WATER ACCUMULATION ON THE VEHICLE DECK OF A DAMAGED RO-RO VESSEL AND PROPOSAL OF SURVIVAL CRITERIA

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SUMMARY

Recent research at the University of Strathclyde culminated in the development of a numerical procedure for assessing the damage survivability of damaged Ro-Ro vessels and, using this as a basis, new survival criteria have been proposed and submitted to IMO. This paper presents the latest results of a fundamental study aimed at enhancing the insight into the flooding process and water accumulation on the vehicle deck of a Ro-Ro vessel during progressive flooding in waves, the emphasis here being on testing the said proposal. The investigation is based on a series of experiments using a scaled model of a typical Ro-Ro vessel. The matrix considered involves a range of ship design and environmental parameters in a number of simplified damage scenarios, starting with a fixed model and progressively introducing more degrees of freedom, building up to six degrees of freedom. The results of the experiments are presented and discussed, leading to recommendations concerning the validity of the proposed survival criteria.

INTRODUCTION

Concerted action to address the water-on-deck problem in the wake of recent well publicised Ro-Ro ferry disasters led to the proposal of new stability requirements, known as the *Stockholm Regional Agreement*, or more commonly as *SOLAS '90+50*, pertaining to compliance of existing Ro-Ro vessels with SOLAS '90 requirements whilst accounting for the presence of a maximum 0.5m height of water on the vehicle deck. In view of the uncertainties in the state of knowledge concerning the ability of a vessel to survive damage in a given sea state, an alternative route has been allowed which provides a non-prescriptive way of ensuring compliance, namely the "*Equivalence*" route, by performing model experiments in accordance with the requirements of IMO Resolution 14. An attractive alternative route to tackling the water-on-deck problem in a way that allows for a systematic identification of the most cost-effective and survivability-effective solutions has been introduced by the Ship Stability Research Centre (SSRC) at the University of Strathclyde, by making use of a mathematical/numerical model, developed and validated over the past years, describing the dynamic behaviour of a damaged ship in seaway whilst subjected to progressive flooding. This model was made the basis during the Joint North West European Project (JNWEP) for formulating and proposing rational survival criteria to deal with water on deck as part of the probabilistic procedure for assessing damage stability, [1]. A relevant paper was submitted to IMO and is currently being considered by the working group on harmonisation of probabilistic standards. In the developed mathematical model and the ensuing criteria the process of water accumulation on the Ro-Ro deck as well as the actual amount of water are dominant features. In this respect, an acceptably accurate model of water ingress/egress is a prerequisite to undertaking any investigations on damage survivability.

Deriving from the above, this paper presents and discusses results from the third series of an extensive experimental programme aimed at enhancing understanding and insight of this complex phenomenon and of producing corroborative evidence to support the proposal of the JNWEP concerning probability of survival with water on deck, a brief introduction of which is given in the following before addressing the experimental programme and derived results.

PROBABILITY OF SURVIVAL WITH WATER ON DECK

The new damage stability framework proposed by the JNWEP is based on the probabilistic concept of survival. This means that the standard of survivability is expressed in terms of the probability that the vessel will survive, given a damage with water ingress has taken place. The total probability of survival depends on two factors: the probability that a compartment is being flooded and the probability that the vessel will survive flooding of that compartment. The concept itself is simple, but it takes a great deal of effort to establish correct formulation of these two factors, particularly when it involves large scale flooding of extensive undivided deck spaces such as the vehicle deck in Ro-Ro ferries. Concerning the latter and taking into account that there are many effects causing a vessel to capsize, the probability of survival can also be divided in two different factors: the probability to survive pure loss of stability, heeling moments, cargo shift, angle of heel and progressive flooding and the probability to survive water on deck as result of wave action.

The calculation of this last factor, referred to as survival factor with water on deck, s_w, is based on a concept whereby the critical wave height at which the vessel will capsize is found, and s_w will simply be the probability that this wave height is not exceeded. In this respect, the critical task has been to formulate a connection between the critical sea state and parameters which can be readily calculated without resorting to costly, time consuming numerical simulations or physical model experiments. For this reason all model tests and simulations have been directed towards this goal, and the result is presented in [1]. A key observation from this work is that vessel capsizal occurs close to the angle where the righting moment has its maximum, i.e. θ_{max}, calculated traditionally by using the constant displacement method and allowing for free-flooding of the vehicle deck when the deck edge is submerged. This fact, coupled with observations from physical model experiments and the experience amassed from studying large numbers of numerical tests led to the development of a "*Static Equivalent Method*" which allows for the calculation of the critical amount of water on deck from static stability calculations. To this end, a flooding scenario is considered in which the ship is damaged only below the vehicle deck but with a certain amount of water on the (undamaged) deck inside the upper (intact) part of the ship. The critical amount of water on deck is then determined by the amount causing the ship to assume an angle of loll (angle of equilibrium) that equals the angle θ_{max}.

Based on this, the volume of water on deck causing the vessel to assume an angle of loll (angle of equilibrium) that equals the angle θ_{max}, was compared with the critical volume of water at the instant of capsize and a good correlation was found. The scenario described above and depicted in Figure 1, is believed to represent closely observations of the flooding process near the capsize boundary or when a stationary (steady) state is reached with the water on deck elevated at an average height, *h*, above the mean water plane, as a result of the wave action and vessel motions. It was subsequently shown that this height is a unique measure of ship survival in damaged condition - the higher the water elevation the higher the sea state needed to elevate the water to this level and the higher the capsizal resistance of the ship - that could be applied universally to all the arrangements studied, involving ship size and shape, subdivision arrangements and loading conditions. It follows, that the relationship between h and Hs will also be unique for a given ship, thus allowing the survivability of the vessel to be expressed as a function of the critical significant wave height as denoted below:

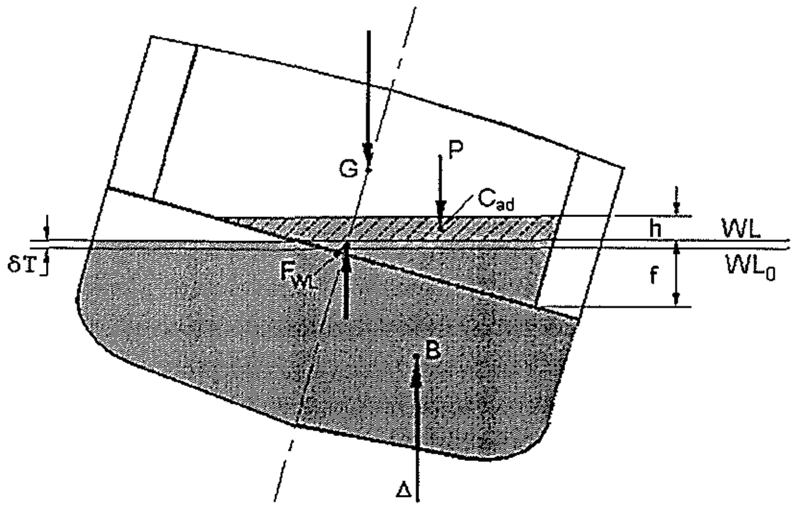

Figure 1: Stability of a Damaged Ship with Water Accumulated on Deck
(*Static Equivalent Method*)

$$h_{crit} = f(Hs) = 0.085\ (Hs_{crit})^{1.3} \tag{1}$$

where, h_{crit} = the difference between the inner and outer waterline at the instant of capsize
Hs_{crit} = the critical significant wave height

Some additional data and a re-examination of the data presented in [1], showed that the effect of damaged freeboard had to be taken into consideration. This, in turn, led to the proposal of the following relationship, [2]:

$$h_{crit} = f(Hs, F) = 0.088\ (Hs_{crit})^{0.97+0.46F} \tag{2}$$

At the time, it was conjectured that Hs is raised into some power other than unity as it was the significant wave height measured relative to the deck of the ship at the location of the damage opening in a way that accounts for the vessel motion (i.e., the significant relative wave height - incident) that was the parameter of interest rather than the nominal significant wave height.

EXPERIMENTAL PROGRAMME

Damage Scenarios and Test Conditions

To foster a better understanding of the water accumulation on Ro-Ro vehicle decks, a series of experiments has been planned and is taking place at the University of Strathclyde. In this paper the results of the third series of tests are presented, addressing the mean asymptotic height of floodwater on the vehicle deck *h*. The results of the first two series were presented in last year's workdhop. The additional parameters in the experimental matrix comprise wave characteristics, freeboard and KG involving the model in six degrees-of-freedom. The model used in these experiments is described in [4] and is a 1:42 scale model of a typical Ro-Ro vessel, the main particulars of which are shown in Table 1. There are two compartments open to the sea: the first is above the vehicle deck and extends from 22.25m to 97.25m from the aft perpendicular and the second between the double bottom and the vehicle deck with a length that was adjusted by inserting blocks of foam to allow for changes in the damaged freeboard as shown in Table 2. Additional values for damaged freeboard could be obtained similarly.

Table 1: Main Particulars of the Ro-Ro Vessel Used in the Experimental Investigation

L_{BP}	(length between perpendiculars)	=	131.0 m
B	(breadth)	=	26.0m
T	(design draught)	=	6.10m
D	(depth to uppermost continuous deck)	=	18.8m
D_{bd}	(depth to bulkhead deck)	=	7.8m
D_{db}	(depth to double bottom)	=	1.6m
Δ	(displacement)	=	12200 tonnes
C_b	(block coefficient)	=	0.582

Table 2: Flooded Compartment Lengths

Length of Compartment (m)	Distance from A.P. (positive forward) (m)		Damaged Freeboard (m)
	Aft End	Forward End	
13.3	52.6	65.9	1.08
22.8	47.15	69.95	0.6
28.7	43.66	72.36	0.2

SERIES 3

In the third series of the experimental programme all three damaged freeboards of Table 2 have been considered but tests were undertaken only in irregular waves as specified in Table 4 and for damage scenario 3. Furthermore, in addition to the fixed, heaving only, rolling only and heaving and rolling modes of motion of series 1 and 2, water accumulation with the model freely drifting and capable of responding in six degrees-of-freedom is investigated in series 3. Three different loading conditions were also tested, corresponding to KG values of 9, 10, and 11 metres.

Presentation of Results and Discussion

Volume of Water on Deck

Considering this parameter, it is noteworthy that the trend observed in the previous two series, i.e., increasing the degrees of freedom results in lesser amount of water accumulated on deck is also clearly demonstratd in these results, as shown in Figure 2. Moreover, the influence of sway in affecting water accumulation deserves special attention.

Height of Water on Deck (h)

The difference between predicted and measured values concerning *h* was shown to decrease with increasing number degrees of freedom. In this respect, the measured *h* when the model is free to move in all degrees of freedom appears to be in reasonable agreement with that predicted by using equation (1). This is shown in Figure 3, with the influence of sway being again noteworthy. In Figure 4, on the other hand, the predicted *h* using equation (2) is compared with the measured values for two freeboards. Again results do not appear to depend critically on freeboard in a way that clear trends emerge. More emphasis on clarifying this will be placed in the forthcoming seies 4 of this on-going experimental programme

CONCLUDING REMARKS

3ased on the results derived in Series 2, the following points are noteworthy:

- Restraining a model changes the flooding process appreciably and is not recommended, particularly when model is not allowed to sway freely.
- Corroborative evidence has now been produced in support of the proposed relationship between the seastate and the height of water on deck and of the probabilistic framework for assessing the damage survivability of passenger/Ro-Ro vessels, proposed by the NWEP.

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[3] Letizia, L.: "*Damage Survivability of Passenger Ships in a Seaway*", Ph.D. Thesis, Department of Ship and Marine Technology, University of Strathclyde, November 1996.

[4] DMI 88116: "*RO-RO Passenger Ferry Safety Studies Model Test for F10 - Final Report of Phase I*", DMI Project Report to the UK Department of Transport, 1990.

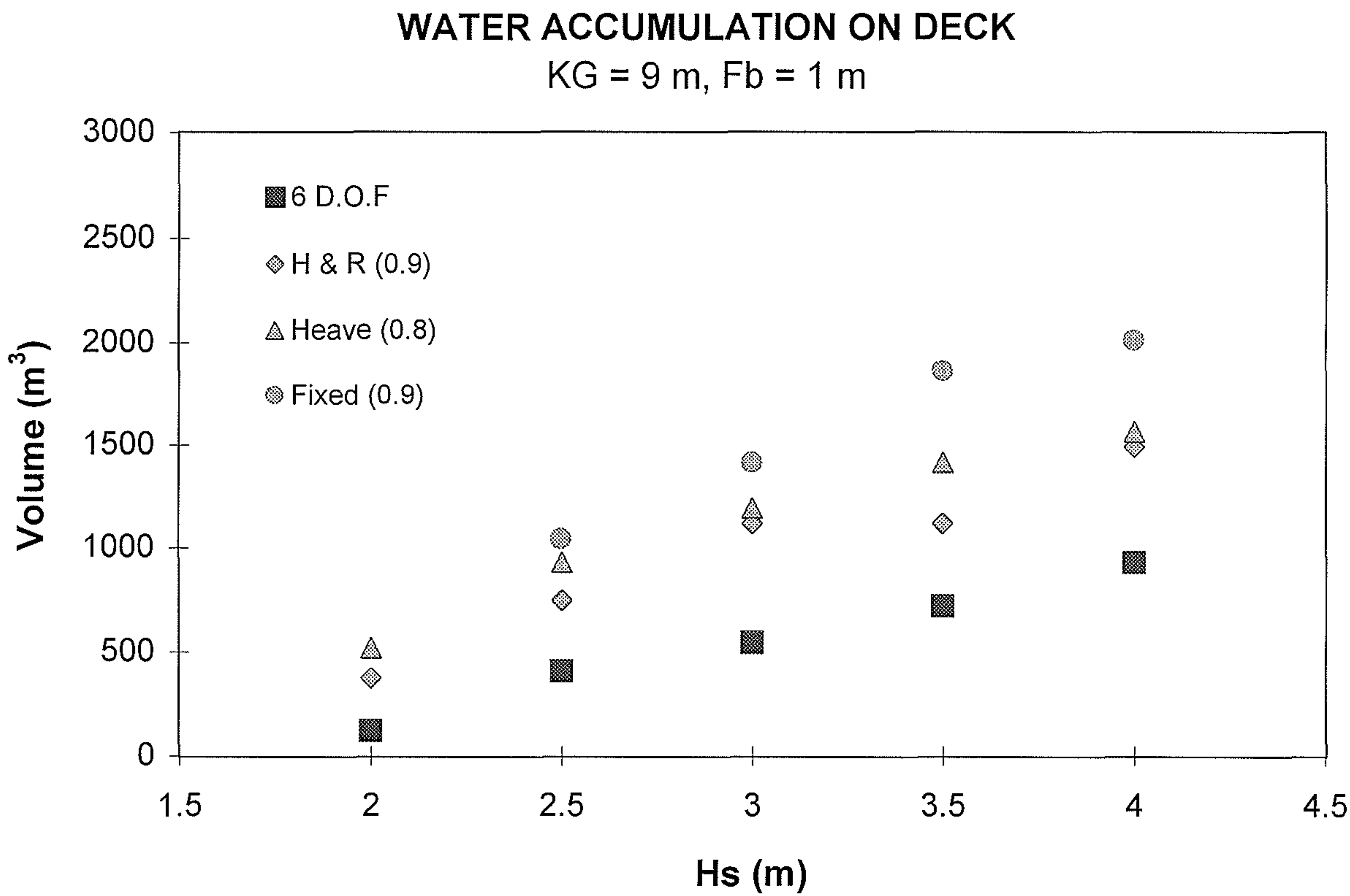

Figure 2: Effect of D.O.F. on Water Accumulation

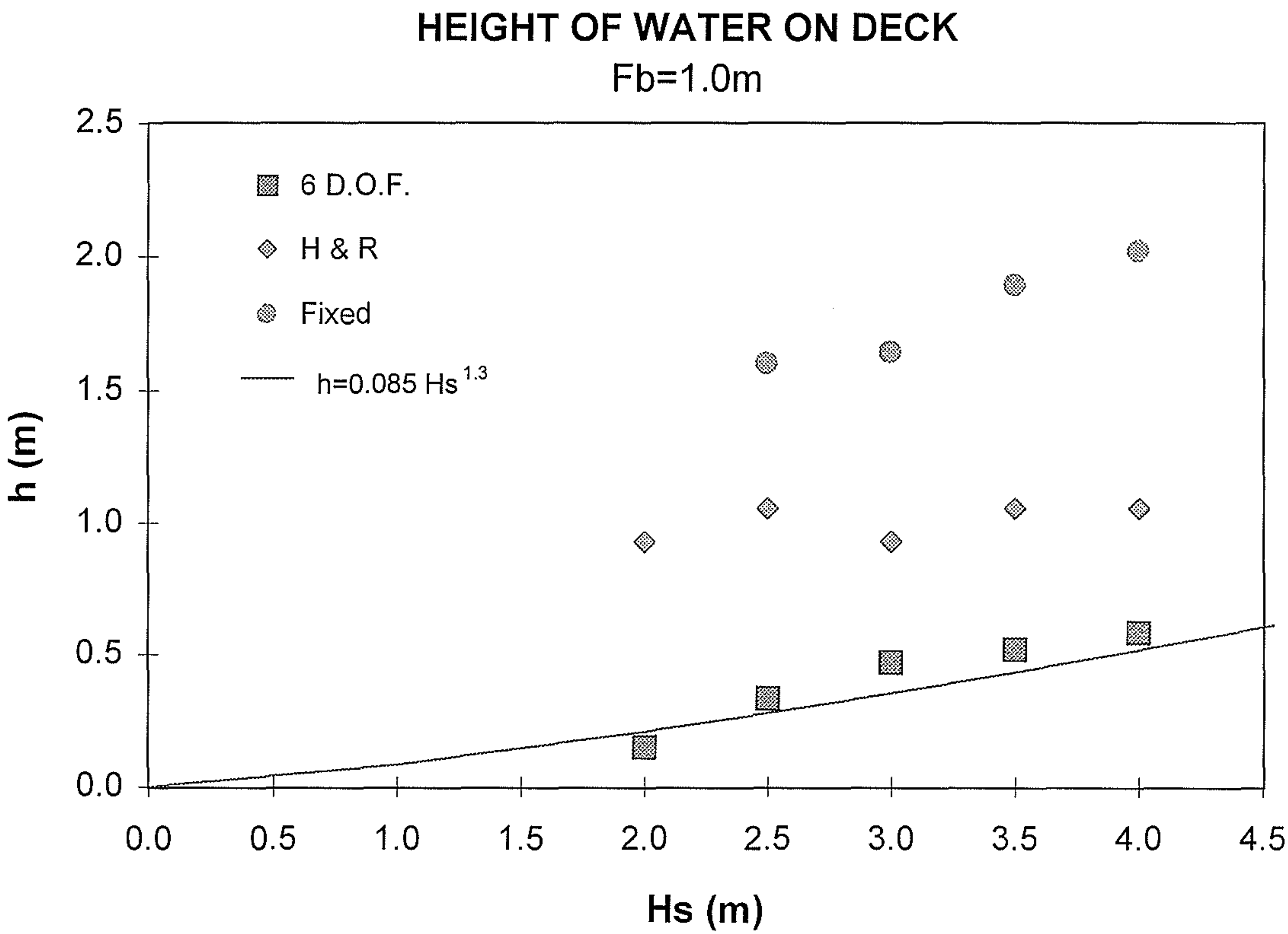

Figure 3: Effect of D.O.F. on Height of Water on Deck

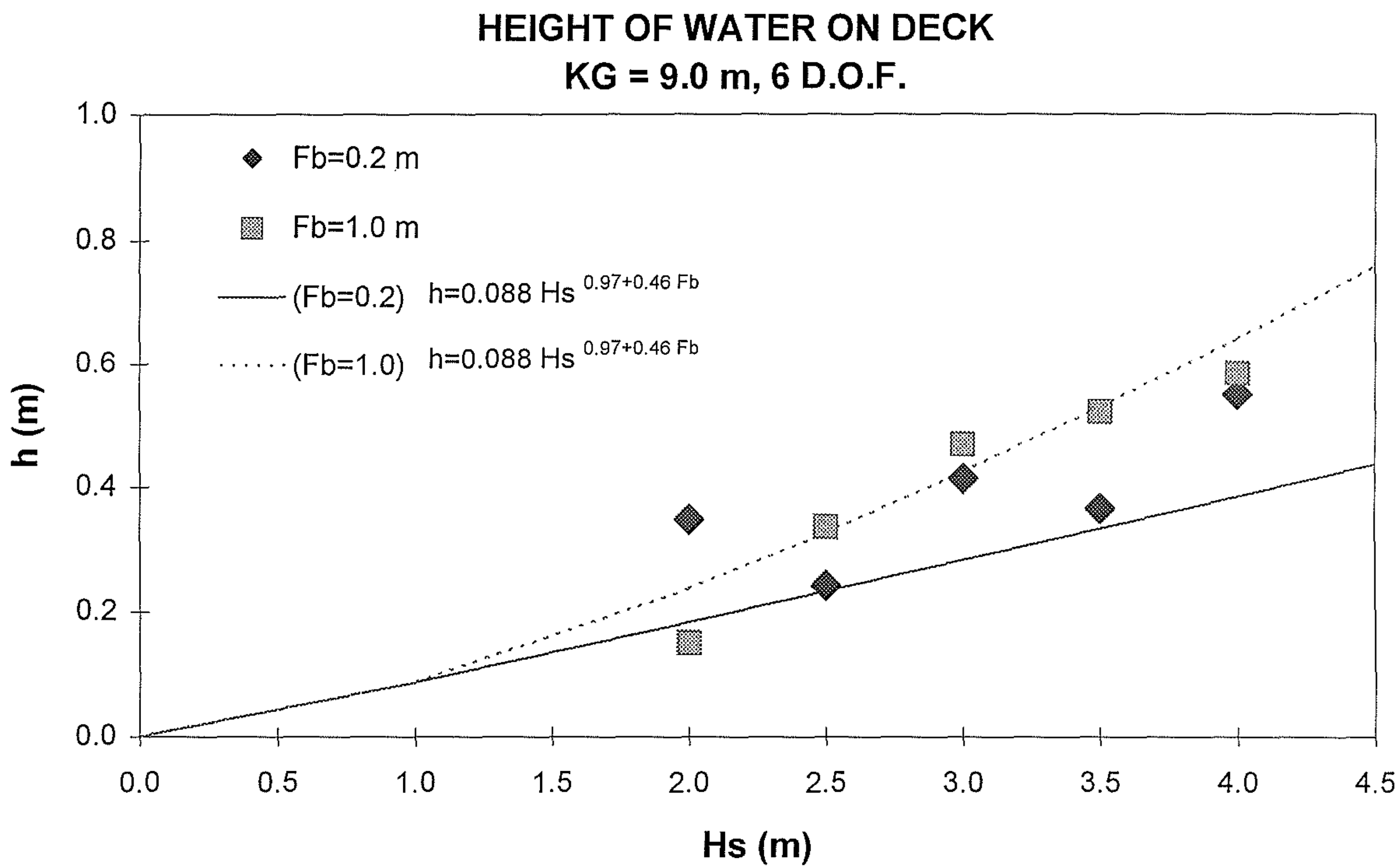

Figure 4: Effect of Freeboard on Height of Water on Deck