Prof. Ryszard Staroszczyk
Institute of Hydro-Engineering
Polish Academy of Sciences
Kościerska 7
80-328 Gdańsk, Poland

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Review of the doctoral dissertation by Ms Olga Podrażka entitled *"Breaking sea wave impact loads on truss structures"*

This review has been prepared on the request of the Scientific Council of the discipline of Earth and Environmental Sciences of the University of Gdańsk, in response to the letter signed by Prof. Wojciech Tylmann, dated 11 July 2023 (ref. no. 0002/1348/2023).

1. Introduction

The submitted doctoral thesis is concerned with the investigation of loads exerted by breaking water waves impacting truss (jacket) structures that can be used for supporting off-shore wind turbines. The principal objective of the research presented in the thesis was to identify and describe quantitatively relationships between breaking wave characteristics and the magnitudes of slamming forces acting on the structure as a whole and on its individual structural members (legs and bracing bars). The analysis of the problem has been based on the results of laboratory measurements conducted in 2013 in the large wave flume at the Coastal Research Center in Hannover, Germany.

The dissertation by Ms Olga Podrażka is written in very good English, and consists of eight numbered chapters, supplemented by an appendix and a bibliography list. The main text is preceded by thesis abstracts in English and Polish, acknowledgements, and the lists of figures, tables, acronyms and symbols. In total, the work comprises xxi + 122 pages.

The first, introductory chapter, gives the motivation for the research carried out by the PhD Candidate and highlights its practical significance, describes the problem under investigation, and concisely presents the main objectives and the scope of the work. Listed are also six papers co-authored by the candidate, the results of which have been used in the thesis. The following Chapter 2 provides some theoretical background, based on the literature, that is necessary, and useful, for the understanding of the basic concepts and the results achieved, together with their discussion, which are presented later in the work. The next Chapter 3 presents very briefly (on only three pages) the approaches that are universally employed to study water waves and their interactions with engineering

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structures. Chapter 4 presents the experimental set-up and techniques used to measure the surface waves parameters and their evolution along the flume, and to measure and record the time-histories of hydrodynamic forces acting on the truss and its members. This is followed by Chapter 5 containing the description of analytical/numerical tools adopted for the analysis of the data recorded during the experiments, focussing on the two methods: the *Frequency Response Function* (FRF) applied for extracting local slamming forces from the recorded signals, and the *Empirical Mode Decomposition* (EMD) approach used for extracting global slamming forces acting on the jacket structure during its interaction with a breaking wave. Chapter 6, the longest in the thesis (including 52 pages, nearly half of the main text length), is devoted to the extensive analysis and discussion of the data obtained in the flume after their processing by the methods outlined in Chapter 5. Discussed in great detail are the results describing the transformation of a surface wave due to its shoaling prior to the impact on the jacket structure, and also discussed are the results defining the characteristics of total and local slamming forces exerted on the structure. An important element of this chapter are empirical relations that have been proposed to approximate, and generalize, the findings from the research. The next Chapter 7 first summarizes the laboratory experiments, the methodology applied, and the results achieved in the course of work, and then presents the most important conclusions following from the research carried out by the PhD Candidate. The concluding, one-page-long Chapter 8, gives some thoughts of the Author on the limitations of the research conducted so far and presented in the thesis, and shares some ideas and plans for the future research work on the breaking wave interactions with engineering structures. Finally, Appendix A contains two sets of additional plots which have not been included in the main text. The Bibliography list at the end of the work contains over 80 references, spanning the period of over 150 years (the oldest paper is from year 1864, and the most recent from year 2022).

2. Comments on the contents of the thesis

The thesis is clearly written and appropriately divided into self-contained chapters. The standard of English is very high – I have spotted only a few linguistic mistakes or typos in the whole text. The introductory Chapter 1 is relatively short, but yet it adequately presents all necessary information, including the motivation, primary objectives and the scope of the research described in the thesis, so that it is clear from the onset what one can expect in the following text. Maybe the literature review might have been more extensive, but part of it, relating to various aspects of gravity wave mechanics, has been moved to the next Chapter 2.

Chapter 2 introduces theoretical background for the considerations presented in the further part of the thesis. First, in Section 2.1, elementary analytical formulae known from water wave mechanics are compiled, including the wave dispersion equations, the relation

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linking the wave phase and group velocities, and the relations expressing the wave energy conservation for refracting waves. The latter expressions could have been much easier understood if a plot illustrating the mechanism of wave refraction over a sloping bed had been presented in this chapter. I think that before presenting the theoretical relations, it should be clearly stated that they describe waves of infinitesimally small amplitudes; hence, their application is limited to linear cases. Therefore, one should be cautious while using these relation for interpreting the laboratory results for breaking waves, that is the waves which are strongly non-linear. First of all, the use of the notion of 'deep water' (often used in the text to denote waves propagating in water of constant depth of $h = 4.3$ (or 4.1) m) is inappropriate, since the longest waves investigated in the flume had lengths L in excess of 30 m, for which the ratio h/L is about 1/7, while it is common to assume that one deals with 'deep water' wave propagation when $h/L \gtrsim 0.5$ (thus, it is appropriate to call the waves analysed in the thesis as 'shallow water waves'). In the further part of Section 2.1 the Iribarren surf similarity parameter ζ is introduced, and based on its values different types of breaking waves are identified, illustrated in Fig. 2.1 and then discussed, which I find useful. In Section 2.2 the non-breaking wave forces F_D and F_M are first defined by applying the well-known Morison equation, and then the breaking wave forces are introduced by adding to the latter equation a term F_S representing the slamming force. At the end of this section, two classical slamming force models, due to von Karman and Wagner, are sketched. The chapter is concluded with one-page-long Section 2.3 that describes wind turbine support structures used in practice. I think this last section is detached from the rest of Chapter 2 which is about the theory. Thus, the better place for this section could be in the introductory Chapter 1.

Chapter 3 discusses, in a very concise manner, four methods which are commonly applied to investigate problems encountered in physical, engineering and related sciences. These four methods (theoretical and numerical modelling, laboratory experiments and field measurements) are widely known and well established, so, in fact, this chapter adds very little to the thesis. Moreover, the title of this chapter, "Comparison of wave experimental data and observations in nature", is misleading, since no comparisons of data can be actually found in the presented text.

Chapter 4 describes the laboratory work carried out in the large wave flume in Hannover. The experimental setup is presented, showing the distribution of wave gauges and ADV meters along the flume, together with the distribution of force transducers on a truss structure (its legs and bracing elements) which was investigated in the laboratory. All relevant physical dimensions and technical details are adequately presented in the text. I find the information and illustrations presented in this chapter to be complete and sufficient for understanding what and how was measured in the flume (though some geometric dimensions of the truss elements are hard to discern in Fig. 4.5 due to the very small lettering!). The only important parameter that is missing is the exact distance

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between the edge of the berm and the truss (though I guess, from Fig. 4.1, that it was about 0.5 m).

The following Chapter 5 is devoted to the description of methodology that was employed to analyse the data from the laboratory, with the focus on the analysis of the fast varying time-series (signals) recorded during wave slamming events by the force transducers mounted on the jacket structure. Two methods are described, named the *Frequency Response Function* (FRF) method used for the extraction of slamming force from the local force signal, and the *Empirical Mode Decomposition* (EMD) method employed to extract the wave slamming force from the global force signal. Some analytical formulae describing the applied methodology are presented in this chapter, together with two flow charts (Fig. 5.2 and 5.5) that help grasp the main ideas of the two methods without the necessity of dwelling too much in all technical details involved, which I find a very useful approach to the reader. On page 43 a few simple formulae are presented for expressing the slamming force coefficient C_S for inclined (i.e. not vertical) cylindrical bars. I have concerns about the correctness of relations (5.14) and (5.15) – see points (f) and (g) in Section 3 below. I hope the Candidate can clarify this issue during the public discussion of the thesis.

No doubt, Chapter 6 is the central part of the thesis, both in terms of its length and contents. It presents a very detailed discussion of the results measured in the flume. The chapter is divided into three sections. The first Section 6.1 is devoted to the analysis of the mechanism of surface wave transformation, when a wave initially propagating in water of constant depth enters a region with a sloping bed and gradually changes its free surface profile, up to the stage when the wave breaks and eventually hits the jacket structure located at the beginning of the next section where the bed is again horizontal. The Author has analysed forty specific wave cases listed in Table 6.1, with the total number of investigated individual waves reaching 1507. All the individual waves are represented in a series of scatter plots which illustrate the effects of various characteristics of waves on the evolution of their free surface profiles as the waves approach the truss structure. This vast dataset has been used to determine which wave parameters are most crucial in terms of the possible wave breaking, and which are less important. It has turned out that the first group includes the initial wave height, wave crest front steepness, wave horizontal asymmetry, wave phase velocity and the surf similarity parameter ζ, while the significance of the wave vertical asymmetry parameter is negligible and can be ignored in the analysis. My impression is that the results presented in this section alone are in its own right a substantial contribution to the field of breaking waves mechanics, as they allow us to identify and better understand the very complex physical mechanisms that are involved in this highly dynamic and non-linear phenomenon. Apart from that, several quantitative formulae have been constructed in this section by correlating assumed analytical forms with the measured data. The formulae enable the straightforward determination of the

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breaking wave position x_b and depth h_b, as well as the breaker depth and height indices and the wave front steepness prior to the wave breaking – all these results are very convenient for practical applications.

The following two sections in this long chapter concentrate on the quantitative analysis of slamming forces which are generated at the wave impact on the truss structure. First, in Section 6.2, the global forces exerted on the structure are investigated, depending on the breaking wave characteristics. 1119 individual waves have been scrutinized. The results of the analysis are shown in a number of scatter plots illustrating the dependence of the peak slamming force on the breaking wave parameters. By correlation with the laboratory data, an approximate formula (6.7) has been proposed, which expresses the product of the slamming force coefficient C_S and the curling coefficient λ in terms of the wave front steepness S_f and the 'effective diameter' D_t. Hence, another useful formula for practical calculations has been proposed.

It is stated at the beginning of this section (p. 65) that the slamming force frequency is very close to the natural frequency of the jacket structure. This statement is subsequently repeated several times in the text. Unfortunately, there is no quantitative data provided in the submitted work which would support this claim. Can the Candidate show such data during the public discussion of the thesis? I think of interest are the natural frequencies of the whole structure as well as of its individual cylindrical elements, measured both in water and in air.

Finally, in Section 6.3, the local slamming forces exerted on individual members of the jacket structure (its legs and inclined bracing bars) are discussed. Again, the results obtained by processing the original time-series are shown in scatter plots, to illustrate the effects of breaking wave characteristics on the peak values of the slamming forces. One of the issues, illustrated in Fig. 6.37 and 6.38 and discussed on page 89, is the dependence of the peak force on the elevation of given points (represented by the pairs of force transducers FTBF02/03 and FTBF01/04, separated by about 0.22 m in the vertical direction). I wonder why for the purpose of such an analysis the measurements from ten transducers mounted on the truss legs are not used, since then the maximum vertical separation, occurring between the instruments FTFL05 and FTFL10, is considerably larger (it exceeds 1 m, as can be inferred from Fig. 4.5). Can this be explained by the Author during the public defence of the thesis?

By correlation with the measured data, an approximate formula (6.8) for the local slamming force coefficient C_S as a function of the wave crest front steepness S_f has been derived. The plots in Fig. 6.42 indicate that the latter formula determines the coefficients for the peak, not average, values of the slamming forces. The comparisons of the results in Sections 6.2 and 6.3 with the data available in the literature show that the results presented in the thesis are comparable to those obtained by other authors in the cases of very steep waves (up to about 1.75). For lower wave steepness values, say below unity,

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the results obtained by the Candidate better agree with the experimental data than those known from the literature. This clearly demonstrates the scientific value and practical importance of the results achieved by the PhD Candidate.

The last two chapters summarize the main contributions of the thesis (Chapter 7) and present some Author's ideas for the possible future research on the breaking waves and their interaction with an engineering structure (Chapter 8). I find the conclusions formulated in Chapter 7 to be fully supported by the results presented and discussed in the thesis. As to the plans for the future research, I think that the problem of modelling the effect of air bubbles trapped in water on the slamming force is the most challenging.

3. Minor remarks

(a) The list of acronyms on page xvii: instead of IPPC, the correct form is IPCC (the same mistake is repeated on p. 1).

(b) The list of symbols on pages xix-xx is incomplete and inconsistent. Some of the symbols (e.g. γ_b and Ω_b defined on p. 13) are not used in the text at all after their introduction (note that the list of symbols includes ω_b, not Ω_b, to denote the breaker depth index). Many symbols used in the work are missing in the symbols list, e.g. C_o, $f(t)$, $H(\omega)$, $Y_F(\omega)$, $Y_f(\omega)$, or i (imaginary unit). Further, water density is denoted as ρ_w in the list, while in the text on p. 9, eq. (2.5), it is represented by ρ. Finally, the slamming coefficient is denoted in the list by the symbol C_S (upper-case subscript), whereas in the text it is often (but not always) referred to as C_s (lower-case subscript, see p. 76, 77, 92, 93).

(c) Page 15, eqs. (2.10) and (2.11): perhaps the terms describing the inertia forces should include the material (convected) time-derivatives Du/Dt, instead of the ordinary derivatives du/dt?

(d) A few surnames od cited authors are misspelt. For instance, Keulegen (not Keulagen, p. 15), Wienke (not Weinke, p. 78, 79, 95), Morison, not Morrison (p. 15, 37, 65 and several other instances).

(e) Fig. 2.7 on p. 19 compares theoretical predictions of various models. One of the plotted curves is labelled as 'own model'. What does in mean? Is it a prediction from a model formulated by the Author of this thesis? If indeed this is the case, then please provide some relevant details, since there is no mention of this model in the entire text of the thesis.

(f) Page 43, equation (5.15): if α defines the angle between the bracing bar direction and the vertical, then, I think, the term $\sin(\alpha)$ should be replaced by $\cos(\alpha)$. Note that in the present form, eq. (5.15) gives for the limit case of the vertical bracing

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bar ($\alpha = 0$) an infinite value for D_t! (while the corrected formula gives $D_t = 2D$ which seems more sensible). In the light of the above, I wonder if the proposed formula (6.7) on p. 77 for the total slamming force coefficient, dependent on D_t, is correct?

(g) Page 43, equation (5.16): the two sides of the equation have different physical units – there is an area A_p with unit [m^2] on the left, and D_t with length unit [m] on the right, so clearly something is wrong. Furthermore, by the analogy with the above remark, I suppose that the term on the right-hand side should be expressed as $D/\cos(\alpha)$, which gives a non-zero value for $\alpha = 0$ (the limit case of the vertical bar), in contrast to the present form which yields zero.

(h) Page 45: a quantity Imp_s is introduced, which is defined as an integral of the slamming force and its duration. I think this quantity should be called *impulse of force* (with unit [kN s]), not *impulse force*.

(i) Table 6.1 on page 48: it would convenient to have the wave lengths L (and possibly the wave phase velocities as well) given in the table.

(j) Page 58, eq. (6.3): it is said that the breaker index coefficient $A = 0.15$ in (6.3) ensures better correlation with the measured data than the original value $A = 0.17$ used by Goda (2010). However, in Table 6.4 the statistical parameters for the case $A = 0.17$ are listed, not for $A = 0.15$. Why?

(k) Fig. 6.18 on p. 70 and Figs. A7–A15 in the appendix: the units on the vertical axes (for the impulse of force) should be [kN s], not [kN/s].

(l) The concluding parts of the text (around 20 lines) in Sections 6.3 and 6.4, p. 83 and 98 respectively, are identical (except one paragraph on p. 83 which is not copied on p. 98). Certainly, such a repetition does not make a good impression.

4. Final evaluation of the thesis

I am sure that the results of Ms Olga Podrażka's research which are discussed in the submitted doctoral thesis are an important and significant contribution to the better understanding of the complex mechanism of breaking wave interaction with a jacket structure. The formulae which are derived by correlations with extensive datasets gathered in the laboratory can be readily used in engineering practice for the evaluation of breaking wave parameters, and further for the approximate estimation of global and local breaking wave-induced slamming forces exerted on truss structures.

The thesis is well written and appropriately organized. The objectives of the research undertaken by the PhD Candidate have been achieved, and all the conclusions are

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fully supported by the results presented in the work. Part of these results has already been published in peer-reviewed journals. Throughout the thesis, Ms Olga Podrażka has convincingly demonstrated her thorough knowledge and the ability to apply rigourous scientific methods to solving complex problems of water wave mechanics and structural dynamics.

5. Recommendation

Based on my evaluation presented above in this review, I recommend the acceptance of the submitted doctoral dissertation for its public defence by the Candidate. In my opinion, providing that the defence is successful and all necessary formal requirements are fulfilled, Ms Olga Podrażka fully deserves a PhD degree in the discipline of Earth and Environmental Sciences.

Ryszard Staroszczyk