

PROBABILISTIC ANALYSIS OF TYPHOON INDUCED HYDRAULIC BOUNDARY CONDITIONS FOR SUO-NADA BAY

E.N. Klaver¹, J.K. Vrijling¹, S.N. Jonkman^{1,2}, P.H.A.J.M. van Gelder¹,
L.H. Holthuijsen¹, S. Takahashi³, H. Kawai³

For risk-based design of flood defence systems it is necessary to know the probability of failure of the system. This can only be derived if the probability of occurrence of the loads on the flood defence is known. Hydraulic loads caused by typhoons such as water levels and wave characteristics are mutually dependent and this has to be included in their joint probability density functions. This paper describes a method to derive the dependent joint probability density functions of hydraulic loads resulting of typhoons for a bay in Japan. An example is given on how to apply the derived probability function of loads to the design and failure analysis of a flood defence.

INTRODUCTION

The design of coastal structures, sea defences or breakwaters is especially difficult at coasts threatened by typhoons, sometimes also indicated as hurricanes or cyclones. The problem is that, although the coast may be hit by a typhoon one or more times per year, it is not unlikely that the exact location of the project has never experienced a hurricane. Further, observations of hydraulic characteristics sometimes fail due to the extreme loads during typhoon events. This may mean that no representative observations of wind velocities, wind set up, wave height and period are available for the project location. In the best case a few observations are available because the project location is hit on average every N -th year by a typhoon. So for a ten year observation period one might expect $10/N$ independent observations, which is insufficient to make a reliable statistical inference about say the 1/50 or 1/100 year design condition by extrapolation of available data. However not only statistical considerations might deem the number of observations insufficient, also a complicated geometry of the coast with shielded bays or protruding headlands may lead to this conclusion. In case of a complicated coastal geometry the project location may very well have been shielded from the full force of the typhoon in the few occurrences, but there is no reason why it will not be hit fully by a future typhoon with a slightly different (unfavourable) path.

¹ Delft University of Technology, Faculty of Civil Engineering, Hydraulic Engineering Section, PO Box 5048, 2600 GA, Delft, The Netherlands

² Rijkswaterstaat, Road and Hydraulic Engineering Institute, PO Box 5044, 2600 GA, Delft, The Netherlands

³ Port and Airport Research Institute, Nagase 3-1-1, Yokosuka 239-0826, Japan

Such a more or less complicated coastal geometry makes the hydraulic data gathered at other locations useless for direct use in the estimation of the say 1/100 year conditions at the project location. Only in case of a long straight coast with parallel depth contours data of other sites might support the estimation of the project's design conditions.

Katrina, the hurricane that flooded New Orleans on 29-th of August in 2005 provides a powerful illustration. Although the coast of the Mexican Gulf is hit by several hurricanes every year, New Orleans was only seriously threatened thirty years before. So observations of surge levels and wave heights along the flood defence were not sufficiently available. In Katrina's case the hurricane was only of category 3 strength, but the path was the most threatening for the city. First the southern storm pushed the water into the waterways, Lake Borgne and Lake Pontchartrain loading the defences with extreme water levels and waves. Some dikes withstood the overtopping, but the dike along the Mississippi River Gulf Outlet and the floodwall protecting the Ninth Ward failed. Then the hurricane moved on the northern storm on the left side swept the increased water mass of Lake Pontchartrain against the lake coast of the city and into the canals. The flood walls along the canals were unable to withstand the pressure and gave way. Not the extreme force of the storm but the combination with the effectiveness of its path caused the extreme and fatal loading of the NO flood defence system.

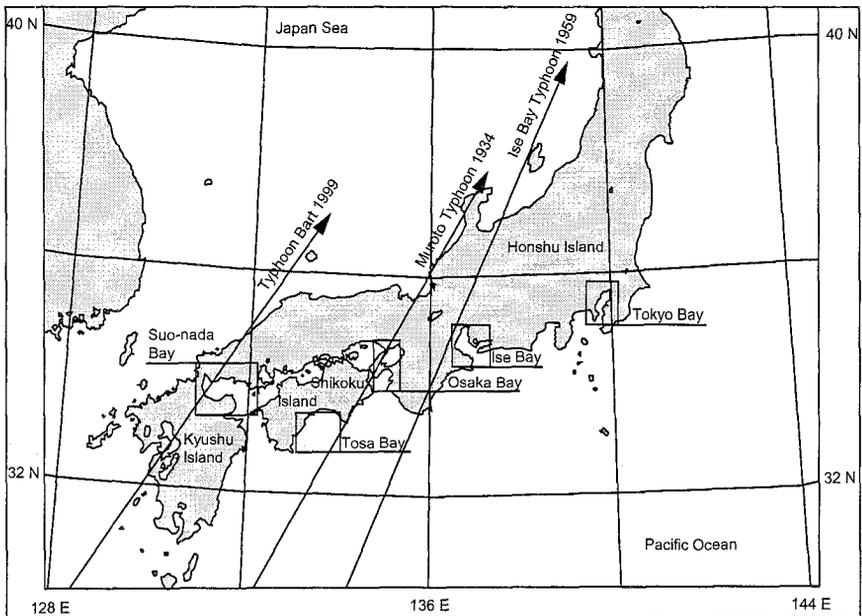


Figure 1: Japanese coastline with relatively shielded bays (www.agora.ex.nii.ac.jp)

Similar situations and conditions are found along the Japanese coast (Fig. 1) where there are many bays that provide shelter against most storms. However a typhoon with the right path may cause an extreme threat for a coastal structure. For coastal design it is important to relate the threat to the probability of exceedance. In this paper it is proposed to solve the question by means of a simulation model of physical phenomena in combinations with probabilistic methods. As an illustration the hydraulic boundary conditions for a location in the Suo-nada Bay in Japan (Fig. 2) are calculated.

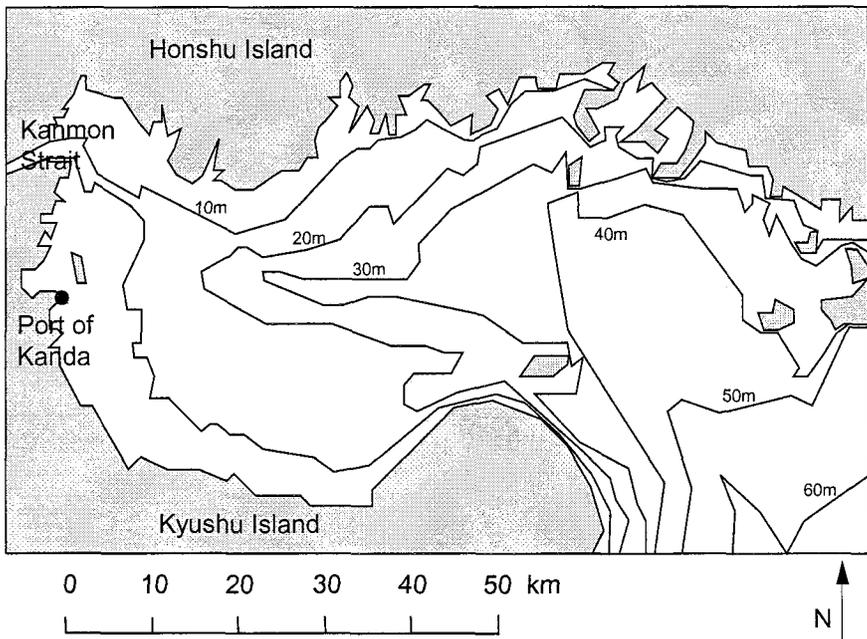


Figure 2: Geometry of Suo-nada Bay (Kawai et al. 2004)

PHYSICAL PHENOMENA

It is clear that a structure on the coast is threatened by the joint occurrence of tide, storm surge and waves. However for reasons explained above only a few observations of such combined occurrences are available due to the rarity of typhoons hitting the bay and the complicated geometry of the bay coast which limits the exposure of the structure to severe loading.

The objective is to determine the joint probability density function of the water level dh resulting from tide level, pressure set up and wind set up, the significant wave height H_s and the peak period T_p . Due to the scarcity of data and the dependence structure between the variables dh , H_s , T_p , the extrapolation to extreme values cannot be based on purely statistical methods. Moreover a

statistical extrapolation neglects physical bounds that may be met in extrapolation such as the depth limitation to wave height.

Therefore a model (Fig. 3) is formulated that derives from the typhoon parameters, the tide level and the geometry/bathymetry of the bay, via the pressure/windfield model, a wave growth model and a wind/pressure set up model the required combination of dh , H_s and T_p at the structures location.

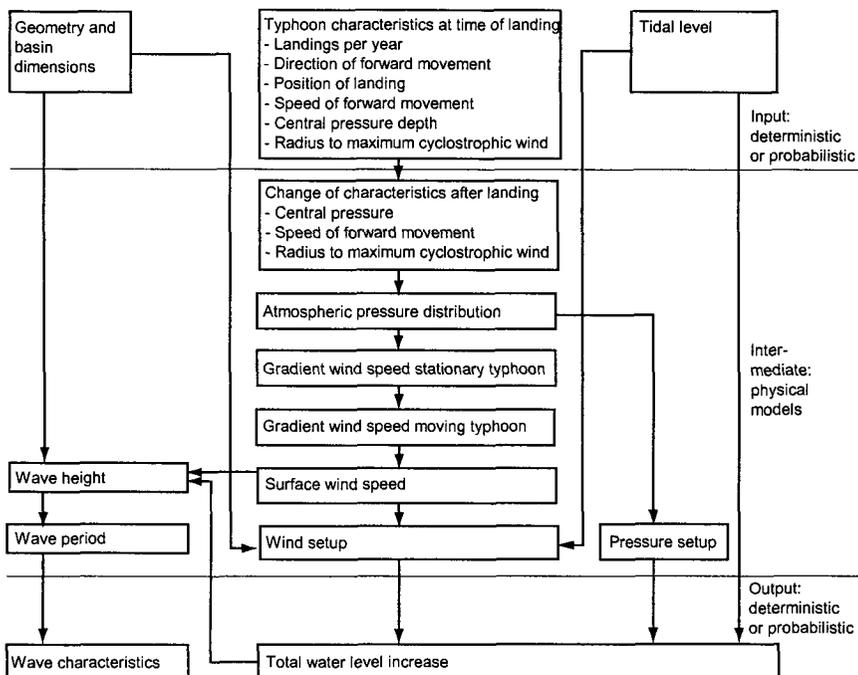


Figure 3: The model to calculate the hydraulic conditions given a typhoon

Although more refined numerical models are available, here simple analytical models are applied to illustrate the principles and to minimise computation time. For the wind/pressure field of the typhoon the model of Schloemer (1954) is used.

Kato and Torii (2002) performed an analysis with an analytical model proposed by the Japan Meteorological Agency (1999) for several Japanese bays. This simple model combines a linear pressure set up model with a quadratic wind set up model. A similar model, with different parameters is applied here.

For the wave height and the period the well known Sverdrup-Munk-Bretschneider model is chosen. The significant wave period is derived from the wave height using the wave steepness.

This combined model was calibrated by hindcasting the available observations with historical typhoons. Typhoon parameters are used from studies

of Mitsuta and Fujii (1986) and Fujii (1998). In only four cases the observed water levels were available overlapping these studies. Wave observations started in 1991; in this respect also four storms have been observed. The result of the calibration is shown in Fig. 4 and Fig. 5.

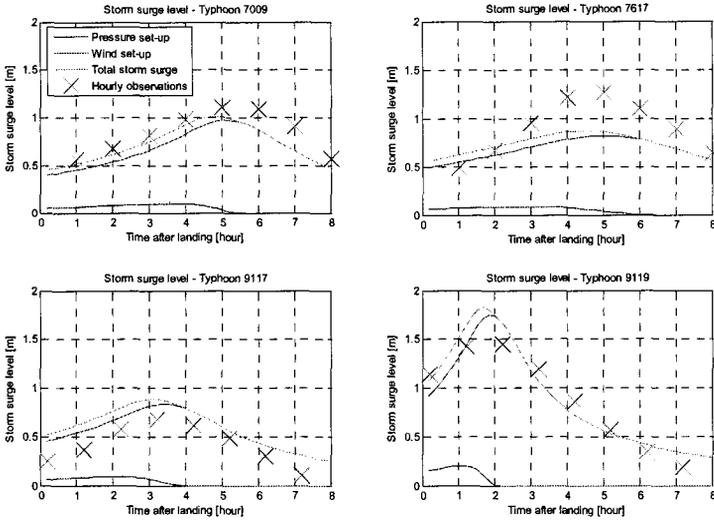


Figure 4: Comparison of observed and calculated water levels during typhoons

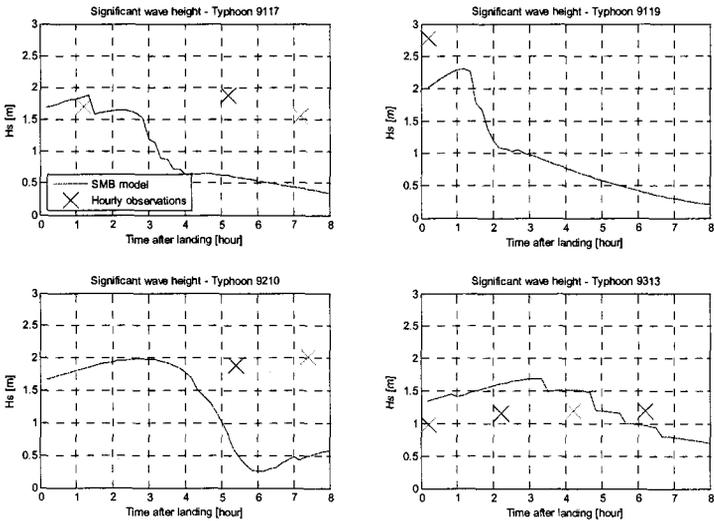


Figure 5: Comparison of observed and calculated wave heights during typhoons

The fit of the models is not perfect, but reasonably in view of the purpose of the project; especially the maxima of water level and wave height are predicted reasonably well and these are most relevant for the design. It is expected that more advanced numerical models will predict the phenomena better and in more detail.

PROBABILISTIC INPUT OF TYPHOON PARAMETERS AND THE TIDAL WATER LEVEL

Probabilistic typhoon characteristics have been analysed by Mitsuta and Fujii (1986) and have been applied in this research. The number of typhoon landings in the studied area is on average 1.04 per year. This number was modelled by a Poisson distribution with a mean of 1.04. The position of the landing is assumed to be uniformly distributed over the stretch of coast perpendicular to the typhoon direction. The characteristics of the typhoon at the time of landing are modelled by log-normal distributions. There seems to be no physical reason for the adoption of this distribution. The parameters of the lognormal distributions are presented in the table below.

Characteristic	Symbol	μ	σ	Units
Central pressure depth	Δp	3.60	0.38	[hPa]
Forward movement	C_{fm}	3.40	0.38	[km/h]
Direction of movement	γ	4.20	0.45	[deg]
Radius to max. wind speed	r_m $0 < \Delta p < 30$	4.61	0.31	[km]
Radius to max. wind speed	r_m $30 < \Delta p < 45$	4.39	0.59	[km]
Radius to max. wind speed	r_m $45 < \Delta p$	4.26	0.41	[km]

The typhoon characteristics increase/decrease slightly at landfall; values from a study of Fujii (1998) have been applied. As the duration of the tidal cycle and the duration of typhoon induced storm surge is of the same order both have to be taken into account as a function of time. The first tidal level at the moment of the passing of the typhoon is drawn randomly from a database containing two years of calculated tidal levels at a location near Kanda. The following levels are taken from the subsequent levels in the database.

MONTE CARLO SIMULATION AND RESULTS

To calculate the joint probability density function (p.d.f.) of the hydraulic boundary conditions at the location of the structure realizations are drawn from the specified p.d.f.'s of the typhoon parameters and the table of the astronomical tide. The model has been run 10000 times to produce sufficient data points to support a statistical analysis.

The results presented in Fig. 6 are the simulated data points and the fitted marginal probability distribution of the raised still water level during typhoons i.e. the sum of astronomical tide and wind/pressure set up caused by the typhoons. It appears that a lognormal distribution fits the simulated data well. The same is done for the wave characteristics.

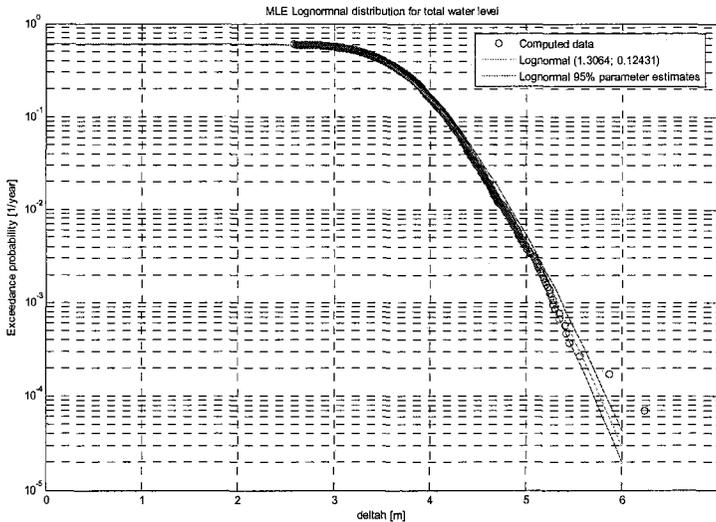


Figure 6: Approximation of the simulated water levels by a lognormal distribution

In reliability analyses the joint p.d.f.'s of the hydraulic loads have to be known as well as these joint loads are of importance for the failure of the structure. The joint distribution can be obtained via independent variables that are related to the hydraulic variables that have to be described with the joint p.d.f. for the reliability function (Vrijling and Van Gelder 2002). The derived independent marginal p.d.f.'s have been multiplied by the Jacobian to determine the dependent joint p.d.f.'s. The results of the water level and the significant wave height are plotted in Fig. 7.

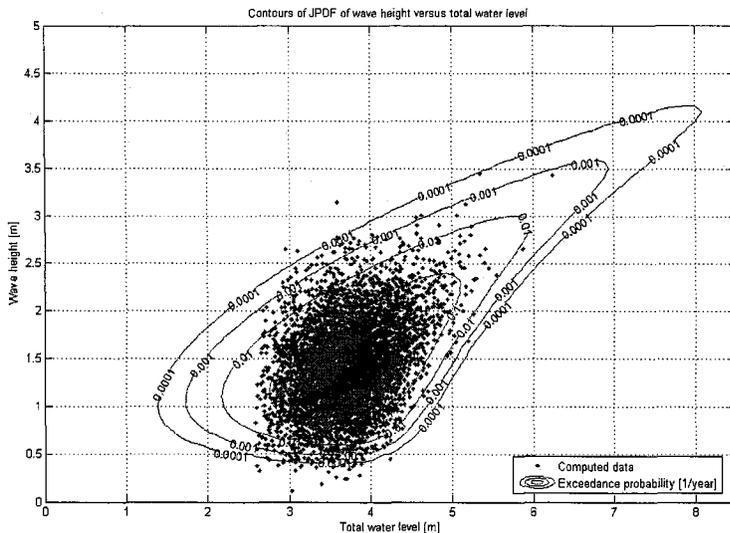


Figure 7: The simulation data of jointly occurring water levels and sign. wave height

It seems that the correlation in the lower regions of water level and wave height is not too strong, but for higher values a clearer dependence can be seen.

In the same way the joint p.d.f. of the significant wave height and the peak period can be found. So the aim formulated at the outset of establishing the joint p.d.f. of water level, significant wave height and peak period is reached. Some observations have been used to validate the joint p.d.f.'s. The results were not exact but the model showed similarity with the observations.

APPLICATION IN A DESIGN

Now the joint p.d.f. of water level, significant wave height and peak period is applied in the design of coastal structures. As an illustration the design of the crest level of a simple dike is shown here (Fig. 8). The crest of the dike is threatened by overtopping. The load, the wave run up is the sum of the water level and the actual wave run up. The actual wave run up is a function of the outer slope of the dike, the significant wave height and the peak period. In Fig. 9 the line gives the combination of all water levels and wave heights that produce a wave run up that just reaches the crest of the dike (the reliability function) according to formulae provided by the TAW (2002).

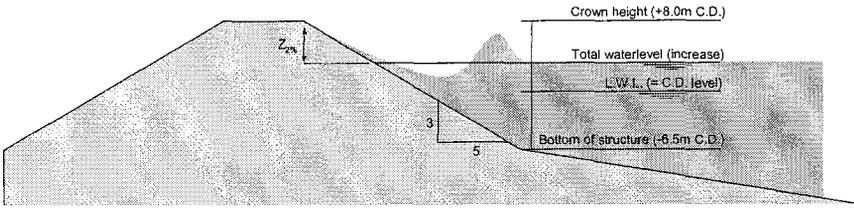


Figure 8: Cross section of a dike threatened by wave overtopping

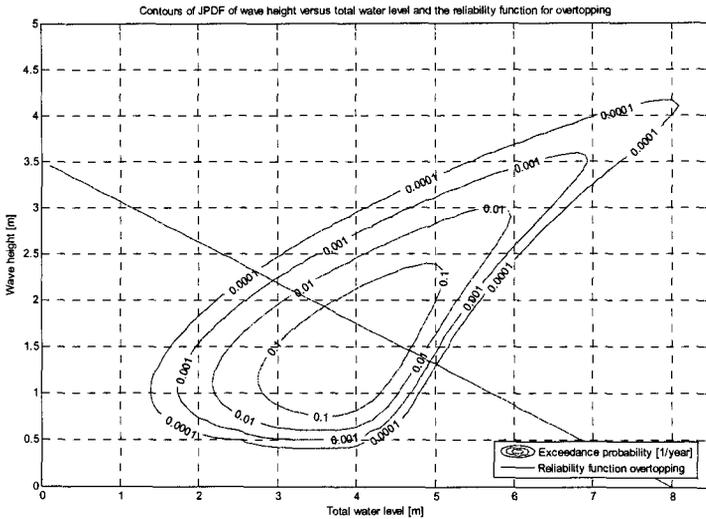


Figure 9: The joint p.d.f. of water level and wave height with the reliability function

The failure probability of this failure mode is the integral of the p.d.f. over the upper right “unsafe” part above the reliability function. This failure probability serves to estimate the risk of flooding. This risk is defined as the expected value of the loss i.e. the product of the probability of failure and the loss in economic and societal terms. When the risk is known a decision can be made about the optimal investment in a higher dike that will reduce the probability of a failure.

CONCLUSIONS

The research presented in this paper has shown that

- The simple deterministic model for wind/pressure set up and wave growth can predict the hydraulic boundary conditions observed during historical typhoons reasonably well.
- By applying Monte Carlo to this model, the marginal and joint p.d.f.'s of the hydraulic boundary conditions can be determined based on the p.d.f.'s of typhoon parameters and the astronomical tide.
- The observations of water levels and wave heights of historical typhoons are reasonably in line with the results of the Monte Carlo simulation.
- It is possible to derive the exceedance probability of the load from the p.d.f., here illustrated with the run up.

Overall, this model provides a simplified method for deriving distributions of wave characteristics and water levels. With these hydraulic boundary conditions a probabilistic evaluation of the safety level of dikes can be given in the context of performance design (Takahashi et al. 2004). The procedure followed provides a pathway for further probabilistic analysis of hydraulic boundary conditions in other areas of Japan.

It is recommended to apply the framework presented here to other bays that suffer from typhoon induced hydraulic loads.

- First use simple models for the hydraulic phenomena to gain experience, but replace them in a later stage with more refined models.
- The models predicting water levels and wave heights should be validated for various bays.
- The knowledge of the statistical properties of typhoon parameters should be extended and generalized.

Finally the good cooperation between Delft University of Technology, the Port and Airport Research Institute of Japan and the Dutch Ministry of Public Works is acknowledged.

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