examine the history of sea storms that have occurred, analyzing at least 10 years of records.

The case studies are located in the Gulf of Alaska (USA) and in the Adriatic Sea (Italy). The chosen buoys are 46001 in the USA and the Ortona buoy in Italy (see Fig. 2). The use of two different locations is to demonstrate the applicability of the new methods proposed in this paper, in different storm conditions.

The data used are provided by the National Data Buoy Center (NDBC) network (USA) and the Italian buoys network, Rete Ondametrica Nazionale (RON)—managed by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA).

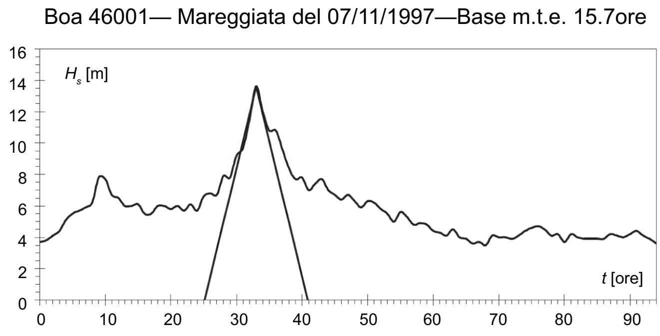

Figure 1. Storm and its relative ETS registered in 1997 in the Gulf of Alaska.

Force Exerted by Surface Waves on Piles

The Morison's equation allows us to calculate the force acting on piles only by unbroken surface waves, considering that at the breaking point, the force acting on a cylinder is impulsive in nature and it is much greater than that produced by unbroken waves.

The equation proposed by Morison et al[1] and rewritten by Borgman[3] is

$$F(t) = c_{in}\rho\pi R^2 a_{sec} + c_{dg}\rho R^2 v_{sec} v_{sec} \tag{1}$$

The first term represents the inertia force, ie the force acting on the equivalent mass of water multiplied by the inertia coefficient, which is generally greater than 1. The second term is the drag force, which is the same kind of force exerted by a steady current. In ideal conditions, the first term is greater than the second, which exerts more influence with the increase of turbulence around the cylinder.

The coefficients c_{in} and c_{dg} depend, respectively, on the Keulegan–Carpenter number and the Reynolds number. The ratio between the Reynolds (Re) number and the Keulegan–Carpenter number (Ke) normally surpasses 10^4 (exceptions are made for cases of small cylinders) so that c_{in} and c_{dg} can assume asymptotic values. Sarpkaya and Isaacson[23] in 1981 obtained the following values:

$$c_{in} = 1.85 \text{ and } c_{dg} = 0.62 \quad \text{for Re/Ke} > 10^4 \tag{2}$$

In this case, the normal direction of the pile is represented by the y-axis. As wave motion in the open field could be considered as potential motion, and the water surface elevation could be considered as an ergodic Gaussian process,[18] the quasi-determinism theory can be applied.

Quasi-determinism, introduced and developed by Boccotti,[18] allows us to obtain an analytical solution, with a probability approaching 1 for the function of free surface displacement, when an exceptionally large wave height occurs in a random Gaussian sea state. The theory is directly applicable to the time series recorded at sea.

Figure 2. Location of the case studies.

The expressions to calculate velocity and acceleration in the y direction are following[18]:

$$v_y(X,Y,z,T) = g\frac{H}{2}\omega^{-1}\int_0^{\infty}\int_0^{2\pi} S(\omega,\theta)k\frac{\cosh[k_i(d+z)]}{\cosh(k_i d)} \sin(kX\sin\theta + kY\cos\theta - \omega T) - \sin[kX\sin\theta + kY\cos\theta - \omega(T-T^*)]d\theta\, d\omega / \int_0^{\infty}\int_0^{2\pi} S(\omega,\theta)[1-\cos(\omega T^*)]d\theta d\omega \tag{3a}$$

$$a_y(X,Y,z,T) = -g\frac{H}{2}\int_0^{\infty}\int_0^{2\pi} S(\omega,\theta)k\frac{\cosh[k_i(d+z)]}{\cosh(k_i d)} \cos(kX\sin\theta + kY\cos\theta - \omega T) - \cos[kX\sin\theta + kY\cos\theta - \omega(T-T^*)]d\theta\, d\omega / \int_0^{\infty}\int_0^{2\pi} S(\omega,\theta)[1-\cos(\omega T^*)]d\theta\, d\omega \tag{3b}$$

The calculation must be carried out for the whole portion of the structure that is under the water surface elevation. It is also necessary to consider the expression of the displacement, η, of the free surface. With reference to the quasi-determinism theory,[18] the expression of the surface displacement is

$$\eta(X,Y,T) = \frac{H}{2}\int_0^{\infty}\int_0^{2\pi} S(\omega,\theta)\Big\{\cos(kX\sin\theta + kY\cos\theta - \omega T) - \cos[kX\sin\theta + kY\cos\theta - \omega(T-T^*)]\Big\}d\theta\, d\omega / \int_0^{\infty}\int_0^{2\pi} S(\omega,\theta)[1-\cos(\omega T^*)]d\theta\, d\omega \tag{3c}$$

According to Barbaro,[19–22] the maximum force acting on piles can be evaluated using the following expression, valid for regular waves, obtained from the manipulation of Eq. (1):

$$F(x) = W_1 x + W_2 x\sqrt{1-x^2} + W_3(1-x^2) + W_4\sqrt{1-x^2}(1-x^2) \tag{4a}$$

for $0 \le x \le 1$, where x stands for $\sin(\omega t)$ and with

$$W_1 \equiv c_{\text{in}}\rho\pi R^2 g\frac{H}{2}\tanh(kd) \tag{4b}$$

$$W_2 \equiv c_{\text{in}}\rho\pi R^2 g\frac{H^2}{4}k \tag{4c}$$

$$W_3 \equiv c_{\text{dg}}\rho R g^2\frac{H^2}{16}\omega^{-2}k\frac{1}{\cosh^2(kd)}[\sinh(2kd)+2kd] \tag{4d}$$

$$W_4 \equiv c_{\text{dg}}\rho R g^2\frac{H^3}{16}\omega^{-2}k^2\frac{1}{\cosh^2(kd)}[\cosh(2kd)+1] \tag{4e}$$

Eq. (4a) can also be expressed as

$$F(x) = F_1(x) + F_2(x) \tag{4f}$$

defining

$$F_1(x) \equiv W_1 x + W_3(1-x^2) \tag{4g}$$

$$F_2(x) \equiv W_2\sqrt{1-x^2}\,x + W_4\sqrt{1-x^2}(1-x^2) \tag{4h}$$

$F_1(x)$ is the force on the portion of the cylinder between the seabed and the average level; $F_2(x)$ is the force on the portion of the cylinder between the average level and the water surface.

$F_1(x)$ is maximized if $W_1 < 2W_3$, otherwise the maximum of $F_1(x)$ is realized at $x = 1$:

if $$W_1 \ge 2W_3 \rightarrow F_{\max} = W_1 \tag{4i}$$

In cases in which the inertia component is totally predominant over the component of drag:

if $W_1 < 2W_3$

$$F_{\max} = W_1 x_1 + W_2\sqrt{1-x_1^2}\,x_1 + W_3(1-x_1^2) + W_4\sqrt{1-x_1^2}(1-x_1^2) \tag{4j}$$

In cases in which the drag component is completely predominant over the component of inertia:

$$x_1 = \frac{1}{2}\frac{W_1 + W_2\sqrt{1-(W_1/2W_3)^2}}{W_3 + W_4\sqrt{1-(W_1/2W_3)^2}} \quad (4k)$$

The Morison's equation (Eq. (1)) and the Barbaro's simplification (Eq. (4a)) can be applied both under ideal and not ideal flow. The hypothesis of ideal flow is satisfied when the Keulegan–Carpenter number is less than 6.[18] Under this hypothesis, the diffraction-based methods can be applied.

It may seem that the ideal conditions usually are not verified, but experiments made at NOEL[12–15] stated that for large cylinders, the Ke is less than 6.[18]

Thus, the force exerted on large cylindrical piles can be obtained as a product of the diffraction coefficient and the Froude–Krylov force, expressed as follows:

$$F_y = \rho W a_y, \quad (5)$$

where ρ is the water density, W is the volume of the equivalent mass water, and a_y is the acceleration of the equivalent mass of water.

To calculate the diffraction coefficient C_{do}, the following expression can be used[18]:

$$C_{do} = \frac{\left|\sin\left(F_R \frac{\pi}{4} k R\right)\right|}{\left|\sin\left(\frac{\pi}{4} k R\right)\right|} \quad (6)$$

where F_R is the reduction factor of the propagation speed of the pressure head waves at the base and R is the radius of the cylinder.

Design Sea State for Offshore Structure

The design wave $H_{max}(P,L)$ is the wave height that has a given probability P of being exceeded in the design lifetime L of the structure, with the wave period T_h.[18]

The evaluation of $H_{max}(P,L)$ is simplified by the ETS model. While some studies in which the equivalent storm could be parabolic have generated interesting results,[24] further study is needed in this area.

The probability that the maximum wave height in the lifetime L exceeds a fixed threshold H is equal to the encounter probability of a storm whose maximum height exceeds H:

$$P(L,R) = 1 - \exp\left(-\frac{L}{R(H)}\right) \quad (7a)$$

where $R(H)$ is calculated as follows:

$$R(H) = \left\{ \begin{array}{l} \int_H^{\infty}\int_0^{\infty} \frac{1}{\overline{T}(h)} p(x;H_s = h)\int_h^{\infty} -\frac{\mathrm{d}\,p(H_s = a)}{\mathrm{d}a} \cdot \\ \left[1 - \frac{\overline{b}(a)}{a}\int_0^a \frac{1}{\overline{T}(h')}\ln[1-P(x;H_s = h')]\right]^{-2} \mathrm{d}a\,\mathrm{d}h\,\mathrm{d}x \end{array} \right\}^{-1} \quad (7b)$$

To obtain the value of $H_{max}(P,L)$, it is necessary to plot the diagram of $P(L,R)$ against H, and to find the corresponding value of H for a fixed value of P.[25–29]

Once $H_{max}(P,L)$ is calculated, it is necessary to obtain the significant wave height of the sea state where the $H_{max}(P,L)$ will occur. The probability density function of the sea state where this wave will occur is calculated here:

$$p(H_s = h; H_{max} = x) = \frac{\left(\begin{array}{l}\frac{1}{\overline{T}(h)} p(x;H_s = h)\int_h^{\infty} -\frac{\mathrm{d}\,p(H_s = a)}{\mathrm{d}a} \\ \exp\left[\frac{\overline{b}(a)}{a}\int_0^a \frac{1}{\overline{T}(h')}\ln[1-P(x;H_s = h')]\,\mathrm{d}h'\right]\mathrm{d}a\end{array}\right)}{\int_0^{\infty}\left(\begin{array}{l}\frac{1}{\overline{T}(h)} p(x;H_s = h)\int_h^{\infty} -\frac{\mathrm{d}\,p(H_s = a)}{\mathrm{d}a} \\ \exp\left[\frac{\overline{b}(a)}{a}\int_0^a \frac{1}{\overline{T}(h')}\ln[1-P(x;H_s = h')]\,\mathrm{d}h'\right]\mathrm{d}a\end{array}\right)\mathrm{d}h} \quad (7c)$$

where $\overline{T}(h)$ is the mean wave period of a wave of height h, $p(x; H_s = h)$ is the probability density function derived from the probability of occurrence expressed by Boccotti, $P(x; H_s = h)$,[17] and $\mathrm{d}p(H_s = a)$ is the probability that H_s falls in a fixed small interval $(a, a + \mathrm{d}a)$, $\overline{b}(a)$ is the base of the ETS, and it is calculated as follows:

$$\overline{b}(a) = b_{10}C_1\exp\left[-C_2\frac{a}{a_{10}}\right] \quad \text{for the "Open Ocean"} \quad (7e)$$

$$\overline{b}(a) = b_{10}\left[1.12 - 0.12\frac{a}{a_{10}}\right] \quad \text{for the Italian coasts} \quad (7f)$$

where a_{10}, b_{10}, C_1, and C_2 are parameters that change with the considered location.

The maximum value of Eq. (7c) is the design significant wave height, H_s. It has been proved that the value of H_s is very close to half of $H_{max}(P, L)$.[18]

Case Study

Gravity-based offshore platforms are structures typically constructed in deep water. They are formed by a large base plate, completely submerged, from which emerge some tapered columns that are connected at the summit to the deck (see Fig. 3). Generally, the value of Ke for the platform base proves to be smaller than the unit. For the columns, Ke is larger but it remains near to the value of 2–3 under the mean water level. Thus, the maximum force on these structures can be obtained as a product of the diffraction coefficient and the Froude–Krylov force. The geometry is the same for the different locations.

Calculation of the horizontal force on the offshore platform. The characteristics of the two locations are reported in Table 1.[24]

The encounter probability, P, for this type of structure is 0.1 and the corresponding lifetime value is 100 years.

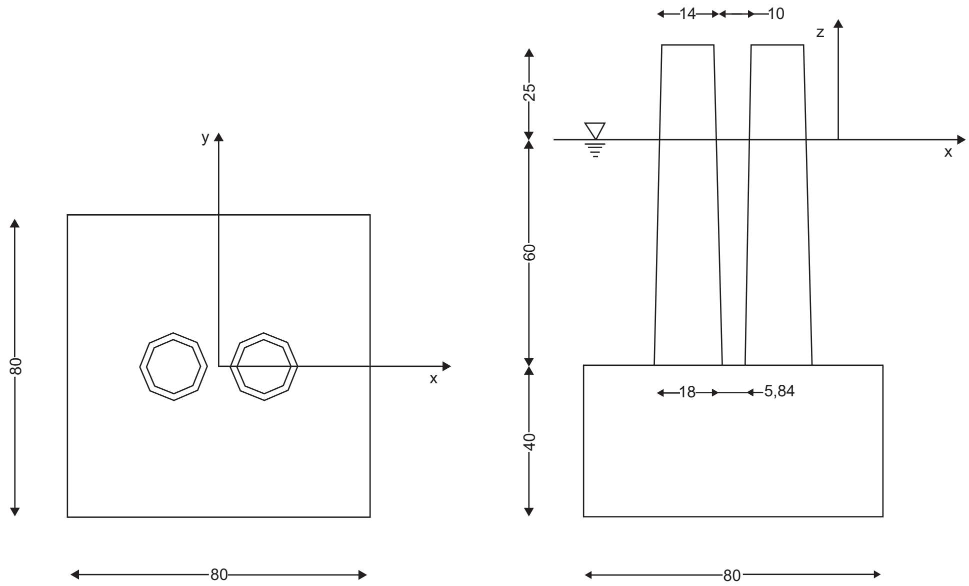

Figure 3. Scheme of the offshore platform.

The design wave evaluated in Ortona was 18 m, whereas in the Gulf of Alaska, it was 32.4 m. The significant wave heights of the sea states in which the design waves occur are 9 m in Ortona and 16.2 m in the Gulf of Alaska. These values have been obtained through Eq. (7).

It is important to point out that the kinetic parameters (a_y and v_y) used in these examples were evaluated through Eq. (3) both for the methodology of Boccotti[18] (Eq. (5)) and using Morison's equation (Eq. (1)). In Barbaro's formula (Eq. (4a)), Stokes' theory was used. Moreover, in the first two cases, the base of the structure was composed of M elements and the kinetic parameters were calculated in the barycenter of each element.

The value of the Froude–Krylov force on the platform resulted from the following expression:

$$F_{\mathrm{F},y} = \sum_{i=1}^{M} F_{\mathrm{F},y_{ci}} \tag{8a}$$

The value of the Morison's force on the platform resulted from the following expression:

$$F_{\mathrm{M},y} = \sum_{i=1}^{M} F_{\mathrm{M},y_{ci}} \tag{8b}$$

Table 1. Parameter characteristics of the locations studied.

ORTONA BUOY		46001 BUOY	
u	0.94	u	1.46
w (m)	0.56	w (m)	2.53
a_{10} (m)	3.30	a_{10} (m)	8.3
b_{10} (h)	61	b_{10} (h)	57
C_1	–	C_1	2.06
C_2	–	C_2	0.73

where $F_{\mathrm{F},y_{ci}}$ and $F_{\mathrm{M},y_{ci}}$ are, respectively, Froude–Krylov and the Morison's force calculated in the barycenter of each element.

Once F_{F} was obtained, it was multiplied for the corresponding diffraction coefficient evaluated using Eq. (6), giving a ratio of 1.17 for the base of platform and 1.73 for the columns in the Adriatic Sea, and 1.53 for the base of the platform and 1.74 for the columns in the Gulf of Alaska.

The probability that the maximum wave height in the lifetime L exceeds a fixed threshold H is reported in Figure 4 both for the Ortona buoy and for the 46001 buoy.

Tables 2 and 3 show the maximum wave force exerted on the platforms in the Adriatic Sea and in the Gulf of Alaska, respectively.

Figures 5 and 6 report the instantaneous water surface elevation and the instantaneous value of the force for the gravity platforms in Ortona and in Alaska, respectively.

Table 2. Maximum wave force on the platform in the Adriatic Sea.

MAXIMUM WAVE FORCE ON THE BASE		
Boccotti	8251 t	–8878 t
Morison	12963 t	–13972 t
Barbaro	8596 t	
MAXIMUM WAVE FORCE ON THE COLUMNS		
Boccotti	1438 t	–1688 t
Morison	1565 t	–1789 t
Barbaro	2300 t	
MAXIMUM WAVE FORCES ON THE ENTIRE PLATFORM		
Boccotti	9573 t	–10566 t
Morison	14376 t	–15761 t
Barbaro	10896 t	

Table 3. Maximum wave force on the platform in the Gulf of Alaska.

MAXIMUM WAVE FORCE ON THE BASE		
Quasi-determinism	31743 t	–35334 t
Morison	38061 t	–42181 t
Barbaro	17754 t	
MAXIMUM WAVE FORCE ON THE COLUMNS		
Quasi-determinism	2187 t	–2568 t
Morison	2414 t	–2695 t
Barbaro	4583 t	
MAXIMUM WAVE FORCES ON THE ENTIRE PLATFORM		
Quasi-determinism	33697 t	–37901 t
Morison	40146 t	–44876 t
Barbaro	22302 t	

Summary and Conclusion

This paper analyzed the force acting on an offshore platform. The geometric scheme of the gravity-based offshore platform is reported in Figure 3.

For the evaluation of the horizontal force, three approaches were used. The first is the method proposed by Boccotti,[18] based on the diffraction theory; the second is the well-known Morison's equation; and the third is the Barbaro's criterion, based on Morison's equation.

The structures were situated in two different locations, Ortona, in the Adriatic Sea (Italy), and the Gulf of Alaska, in the Pacific Ocean (USA). The design parameters characteristic of the locations are reported in Table 1.

The design sea state was calculated through Eqs. (7a–f). In Figures 5 and 6, the instantaneous horizontal force on the platform is reported. Results illustrate that the Morison's equation gives higher values than the ones obtained using the method proposed by Boccotti[18] only for the base of the platform. The ratio between the two forces for the entire structure is 1.50 in the Adriatic Sea and 1.19 in the Pacific Ocean. Considering only the base of the platform, the ratio is 1.57 in the

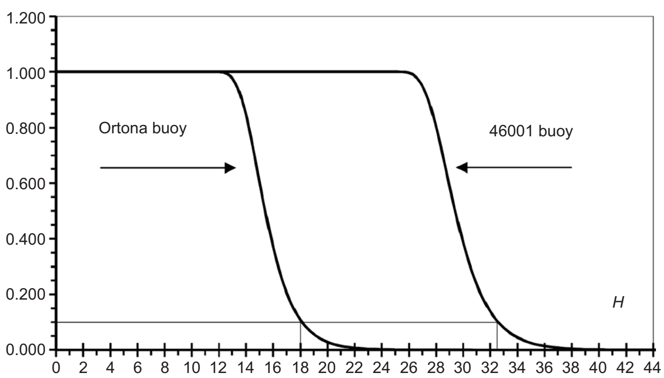

Figure 4. $P(R,L)$ versus H in Ortona buoy, and in 46001 buoy for $L = 100$ years.

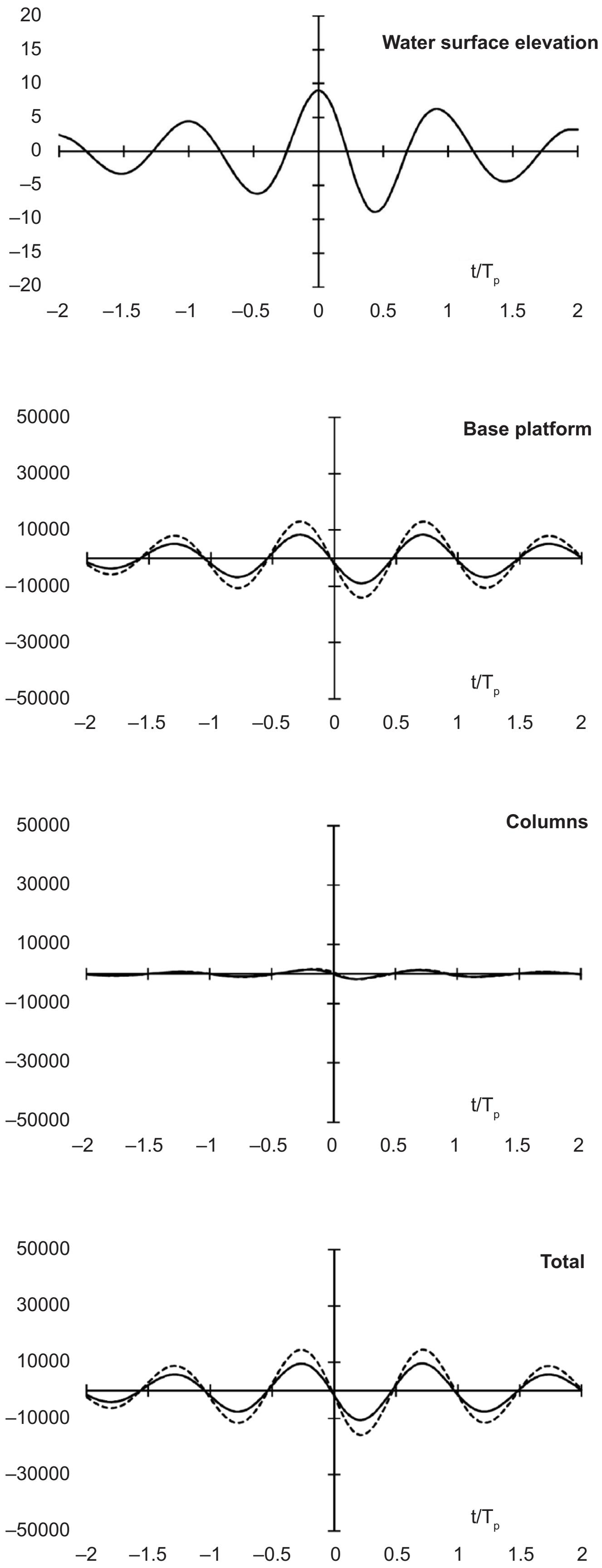

Figure 5. Horizontal forces on the gravity platform in the Adriatic Sea. The continuous line is for the methodology of Boccotti[18] and the dashed line is for Morison's equation.

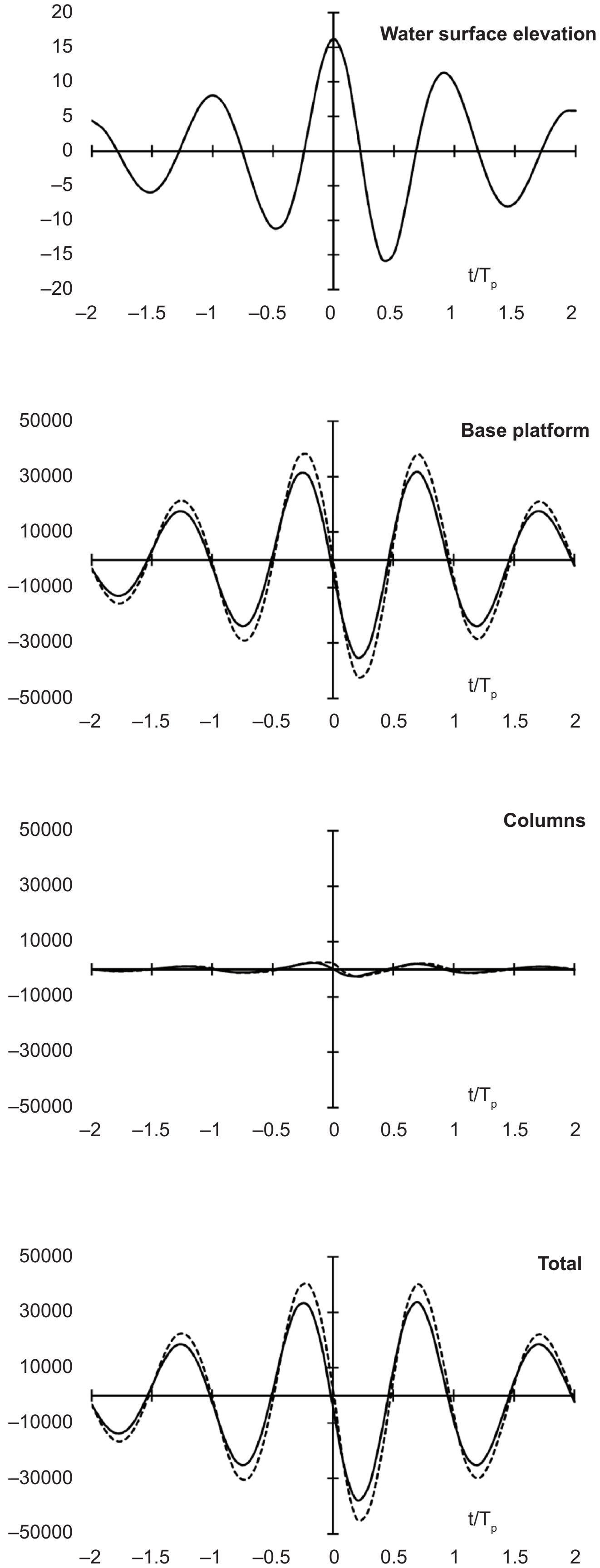

Figure 6. Horizontal forces on the gravity platform in the Gulf of Alaska.
Note: The continuous line is for the methodology Boccotti18 and the dashed line is for Morison's equation.

Adriatic Sea and 1.19 in the Pacific Ocean. Considering only the columns, the ratio is 1.1 in both locations.

The criterion proposed by Barbaro, in the case of the columns, seems to overestimate the force value in comparison to the results obtained through the other methods, and in the case of the base of the platform, it underestimates the force value. The difference between the Barbaro and Morison's results depends on two factors: the kinetic parameters and the method of calculation. In the Barbaro's criterion, Stoke's theory is used, whereas in the Morison's equation, quasi-determinism is used. A further factor is that the volume of water in which the equations are applied in the two cases is slightly different. In the first case, the volume is considered as the entire element of the structure. In the second case, each element is composed of M sub-elements, as previously stated. In fact, the difference between the results is less in the two columns than in the base of the platform.

Finally, the criterion proposed by Barbaro[19] can be used to analyze the forces on offshore structures and also for coastal structures[30–35] but only for a preliminary analysis. To gain a more complete understanding of the force acting on a structure, it is preferable to apply a more reliable model, such as those proposed by Morison or Boccotti.

List of Symbols

c_{in}, inertia coefficient; c_{dg}, drag coefficient; a_{sect}, acceleration vectors normal to the pile; v_{sect}, velocity vectors normal to the pile; ρ, water density; R, radius of the pile; Ke, Keulegan–Carpenter number; Re, Reynolds number; ω, angular frequency; θ, angle between the y-axis and the direction of wave advance; $S(\omega, \theta)$, directional spectrum; k, wave number; T^*, abscissa of the absolute minimum of the autocovariance function; $\Psi(T)$, autocovariance function; T_p, peak period; X, ancillary variable related to H_s; Y, ancillary variable related to H_s; $x_0(x_0, y_0)$, fixed point of the horizontal plane; H, H_s, significant wave height; d, water depth; g, gravity acceleration; $H_{max}(P,L)$, design wave; η, water surface elevation; L, design lifetime; $R(H)$, return period; $\overline{T}(h)$, mean wave period of a wave of height h; $p(x; H_s = h)$, probability density function derived from the probability of occurrence; $P(x; H_s = h)$, probability of occurrence; $dp(H_s = a)$, probability that H_s falls in a fixed small interval $(a, a + da)$; $\overline{b}(a)$, base of the ETS; a_{10}, parameter of the ETS model; b_{10}, parameter of the ETS model; C_1, parameter of the ETS model; C_2, parameter of the ETS model; $H_{max}(P,L)$, maximum expected wave height of storm; $F_{F,y}$, Froude–Krylov force in the y direction; $F_{M,y}$, Morison force in the y direction.

Author Contributions

Conceived and designed the experiments: GB. Analyzed the data: CLS. Wrote the first draft of the manuscript: CLS. Contributed to the writing of the manuscript: GB. Agree with manuscript results and conclusions: GB, GF, CLS. Jointly developed the structure and arguments for the paper: CLS.

Made critical revisions and approved final version: GB, GF. All authors reviewed and approved of the final manuscript.

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