# LIMITS OF THE NEW TRANSMISSION FORMULA FOR Π-TYPE FLOATING BREAKWATERS

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The aim of this work is to assess, by means of available experimental results and numerical simulations, the possible extension of the range of application of the formula proposed by Ruol et al. (J. Wat. Port, Coast. Ocean Eng., **1**, 2013), giving wave transmission for chain-moored Π-type floating breakwaters. The formula is here applied out of the range used for its calibration and even to other types of FBs. The error between predicted and measured values is described and discussed with reference to the main geometrical variables. It appears that the formula performs fairly well for the box-type FB, but not in cases characterized by very different mooring stiffness compared to the one used for calibration. For instance in case of fixed or tethered FBs, the formula significantly overestimates the wave transmission.

## INTRODUCTION

A growing number of companies provide pre-fabricated modules for floating breakwaters (FBs), a traditional protection system with multiple benefits especially for the environment, suited for small marinas in mild sea conditions (wave periods up to 4.0 s and wave heights smaller than 1.5 m).

The most used type of pre-fabricated module is a chain-moored rectangular caisson with two vertical plates protruding downwards from the sides. As these shapes resemble a Greek Π, they are referred to as Π-type FBs. It is believed that these devices are more economical compared to other with different geometries, such as the simple rectangular shape usually named "box type".

The efficiency of a floating breakwater is expressed in terms of the transmission coefficient $k_t$, defined as the ratio between transmitted and incident wave height. Ruol et al. (2012) proposed a formula for $k_t$, suited to chain moored Π-type FBs, and introduced an important nondimensional parameter $\chi$, basically equal to the ratio between the incident peak wave period and the FB natural period of oscillation.

Recently, several studies investigated on the sensitivity of the transmission coefficient relative Floating Breakwaters on non-dimensional parameters such as $d/h$ (relative draft) and $w/h$ (relative width).

Koftis and Prinos (2011), by means of an extensive experimental dataset, analyse the performance of FBs in terms $k_t$. They recognize that fixed and moored FBs have a very different behavior, and propose two simple formulas given as a function of $h/L$ (L being the wavelength of incident waves), $d/h$ and $w/h$.

Martinelli et al (2012) performed 2D numerical simulations considering FB under regular waves, fully constrained (in order to roughly simulate tethered conditions), free to move vertically (simulating pile supports) and moored with loose springs (simulating the chain mooring). It was seen that the type of mooring system, not included in the formula, has a significant effect. FBs moored with loose chains are less effective than tethered ones. Considering wave periods smaller than the natural period of oscillation ($\chi_m < 1$) and relative drafts $d/h > 0.2$, FBs where roll and surge is impeded perform better than fixed ones. For periods close to the natural period of oscillation and drafts $d/h > 0.1$, FBs where roll and surge is impeded perform better than chain moored FBs. From these considerations, it must be concluded that the arbitrary application of the formula to FBs moored with other than loose chains leads in most cases to an over prediction of the transmission coefficient.

Abdolali et al. (2012) investigated FBs subject to regular waves constrained to move only vertically. They compared numerical simulations, experimental observations and the formula proposed by Ruol et al. (2012). The tested range included large values of $\chi$ (ranging from 1 to 7), and large values of relative draft ($d/h$ between 0.20 to 0.45) and relative width ($w/h$ between 0.66 to 1.66). Also these numerical investigations confirm that in these conditions the formula significantly overpredicts the numerical data.

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The aims of this work are to assess the validity of the Ruol et al. (2012) formula when applied to other types of moorings or other types of FBs. For instance, if the vertical plates have zero extension, the Π-type degenerates onto a "box type".

The formula is briefly presented at first, together with its proposed range of application. A numerical investigation is used to evaluate the sensitivity of the formula to different mooring systems and geometries. Then, a list of data collected from the literature is presented: the formula is applied to such literature experimental results. Finally conclusions are drawn.

## THE FORMULA DEVELOPED FOR Π-TYPE FBS MOORED WITH LOOSE CHAINS

Ruol et al. (2012) proposed a formula that is a modification of the Macagno's analytical relation. The Macagno's relation is given by the following Eq. (1):

$$k_{tM} = \frac{1}{\sqrt{1 + \left[ kw \dfrac{\sinh kh}{2\cosh(kh - kd)} \right]^2}} \tag{1}$$

This relation is valid for a rectangular, fixed and infinitely long FBs (representing many aligned modules connected to each other) with draft $d$ and width $w$, subject to regular waves. In Eq. (1), $h$ is the water depth and $k$ is the wave number relative to a regular wave. For irregular waves, where $T_p$ is known, we evaluate the wavenumber assuming an equivalent period $T=T_p/1.1$.

Since Macagno's relation is based on linear wave theory in absence of displacements and dissipations, it is not expected to predict accurate results in presence of movements. Furthermore, it is not meant to be applied to floating Π-type FBs.

Ruol et al. (2012) introduced a non-dimensional parameter $\chi$, that interprets the ratio between the peak period of the incident wave $T_p$ and the natural period of the heave oscillation $T_{heave}$ (in absence of mooring):

$$\chi = \frac{T_p}{2\pi} \sqrt{\frac{g}{d + 0.35w}} \tag{2}$$

The symbol $\chi_m$ is used if the mean wave period $T$ is used rather than the peak wave period $T_p$.

The method proposed by the Authors consists in evaluating $k_t$ by the multiplication of the Macagno's relation by a function of $\chi$.

The proposed transmission coefficient is written in the form of Eq. (3):

$$k_t = \beta(\chi)k_{tM} \tag{3}$$

Based on the experiments carried out in the wave flume of Padova University, $\beta$ is given by the following expression:

$$\beta = \frac{1}{1 + \left( \dfrac{\chi - \chi_o}{\sigma} \right) e^{-\left( \dfrac{\chi - \chi_o}{\sigma} \right)^2}} \tag{4}$$

where $\chi_o = 0.7919$ (with 95% confidence interval 0.7801, 0.8037) and $\sigma = 0.1922$ (0.1741, 0.2103). Eq. 4 is valid in the range $\chi \in [0.5;1.5]$. The tested range of $d/h$ is [0.2-0.45].

For oblique waves, the it is proposed that $\chi$ is evaluated with an equivalent (longer) wave period, obtained by the apparent wavelength ($L/\cos\theta$).

Note that Eq. 4 is merely a fitting of the experimental results. The core of the proposed method is given by Eq. 3, that assumes $\chi$ as the most relevant variable of the process beside the prediction based on Macagno's relation.

The fitted results derive by several physical model tests carried out on the 6 structures described in Table 1. Each investigation is characterised by a "Model code" that identifies the studied structure and configuration. The first letter is not relevant in this context. The second letter describes the mooring system (c=chains, ..); a digit for the structure orientation (0 if perpendicular to the waves); a digit for the facility hosting the tests (c=flume, ..); eventually a group of 4 characters with the target model mass and its unit measure (xxkg).

| Table 1. Structures tested in the wave flume in Padova | | | | | |
|---|---|---|---|---|---|
| Model Code | Weight (kg) | Width $w$ (m) | Height $h_s$ (m) | Draft $d$ (m) | Water depth $h$ (m) |
| Sc0c16kg | 16.20 | 0.25 | 0.150 | 0.100 | 0.515 |
| Dc0c32kg | 32.00 | 0.50 | 0.150 | 0.100 | 0.515 |
| Dc0c56kg | 56.30 | 0.50 | 0.283 | 0.178 | 0.515 |
| Dc0c76kg | 76.30 | 0.50 | 0.283 | 0.238 | 0.515 |
| Mc0c76kg | 76.30 | 0.50 | 0.343 | 0.238 | 0.515 |

All devices of Table 1 were moored with 4 chains, with submerged weight of approximately 70 g/m, anchored at a distance equal to twice the water depth (h=0.5 m). The initial pretension is always very low, equal to the total chain weight. In shallow waters, chains may become fully extended in case of large waves. The sharp impact load that develops in case the chain is fully extended was studied in Martinelli et al (2008).

The formula was fitted to cases with incident waves smaller than the freeboard ($F_r$). Comparison with literature data also showed good agreement, at least for small incident wave heights. In case of large waves, the transmission is seen to be slightly under-predicted for small $\chi$ and over-predicted for large $\chi$.

## COMPARISON WITH NUMERICAL SIMULATIONS

An exploratory investigation on the type of mooring system and on the main geometrical parameters is carried out by means of numerical simulations.

A first order potential flow numerical model is used to study the FB dynamics in the wave flume. Since only heave, sway and roll are allowed in the flume (due to the presence of the side walls), the problem is essentially 2D. The code, based on the Finite Element Method (FEM), is only slightly different from the one described in Martinelli and Ruol (2006). In fact, an energy conservation approach is used, following the procedure of Yamamoto (1980) rather than that of Fugazza and Natale (1988).

Three different types of mooring systems are (both experimentally and) numerically analysed:
•        'Heave': a case with only vertical movements allowed (resembling the case of piles, but with important discrepancies in terms of results); "heave" cases are analyzed by "freezing" surge and roll;
•        'Fixed': a case where movements are negligible (resembling the case with tethered lines, since linear horizontal and vertical reactions allow only for small movements);
•        'Free': a case with a loose linear spring system (resembling the case of chains providing a reaction with very low stiffness). Spring reaction is modeled assuming a linear spring coefficient due to an initial pretention of 100% of the total weight of the chain, as it happens in the physical model case. The obtained linearized stiffness is a very small value allowing large movements. This simulation represents the case of a very compliant system where the mooring only absorbs the second order drift load. Application of a full non-linear approach was not carried out for simplicity. A more refined approach is on the other hand not justified, given the limited accuracy of the potential approach.

Several different Π-type geometries are studied, $w/d \in [0.2;0.7]$, $d/h \in [0.07;0.9]$, $a/d \in [0.05;0.75]$, where $d$ is draft, $w$ is width, $h$ is water depth, $a$ is the height of the vertical plate protruding downwards of the FB rectangular core.

For very low $a/d$ values, the geometry resembles that of a box-type FB.

Since the result is proportional to the wave height for definition of linearity, the incident wave has always unit value. The regular incident wave period $T$ varies in a range (in 10 steps) included between half and twice the natural period of the heave oscillation $T_h$.

**Mooring stiffness**

Eq. (3) demands that the transmission coefficient is predicted by the Macagno's relation and then corrected by a function $\beta$ only dependent on the variable $\chi$.

This Section investigates the numerical prediction of the shape of the $\beta$ function, in case the FBs are moored by different systems.

Figs. 1, 2 and 3 show the ratio between the wave transmission measured with Macagno's relation and the simulated value, separating with colors the structures in three classes with different values of $w/L$, for structures 1) moored with loose chains, 2) constrained to move only vertically and 3) fixed in the static floating position. The abscissa reports the $\chi$ variable (adapted to the regular wave case), and for the interpretation it should be recalled that, according to the Macagno's relation, the transmission coefficient $k_t$ increases monotonically with $\chi$.

By comparing Figs 1, 2 and 3, it is clear that the different constraints have large effects. We interpret that the degree of constraining, and therefore the *mooring stiffness*, increases moving from the condition shown in Figure 1 (loose chains) to the condition in Fig 2 (heave allowed) and finally to the one in Fig. 3 (completely fixed). As the *mooring stiffness* increases, for low values of $\chi$, the numerically simulated transmission coefficient becomes significantly smaller compared to the Macagno's relation. In fact, in order to limit the figure axis, the cases with $k_t$ lower than 0.1 were not plotted. In all practical cases, it is of little interest to know if $k_t$ is equal to 0.1 or 0.01 and, in fact, in this case even an error of one order of magnitude is acceptable.

Fig. 2 and Fig. 3 clearly show that, for a given (low) $\chi$ value the simulated $k_t$ is much smaller than predicted by the Macagno's relation, for high mooring stiffness. From these simulations, we conclude that the proposed fitting Eq. (4) cannot be applied to structures where sway and/or roll is inhibited. The case of structures supported by piles do not entirely falls in this situation, since when the FBs are supported with piles, roll is in general possible, although large oscillations may be prevented by a collision of the structures with the pile.
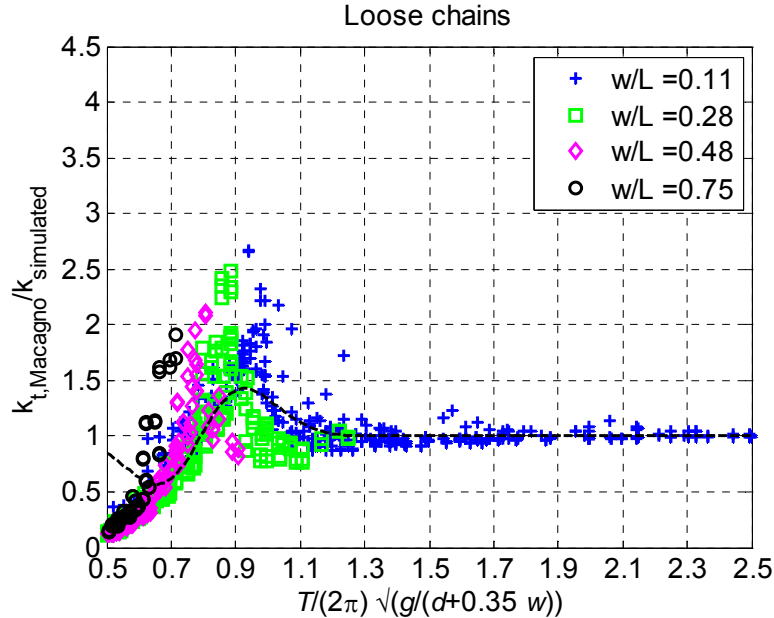


**Figure 1: Macagno and numerically simulated transmission for FBs moored with loose chains**
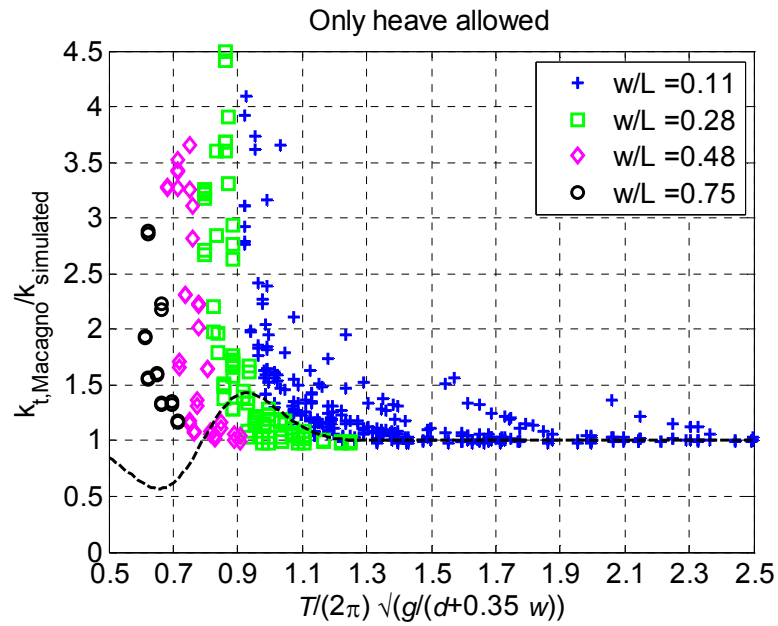
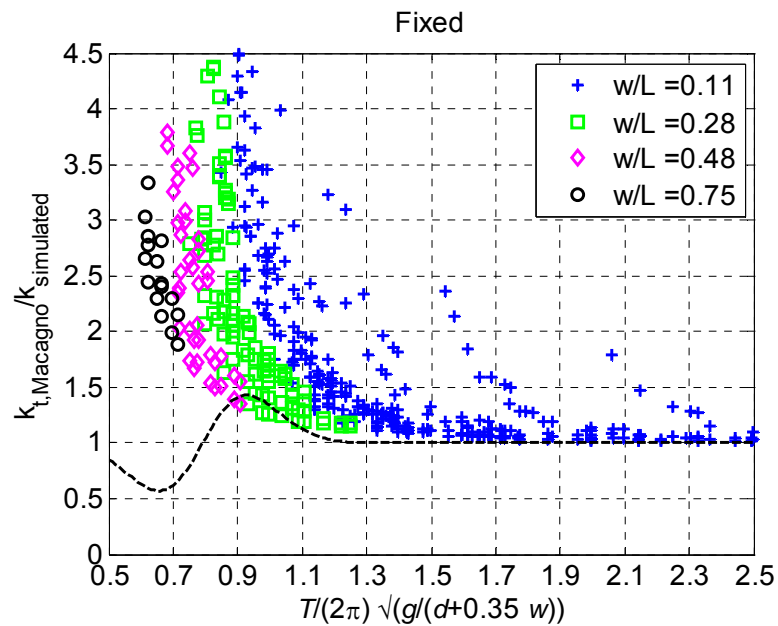**Figure 2: Macagno and numerically simulated transmission for FBs constrained to move only vertically.**



**Figure 3: Macagno and numerically simulated transmission for FBs fixed at the buoyancy level.**

**Relative draft**

Numerical simulations have been also used to check whether the validity of the formula can be extended outside the tested range of $d/h$, given by [0.20-0.45]. In fact, the simulations with $d/h$=0.6 appeared be accurately predicted by the fitting Eq. (4).
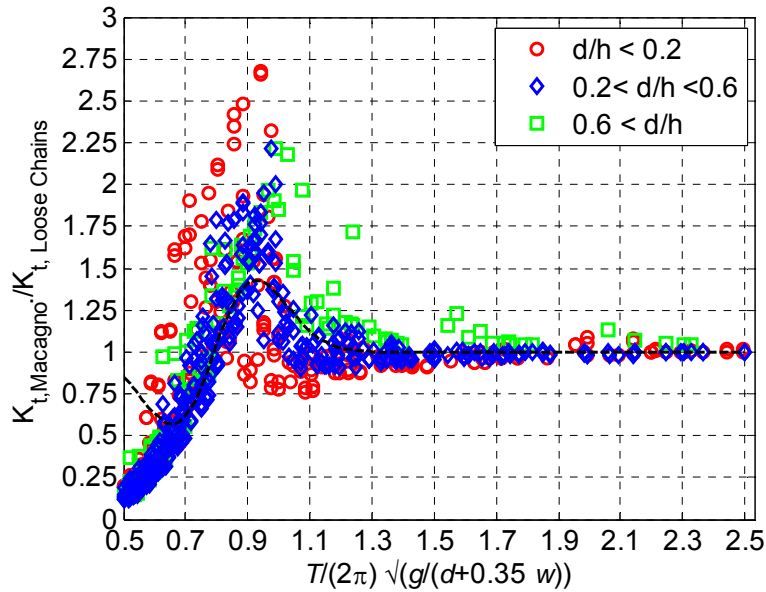
**Figure 4: Formula range of validity: numerically simulated transmission for FBs moored with loose chains**

Fig. 4 shows the ratio between the wave transmission measured with the Macagno's relation and the simulated value, for the structures moored with loose chains, separating the structures in three classes of values of $d/h$. The figure shows that the suggested fitting of the $\beta$ function (Eq. 4) gives an accurate estimate for structures with a relative draft $d/h$ in the range 0.2-0.6, which is larger than the previously suggested one.

## COMPARISON WITH EXPERIMENTS

In order to compare the proposed formula with experimental results, a large database has been collected. Several reports are in fact available from the literature, providing wave transmission for FBs.

| Table 2. Dataset used for comparison | | | | |
|---|---|---|---|---|
| Code | FB-Type | Moorings | Waves | Reference |
| R12 | Π | chain | irregular | Ruol et al., 2012 |
| M08 | Π | chain | irregular | Martinelli et al., 2008 |
| G06 | Π | chain | regular | Gesraha, 2006 |
| K05a | Π | heave | regular and irregular | Koutandos et al., 2005 |
| K05b | Π | blocked | regular and irregular | Koutandos et al., 2005 |
| B88a | Box | pile | regular | Blumberg and Cox, 1988 |
| B88b | double box | pile | regular | Blumberg and Cox, 1988 |
| B88c | triple box | pile | regular | Blumberg and Cox, 1988 |
| B88d | double with short skirt | pile | regular | Blumberg and Cox, 1988 |
| B88e | double with medium skirt | pile | regular | Blumberg and Cox, 1988 |
| B88f | double with long skirt | pile | regular | Blumberg and Cox, 1988 |
| B88g | Catamaran | pile | regular | Blumberg and Cox, 1988 |
| C07a | Π | pile | irregular | Cox et al., 2007 |
| C07b | Π | pile | regular | Cox et al., 2007 |
| C00a | Alaska | chain | regular | Christian, 2000 |
| C00b | Alaska | chain | regular | Christian, 2000 |
| C00c | Alaska | chain | regular | Christian, 2000 |
| P11a | Π | cross-type elastic lines | regular | Peña et al., 2011 |
| P11b | Π | cross-type elastic lines | regular | Peña et al., 2011 |
| P11c | Π | cross-type elastic lines | regular | Peña et al., 2011 |
| R06 | Π | tethered | regular | Rahman et al., 2006 |

In some cases, however, the accuracy of the data is questionable; the analysis methods do not separate incident and reflected waves, the wave flume is very short and the gauges are placed at a distance smaller than a wavelength form the wave generator or from the structure or from the rear absorber. In some other cases, essential information is missing, the data is given in aggregate form or the proposed non-dimensionalisation did not allow the comparison.

In short, the database used for comparison was reduced to the one given in Table 2. Data are mostly derived graphically.

**Π-type, chain moored**

Figure 5 shows the comparison between predicted and measured $k_t$ results for π-type structures anchored with chains or very compliant elastic lines. The figure shows that in general a good agreement is found (+/- 20%), even for cases where the mooring lines are crossed (red points, P11a-c). Only few cases relative to low $k_t$ values are significantly underpredicted. In order to better analyze these cases, the same data plotted in Fig. 5 are plotted in Fig. 6, where the dependence of the prediction inaccuracy is given as a function of the variable χ, together with the β(χ) curve (solid black line)

Fig. 6 shows that the observed underprediction is mainly associated to small values of χ. The numerical investigation presented in the previous section (Fig. 4) suggests in fact the same trend.
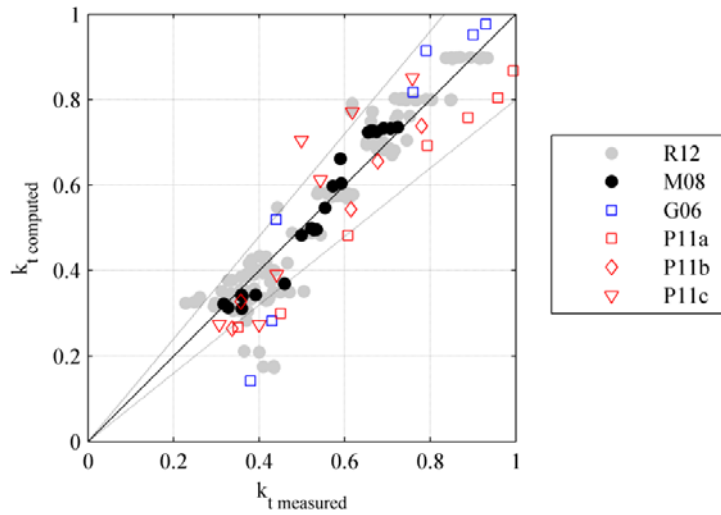


**Figure 5: π-types FBs. Π-type moored with chains. Comparison between kt computed with Eq. (3) and measured values.**
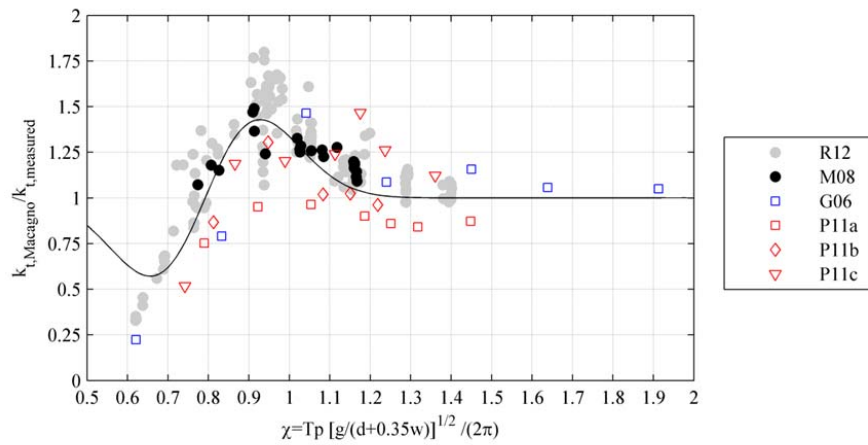


**Figure 6: π-types FBs. Π-type moored with chains. Comparison between $k_t$ computed with Eq. (3) and measured values. The β curve Eq. (4) is also plotted.**

**Alaska type structures, moored with chains**

The analysis of alaska-type FBs in Table 2, shows that the $k_t$ obtained with the Macagno's relation, at least in the plotted range of $\chi$, is in general underpredicted (approx. 20%), with a trend that does not follow the $\beta(\chi)$ curve. Actually, a larger underprediction was observed for values of $\chi$ smaller than 0.5 (out of range).

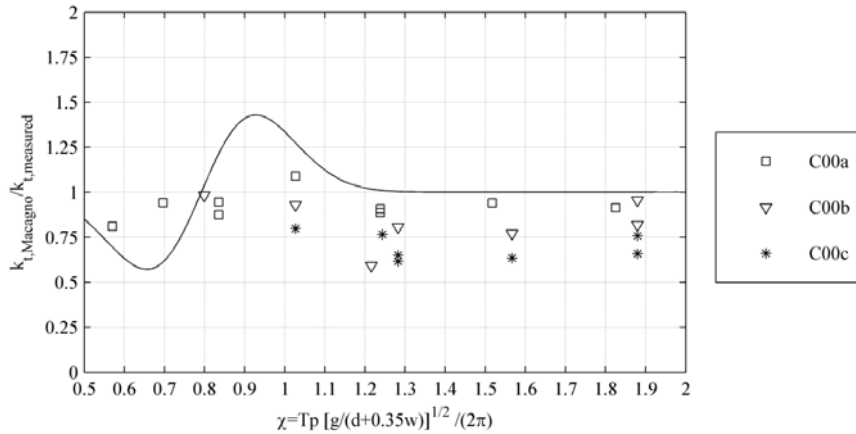It may be concluded that the fitting proposed by Eq. 4 is not suited to alaska-type FBs.



**Figure 7: Comparison of formula for chain moored alaska-type FBs.**

**Other structures not moored with chains**

Figures 8 and 9 show the application of the formula to all structures not moored with chains, gathered in Tab. 2. They are box-type, T-type or Π-type.

According to the numerical simulations (Fig. 2 and Fig.3), it is expected that for stiff mooring systems (K05a-b and R06) the $k_t$ is overpredicted by the formula whenever $\chi$ is small. This behaviour is confirmed by the experimental results.
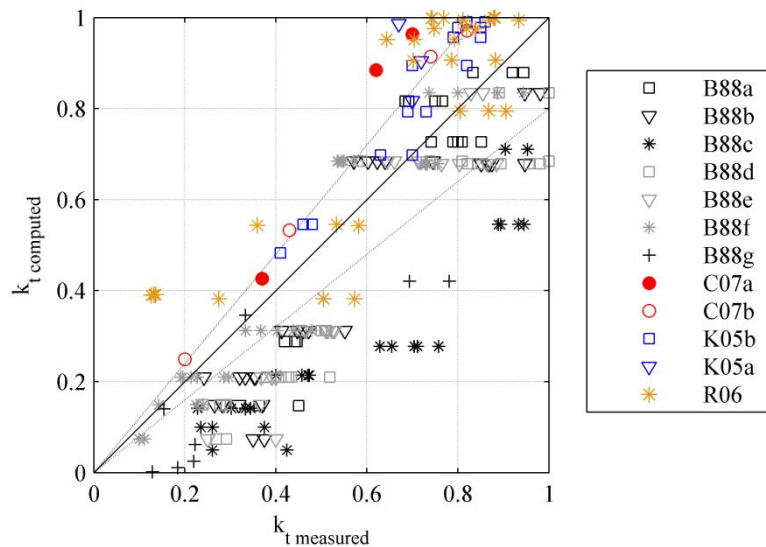


**Figure 8: Comparison of predicted ratio between Macagno's $k_t$ values and measured ones: non chain-moored, non π-type FBs.**
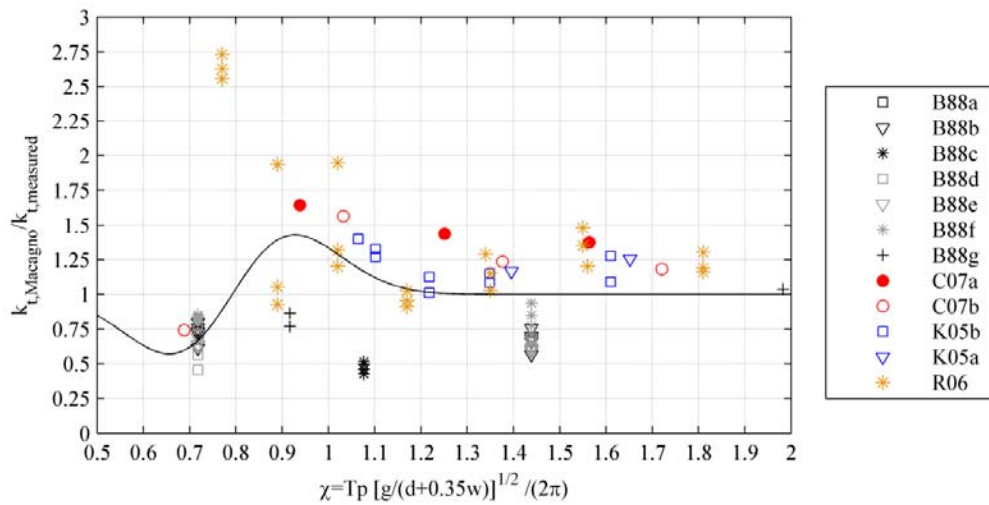
**Figure 9: Same as Figure 8 (comparison of formula for non chain-moored non π-type FBs) but plotting data VS χ (interval restricted to [0.5 - 2]).**

For the Blumberg and Cox (1988) and Cox et al. (2007) data, supported by piles and relatively free to roll and heave, underprediction is observed, for very low χ. This behaviour is different from the simulations given in Fig. 2, where roll was impeded, and more similar to the case shown in Fig. 1, although in such simulations the structures are also allowed to sway.

Case B88c represents a very large box-type FB, with relative draft "out of range", and again the expected $k_t$ is smaller than the observed one. Cases B88a-b are box-type FBs, and for these devices the agreement between measures and formula is satisfactory.

**CONCLUSIONS**

This notes investigates on the range of validity of the formula by Ruol et al. (2012), providing the wave transmission coefficient ($k_t$) for chain moored Π-type floating breakwaters (FB). The paper examines possible applications of the formula out of the range of variables used for calibration and to other types of moorings or even to other types of FBs.

According to numerical simulations and to a large database of small scale experimental results, the following conclusions are drawn:

- the formula proposed by Eqs. 3-4 can be used for Box-type as well as Π type FBs, anchored with chains;
- the formula proposed by Eqs. 3-4 is not suited to Alaska-type FBs;
- although the fitting was initially based on structures with relative draft $d/h$ in range [0.20-0.45], a good prediction was observed in a wider range ($d/h$ in range [0.20-0.60]);
- for low χ values, even within the calibration range ([0.5-1.5]), a very low transmission coefficient is found and the relative error is sometime quite large. The error is anyway not significant from a practical point of view, since the absolute error is rather small;
- the formula does not account for the effect of the mooring stiffness, that is known to considerably influence the FB efficiency. Predictions of $k_t$ based on the proposed fitting Eqs. (3-4) do not fit the numerical simulations when FBs are tethered with lines, fixed or supported with piles: large deviations (usually large over-predictions for χ smaller than 1.0) are observed. Experimental results show again a poor agreement with the formula for these cases, although the overprediction is less pronounced.

Due to the limitations of the numerical approach and to the available dataset, limited to small scale investigations, it was not possible to investigate the effect of wave height, which is expected to play an important role at prototype scale. Similarly, the effect of wave direction was not investigated.

**ACKNOWLEDGMENTS**

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