REBUILDING COMPOSITE BREAKWATERS FOLLOWING THE 2011 TOHOKU TSUNAMI: LESSONS LEARNT AND DOES IT MAKE SENSE TO REINFORCE?

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Currently there are no formulas to design armour units against tsunami attack. The present work described laboratory experiments and field work that attempts to clarify the failure mechanism of these types of structures, and compares them with well established formulas such as that of Van der Meer or Hudson. It thus appears that the Hudson formula can be used to provide an indication of how large armour units would have to be to survive a tsunami attack with relatively little damage.

Key Words **:** *breakwaters, Tohoku, tsunami, armour units, laboratory experiments*

1. INTRODUCTION

The reliability of the different available tsunami counter-measures is being re-assessed following the March 2011 Tohoku tsunami. In this area a number of composite breakwaters and sea dykes were protected by armour units on their seaside face. Although many of these structures were designed primarily against storm waves, they nevertheless resisted comparatively well the forces exerted on them by the tsunami. The most important question at this point, however, is whether any such armoured structures should be given preference when designing tsunami counter-measures, and whether these counter-measures should be attempted at all. To date, a fair amount of research has been carried out on vertical structures and dykes. Tanimoto et al. (1984) performed large-scale experiments on a vertical breakwater by using a sine wave and developed a formula for the calculation of the wave pressure. Ikeno et al (2001) conducted model experiments on bore type tsunamis and modified Tanimoto's formula by introducing an extra coefficient for wave breaking. Subsequently Ikeno et al (2003) improved the formula to include larger pressures around the still water level, where the largest wave pressure was observed to occur. Mizutani and Imamura (2002) also conducted model experiments on a bore overflowing a dike on a level bed and proposed a set of formulae to calculate the maximum wave pressure behind a dike. Esteban et al. (2009) calculated the deformation of the rubble mound foundation against different types of solitary waves, allowing for the determination of the caisson tilt.

However, to the authors' knowledge no research has been carried out on the behaviour or armour units (in rubble mound or composite breakwaters) against tsunami attack. This paper will explore this from the dual point of view of breakwater design methodology and disaster risk management.

2. FIELD SURVEY

The authors of the present chapter conducted field surveys as a part of the larger 2011 Tohoku Earthquake Tsunami Joint Survey Group in Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures (Mori et al. 2012, Mikami et al. 2012). During these inspections detailed surveys of the failure of armour layer at various breakwater locations along the affected coastline were made. Two of these were composite breakwaters, those of Hikado and Ooya ports (see Fig. 1), located close to Kesennuma City. These two breakwaters are situated fairly close to each other and are facing the open sea, meaning that the tsunami waves would have attacked them directly. Three different measurements of wave heights were taken in this area, 15.7m (by the authors themselves) and 16.55 and 15m (by other members of the Tohoku Earthquake Tsunami Joint Survey Group). In the present analysis the authors have thus adopted their own value of 15.7m for the tsunami height at the breakwater, as it sits roughly half way between the other two values measured by the other teams.

Three different types of armour units were present at the breakwaters surveyed. Ooya port is made of Sea-Lock, and Hikado port has both X-block and Hollow Pyramid units along the breakwater (X-blocks in the body of the breakwater and heavier Hollow Pyramids at the head). The X-blocks and Sea-Blocks armour completely failed, and the armour units were scattered over a wide area in front of the breakwater, with only the top of some of the units still showing above the water surface. The exact failure mechanism is unclear, and whether the units were displaced by the incoming or the outgoing wave is not so easily established. In any case, the breakwater was overtopped with the whole of the area being completely underwater at one point during the tsunami attack (which would have also generated large underwater currents in the area).

A summary of these units can be found in Table 1 (along other typical armour units shown for comparison). The table also shows the Hudson Damage Coefficients (K_D) that were used for each of these armour units in the analysis.

Table 1. Summary of armour units surveyed

Unit	Approximate Weight	K_D
Sea-Block	3.2 tons	10
X-Block	5.76 tons	8
Hollow Pyramid	28.8 tons	10
Rock	N/A	4
Tetrapods	N/A	8
Tribar	N/A	10
Modified Cube	N/A	7.5

Fig.1 Damaged Sea-Block armour at Ooya Port

3. LABORATORY EXPERIMENTS

Laboratory experiments were carried out using solitary waves generated by a wave paddle in a wave flume at Waseda University in Japan as shown in Figs. 2 and 3 (dimension 14m long, 0.6m high, 0.41m wide). On one side of the tank a caisson breakwater was placed, which was protected by an armour layer made up of stones of different sizes (a total of 3 different stone sizes were used, with median weights W of 27.5, 32.5 and 37.5g) to test the sensitivity of armour weight on breakwater damage. Two different breakwater configurations were also tested (with a seaward angle θ of 30 and 45°). Each of the breakwater configurations was also tested for three different water depths, h = 17.5, 20 and 22.5cm. The number of armour units extracted after one solitary wave was counted with the aid of a high-speed photographic camera, and each of the experimental conditions was repeated 15 times to ensure accurate results.

The wave profile was measured using two wave gauges, one located approximately in the middle of the tank and the other one just before the breakwater, in order to measure the incident wave height. The solitary waves that were used were thus measured to have a half-period T/2=3.8sec, which would thus correspond to a T=76sec. The experiments were carried out in a 1/100 scale, which would represent a T=76sec wave in the real world. The waves generated were 8.4cm in height, thus corresponding to 8.4m in the real world. The wave profile as recorded by the measuring software is shown in Fig. 4.

Fig.2 Experimental layout of the breakwater

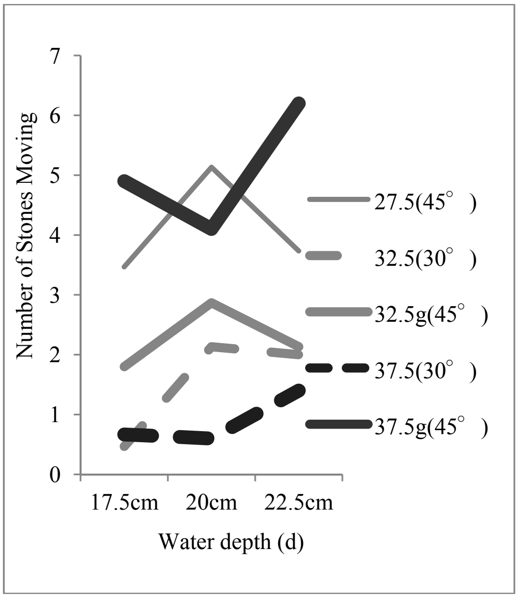

Fig.3 Average number of stones moved in each experimental condition

4. RESULTS

Fig. 4 shows the average number of armour units (*N*) extracted from the breakwater for each of the breakwater layouts, armour unit weighs and depths of water. Generally damage to the 45° structure was far greater than to the 30°, as expected. No pattern of damage could be clearly observed from the depth of water in front of the structure, and indeed the wave profile did not appear to significantly change between them (and which always looked like a solitary wave). This is different from the results of Esteban et al. (2009) which found that different types of waves could be generated for different depths (bore-type, breaking and solitary types waves), though in this case the depth of water did not change substantially between each experimental condition.

According to these, an armour damage parameter *S* similar to that used in Van der Meer (1987) was obtained for each of the breakwater configurations.

5. ANALYSIS

The values of *S* obtained from the experiments were compared with the theoretical values that would have been obtained using Van der Meer's equation, using only one wave (*N*=1). The results for each of the experimental conditions are shown in Figs. 4-8

In order to compare how well the results of the present experiments compared with the field data, the actual weight of armour (*R*) that would be required according to the Hudson formula over the actual weight of the armour at the two breakwaters in the field and the experimental results was plotted in Fig. 9. This figure shows the results for each of the types of armour layers and how those that have lower values of *R* failed completely (represented by S values of 15) whereas those units with higher values of R did not fail catastrophically. However, it is important to understand also that the field results represent breakwaters that were overtopped whereas those in the laboratory were not, and hence it is not clear that both results are comparable.

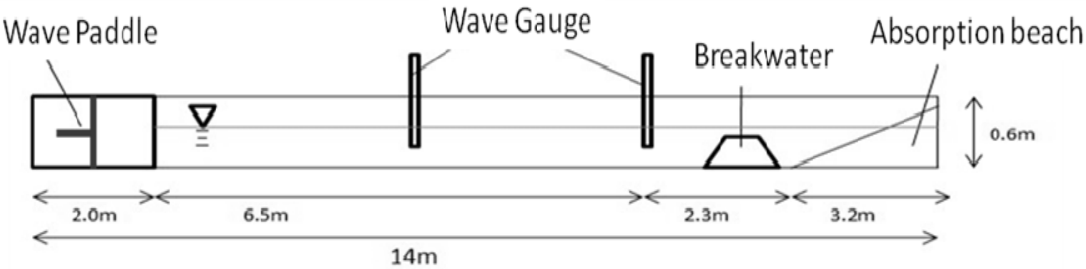

Fig.3 Experimental set-up

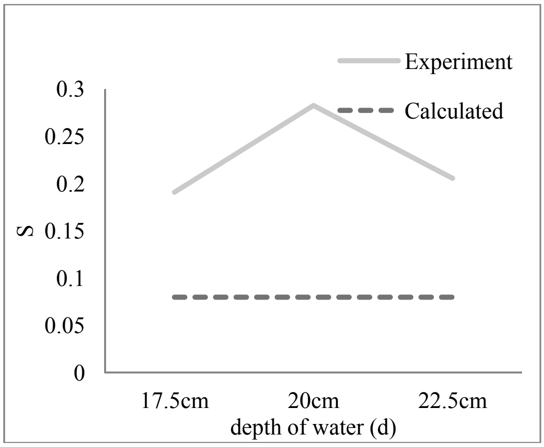

Fig.4 Experimental and calculated values for θ=45° and *W*=27.5g

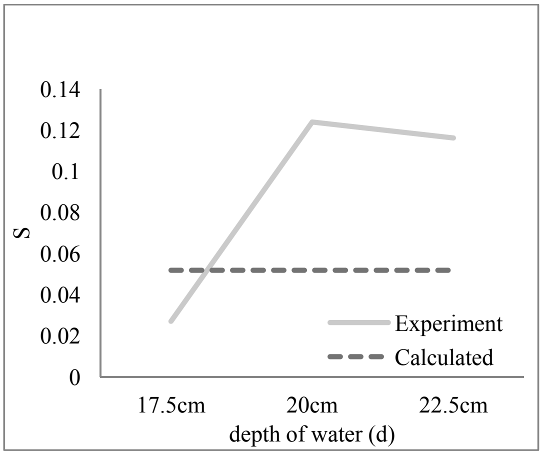

Fig.5 Experimental and calculated values for θ=30° and *W*=32.5g

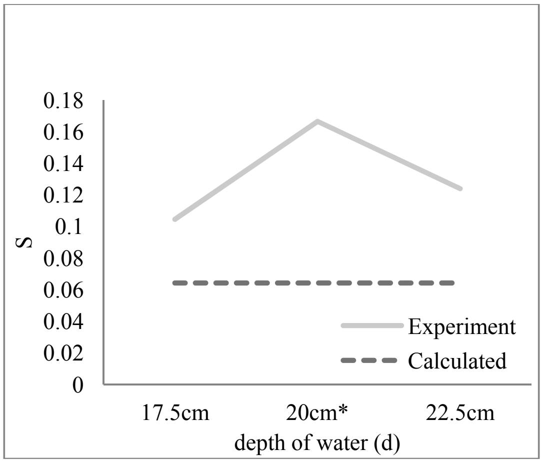

Fig.6 Experimental and calculated values for θ=45° and *W*=32.5g

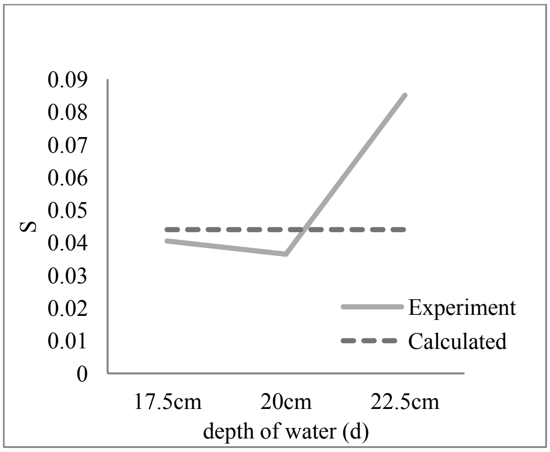

Fig.7 Experimental and calculated values for θ=30° and *W*=37.5g

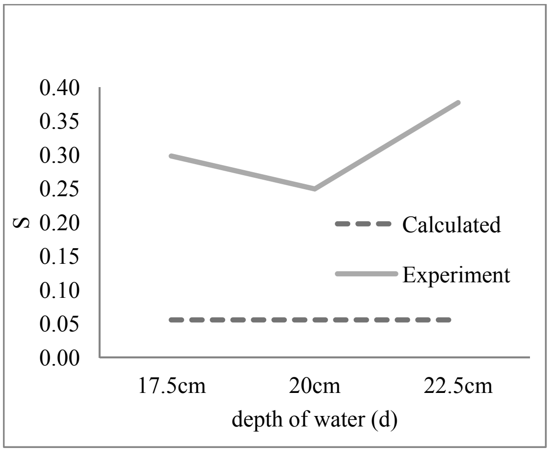

Fig.8 Experimental and calculated values for θ=45° and *W*=37.5g

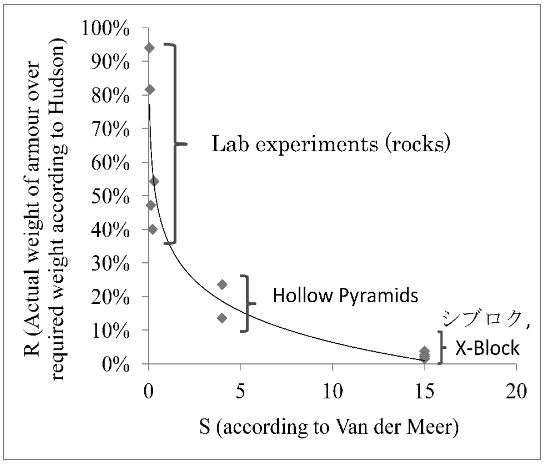

Fig.9 Plot of the actual over required weight of armour and the damage to each breakwater section

6. IMPLICATIONS FOR DISASTER MANAGEMENT AND CONCLUSIONS

Generally structures in Japan are designed by building them higher than the expected tsunami wave height, though following the 2011 Tohoku tsunami there is a general perception that structures must be designed to fail in a non-catastrophic way, even if their design criteria is exceeded. These were described by Kato (2012) as "tenacious structures", representing a structure that would slowly fail over the course of the event, while retaining some functionality, as opposed to a "resilient" structure, which would indicate a structure that would suffer limited damage even if its design load was greatly exceeded. Such a difference could be seen in the failure of the breakwaters at Kamaishi (which could be regarded as a "tenacious structure", as it suffered great damage but somehow survived the event) and that at Ofunato (which was completely wiped out).

The present work concerned itself mainly on breakwaters, though it is also relevant to coastal dykes, as in Japan these are often protected by armour units on their seaside, either placed directly in front of the dyke or a few dozen metres in front of it (in the beach or just immediately in front of the beach).

Currently, there is research going on in Japan on whether protection structures (such as dykes) should be reinforced in the future. Recommendations are thus being made on how to improve the resilience ("tenacity") of dykes, by improving their armouring or placing scour protection measures at their backside or at the toe of the structure (especially at the toe at the landside part of the structure).

Despite this, no formula has been developed in the past to design the armour of rubble mound breakwaters against tsunami attack. The question of whether to construct such structures to defend against a tsunami is controversial. Currently it is believed that such structures can protect property in the event of a level 1 event, though will have little effect for the case of a level 2 event. The erection of vertical barriers and dykes, however, can clearly give extra time for residents to escape, as seen by footage of videos during the disaster. Although these barriers can be ultimately destroyed by a level 2 event, it is unclear how much extra protection the armour units would provide, and whether it would be preferable to just create a wider concrete barrier. Much is still not understood about the failure of protective measures in the event of a tsunami, and their ability to delay the arrival of the flooding water must be carefully balanced against the extra cost of the armour units.

In this respect, much research is still needed to ascertain the failure mechanism of armour units, and whether the placement of these armour units will increase the forces acting on the caissons behind them, especially if the armour units fail (Esteban at al. (2012). Also, it would be important to establish the failure mechanism of the breakwater against the outgoing wave, as this can generate strong currents that could displace the armour. As a tsunami event is made of more than one wave, it is important also that the structure can offer some protection against the second or third waves (that can sometimes be stronger than the first)

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