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ADAPTATION OF DIFFERENT SCALES IN THE SAME 3D PHYSICAL MODEL TO ASSESS THE DIFFERENT ARMOUR SIZES

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ABSTRACT

While assessing the breakwater stability through a 3D physical model, the normal practice is to modify the structure element if the breakwater is unstable. However, casting a larger number of different sizes of concrete armour is time-consuming and costly. Therefore, the present study assessed the utilisation of the constructed model with 6.5T(1:41.37) to represent the 10.0T(1:47.82) and 12.5T(1:51.51) tetrapod (TTP) armours by using 88g TTP units in the model. Only the stability of the main armour at the roundhead was considered with new scales. Further, the same structure freeboard in the prototype was considered for new scales. Since the measured wave heights at the breakwater including the wave reflection from the structure, wave condition at the paddles were considered while selecting the input signals for the new scales during the trial runs. The selected inputs for the trail runs were verified with the post-calibration done for a 1:51.51 scale. Originally proposed 6.5T units were replaced by the hydraulically stable 12.5T units at the roundhead based on the model results done with different scales.

KEYWORDS: 3D physical model, Different prototype sizes, Different scales, Same model weights, Tetrapods Placement

1 INTRODUCTION

3D modelling has been carried out to assess the stability of the roundhead and the part of the outer trunk breakwater (~200 m) of the proposed layout. The proposed structure consisted of the core (inner core with existing breakwater materials considered as impermeable core and outer core with 1-500 kg quarry run), underlayer (0.3-1.0T rock) and 6.5 T tetrapods (TTP) at the head and, 5.0 T TTP at the trunk. The lee side of the trunk utilizes the 1.0-3.0 T rock instead of TTP units (Figure 1). During the testing, it was identified that the main armour at the head was not stable and all the other armour layers in the tested layout were stable for all the wave conditions. Therefore, the focal point was the main armour stability at the breakwater head. If the breakwater is unstable the normal practice is to modify the structure element while assessing the breakwater stability through a 3D physical model. However, casting a large number of different sizes of concrete armour is time-consuming and costly. Hence, an alternative method was identified to utilise the constructed model to assess the different sizes of TTP units. Therefore, the objective of this study was to utilise the different scales to represent the 6.5 T, 10.0 T and 12.5 T tetrapod armours by using 88 g TTP units in the 3D model.

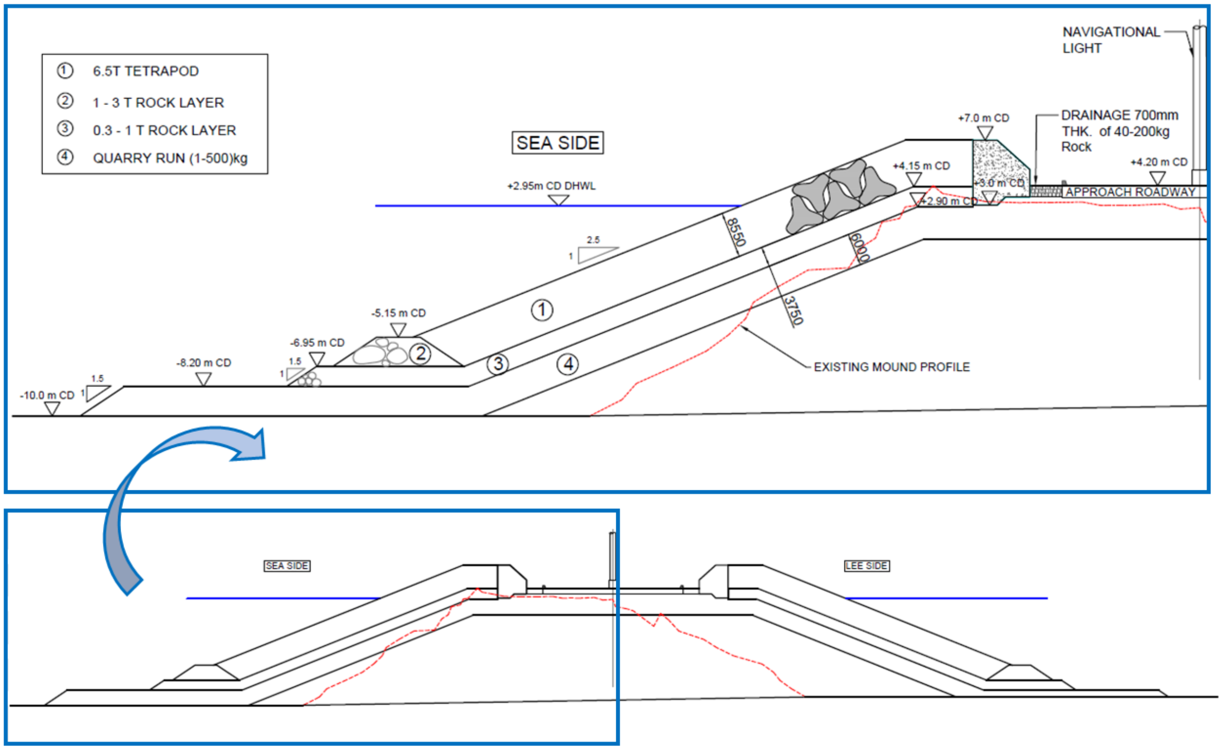

Figure 1. Cross section of modelled breakwater roundhead (Section X-X)

2 METHODOLOGY

2.1. Model Setup and Testing Procedure

Initially, the 1:41.37 scale was selected for 3D modelling by considering the basin dimensions (35 m long, 25 m wide and 1.0 m deep) and the available precast model units. According to the basin dimension, model scale and bathymetry of the site, it was decided to use the flatbed with -10 m CD (Chart Datum) depth for the selected layout. Waves need to be generated in the model a sufficient distance away from the area of interest in order to ensure the full development of waves by the time they reach the area of interest (IAHR, 2011). Therefore, a horizontal length of more than four wavelengths has been kept from the paddle to breakwater allowing the generated waves to be fully developed while they reach the structure. Wave-guide walls (18 mm thick plywood sheets) were placed at the sides of the wave generators to reduce undesirable wave spreading. In order to minimize the reflected waves being penetrated into the model area, wave absorbers have been placed along the boundary wall of the model basin.

The 3D model testing has been carried out at the Lanka Hydraulic Institute (LHI) laboratory's wave basin. The wave is generated in a particular direction using movable type paddles operating side by side controlled by a PC-based Wave Synthesizer software. In the wave generation process, wave parameters of wave height and wave period were specified and the JONSWAP spectrum based on these parameters was used to create input water level time series through inverse Fast Fourier Transformation (FFT) ((MIKE, 2009)). Resistance-type wave gauges which comprise two thin, parallel stainless-steel electrodes were used to measure the water surface elevation at appropriate locations in the basin to monitor the wave conditions.

The wave paddles have been calibrated for the original scale of 41.37 for different wave conditions (Table 1) to obtain the required input wave conditions for the wave maker. These input parameters have been used to obtain desired wave conditions at the proposed location of the model breakwater in the basin. This is to ensure that the waves are fully developed to the required wave spectrum a distance away from the wave paddles. Therefore, in order to achieve this, input parameters to be specified to the software operating the wave paddles have been found by analyzing the output signals acquired through the wave gauges placed in front of the wave paddles (N1, N2 and N3 in Figure 2) and near the structure (C1-C5 in Figure 2). Even though the layout was tested for two different directions of 350˚ and 280˚, this paper focuses on the 350˚ directional tests only as it was more significant than the other direction. A wave gauge which is located at the centre part of the paddles was considered to represent the wave climate at the structure location under each direction. Therefore, the C5 gauge is selected as the target point while obtaining the relevant inputs for the paddle (Figure 2). The calibration was carried out with a wave absorption system consisting of a perforated rubber sheet and a rubble mound slope placed at the boundaries/waveguide walls to minimize the reflection effects (Figure 2). Further, calibration curves have been developed for waves of different wave periods propagating from the different wave directions at different water levels in the 41.37 scale. These calibration curves have been applied to the input wave conditions to ensure the required wave conditions are achieved at the paddle during the testing. Further, during the testing, the T8 gauge was positioned at same location of C5 to identify the difference in wave climate with the presence of the breakwater structure.

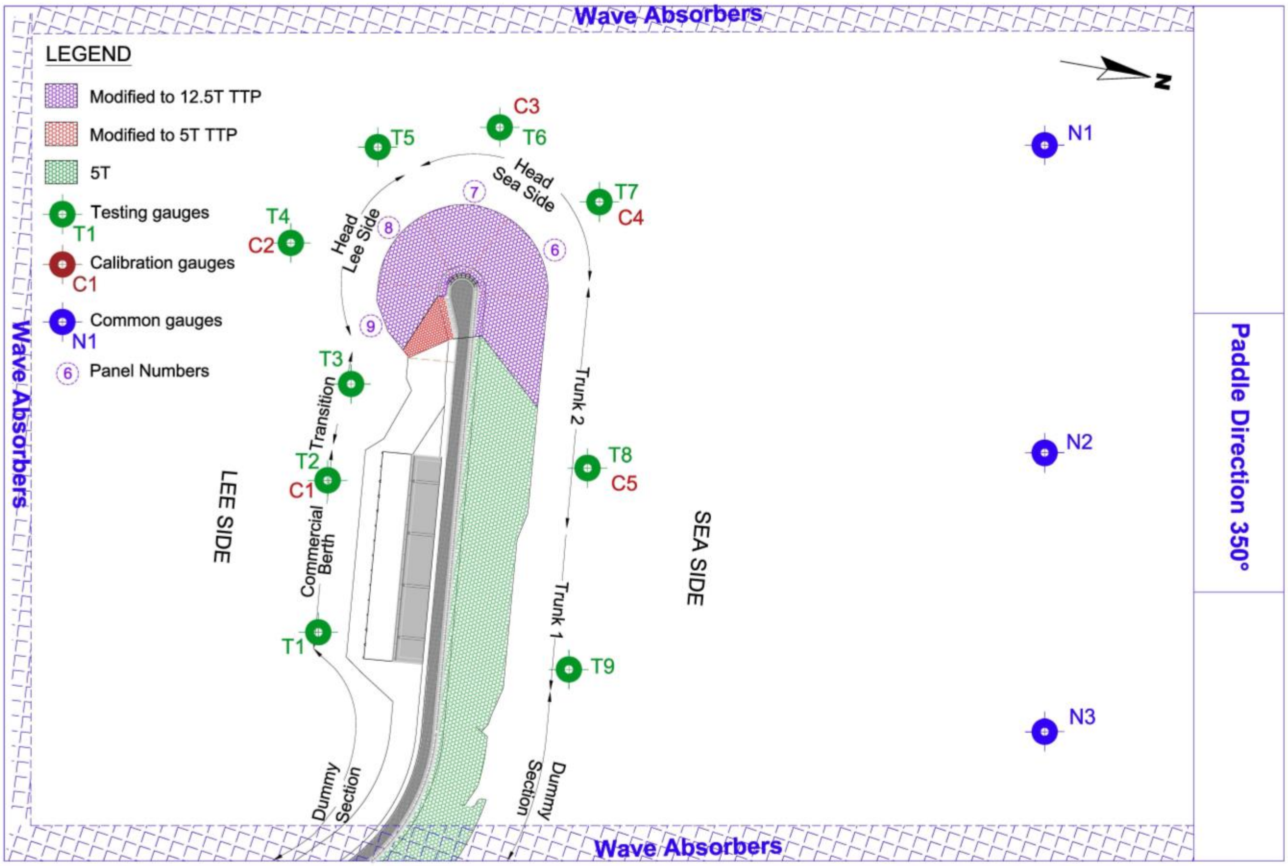

Figure 2. Model setup, gauge arrangement for calibration and model testing and proposed modification

2.2. Model Construction and Placement of TTP Units

The selected layout for the 3D model has been reproduced as a means of cross-sections at each chainage along the breakwaters. Prepared drawings of cross sections of the breakwater at stipulated locations to facilitate the construction of the structural section on the model bed. Gradation of armour units for the model tests has been done according to the standard specifications (CIRIA (2007)). The structural sections were constructed to the Geometrically Similar scales and the filling of layers follows in a sequence from the core, under layer, toe and main armours (Tetrapods and rocks) and the crest placing. Construction of the crown wall for the breakwater has been done as pre-cast single units and was placed at the crest.

As it is proposed to use the existing breakwater mound as the core of the new breakwater section, the existing mound has been formed as an impermeable core with constant slopes such that a layer of new quarry run is placed between the new armour and the existing mound (1 m thick on the lee side and 2 m thick on the seaside). Therefore, the actual condition of the existing core was represented in the model as a mortar bed. The representative TTP units for the main armour were cast using the available moulds maintaining the density to achieve the required model layer thickness and weight. The top surface of rock armours on all sections of the seaward and leeward slopes were painted with different colours to improve the damage assessment. Further, two separate colours were applied for each layer of the main armour which was placed in the side slope.

As the main objective is to assess the stability of the selected layout including the head section and part of the trunk of the main breakwater, the possible maximum scale of 1:41.37 was selected. Hence, necessary care has been taken on the boundary effect and to minimize that boundary effect on the interested area the main breakwater has been extended as a dummy section. In this 3D model, the main breakwater head (X-X) and some parts of the trunk have been properly scaled down and modelled while a part of the breakwater was constructed as a dummy section. The method of construction of armour and other units was done according to the specified placement patterns of the prototype in order to ensure that correct packing density and hydraulic stability were achieved. Additionally, the layout was split into 1.0-2.0 m sections and separated by a coloured line to enhance the stability assessment (Figure 2).

The placement method of the Tetrapod units on the primary armour layer is one of the important factors for breakwater hydraulic stability. Wear and breakage have been experienced in several structures caused by the rocking of the units in the top layer (Rock Manual, CIRIA 2017). The placement of the units as per the recommended standards is essential to guarantee the interlocking and the required porosity of the armour layer (Rock Manual, CIRIA, 2017). Random placement of Tetrapod units was proposed for the breakwater.

Figure 3a shows the random placement of Tetrapod units for the main armour of the breakwater. The top portion of the Figure 3a represents the first (lower) layer, these units can only be random around an axis normal to the slope. The bottom portion of Figure 3a shows the same part of the structure including the second (upper) layer. The placement grid is defined by the distances in X and Y directions, where Y is defined in the upslope direction and X is defined along the structure. The Rock Manual (CIRIA, 2017) gives the placement distance as $\Delta X = 1.98*D_n$ and $\Delta Y = 0.99*D_n$, with D_n being the nominal diameter of the unit (Figure 3b). The first, lowermost Tetrapods in the toe are placed on a horizontal face of 1-3T rock. From these two horizontal units, the lower layer is extended upslope using the placement grid as defined above. The upper layer is placed in the middle between the unit positions of the lower layer, thus resulting in the same placement distance.

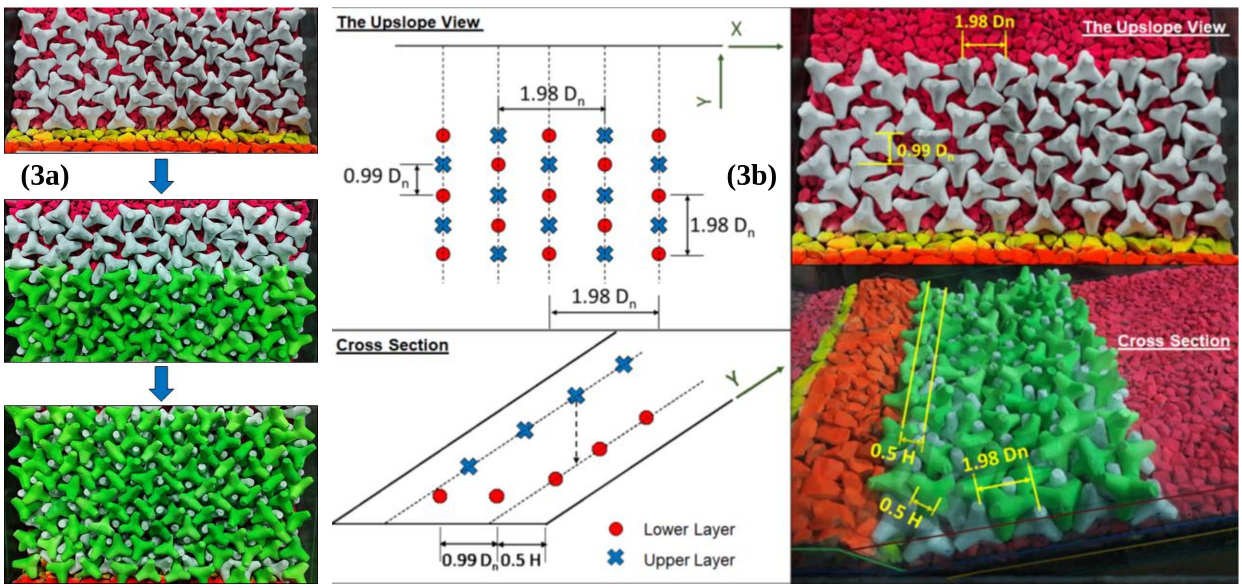

Figure 3. Plan view of the bottom and top layer placing (left-3a) and the schematic view of tetrapod placement in upslope and cross-section (right-3b)

Certain rules must be followed when placing units on the roundhead. The conical shape implies that the dimension of the crest will be different from the dimension of the toe. As a result, the number of units on each line can be significantly different from the toe line to the crest line. The horizontal and the upslope distances have to be modified in order to maintain a perfect interlocking between the units and a proper packing density. Templates have to be used for the placement. The use of a string indicating the position of the gravity centres is preferable. Attention is to be paid to where to place the string. It is recalled that the points drawn on the string represent the “gravity centre” then it would be wrong to put the string along the edge of the underlayer toe. It should be placed at 0.5 x H from the toe edge (Haskoning DHV, 2021; LHI, 2021).

At the toe of the roundhead, the horizontal distance between two gravity centres will be increased in function of the radius of the curve. This modified distance is to be called ΔX’ which varies depending on the radius of the curve. As a result, when placing the 1st-row Tetrapod units in the bottom layer of the roundhead, the ΔX placement distance has been increased by 10% of the theoretical value. ΔX’ distance has been kept consistent around the roundhead when placing the 1st row. The units in the 2nd row (bottom layer) were placed centrally between the units in the 1st row. In other words, the spacing between units decreases progressively going up the rows of the mound. Therefore, a transition row has been introduced after each 6th row i.e. at the 7th and 13th rows and ΔX was reset. The distances between the lines will considerably vary in function of their location on the slope in order to maintain the packing density as much as possible close to the theoretical values. The number of lines in the slope has to be checked in order to make sure that the packing density is in compliance with the theoretical values (LHI, 2021).

The distances between units in the lower layer must leave sufficient space to place the upper layer units and maintain the overall layer thickness. Placement of Tetrapod units starts from the seaside trunk section working toward each quadrant of the roundhead with a diagonal leading edge. **Error! Reference source not found.** indicates the key steps followed while placing the TTP units at the roundhead.

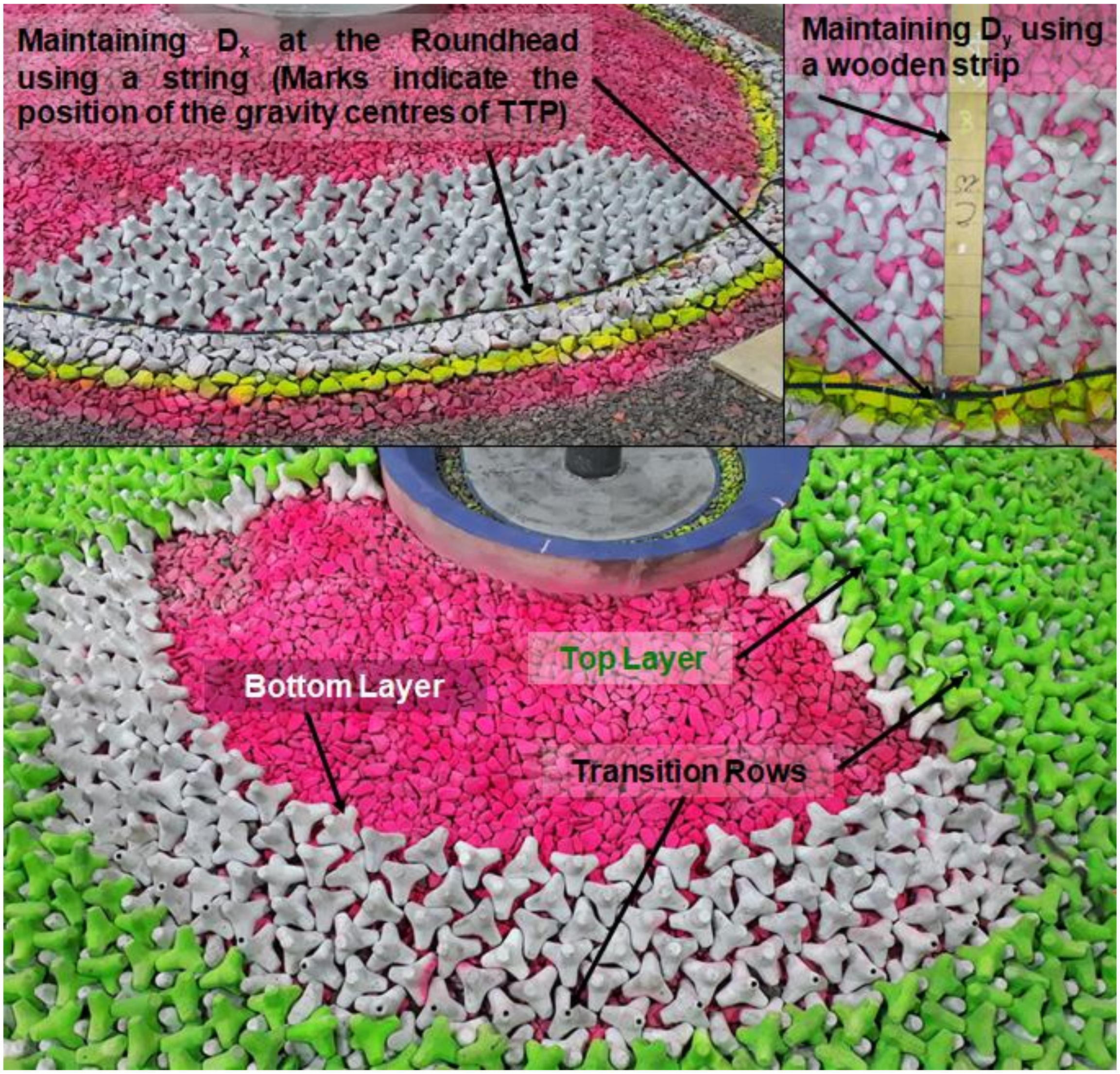

Figure 4. Tetrapods (TTP) placing at roundhead in 3D (basin)

2.3. Utilizing the Same Model Weight to Represent the Different TTP Sizes

Since the main armour size of 6.5 T (88 g in the Model) at the roundhead had to be changed during the testing model scale was changed accordingly to utilize the same constructed model to represent the higher TTP sizes. The 1:47.82 and 1:51.51 scales were selected to represent the 10 T and 12.5 T TTP units in the model respectively. The selection of the new model scale has been done using the following scale relationship, developed under Hudson's Stability Number Criterion (1979).

$$\frac{(W_{n50})_m}{(W_{n50})_p} = \frac{(H_s)_m{}^3 \rho_{s_m} \left[\frac{\rho_s}{\rho_w} - 1\right]_p^3}{(H_s)_p^3 \rho_{s_p} \left[\frac{\rho_s}{\rho_w} - 1\right]_m^3}$$

Where; $(W_{n50})_m$ = Weight of armour in the model, $(W_{n50})_p$ = Weight of armour in the prototype, $(H_s)_m$= Significant wave height in the model, $(H_s)_p$= Significant wave height in the prototype, $(\rho_s)_m$= Density of armour in the model, $(\rho_s)_{.p}$ = Density of armour in the prototype, $(\rho_w)_m$= Density of water in the model (Fresh Water), $(\rho_w)_p$= Density of water in the prototype (Sea Water).

Since the pre-calibration has not been done for the new scales trial runs were conducted with the structure to obtain the required input waves for different scales. As the measured H_s at the breakwater includes wave reflection from the structure wave condition at the paddles was considered while selecting the input signals for the new scales using trail runs. However, the post-calibrations were done to verify the input conditions selected based on the trial runs.

Out of the several wave conditions simulated 100 YRP waves with +2.55 m CD (N2: H_s=3.70 m, T_p=10.13 s), +2.95 m CD (N3: H_s=3.83 m, T_p=10.13 s) and +3.25 m CD (N4: H_s=4.44 m, T_p=12.16 s) water levels were considered while finalizing the main armour at the round head (Table 1). However, only the stability of the main armour at the roundhead was considered with the new scales as the structure dimensions and the rock armour details were also changed with the new scales. Furthermore, the same structure freeboard in the prototype was considered while adjusting the water levels for new scales in the model (Figure 5). The post-calibration runs were undertaken for a model scale of 1:51.51 to confirm the model inputs used in the test conditions. The details of the trail run and post-calibration are given in Table 1.

Both the selected inputs for the 12.5T-N3 and 12.5T-N4 tests were able to generate slightly higher wave heights than required at the target point during the post-calibration tests. Therefore, selected inputs for the 51.51 scale tests were successfully verified by post-calibration.

Table 1: Details of the trial runs for different scales

Test No.	WL (m CD)	Required			Scale	Main Armour	Input Hs (m)	Calibration Output at -10 m CD Depth				Selected Input Signals as Hs (m)
		@ BW		@ Paddle				@ BW (T8)		@ Paddle		
		Tp (s)	Hs (m)	Hs (m)				Hs (m)	Tp (s)	Hs (m)	Tp (s)	
K-8T-N2-Trail 1	+2.55	10.13	3.70	3.98	44.39	8.0T	3.81	3.81	10.03	3.93	10.03	3.85
K-10T-N2-Trail 2	+2.55	10.13	3.70	3.98	47.82	10.0T	3.68	3.83	10.41	3.74	09.83	3.90
K-12.5T-N2-Trail 3	+2.55	10.13	3.70	4.08	51.51	12.5T	4.03	3.94	10.20	4.17	10.20	4.16
K-12.5T-N3-Trail 4	+2.95	10.13	3.83	4.05	51.51	12.5T	4.05	4.12	10.20	4.14	10.20	4.05
K-12.5T-N4-Trail 5	+3.25	12.16	4.44	4.57	51.51	12.5T	4.54	4.58	12.25	4.63	12.25	4.54
K-12.5T-N3-PC	+2.95	10.13	3.83		51.51	12.5T	4.05	3.86	10.81	4.13	10.20	4.05 Verified
K-12.5T-N4-PC	+3.25	12.16	4.44		51.51	12.5T	4.54	4.64	13.12	4.63	11.48	4.54 Verified

Trial 1&2: Similar Wave Climate @ paddle: Trial 3: 10% Reflection @ T8

Trial 4&5: Req/Obs @ paddle is 1.01 (Taken from tests conducted thus far); Input/Paddle is 1.01 (Taken from N4 Calibration for 320 mm water depth)

PC-Post Calibration

N2				N3				N4				Test Condition
6.5	8.0	10.0	12.5	6.5	8.0	10.0	12.5	6.5	8.0	10.0	12.5	Main Armour @ Head(T)
41.37	44.39	47.82	51.51	41.37	44.39	47.82	51.51	41.37	44.39	47.82	51.51	Scale
0.411	0.411	0.411	0.411	0.411	0.411	0.411	0.411	0.411	0.411	0.411	0.411	Structure Height Model(m)
17.00	18.24	19.65	21.17	17.00	18.24	19.65	21.17	17.00	18.24	19.65	21.17	Structure Height Prototype(m)
10.00	11.24	12.65	14.17	10.00	11.24	12.65	14.17	10.00	11.24	12.65	14.17	Bed Level Prototype (- m CD)
12.55	13.79	15.20	16.72	12.95	14.19	15.60	17.12	13.25	14.49	15.90	17.42	Water Depth Prototype(m)
0.303	0.311	0.318	0.325	0.313	0.320	0.326	0.332	0.320	0.327	0.333	0.338	Water Depth Model(m)

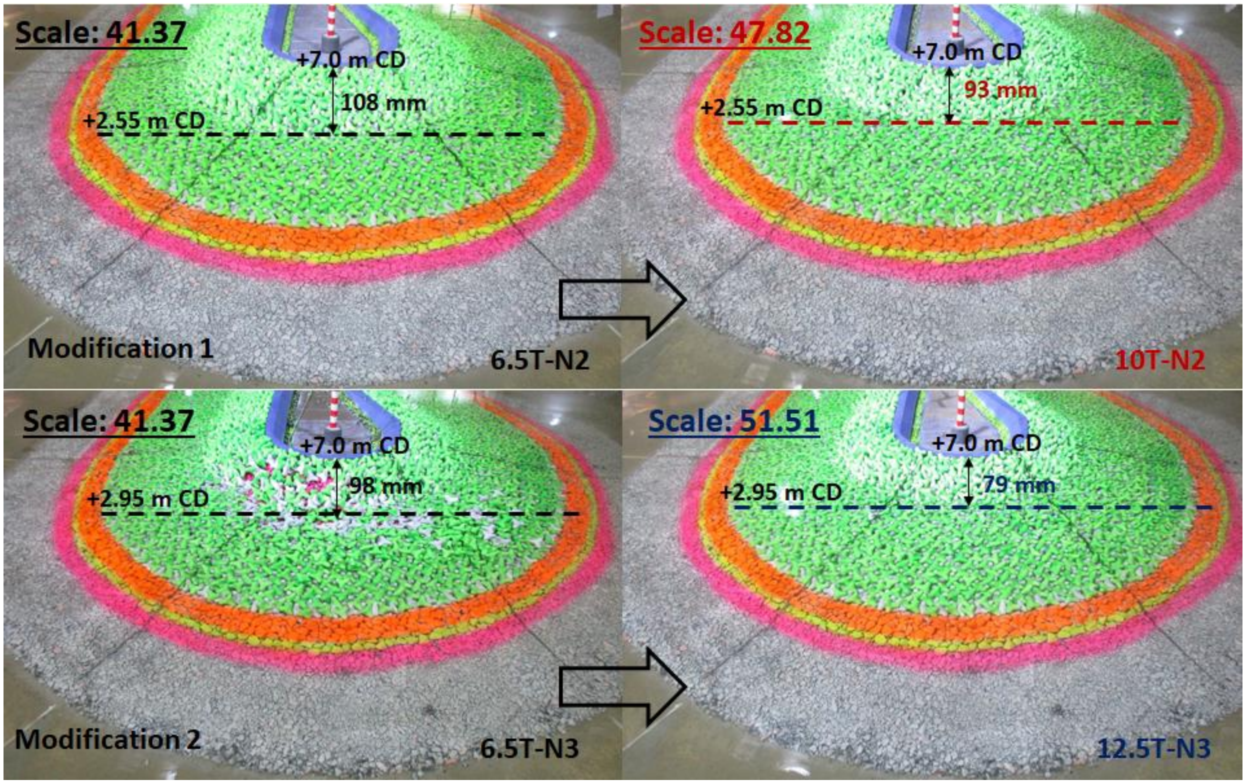

Figure 5. Representation of different armour sizes maintaining the same structure freeboard

3 DISCUSSION ON RESULTS

The N2 test done with a +2.55 m CD water level indicated 3.2% damage at the seaside of the Roundhead (Panel 6 & 7 in Figure 2). Even though the damage is calculated considering the entire section, the damage was concentrated in a particular area around the water level. The severity of the damage during the N2 could be identified as a few underlayer rocks were visible due to displacement of the TTP units at the bottom layer. As this localized damage could be progressive when the series is continued, it was decided to increase the armour at the roundhead up to 10T. However, damage analysis done for 6.5T TTP for the N3 test carried out at the end of the test series with +2.95 m CD water level confirmed the pre-judgement with the damage percentage of 8.82% which was also concentrated around the water level. Further, a higher number of units from the bottom layer of the TTP units was removed at a particular area of the roundhead by exposing the underlayer area due to the N3 test. Therefore, an increased weight of 10T TTP was tested for the 10T-N2 test and the localized damage was reduced to 0.95% (Figure 6 and Table 2).

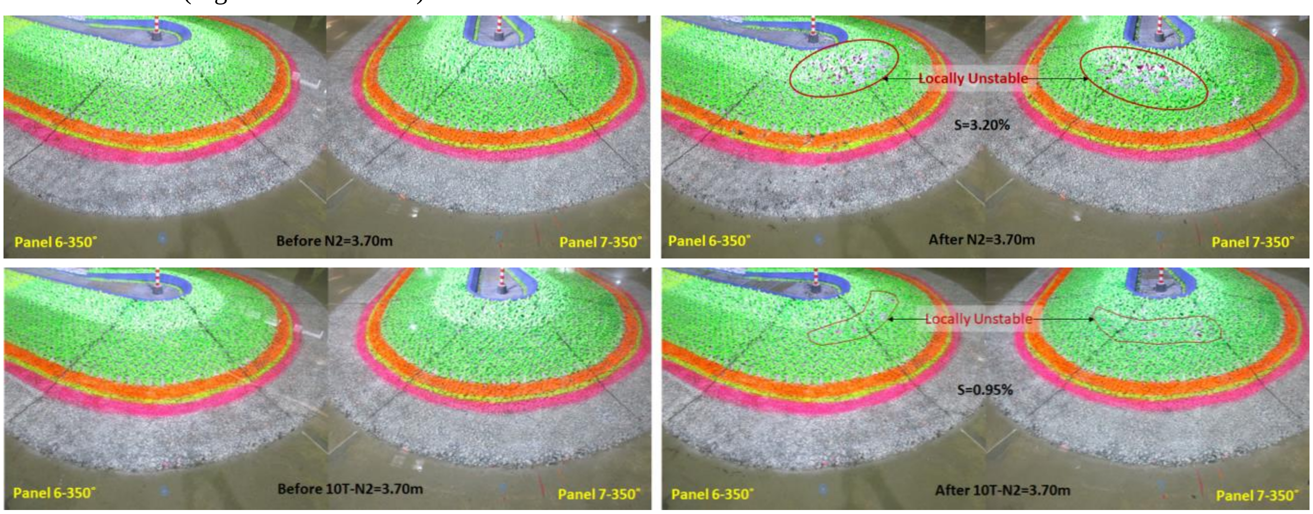

Figure 6. Stability condition of 6.5T(top) & 10.0T (bottom) TTP armours at roundhead for N2 test

However, armour size at the Roundhead was further increased to 12.5T expecting more damage during the 10T-N3 if it continues with 10T TTP. Finally, a significant reduction of the damage at the roundhead was observed for 12.5T-N3 and 12.5T-N4 tests with estimated damage of 0.43% and 1.30% respectively (Figure 7 and Table 2). Further, there are no displaced units from the bottom layer of 12.5T TTP units even after the 12.5T-N4 (overload) test (Figure 8 and Table 2). Therefore, 12.5T TTP units were hydraulically stable as the main armour at the roundhead.

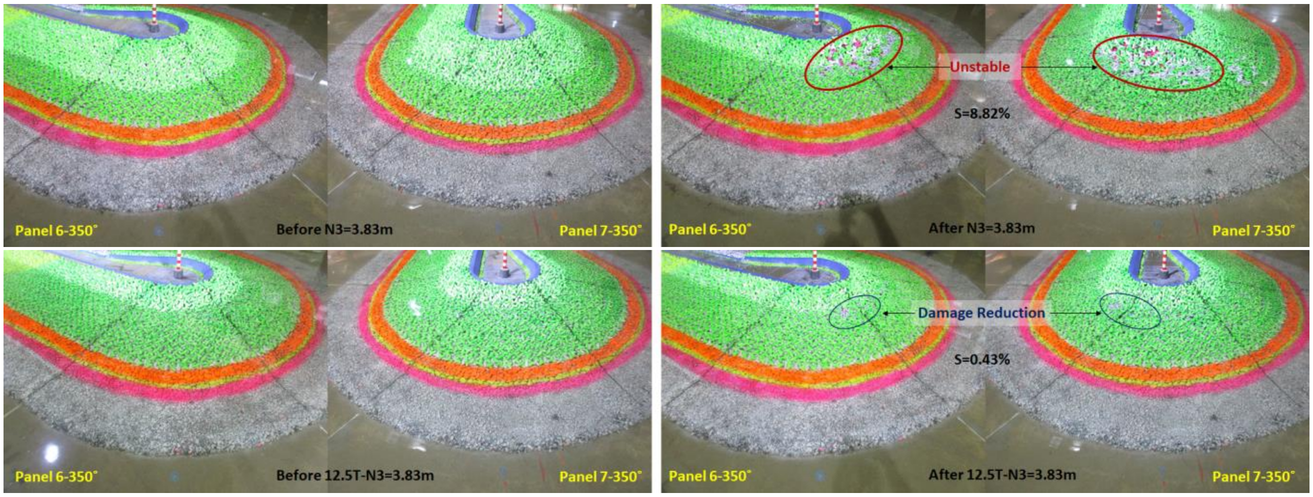

Figure 7. Stability condition of 6.5T(top) & 12.5T (bottom) TTP armours at roundhead for N3-design test

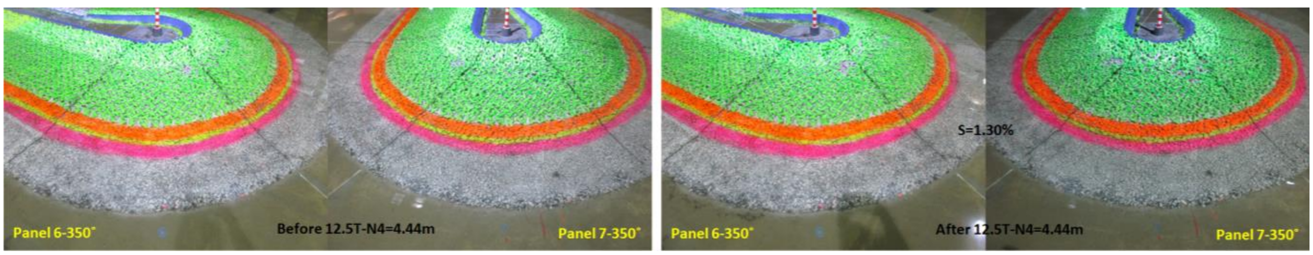

Figure 8. Stability condition of 12.5T TTP armours at roundhead for N4-overload test

However, no damage has been observed at the lee side of the Roundhead (Panel 8 & 9 in Figure 2) even during the N3 (100YRP Design) test done for 6.5T TTP armours (Figure 9).

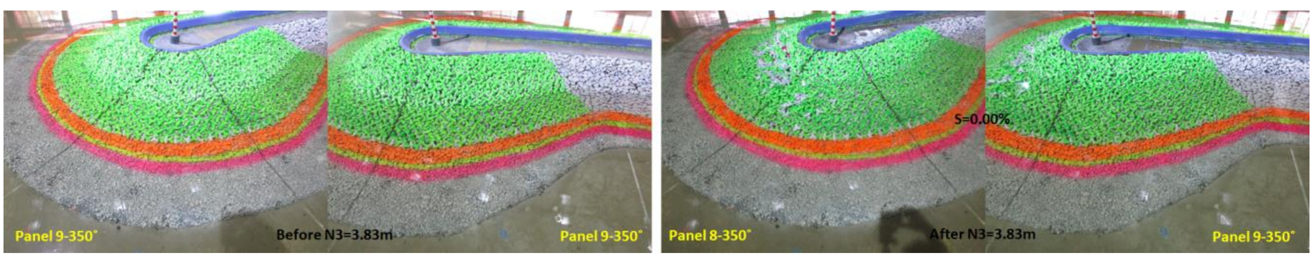

Figure 9. Stability condition of 6.5T TTP armours at roundhead lee side for N3-design test

Figure 10 indicates the stability condition of the different armour sizes at the sea side of the roundhead.

The estimated N_{od} values for the front toe during the N5 (100YRP-CLWL) and N6 (Overload-CLWL) were as low as 0.02 (<0.5) and 0.07 (<2.0). Hence, 1-3T rock armours are stable at the Roundhead as the toe armours as the N_{od} values are well below the allowable limits. However, a redesign of the toe armours is to be done to be compatible with 12.5T TTP units.

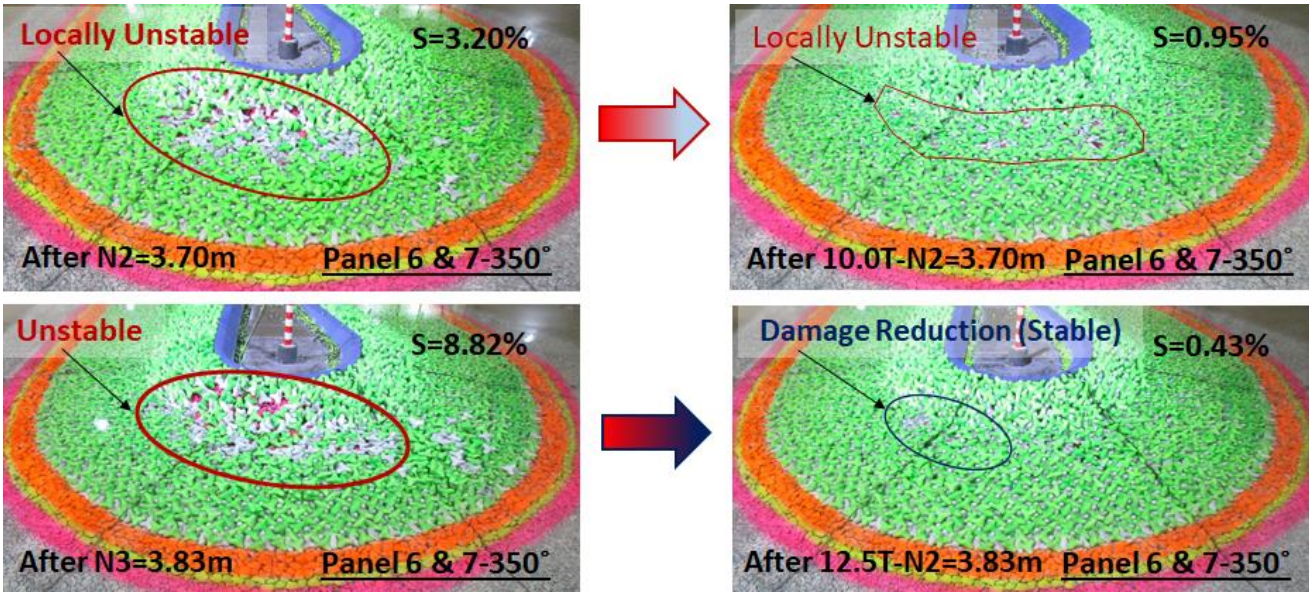

Figure 10. Stability condition of the sea side of the roundhead for different TTP unit sizes

Table 2: Stability analysis for different TTP units at roundhead

Test ID.	Description	Required @ -10 m CD		WL (m CD)	Observed Hs (m) @ -10 m CD		Stability Criteria	Armour Size @ Head	Roundhead Seaside (Panel 6 & 7)		
		Tp (s)	Hs (m)		T7	T8			# Units Displaced >1.0Dn	% of Damage	Stability Condition
K-N1	1YRP-DWL	17.03	0.77	+1.70	0.82	1.14	<5%	6.5T	0	0.00	Stable
K-N2	100YRP-DHWL	10.13	3.70	+2.55	3.95	4.06	<5%	6.5T	37	3.20	Locally unstable
K-N3	100YRP-DHWL	10.13	3.83	+2.95	3.81	3.85	<5%	6.5T	102	8.82	Unstable
K-10T-N2	100YRP-DHWL	10.13	3.70	+2.55	3.83	3.97	<5%	10.0T	11	0.95	Locally unstable
K-12.5T-N3	100YRP-DHWL	10.13	3.83	+2.95	3.95	4.08	<5%	12.5T	5	0.43	Stable
K-12.5T-N4	Overload-DHWL	12.16	4.44	+3.25	4.71	4.48	<10%	12.5T	15	1.30	Stable

Total # Units=1156

4 SUMMARY AND CONCLUSIONS

- Initial tests done with a 1:41.37 scale indicated the instability of 6.5 T TTP units at the sea side of the roundhead while verifying the stability of the other proposed armour (rock and TTP) at the trunk and the head.
- An alternative method was used to check the stability of different TTP weights by utilizing the same model units with 88 g. Therefore, new scales of 1:47.82 and 1:51.51 were proposed to represent the 10 T and 12.5T TTP units at the roundhead by accommodating initially used TTP model units of 88 g weight. The same structure freeboard in the prototype was considered while adjusting the water levels for new scales in the model.
- Since the pre-calibrations were not done for the new scale, the trial runs were conducted to obtain the required wave climate at the C5/T8 location. while selecting the inputs for the trial runs, special care was taken regarding the structure reflection and its impact on the gauges located at the paddles considering previously conducted tests and the calibration runs. The selected inputs for the new scales using trail runs were successfully verified by post-calibration as it produced slightly higher wave heights at the gauge C5/T8 than required. Therefore, the constructed model with a 1:41.37 scale to represent the 6.5 T TTP units was successfully used to represent the 10 T and 12.5T TTP units by adopting the new scales of 1:47.82 and 1:51.51respectively.
- Originally proposed 6.5 T TTP units were unstable at the roundhead and they were replaced by 12.5 T TTP units which were hydraulically stable based on the model results with different scales.

- Even though the pre-judgement of the input waves for the new scales was not a straightforward exercise due to the structure reflection of the constructed model, using new scales is cost-effective and less time-consuming than the casting of a larger number of model units.

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REFERENCES

CIRIA, CUR, CETMEF, 2007, The Rock Manual-The use of rock in Hydraulic Engineering, 2nd Edition, London

Danish Hydraulic Institute (DHI), 2009, Wave Synthesiser for Windows-Data Analysis

Danish Hydraulic Institute (DHI), 2009, DHI Wave Synthesiser - documentation for Wave Generation and Data Acquisition Data Analysis Plot Composer

Haskoning DHV UK Ltd. Maritime & Aviation, 2021, Technical note on KKS Breakwater Rehabilitation – Data for 3D Basin Physical Model Testing (Rev 1)

International Association for Hydro-Environment Engineering and Research (IAHR), 2011, Design Manual-Users Guide to Physical Modelling and Experimentation-Experience of the HYDRALAB Network,

Lanka Hydraulic Institute Ltd. (LHI), 2021, Final Report on Physical Model Studies of Breakwater for Rehabilitation of Kankesanthurai Harbour, Sri Lanka: 3D (Basin) Physical Modelling