Proceedings of Coastal Engineering, JSCE, Vol.2, 2011, November

DESIGN OF COMPOSITE CAISSON BREAKWATERS UNDER EXTREME SEA LEVEL RISE SCENARIOS

Miguel Esteban[1], Hiroshi Takagi[2] and Tomoya Shibayama[3]

[1]Dept. of Civil and Environmental Engineering, Waseda University, esteban.fagan@gmail.com
[2]Department of International Development Engineering, Tokyo Institute of Technology, htakagi.jp@gmail.com
[3] Dept. of Civil and Environmental Engineering, Waseda University, shibayama@waseda.jp

Climate change and sea level rise will pose considerable problems for the future design of breakwaters. In the present paper the problems related to the design of composite caisson breakwaters are discussed. It appears that the philosophy behind the design of the armour will have to change, possibly adopting the limiting breaker height as the main design parameter, to deal with future uncertainties in wave climate and sea level rise. It will also be shown how the armour must be well designed, as any erosion to it can result in a big increase in the forces applied by the waves to the caisson, which would precipitate its failure.

Key Words **:** *climate change, composite breakwaters, sea level rise, armour units, caissons*

1. INTRODUCTION

Sea level rise due to global warming is accepted nowadays as a scientific fact, and it is estimated that during the 20th century the global average sea level rose by an average of around 1.7mm per year. Satellite observations available since the 1990's have shown that since 1993 sea level has been rising at an annual rate of around 3mm, according to the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 4AR). According to this report, the consequences of increased concentrations of greenhouse gases in the atmosphere will result in further increases in sea level, which is projected to rise by between 0.18 and 0.59m by the end of the 21st century, though more recent research predicts even higher levels of sea level rise (Vermeer and Rahmstorf, 2009).

Typically, the effect of climate change is ignored when designing breakwaters, which could lead to them being under-designed towards the end of their life. The effect of sea level rise on caisson breakwaters was investigated by Okayasu and Sakai (2006), who found that the probability of sliding failure could increase by up to 50% in the period ranging from 2000 to 2050 (assuming a design life of 50 years). Takagi et al. (2010) used a SWAN-based model to show how a 10% potential increase in the future wind speed of typhoons resulting from the warming of surface sea temperatures can lead to a 21% increase in the significant wave height generated by these winds. This effect, together with the rise in sea level detailed in the IPCC 4AR could make the expected sliding distances for the breakwaters at Shibushi Ports in Japan up to five times greater than at present.

Caisson breakwaters, however, are often protected by armour units that dissipate the energy of the incoming waves. These types of breakwaters are referred to as composite caisson breakwaters, and to the authors' knowledge, no research has been carried out on the effect of sea level rise on these types of structures. The present paper will try to establish some of the problems facing these structures under extreme sea level rise scenarios, and why it is important to modify current design practices in order to take into account the effect of global warming.

2. METHODOLOGY

(1) Sea Level Rise Scenarios

To understand the effect that climate change will have on composite breakwater design it is important to consider not only the effects of sea level rise, but the effect that a climate change induced acceleration in sea level rise can have on the design of these structures. Future patterns in sea level rise are highly uncertain due to a lack of understanding of the precise working of global climate and its interaction with the physical environment. A lot of this is down to uncertainty in the response of the big ice sheets of Greenland and Antarctica (Allison et al., 2009). In fact, it is currently believed that sea level is likely to rise much more by 2100 than the range of 0.18-0.59m given in the IPCC 4AR. In this report, the coupled models used for the 21st century sea level projections did not include representations of dynamic ice sheets, but merely estimated it by simple mass balance estimates of the contributions from Greenland and the Arctic ice sheets. In fact the IPCC 4AR assumed that ice was accumulating over the Antarctic ice sheet, though this is currently losing mass as a consequence of dynamical processes, as shown in Allison et al., (2009). Recent research such as that by Vermeer and Rahmstorf (2009) obtain that for the future global temperatures scenarios given in the IPCC 4AR the projected sea level rise for the period 1990-2100 could be in the 0.75 to 1.9m range. This research was done by linking sea-level variations on time scales of decades to centuries to the global temperature, which could explain around 98% of the variance in the data.

Four scenarios are considered in the present work, taking into account different levels of sea level rise for the period 2000 to 2050 and 2050 to 2100 (IPCC 4AR and Vermeer and Rahmstorf, 2009),

- Scenario 1: 0.15m increase, which would correspond to an annual increase of 3mm, similar to that at the end of the 20th century
- Scenario 2: 0.44m increase, which would be similar to the increase suggested by the worst IPCC 4AR in the period between 2050 and 2100
- Scenario 3: 0.9m increase, which would be half-way between scenarios 2 and 4.
- Scenario 4: 1.3m increase, similar to the increase suggested by Vermeer and Rahmstorf (2009) in the period 2050 to 2100.

(2) Design of Breakwater Armour

Composite caisson breakwaters consist of two parts, the caisson itself and the armour layer on the seaside of the caisson (see Fig. 1) The design of the armour was carried according to the Van der Meer (1987) formula. In order to simplify the problem, the authors only considered simple rock as armour, as considering different types of concrete armour would make the results more difficult to interpret without adding anything to the overall argument of this paper.

In designing composite caisson breakwaters there is the problem of attempting to guess what the future climate will look like. In a future where climate is expected to change, engineers will not be able to rely on past records to predict the wave heights at the middle or end of the life of a breakwater. Mori et al. (2010) analysed the annual averaged and extreme sea surface winds and waves throughout the world as a consequence of climate change, and found that there are clear regional dependences of both annual average and also extreme wave height changes from present to future climates. They thus believe that the wave heights in the future will increase at both middle latitudes and also in the Antarctic Ocean, with a decrease at the equator. However, like many climate predictions, this kind of work is highly uncertain, and it is likely that other work in the future will arrive at different conclusions. It is inherently difficult to predict the future, especially due to our lack of a complete understanding of how the planet operates. The practicing coastal engineer would thus be left in a situation of uncertainty regarding future wave climate and would hence have to design a breakwater relying on the only measure for which would give some degree of confidence on the wave heights, which would be the "Limiting Breaker Height", or H_b.

Assuming a rapidly changing climate which is not completely understood, the most important design parameter will become H_b rather than the significant wave height (H_s), as it is at present. As waves approach the coast line they are affected by the friction of the bottom floor and undergo a series of changes known as shoaling. Because of the horizontal component of the fluid velocity associated with the wave motion the crest of the wave steepens as the amplitude increases, till the wave eventually breaks. The term "Limiting Breaker Height" is often used, as there is an upper limit to the waves physically possible at a certain water depth for a given wave period. This parameter will have a crucial influence on the behaviour of a rubble mound breakwaters in with the event of rapidly rising seas, as it will increase the height of the waves that will be able to reach the structure. To date, many indexes for the limiting breaker height have been proposed. In the present work, the following equation proposed by Goda [1985] is used for evaluating the limit wave height that is possible in front of the breakwater H_b.

$$H_b = 0.17L_0\left\{1 - exp\left[-1.5\frac{\pi h}{L_0}\left(1 + 15tan^{4/3}\alpha\right)\right]\right\} \quad (1)$$

in which h is the water depth at the breakwater, L_0 is the deep water wave length and α is the slope of the sea bottom.

A total of 12 breakwaters sections were calculated, in water depths ranging from 3 to 25m. Each section was then calculated for a variety of significant wave heights (H_s), ranging from 3 to 15m. Each H_s was calculated for a total of 5 wave periods (ranging from 6 to 14 sec). Furthermore, all breakwater sections were calculated for 4 different bottoms slopes in front of the breakwater (θ) and for 2 different angles of the front slope of the structure (ω). All these combinations resulted in a total of 5440 different cases, providing a comprehensive understanding of the effect of sea level rise on composite breakwaters (see Fig. 1).

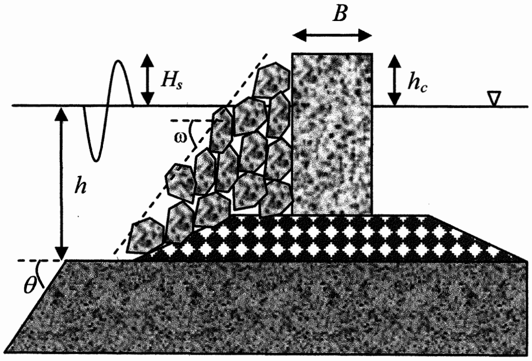

Fig.1 Schematic of a composite caisson breakwater showing the main parameters that govern its design

(3) Design of Caisson Units

For the design of caisson breakwater it is currently recommended that 3rd order reliability design methods should be used. One such method is that by Shimosako and Takahashi (2000) with the modifications proposed by Esteban et al. (2007). Both the models of Shimosako and Takahashi (2000) and Esteban et al. (2007) rely on the Goda formula (1974) as modified by Takahashi et al. (1994) to determine the pressure of the wave on the face of the caisson breakwater. However, this formula was not designed for an armour protected caisson breakwater. In order to correctly evaluate the failure of a caisson breakwater protected by a partially damaged armour layer Esteban et al. (2009) introduced an extra parameter to the Goda formula to take account this magnifying effect.

Goda (1985) indicates how the bearing capacity of the foundation is to be analysed by means of the methodology of foundation engineering for eccentric inclined loads. However, for sites where the seabed consists of a dense sand layer or soil of good bearing capacity a simplified technique of examining the magnitude of the heel pressure can be used. In this case, it is assumed that a trapezoidal or triangular distribution of bearing pressure exists beneath the bottom of the upright section, and the largest bearing pressure at the heel p_e can be calculated by using:

$$p_e = \frac{2W_e}{3t_e} \qquad : t_e \le \frac{1}{3}B$$

$$p_e = \frac{2W_e}{B}\left(2 - 3\frac{t_e}{B}\right) \qquad : t_e > \frac{1}{3}B \qquad (2)$$

in which

$$t_e = \frac{M_e}{W_e}, \qquad M_e = W't - M_U - M_P, \qquad W_e = W' - U \quad (3)$$

Where W' is the weight of the caisson per unit extension in still water, t the horizontal distance between the centre of gravity and the heel of the upright section, U the total uplift pressure, M_u the momentum around the heel of the caisson due to this uplift, M_p the moment around the bottom of an upright section due to the pressure at the face of the breakwater and B the width of caisson.

According to the modifications carried out by Esteban et al., eq. (2) would include a new parameter, α_a, which describes the influence of the armour on the load applied to the foundations:

$$p_e = \alpha_a \frac{2W_e}{3t_e} \qquad : t_e \le \frac{1}{3}B$$

$$p_e = \alpha_a \frac{2W_e}{B}\left(2 - 3\frac{t_e}{B}\right) \qquad : t_e > \frac{1}{3}B$$

$$(4)$$

Esteban et al. (2009) carried out laboratory experiment to determine the value of α_a as shown in Table 1. These values were obtained for different levels of erosion of the armour layer, ranging from no erosion for a full armour layer (layout A), to all armour being eroded (layout D), as shown in Fig. 2. An example of a real case of erosion of armour is shown in Fig. 3, which would correspond to Case B in the current paper. This case B is particularly dangerous, as breaking waves would exert over 3 times their normal force on the caisson, as shown on Table 1. Case D would correspond to a caisson breakwater with no armour, where the forces acting on the caisson would be calculated by the Goda formula (1974) as modified by Takahashi et al. (1994).

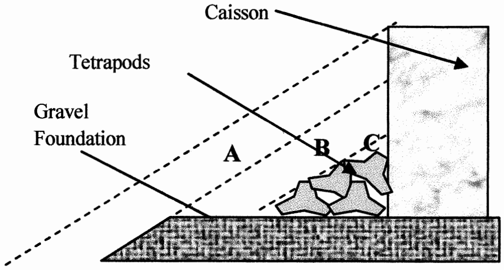

Fig.2 Different levels of armour erosion going from a full layer of armour (A) to all armour being removed (D).

Table 1. α_a parameter map

	A	B	C	D
Overtopping Waves	2.0	2.2	1.7	1.0
Breaking Waves	1.4	3.3	1.8	1.0
Non-breaking Waves	0.2	0.7	0.8	1.0

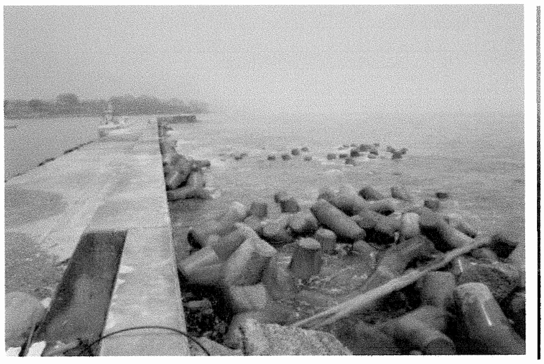

Fig.3 Erosion of armour layers in front of a caisson breakwater

3. RESULTS

An example of the influence that the water depth (*h*) in front of the breakwater and the period play on the increase in armour size between a control (no sea level rise) for two sea level rise design scenarios can be seen in Figs. 4 and 5. Fig. 4 shows the required weight of armour rocks for Scenario 2, compared with a control scenario where these is no sea-level rise. The figure plots the effect that sea level has on different values of *h*, for a θ=1:30 and a H_s=9m, showing how especially for the lower values of *h* the requirements in armour will increase substantially, as the H_b parameter will increase and hence higher waves will reach the breakwater. The effect is far more severe for Scenario 4, as shown on Fig. 5. Thus, for breakwaters designed in an environment where quick rises in sea level are expected, it will be necessary to design for much bigger armour units than what would otherwise be required, which will represent the added cost of adapting to climate change.

The effect of the increase in required armour is greater for the case of the sections with lower *h*, as for these cases an increase in sea level will also increase H_b. On the other hand, for the deeper sections H_b is less likely to be affected, and hence the armour requirements will not change substantially or at all, as shown in Figs. 4 and 5.

Regardless of the *h* at which the caisson are located, all breakwaters will require initial overboards that are greater than those with which they are designed today, as the overboard will have to be designed with the expected sea level at the end of the life of the breakwater. Again, this will represent an additional cost of adapting infrastructure to sea level change.

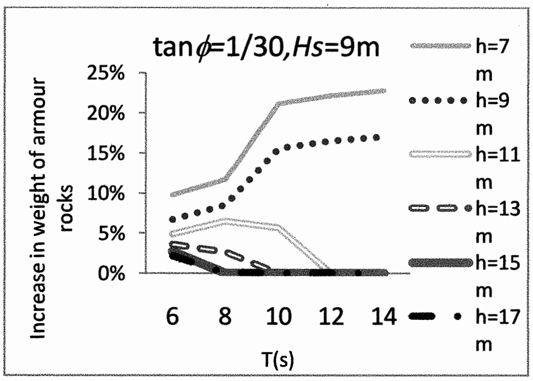

Fig. 4 Increase in the required weight of armour rocks for Scenario 4(1.35m sea level rise right), compared with no sea-level rise, for an H_s=9m

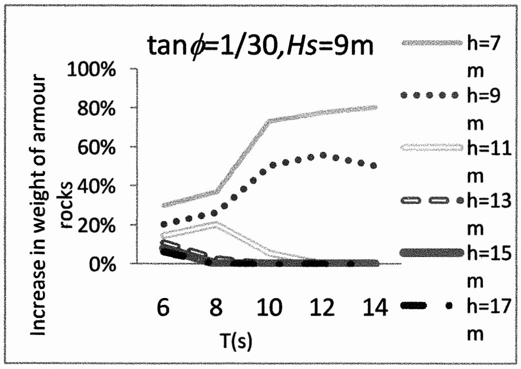

Fig. 5 Increase in the required weight of armour rocks for Scenario 2 (0.44m sea level rise over a 50 year period, left), compared with no sea-level rise, for an H_s=9m

4. CONCLUSIONS

A key problem for the design of breakwaters is the effect that progressively higher concentrations of greenhouse gases will have on the rate of sea level rise, which is expected to speed up in the second half of the 21st century (according to the IPCC 4AR). Thus, while a breakwater designed for an expected annual rise of 3mm would only require slightly stronger armour by the end of its life (see Fig. 4), for the case of accelerated sea level rise much heavier armour would be required (Fig. 5). As breakwaters are rather expensive infrastructure, this effect cannot be ignored and should be included in the computation of the cost of adapting coastal defences to the effects of climate change.

The methodology proposed by Esteban et al. (2010) highlights the problems posed by caissons protected by incomplete armour layers, and how these can magnify the forces exerted by the waves on the structures. It is thus imperative that the caissons are always protected by a full layer of armour. Incorrectly designed armour appears to be a greater problem than having no armour at all, and in a future of changing climate and raising sea levels it is thus more important than ever for the armour to be correctly designed.

The combined effect of sea level rise and changing wave patterns in the future (Mori et al., 2010) also casts doubt on the validity of current design methods based on historical data, and possibly warrant the need for future designs to be based on the concept of limiting breaker height. This represents a substantial deviation from the philosophy of current design methodology, but appears to be the only way to be sure that the breakwaters designed will be able to survive future changes in the climate.

ACKNOWLEDGEMENTS

The present work is supported by grant in aid for scientific work (Japan Society for Promotion of Science) (B) No. 22404011 and the Waseda university project research support for East-Japan Earthquake Research-Composed Crisis Research Institute.

REFERENCES

Allison, I., Bindoff, N.L,. Bindschadler, R.A., Cox, P.M., Noblet, N. de, England, M.H., Francis, J.E. Gruber, N. Haywood, A.M. Karoly,, D.J., Kaser, G,. Quéré, C. Le, Lenton, T.M., Mann, M.E., McNeil, B.I., Pitman, A.J., Rahmstorf, S., Rignot, E., Schellnhuber, H.J., Schneider, S.H., Sherwood, S.C., Somerville, R.C.J., Steffen, K., Steig, E.J., Visbeck, M., Weaver A.J. (2009).Copenhagen Diagnosis".*The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science*. http://www.copenhagendiagnosis.org/read/default.html, retrieved 26th January 2010.

Esteban, M., Takagi, H. and Shibayama, T. (2007). Improvement in Calculation of Resistance Force on Caisson Sliding due to Tilting. *Coastal Engineering Journal (CEJ)*, Vol. 49, No.4 (2007) pp 417-441

Esteban M., Takagi H. and Shibayama T. (2009) Modification of the Goda Formula to Evaluate the Movement of a Caisson Breakwater Protected by Failed Armour, *Proc. Of Coasts, Marine Structures and Breakwaters 2009*, 16-18 Sept, Edinburgh, UK.

Esteban, M, Takagi, H, and Shibayama, T. (2010) Modified Goda Formula to Simulate Sliding of Composite Caisson Breakwater. *Proc. of 32nd Int. Conf. on Coastal Engineering (ICCE 2010)*, Shanghai, China https://journals.tdl.org/ICCE/article/view/1046/pdf_272

Goda, Y. (1974)." New wave pressure formulae for composite breakwaters", *Proc 14th Int. Conf. Coastal Eng.*, Copenhagen, ASCE, pp.1702-1720.

Mori, N., Yasuda, T., Mase, H., Tom, T. and Oku, Y. (2010). Projection of Extreme Wave Climate Change under Global Warming, *Hydrological Research Letters*, 3, 15-19.

Okayasu, A. & Sakai, K. 2006. Effect of sea level rise on sliding distance of a caisson breakwater –optimization with probabilistic design method-, Coastal Engineering 2006, *Proceedings of 30th International Conference on Coastal Engineering, ASCE*, pp.4883-4893.

Takagi, H., Kashihara, H., Esteban, M. and Shibayama, T. (2011) Assessment of Future Stability of Breakwaters under Climate Change, *Coastal Engineering Journal*, Vol. 53, No. 1, pp. 21-39.

Takahashi,S., Tanimoto, K. & Shimosako, K. (1994). A Proposal of Impulsive Pressure Coefficient for Design of Composite Breakwaters, *Proc. of the International Conference of Hydro-Technical Engineering for Port and Harbour Construction*:489-504

Van der Meer, J. W. 1987. Stability of Breakwater Armour Layers. *Coastal Engineering*, Vol 11, p. 219-239.

Vermeer M. and Rahmstorf S. *Proc. National Academy of Sciences* PNAS 2009;106:21527-21532