REPORT DOCUMENTATION SHEET	
TECHNICAL REPORT NO. 5914	**APRIL 2021**

Title : **DESK AND WAVE FLUME STUDIES FOR THE DESIGN OF PROTECTION STRUCTURE/ BREAKWATER WITH ACCROPODE^{TM} II ARMOUR UNITS TO THE PROPOSED MAIN DAM OF KALPASAR PROJECT IN GUJARAT**

Officers Responsible for Conducting the Studies:

The studies have been conducted and Technical Report prepared under overall guidance and the supervision of Shri A.V.Mahalingaiah, Scientist-E and Dr. Prabhat Chandra, Scientist-E. The studies have been carried out and assisted for preparation of Technical Report by Shri Uday B. Patil, Scientist-B, Shri CV Ramana Murthy, Scientist-C, and Shri Ganesh N.S., Research Assistant. Shri N V Gokhale and Shri A J Jatkar, Scientist-C was present during the course of studies.

Name and Address of Organization Conducting the Studies:

Coastal Hydraulic Structure Division
Coastal and Offshore Engineering Laboratory
Central Water and Power Research Station, Pune, India

Name and Address of Authority Sponsoring the Studies:

Superintending Engineer
Gulf of Khambhat Development Project
Project Implementation Unit-1
Oanchashil Society Plot No. 1794
Sardarnagar, Bhavnagar-364001

Synopsis:

The Kalpasar Project envisages building a 30 km long dam across the Gulf of Khambat in India for establishing a huge fresh water coastal reservoir for irrigation, drinking and industrial purposes. In this regard, Kalpasar department approached CWPRS to conduct various model studies for development of this project. The detailed Desk and Wave flume studies for the design cross-sections of protection structure/breakwater to the proposed main dam considering the maximum Design Water Level (DWL) of +8.765 m w. r. to MSL and maximum Significant Wave height (H_s) of 8.1 m will be conducted with Accropode^{TM} II and XblocPlus patent blocks recommended by Kalpasar Department. The section is designed and evolved for different bed level of the protection structure/breakwater from +/- 5 m to - 25 m. In present studies section consists of 14 m^3 (33.6 t) Accropode^{TM} II in the armour layer with 1:1.33 slope on sea side and 2 to 4 t stones in the armour with 1:1.5 slope on lee side. The top of the crest slab is fixed at el. + 17.5 m level with a parapet top at el. +19.0 m. A clear carriage way width of 10 m is provided on the crest slab.

Keywords: Armour unit, Breakwater, Breaking Waves, Accropode^{TM} II, XblocPlus, Hydraulic Stability, Tides, Toe Berm, Wave Flume.

CONTENTS

LIST OF FIGURES

LIST OF PHOTOGRAPHS

GOVERNMENT OF INDIA
MINISTRY OF JAL SHAKTI
DEPARTMENT OF WATER RESOURCES, RIVER DEVELOPMENT & GANGA REJUVENATION
CENTRAL WATER AND POWER RESEARCH STATION
KHADAKWASLA, PUNE - 411 024

TECHNICAL REPORT NO. 5914	**APRIL 2021**

DESK AND WAVE FLUME STUDIES FOR THE DESIGN OF PROTECTION STRUCTURE/ BREAKWATER WITH ACCROPODE^{TM} II ARMOUR UNITS TO THE PROPOSED MAIN DAM OF KALPASAR PROJECT IN GUJARAT

1. INTRODUCTION

Kalpasar Project envisages building a 30 km dam across the Gulf of Khambat in India for establishing a huge fresh water coastal reservoir for irrigation, drinking and industrial purposes. The project with 30 km long sea dam will have the capacity to store 10,000 million cubic meters (Mcum) fresh water, equating to 25% of Gujarat’s average annual rainwater flow, from the rivers of Saurashtra region namely Narmada, Mahi, Dhadhar, Sabarmati, Limbdi-Bhagovo, and two other minor rivers. A road link will also be set up over the dam, greatly reducing the distance between Saurashtra and South Gujarat. The proposed project would create world's largest freshwater lake in marine environment and construction of the main "Kalpasar dam" across Gulf of Khambat and another Bhadbhut barrage on Narmada River. The typical index and location/layout plan of proposed main dam to Kalpasar Project in Gujarat as shown in Figure 1.

In this regard, Kalpasar department requested CWPRS to conduct various studies for development of this Project. The interim report on the conceptual cross sections on the basis of desk studies carried out at CWPRS was sent on 15/07/2020. Further, the studies for design cross-sections of protection structure/breakwater on the seaside of the proposed main dam of Kalpasar project considering the effect of coastal parameters such as wave and tides were also carried out using the wave flume equipped with random wave generation facilities at CWPRS. The design of reservoir protection is required to be carried out considering cutoff wall, road width and inverse filter etc.

In the present report, the details of desk studies carried out to evolve the conceptual design cross-sections of protection structure/breakwater at various bed levels considering the different design wave heights and the detailed wave flume studies with Accropode^{TM} II as armour units have been described.

2. SCOPE OF STUDIES

Desk and Wave flume studies for the design cross-sections of protection to the Kalpasar main dam, Kalpasar Project in Gujarat. The wave flume tests will be conducted with Accropode^{TM} II and XblocPlus patent blocks suggested by Kalpasar Department. The patent blocks of suitable weight according to the model scale required for the wave flume studies for the protection structure will be supplied by the project authorities. At present Desk and Wave flume studies for the design cross-sections of protection to the Kalpasar main dam, Kalpasar Project in Gujarat have been conducted with **Accropode^{TM} II** and described in this report.

3.0 DESIGN CONDITIONS

During the video conference held on 21/10/2019 with Prof. Ioan Nistor and Project Officials from Kalpasar Department, Officers from NIOT and CWPRS Officers, it was decided to consider the maximum Design Water Level (DWL) of +8.765 m w. r. to MSL and maximum Significant Wave height (H_s) of 8.1 m for design of protection structure/breakwater to the proposed main dam.

4.0 DESIGN OF PROTECTION STRUCTURE/BREAKWATER

The protection structure/breakwater to the main dam of Kalpasar project is proposed from either side of the bank, which extending up to - 25 m depth contour w. r. to MSL. It is proposed to design rubble mound protection structure/breakwater with Accropode^{TM} II and XblocPlus as primary armour. The desk studies have been conducted for evolving cross-sections of protection structure/breakwater with Accropode^{TM} II in the armour at different bed levels based on empirical formulae as per the existing conditions at the site. Initially, the stable unit weight of Accropode™ II for protection structure/breakwater sections at various bed levels at suitable design wave conditions have been worked out using the equation by Hudson formula. The stability coefficient (K_D) depends on the slope of the seabed and K_D values to be used in the design are for non breaking waves and based on safe engineering practice, guidelines by Concrete Layer Innovations (CLI), the License holder for the design of Accropode™ II armour layers who recommended maximum values of Hudson's stability coefficient K_D of 16 for trunk section and 12 for round head section. The trunk and roundhead sections were designed for K_D values, corresponding to non-breaking waves and a seabed slope of 1% for conservative sides. According to BS: 6349-Part-7, the relevant configuration of the toe-berm for the rubble mound protection structure/ breakwater have been designed. The under layer is extended to form the toe mound and the same size of rocks to be assumed for preliminary design. The toe designs have been checked for relevant low and high water levels and also in corresponding wave conditions. The protection structure/breakwater sections include design of wave wall, which resist the impact pressures from wave up-rush. The wave wall design also includes vehicular and non-vehicular loads as per IRC Class 70 R loading.

4.1 Damage criteria

The damage criteria associated environmental loads for the seaside and rear side rocks shall be limited to s = 2% as per BS Code, and CIRIA rock manual, Similarly the armour layer of Accropode™ II, designed for no damage criteria (N_{od} = 0).

4.2 Permissible wave overtopping

The allowable overtopping rate for safety and structural design shall be as per the specification in EurOtop manual and no vehicle shall access the breakwater crest during the cyclone event. Therefore, the breakwaters shall be designed based on the wave overtopping criteria of 100 lit/s/m to estimate the crest level of the breakwater. The permissible overtopping for rubble mound breakwater with Accropode™ II as primary units in the range of 50-200 lit/s/m will not damage the crest and rear slope of the breakwater if these are well protected.

The wave overtopping will be estimated using the following method by Eurotop, (Equation 5.9) as presented below.

$$Q \quad = \quad C_r \times (\sqrt{g \times H_{mo}^3}) \times 0.2 \times \exp(-2.3 \times \left(\frac{R_c}{H_{mo} \times \gamma_{f} \times \gamma_{\beta}}\right)$$

Where,

- Q = Discharge in m3/s/m
- C_r = Crest width reduction factor (-): 3.06× exp (−1.5 × ($Cw\ Hmo$))
- C_w = Crest width (m)
- H_{mo} = Spectral significant wave height (m)
- R_C = Vertical distance between water level and rock crest (m)
- γ_f = Roughness factor (-)
- γ_β = Reduction factor due to oblique wave attack (-)

The crest width in front of wave wall consists of 3 units of primary armour.

4.3 Road on breakwater crest

The road on the breakwater crest shall have a minimum width of 10 m wide. The crest element shall be founded on the breakwater quarry run. The roadway on top of the breakwater shall be designed as Reinforced Cement Concrete (RCC) element for loading condition as per IRC 70R.

4.4 Armour stability of Accropode™ II concrete blocks

The equation to estimate the stable size of Accropode™ II for both trunk and round head sections shall be estimated using the following equation by famous Hudson formula,

$$W = \frac{w_r . H_s^{\ 3}}{K_D \times (Sr - 1)^3 . \cot \theta}$$

$N_s = Hs/\Delta \times D_{n50} = (K_D \times \text{Cot}\ \theta)^{1/3}$

Where,

- W = Weight of Armour
- H_s = Significant wave height (m)
- K_D = Stability coefficient,
- S_r = Specific Gravity of Armour relative to Water at the structure (w_r/W_w)
- w_r = Unit Weight of Armour ,
- W_w = Unit Weight of sea water
- Cot θ = Slope of armour
- N_s = Stability number
- $\Delta = (\rho r/\rho w) - 1$ = Relative buoyant density
- D_{n50} = Nominal diameter (m)

The stability coefficient depends on the slope of the seabed. K_D values to be used in the design are for non breaking waves and based on safe engineering practice, CWPRS world wide experience in similar breakwater projects with monolayer armour units and guidelines from the developer of the concrete armour units.

4.5 Design of secondary layer

As per BS: 6349-part 7, the weight of the secondary layer rock for concrete armour shall vary between W/7 to W/15 of the weight of Accropode™ II. However, 0.2 to 0.3 t, 1 to 2 t and 2 to 4 t stones are proposed as secondary layer and apron extended from underneath toe mound to seabed for preliminary design.

4.6 Layer thickness

Rock armour and secondary layers shall have a minimum thickness equivalent to two rock layers for stability and to act as filter. The layer thickness shall be determined by the stone size as follows:

Thickness = 2 * D_{n50} * k_t,

Where k_t applied is 1.02 for Accropode™ II layers, the rock size recommended by CLI will be used as under layer.

4.7 Design of Filter criteria for various layers

The British Standard BS 6349, Part 7, clause 4.4.3 provides guidance for sizing of under layers. The functionality of the filter is described as:

- To act as filter between core and armour layer,
- To provide a stable bed for the armour layer,
- To dissipate wave energy passing through the armour layer, and
- To protect the core material from moderate storms during construction.

The sizing of the under layer material for Accropode™ II shall be as defined in BS6349 - Part 7, clause 4.4.3 and as recommended by the Accropode™ II developer. The filter stability between the core and filter shall be checked by the Terzaghi filter criteria (see BS 6349).

› $D_{15a} / D_{85u} < 4$ to 5
› $D_{15a} / D_{15u} < 20\text{-}25$

Where

- D_{xx} is the sieve rock diameter
- ‘u’ denotes under layer, and
- ‘a’ denotes armour

The Thomsen and Shuttler criteria shall be applied for filter criteria between filter and armour layer only:

› $D_{50a} / D_{50u} < 7$

The core material shall be quarry rock and well graded. It is important that the core material is not washed through the armour layers. From past experience in breakwater construction, the Terzaghi criteria shall be fulfilled between the size of armour and the filter or core material.

4.8 Design of toe-berm

According to BS:6349, Part-7, as per the toe configuration for rubble mound Breakwater in deep water, the secondary layer is extended to form the toe mound and the same size of rock may be assumed for preliminary design where the water depth exceeds twice the design H_s. The toe design is checked for relevant low and high water levels and corresponding wave conditions.

In shallow water, the toe of rubble mound breakwater is exposed to breaking wave action, which leads to high water particle velocity and reversal in the flow gradient. This can cause erosion of seabed material, as a result of which there will be a significant settlement in toe. Such settlement can be prevented by providing suitable toe protection. An important function of the toe mound is to provide the support to the armour. The width of the toe-berm should be provided to accommodate at least four rocks, and accordingly toe-berm on seaside consist of one Accropode™ II unit and 3 units of rocks, which satisfy the BS standard for minimum 4 units as toe. The toe stability shall be checked by physical model test for design low water level. The stability of toe berm formed by two layers of rocks on variable berm width & slope structure is given by Van der Meer et al (1995). The equation to calculate the toe size is given below as:

$$\frac{H_s}{\Lambda D_{n50}} = \left[2 + 6.2 \left(\frac{h_t}{h} \right)^{2.7} \right] n_{od}^{0.5}$$

Where,

- H_s = Significant wave height (m)
- $\Delta = (\rho r / \rho w) - 1$ = Relative buoyant density
- D_{n50} = Nominal diameter (m)
- h_t = Water depth on Toe (m)
- h = Water depth near sea bed (m)
- N_{od}= number of unit displaced

The damage level for toe is measured in terms of N_{od} and is defined as number of unit displaced with in a strip width of D_{n50}. The stability of toe for design shall be as per the following conditions.

$$N_{od} = \begin{cases} 0.5 & \text{No damage} \\ 2.0 & \text{Acceptable damage} \\ 4.0 & \text{Severe damage} \end{cases}$$

The unit weight of the stones in toe-berm calculated based on Van der Meer improved formulae (Eq. 5.187 and 5.188) of CIRIA rock manual. Although, 1 to 2 t stones are provided as toe berm for section A-A, higher size of rocks are proposed for sections B-B (2 to 4 t), for section C-C (4 to 6 t), and 8 to 10 t stones for D-D & E-E sections, which were tested successfully in physical the model test.

4.9 Design of Wave wall

The breakwater sections shall include a wave wall and the requirement of concrete and steel for the wave wall as per BS:6349-Part 7, The wave wall on these sections shall resist impact pressures from wave up-rush. Wave wall design includes vehicular and non-vehicular loads as per IRC Class 70R loading. The structural design of crest slab and parapet wall are required to be carried out by Project Authorities. The impact pressure on the crest element and the uplift forces is determined based on equation presented below.

Wave pressure,

$$P_w = K\, W_w\, L((H_s/H_c)-0.5)$$

Where,

- Hs = Significant wave height (m)
- K = Constant(-)'
- W_w = Seawater density(kg/cum)
- L = Wave length corresponds to significant wave period (m)
- H_c = Height of breakwater crest from design water level (m)

4.10 Design of Core

The core material shall consist of 10 to 500 kg well graded quarry run. Gradation of core will be estimated based on the filter criteria. The core rock with weight less than 10 kg shall be restricted to 1% and 5% of total volume respectively. The porosity of 37 % may be considered in the rock gradation.

4.11 Rear armour

Rear rock armour is designed based on the permissible wave overtopping and non breaking waves propagating into the harbour, which are estimated from numerical modelling studies. The stability of rear armour under wave overtopping during the design storm event will be validated during 2D physical modelling tests.

A conceptual design of protection structure/breakwater has been evolved based on the desk studies. The design of breakwater cross-sections at different bed levels with Accropode™ II in the armour was finalized through 2D wave flume studies. The design of cross-sections of breakwaters with Accropode™ II in the armour considering the design wave condition at different bed levels are shown in Figures 1 to 5. The design of these cross-sections at different bed levels are described below:

i) Cross-section of protection structure/breakwater from bed level - 5 m to - 25 m

The section is designed to provide from -5 m to -25 m bed level of the protection structure/breakwater as shown in Figure 2. This section consists of 14 m^3 (33.6 t) Accropode™ II in the armour with 1:1.33 slope on sea side and 2 to 4 t stones in the armour with 1:1.5 slope on lee side. A 9.0 m wide toe-berm consists of 8 to 10 t stones have been provided at the level -9.50 m on sea side. A secondary layer consists of 2 to 4 t stones has been provided below the armour units and crest slab and 0.5 to 1 t provided below the toe-berm. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 17.5 m level with a parapet top at el. +19.0 m. A clear carriage way width of 10 m is provided on the crest slab.

ii) **Cross-section of protection structure/breakwater from bed level 0.0 m to -5.0 m**

The section is designed to provide from 0.0 m to -5.0 m bed level of the protection structure/breakwater as shown in Figure 3. This section consists of 14 m^3 (33.6 t) Accropode™ II in the armour with 1:1.33 slope on sea side and 2 to 4 t stones in the armour with 1:1.5 slope on lee side. A 9.0 m wide toe-berm consists of 8 to 10 t stones have been provided at the level -0.40 m on sea side. A secondary layer consists of 2 to 4 t stones has been provided below the armour units and crest slab and 0.5 to 1 t provided below the toe-berm. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 17.5 m level with a parapet top at el. +19.0 m. A clear carriage way width of 10 m is provided on the crest slab.

iii) Cross-section of protection structure/breakwater from bed level +2.0 m to 0.0 m

The section is designed to provide from + 2.0 m to + 0.0 m bed level of the protection structure/breakwater as shown in Figure 4. This section consists of 6 m^3 (14.4 t) Accropode™ II in the armour with 1:1.33 slope on sea side and 1 to 2 t stones in the armour with 1:1.5 slope on lee side. A 6.22 m wide toe-berm consists of 4 to 6 t stones have been provided at the level + 4.1 m on sea side. A secondary layer consists of 1 to 2 t stones has been provided below the armour units and crest slab and 0.5 to 1 t provided below the toe-berm. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 15.5 m level with a parapet top at el. +16.5 m. A clear carriage way width of 10 m is provided on the crest slab.

iv) Cross-section of protection structure/breakwater from bed level +5.0 m to +2.0 m

The section is designed to provide from +5.0 m to +2.0 m bed level of the protection structure/breakwater as shown in Figure 5. This section consists of 3 m^3 (7.2 t) Accropode™ II in the armour with 1:1.33 slope on sea side and 1 to 2 t stones in the armour with 1:1.5 slope on lee side. A 5.2 m wide toe-berm consists of 2 to 4 t stones have been provided at the level + 5.7 m on sea side. A secondary layer consists of 1 to 2 t stones has been provided below the armour units and crest slab and 0.5 to 1 t provided below the toe-berm. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 14.0 m level with a parapet top at el. +15.0 m. A clear carriage way width of 10 m is provided on the crest slab.

v**) Cross-section of protection structure/breakwater from the root to +5.0 m bed level**

The section is designed to provide from the root of the protection structure/breakwater up to +5.0 m bed level as shown in Figure 6. This section consists of 0.5 m^3 (1.2 t) Accropode^{TM} II in the armour with 1:1.33 slope on sea side and 0.5 to 1.0 t stones in the armour with 1:1.5 slope on lee side. A 3.76 m wide toe-berm consists of 0.3 to 1 t stones have been provided at the level +7.45 m on sea side. A secondary layer consists of 200 to 300 kg stones have been provided below the armour units and crest slab. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 11.50 m level with a parapet top at el. +12.0 m. A clear carriage way width of 10 m is provided on the crest slab.

The technical specifications of Accropode^{TM} II armour units as shown in Figure 7.

5.0 HYDRAULIC MODEL STUDIES

5.1 Wave flume test procedures

The section of a protection structure/breakwater is tested under a normal attack of waves in a 2-D random wave flume for its hydraulic stability. The models of protection structure/breakwater cross-sections were constructed to a Geometrically Similar (GS) scale in a wave flume. The dimensions of the random wave flume are 45 m length, 1.00 m width and 1.10 m depth and the regular wave flume are 50 m length, 1.20 m width and 1.80 m depth. Both regular as well as random waves of desired wave height & period and desired standard wave spectrum respectively could be generated. The number of Accropode^{TM} II / stones provided in the armour and in the toe was counted initially, before starting the test. After conducting the wave flume model tests for one-hour duration, the number of Accropode^{TM} II / stones displaced from its original position were recorded and percentage of damage to the armour of breakwater was determined. During the test, extent of splashing/overtopping over the crest was also observed and recorded. The damage is expressed as percentage of number of Accropode™ II / stones displaced from their original position.

5.2 Model Scale of protection structure/breakwater

The model tests for the design of protection structure/breakwater were conducted in 2-D random wave flume by reproducing the section to Geometrically Similar scales of 1:60, 1:44 and 1:35. The model was based on Froude's criterion of similitude. The various scales obtained are as follows:

The section of protection structure/breakwater at -25 m bed level wrt MSL to a Geometrically Similar scale of 1:60 reproduced in the wave flume and other scale are as below;

Model scale 1:60		
• Length	- L	= 1:60
• Area	- L^2	= 1:3,600
• Volume	- L^3	= 1:2,16,000
• Time	- $L^{1/2}$	= 1:7.746
• Velocity	- $L^{1/2}$	= 1:7.746

The section of protection structure/breakwater at 0.0 m bed level wrt MSL to a Geometrically Similar scale of 1:44 reproduced in the wave flume and other scale are as below;

Model scale 1:44		
• Length	- L	= 1:44
• Area	- L^2	= 1:1,936
• Volume	- L^3	= 1:85,184
• Time	- $L^{1/2}$	= 1:6.633
• Velocity	- $L^{1/2}$	= 1:6.633

The section of protection structure/breakwater at +2 m bed level wrt MSL to a Geometrically Similar scale of 1:35 reproduced in the wave flume and other scale are as below;

Model scale 1:35		
• Length	- L	= 1:35
• Area	- L^2	= 1:1,225
• Volume	- L^3	= 1:42,875
• Time	- $L^{1/2}$	= 1:5.916
• Velocity	- $L^{1/2}$	= 1:5.916

5.3 Compensation for weight of stones

The density of stones in the prototype was considered as 2.6 t/cum and density of seawater is 1.025 t/cum. However, the density of stones in the model was 2.80 t/cum and fresh water with density 1.0 t/cum was used in the flume. As such, the weights of stones used in the model were compensated for these density differences by applying a weight factor, which was worked out as below:

$$\frac{W_1}{W_2} = \frac{2.6H^3 \Big/ \left(\frac{2.6}{1.025}-1\right)^3}{2.8H^3 \Big/ \left(\frac{2.8}{1.0}-1\right)^3}$$

Where,

$W_2 = 0.6678\, W_1$

- $W_1 =$ Weight of stones with density in prototype -- 2.6 t/cum
- $W_2 =$ Weight of stones with density in model -- 2.80 t/cum

Hence considering the weight factor of 0.6678 for stones and 0.88 for Accropode™ II concreter units in the model were worked out.

The weight reduction factor of Accropode™ II is also can be calculated based on scale similitude by following Hudson formulae for buoyancy:

$$C = \frac{V_p}{V_m \times E^3} = \frac{H_{Sp}^{\;3}}{K_D\left[\frac{d_p}{d_{0p}}-1\right]^3 \cot g\alpha \times E^3} \times \frac{K_D\left[\frac{d_m}{d_{0m}}-1\right]^3 \cot g\alpha}{H_{Sm}^{\;3}} = \frac{\left[\frac{d_m}{d_{0m}}-1\right]^3}{\left[\frac{d_p}{d_{0p}}-1\right]^3}$$

Prototype volume = $V_p = V_m \times E^3 \times C$

“E” being the scale factor

The Accropode™ II model units in the range of 142 gram to 152 gram received at CWPRS Laboratory. The studies carried out considering the model units not exceeding 149.2 gr (represent 14 m^3) for model scale of 1:60 and also for model scales of 1: 44 (represent 6 m^3) and 1: 35 (represent 3 m^3).

5.4 Random Sea Wave Flume

The random sea wave flume having dimensions 45 m (length) x 1 m (width) x 1.10 m (height) was utilised for the wave flume tests. The system is capable of generating maximum wave height of 0.4 m at a water depth of 0.6 m for wave periods ranging between 0.3 and 3.0 sec. The flume facility is equipped with a fully automated computerised random wave generating system comprising of hydro-servo system and wave board assembly. The command signals are sent by the computer to the servo-valve through which pressurised oil supplied by hydraulic power pack flows into the actuator. A *To* and *Fro* motion of the piston drives the wave board, which in turn generates waves in the flume.

5.5 Wave Measurement and Calibration

The wave heights were measured by capacitance type wave probes. A gauge was fixed at about 30 m water depth in Prototype and at corresponding depth for geometrical scale adopted, in front of the model and was analysed by computer. The desired wave conditions in front of the model were obtained by matching of desired spectrum and achieved spectrum by iterative procedure. The typical wave spectrum (Pierson-Mosckowitz (PM) spectrum) generated during wave flume studies as shown in Figure 8 & 9.

5.6 Wave flume test procedure

The section of the breakwater was constructed to a geometrically similar model scale of 1:60 in the 2-D flume. The number of Accropode™ II units provided in single layer, on the seaside as armour and number of stones in the toe-berm were counted initially, before starting the test. After conducting the tests for one-hour duration, the numbers of Accropode^{TM} II units displaced from its original position were recorded and percentage damage to the armour of breakwater was determined. During the test, extent of splashing / overtopping over the crest was observed.

The details of the wave flume tests for various cross-sections are described in the following paragraphs:

5.7 Test conditions for the trunk portion of breakwater

I) The cross-sections was tested under wave height of H_s =8.1 m at -25.0 m bed level with Design Water Level (DWL) of +8.765 m.

II) The marginal overtopping and splashing permitted for long duration test during Design Water Level of +8.765 m.

5.8 Wave flume studies

5.8.1 2-D wave flume test in the RSWG for protection with Accropode^{TM} II units Structure / breakwater at -25.0 m bed level wrt MSL

The number of Accropode^{TM} II blocks required in the 2-D wave flume model was derived by packing density calculations. The armour geometry and packing density coefficient of 0.635 is considered for the calculations. The random sea wave flume having dimensions 45 m (length) x 1 m (width) x 1.20 m (height) was utilised for the wave flume tests. Total 364 nos. of Accropode^{TM} II blocks were placed in the armour of the protection structure/breakwater. A wooden template consists of horizontal / vertical distance between the two consecutive gravity centres of the block has been made for guiding the placement of the Accropode^{TM} II blocks (D_h=7.14 cm and D_v= 3.56 cm) for geometrical scale of 1:60. The 2-D wave flume tests in the RSWG for protection structure/breakwater at -25.0 m bed levels as follows:

The section is designed to provide from - 5 m to - 25 m bed level of the protection structure/breakwater as shown in Figure 6. This section consists of 14 m^3 (33.6 t) Accropode^{TM} II in the armour with 1:1.33 slope on sea side and 2 to 4 t stones in the armour with 1:1.5 slope on lee side. A 9.0 m wide toe-berm consists of 8 to 10 t stones provided at the level -9.5 m on sea side. A secondary layer consists of 2 to 4 t stones provided below the armour units & crest slab and provided 0.5 to 1 t stones below the toe-berm. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 17.5 m level with a parapet top at el. +19.0 m. A clear carriage way width of 10 m is provided on the crest slab.

Initially, the test was conducted at the Design Water Level (DWL) of +8.765 m with respect to Mean Sea Level (MSL) under the attack of random waves with significant wave height (H_s) 8.1 m (Pierson-Mosckowitz (PM) spectrum). There was no overtopping and marginal splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +18.2 m and +2.0 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

The test was also conducted at the Highest Astronomical Tide (HAT) of + 5.3 m with respect to MSL under the attack of random waves with significant wave height (H_s) 8.1 m (PM-Spectrum). There was no overtopping and splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +13.1 m and 0.0 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

The test was also conducted at the Mean Sea Level (MSL) of + 0.0 m under the attack of random waves with significant wave height (H_s) 8.1 m (PM-Spectrum). There was no overtopping and splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +7.8 m and -4.8 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

The test was also conducted at the Lowest Low Water Level (LLWS) with respect to MSL of - 4.8 m under the attack of random waves with significant wave height (H_s) 8.1 m (PM-Spectrum). There was no overtopping and splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +2.1 m and -7.7 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

The test were also conducted at different water levels with respect to Mean Sea Level under the attack of regular waves with significant wave height (H_s) 8.1 m and equivalent breaking wave height (H_{10}) of 10.3 m. There was no overtopping and splashing of waves. No damage was seen to any component of the protection structure/breakwater. The maximum run-up & run-down of waves was at +18.25 m and -7.7 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

5.8.2 2-D wave flume test for protection with Accropode™ II units protection structure/breakwater at 0.0 m bed level wrt MSL

The number of Accropode™ II blocks required in the 2D wave flume model was derived by packing density calculations. The armour geometry and packing density coefficient of 0.635 is considered for the calculations. The regular sea wave flume having dimensions 50 m (length) x 1.20 m (width) x 1.80 m (height) was utilised for the wave flume tests. Total 288 nos. of Accropode™ II blocks were placed in the armour of the protection structure/breakwater. A wooden template consists of horizontal / vertical distance between the two consecutive gravity centres of the block has been made for guiding the placement of the Accropode™ II blocks for geometrical scale of 1:44 (D_h =7.33 cm and D_v = 3.66 cm) and are worked out using the formula as per CLI manual.

- Horizontal distance between two consecutive gravity centres

  $D_h = 1.775*D_n$….cm
- Up slope distance (Vertical) between two consecutive gravity centres distance

  $D_v = 0.887*D_n$…..cm

  Where,
- D_n = Unit nominal diameter = $V^{1/3}$
- V = Volume of model unit (cm^3)

The 2-D wave flume tests in the regular wave generation for protection structure/breakwater at 0.0 m bed levels as follows**:**

The section is designed to provide from + 2.0 m to + 0.0 m bed level of the protection structure/breakwater as shown in Figure 4. This section consists of 6 m^3 (14.4 t) Accropode™ II in the armour with 1:1.33 slope on sea side and 1 to 2 t stones in the armour with 1:1.5 slope on lee side. A 6.22 m wide toe-berm consists of 4 to 6 t stones have been provided at the level + 4.1 m on sea side. A secondary layer consists of 1 to 2 t stones has been provided below the armour units and crest slab and 0.5 to 1 t provided below the toe-berm. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 15.5 m level with a parapet top at el. +16.5 m. A clear carriage way width of 10 m is provided on the crest slab.

Initially, the test was conducted at the Design Water Level (DWL) of +8.765 m with respect to Mean Sea Level (MSL) under the attack of Maximum Breaking Wave height (H_b) of 6.83 m. There was no overtopping and marginal splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +15.0 m and +7.0 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

The test was also conducted at the Highest Astronomical Tide (HAT) of + 5.3 m with respect to MSL under the attack of maximum breaking wave height (H_b) of 4.1 m. There was no overtopping and splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +8.5 m and +4.0 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

5.8.3 2-D wave flume test for protection with Accropode™ II units protection structure/breakwater at +2.0 m bed levels wrt MSL

The number of Accropode™ II blocks required in the 2D wave flume model was derived by packing density calculations. The armour geometry and packing density coefficient of 0.635 is considered for the calculations. The regular sea wave flume having dimensions 50 m (length) x 1.20 m (width) x 1.80 m (height) was utilised for the wave flume tests.

Total 167 nos. of Accropode™ II blocks were placed in the armour of the protection structure/breakwater. A wooden template consists of horizontal / vertical distance between the two consecutive gravity centres of the block has been made for guiding the placement of the Accropode™ II blocks (D_h=7.28 cm and D_v= 3.64 cm) for geometrical scale of 1:35. The 2-D wave flume tests in the regular wave generation for protection structure/breakwater at +2.0 m bed levels as follows**:**

The section is designed to provide from +5.0 m to +2.0 m bed level of the protection structure/breakwater as shown in Figure 3. This section consists of 3 m^3 (7.2 t) Accropode™ II in the armour with 1:1.33 slope on sea side and 1 to 2 t stones in the armour with 1:1.5 slope on lee side. A 5.2 m wide toe-berm consists of 2 to 4 t stones have been provided at the level +5.7 m on sea side. A secondary layer consists of 1 to 2 t stones has been provided below the armour units and crest slab and 0.5 to 1 t provided below the toe-berm. Core consists of 10 to 500 kg stones and a bedding layer of stones up to 10 kg weight are proposed. The top of the crest slab is fixed at el. + 14.0 m level with a parapet top at el. +15.0 m. A clear carriage way width of 10 m is provided on the crest slab.

Initially, the test was conducted at the Design Water Level (DWL) of +8.765 m with respect to Mean Sea Level (MSL) under the attack of maximum breaking wave height (H_b) of 5.27 m. There was no overtopping and marginal splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +14.5 m and +7.0 m respectively. No damage was seen to any part of the breakwater was observed in the case of random & regular tests.

The test was also conducted at the Highest Astronomical Tide (HAT) of + 5.3 m with respect to MSL under the attack of maximum breaking wave height (H_b) of 2.57 m. There was no overtopping and splashing of waves. No damage was seen to any component of the protection structure/breakwater. The run-up & run-down of waves was at +7.5 m and +4.2 m respectively. No damage was observed to any part of the breakwater during model studies pertaining to random & regular tests.

The typical photographs of the wave flume facilities, wave flume studies and placement of Accropode™ II model units in the wave flumes are enclosed.

6.0 DISCUSSIONS OF RESULTS

The design cross-sections of protection structure/breakwater at various bed levels on the seaside due to coastal parameters such as wave and tides have been evolved at different bed levels and are shown in Figures 2 to 6. The confirmation of hydraulic stability of the cross-sections of protection structure/breakwater with Accropode^{TM} II model units through wave flume studies have been completed. The placement of Accropode^{TM} II model units carried out at wave flume studies were informed to M/s CLI.

The design of reservoir protection is required to be carried out considering cutoff wall, and inverse filter etc. It is also confirm the requirement of top width (road width) of the protection structure/breakwater to the main dam. The structural design of crest slab and parapet wall is required to be carried out by Project Authorities. It is presumed that, the seabed strata below the construction of protection structure/breakwater are adequate to sustain the load of the structures. In order to ensure the foundation conditions, it is suggested to carry out the sub-soil investigations such as soil characteristics borehole data at different locations along the proposed protection structure/breakwater site.

7.0 CONCLUDING REMARKS AND RECOMMENDATIONS

Based on the desk and wave flume studies carried out for the design cross-sections of protection to the main dam of Kalpasar Project in Gujarat, the following concluding remarks are depicted:

1. The design cross-sections of the breakwater with Accropode™ II units at various bed levels are shown in Figures 2 to 6. These breakwater sections are hydraulically stable under the design wave conditions.

2. The density of concrete and stones to be used for the construction of the breakwaters should be about 2.4 t/cum and 2.6 t/cum respectively.

3. There should not be any deviation from the design during the construction for the breakwaters in respect of the levels, slopes and the weights of stones. The crest slab, the parapet wall and the key provided on the crest of the breakwaters should be constructed monolithically.

4. The construction of the breakwater may not be possible during one season. As such, a temporary roundhead may be provided wherever the work is curtailed.

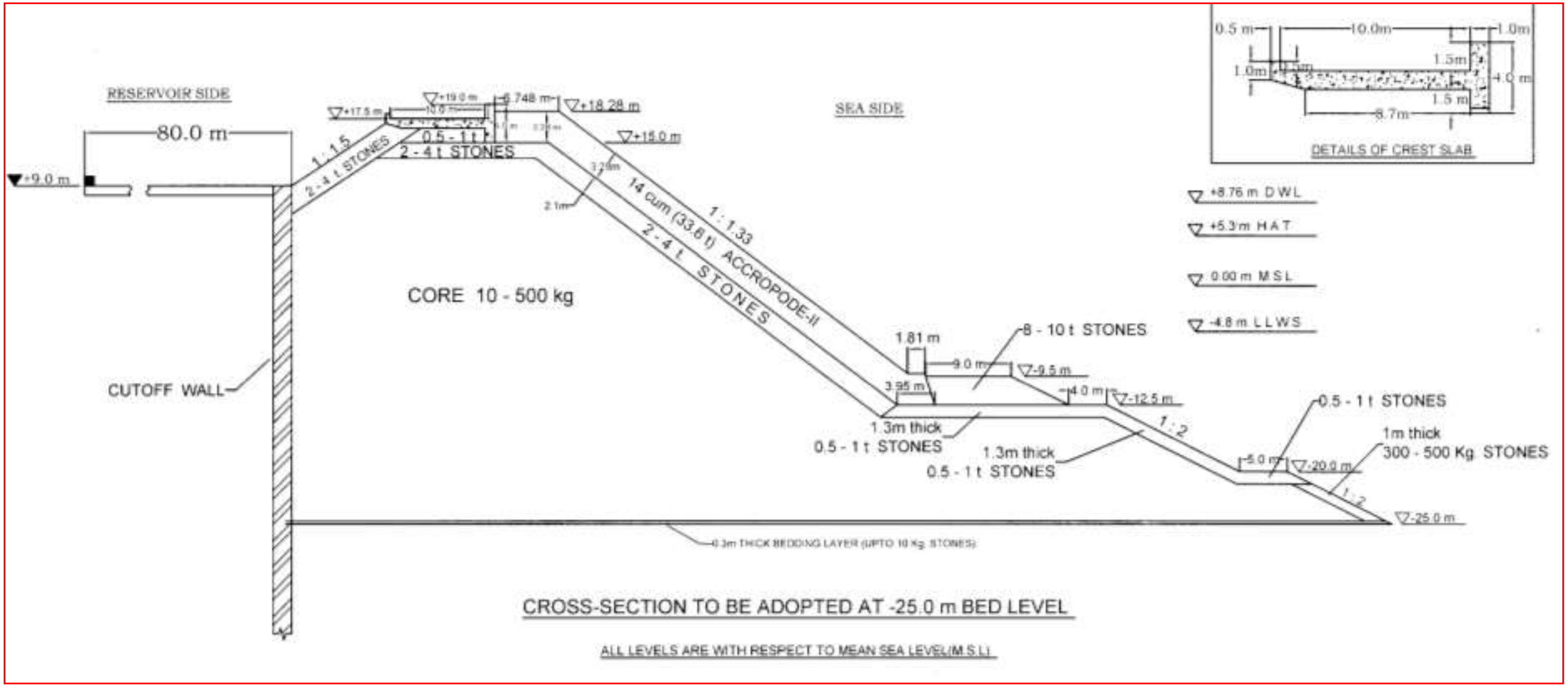
5. The rubble mound structures are flexible structures and it is essential to monitor and maintain them regularly. Therefore, periodic survey and maintenance of the breakwater as and when damage occurs may be undertaken.

6. The grading of the stones to be used in the construction for the restoration of the damaged south breakwater should be as follows:
   - 8-10 t stones – 50% stones should be higher than 9 t
   - 4-6 t stones - 50% stones should be higher than 5.0 t
   - 3-6 t stones - 50% stones should be higher than 4.5 t
   - 2-4 t stones - 50% stones should be higher than 3.0 t
   - 1-2 t stones - 50% stones should be higher than 1.5 t
   - 0.5 -1 t stones - 50% stones should be higher than 750 kg
   - 0.3 -1 t stones - 50% stones should be higher than 650 kg
   - 200-300 kg stones - 50% stones should be higher than 250 kg

8.0 REFERENCES

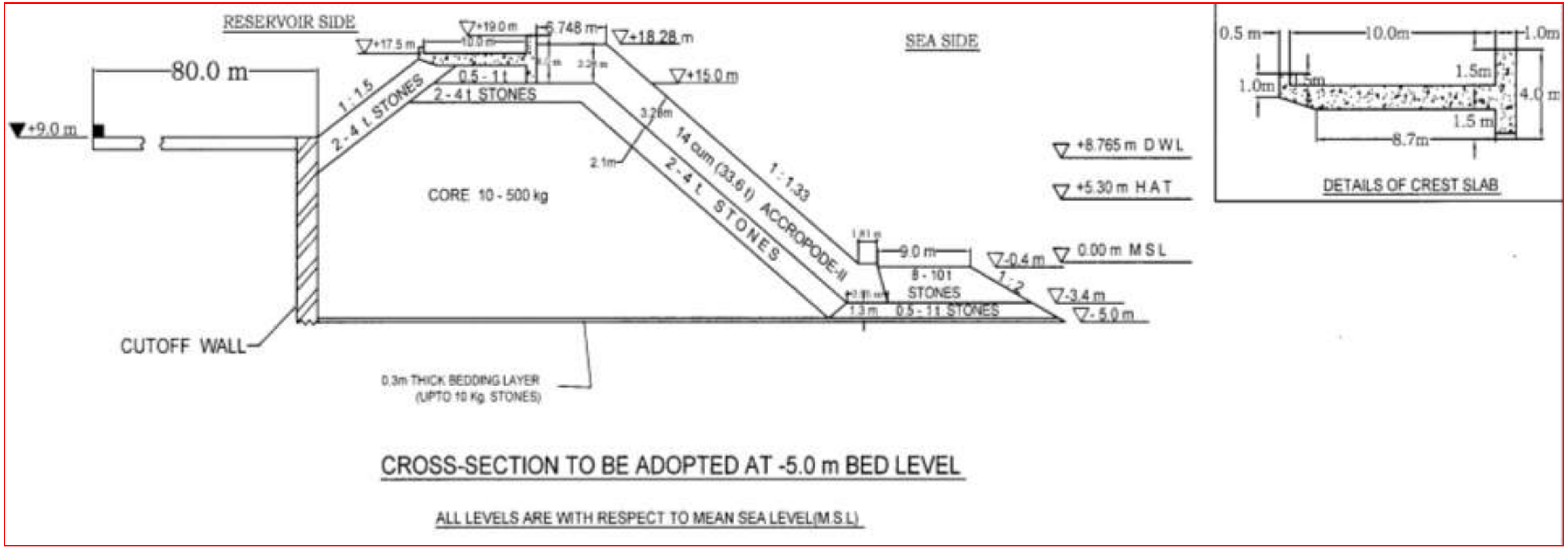
1. IS 4651: Part IV (2014): Code of practice for planning and design of ports & harbours
2. BS 6349: Part 1-1 (2013): Code of practice for planning and design for operations.
3. BS 6349: Part 7 (1991): Guide to the design and construction of breakwater.
4. CIRIA C683, 2nd Edition, London 2007: The Rock Manual - The use of rock in hydraulic engineering
5. EurOtop (2007): Wave Overtopping of Sea Defence and Related Structures: Assessment Manual, August 2007.
6. US Army Corps of Engineers, Coastal Engineering Research Centre: Coastal Engineering Manual EC 1110-2-1100, Sept. 2006.
7. Indian Road Congress (IRC) code and standards.

Figure 1: Index and location/layout plan of protection structure/breakwater for proposed main dam of Kalpasar Project in Gulf of Khambhat, Gujarat



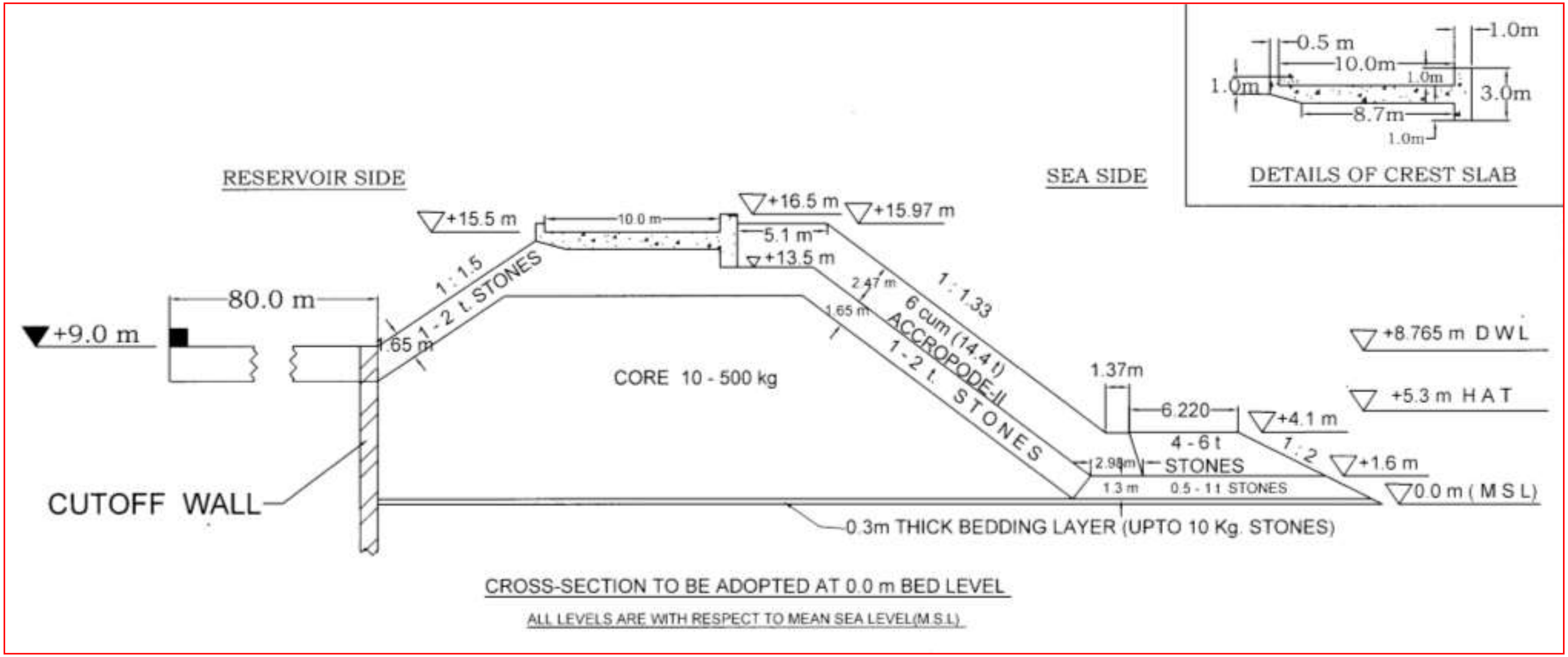
Section A-A

Figure 2: Cross-section of protection structure/breakwater for the proposed main dam of Kalpasar Project, Gujarat



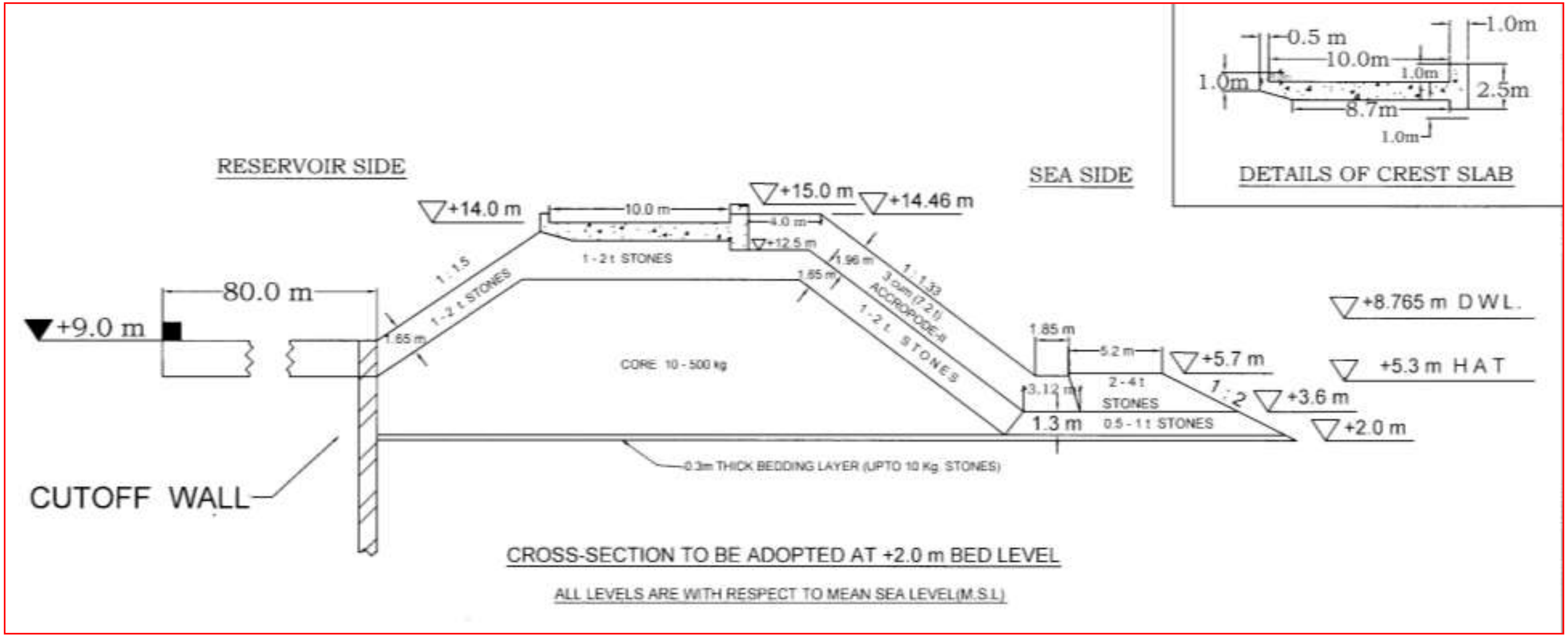
Section B-B

Figure 3: Cross-section of protection structure/breakwater for the proposed main dam of Kalpasar Project, Gujarat



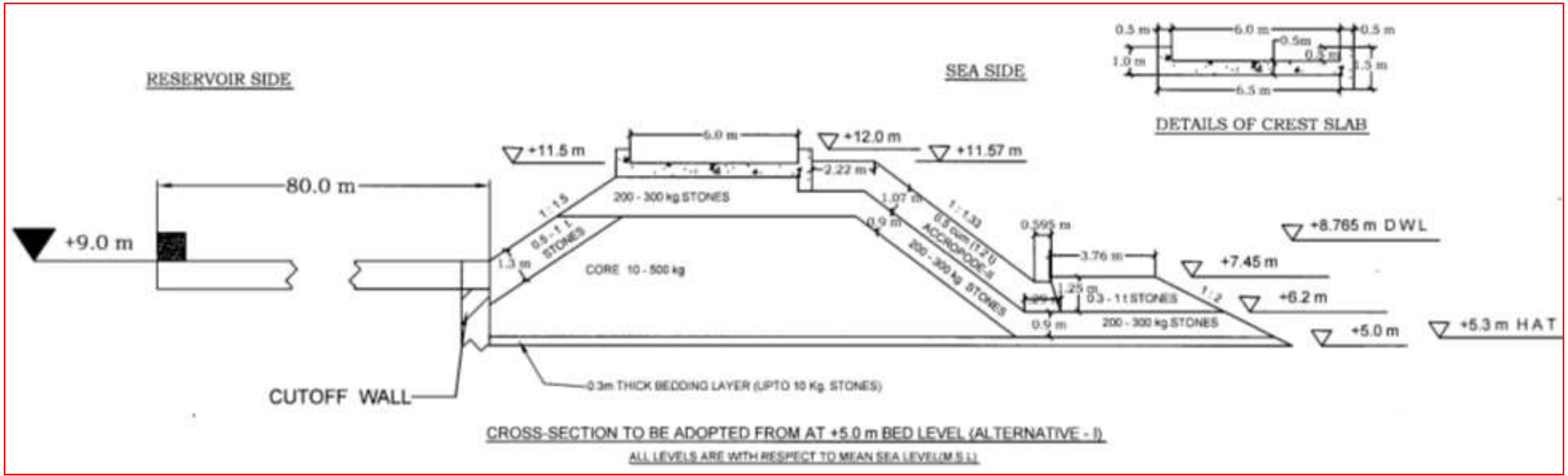
Section C-C

Figure 4: Cross-section of protection structure/breakwater for the proposed main dam of Kalpasar Project, Gujarat



Section D-D

Figure 5: Cross-section of protection structure/breakwater for the proposed main dam of Kalpasar Project, Gujarat



Section E-E

Figure 6: Cross-section of protection structure/breakwater for the proposed main dam of Kalpasar Project, Gujarat

ACCROPODE™ II - ECOPODE™ Design Guide Table

The ECOPODE™ unit size is limited to 10m³ →

Unit Volume (m³)	V = 0.2926H³		**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**	**10.0**	**12.0**	**14.0**	**16.0**	**18.0**	**20.0**	**22.0**	**24.0**	**28.0**
Unit Height (m)	H = (V/0.2926)^(1/3)		1.51	1.90	2.17	2.39	2.58	2.74	3.01	3.25	3.45	3.63	3.80	3.95	4.09	4.22	4.34	4.57
Equivalent Cube Size (m)	Dn = V^(1/3)		1.00	1.26	1.44	1.59	1.71	1.82	2.00	2.15	2.29	2.41	2.52	2.62	2.71	2.80	2.88	3.04
Armour Thickness (m)	T = 1.36 Dn		1.36	1.71	1.96	2.16	2.33	2.47	2.72	2.93	3.11	3.28	3.43	3.56	3.69	3.81	3.92	4.13
Armour concrete consumption and coverage	Packing density Φ (-)		0.635	0.635	0.635	0.633	0.631	0.629	0.625	0.622	0.618	0.614	0.610	0.610	0.610	0.610	0.610	0.610
	Consumption (m³/m²)		0.635	0.800	0.916	1.005	1.079	1.143	1.251	1.339	1.414	1.479	1.537	1.599	1.656	1.709	1.760	1.852
	Number of units (u/m²)		0.635	0.400	0.305	0.251	0.216	0.191	0.156	0.134	0.118	0.106	0.096	0.089	0.083	0.078	0.073	0.066
	Porosity (%)		53.31	53.31	53.31	53.45	53.59	53.73	54.02	54.30	54.58	54.86	55.15	55.15	55.15	55.15	55.15	55.15
Filter stone underlayer - to meet the following requirement NUL/NLL < 3.0	**NLL (tons)**	**Standard**	0.17	0.34	0.50	0.67	0.84	1.01	1.34	1.68	2.02	2.35	2.69	3.02	3.36	3.70	4.03	4.70
		Min/Max*	0.1 0.2	0.2 0.4	0.4 0.7	0.5 0.9	0.6 1.1	0.7 1.3	0.9 1.7	1.2 2.2	1.4 2.6	1.6 3.1	1.9 3.5	2.1 3.9	2.4 4.4	2.6 4.8	2.8 5.2	3.3 6.1
	NUL (tons)	**Standard**	0.34	0.67	1.01	1.34	1.68	2.02	2.69	3.36	4.03	4.70	5.38	6.05	6.72	7.39	8.06	9.41
		Min/Max*	0.2 0.4	0.5 0.9	0.7 1.3	0.9 1.7	1.2 2.2	1.4 2.6	1.9 3.5	2.4 4.4	2.8 5.2	3.3 6.1	3.8 7.0	4.2 7.9	4.7 8.7	5.2 9.6	5.6 10.5	6.6 12.2
	Thickness (m) for standard NLL&NUL Specific density 2,6 t/m3	**Kt=1,15**	1.06	1.33	1.52	1.68	1.81	1.92	2.11	2.28	2.42	2.55	2.66	2.77	2.87	2.96	3.05	3.21
		Kt=0.9*	0.83	1.04	1.19	1.31	1.41	1.50	1.65	1.78	1.89	1.99	2.08	2.17	2.24	2.32	2.38	2.51

This table is to be used together with the note "Additional essential information regarding the tables" here appended.

: Geometrical characteristics of unit

: Recommended values for use at preliminary design stage

: (*)The information in this section is to be used with a compulsory analysis by a experienced coastal engineer even at preliminary stage - Ratio NUL/NLL should be kept between 2 and 3

This proprietary information of CLI is provided for preliminary guidance only. Hence, it is not a substitute for analysis by an experienced coastal Engineer. CLI provides assistance to the owners, developers, designers and contractors at all stages of projects. CLI reserves the right to make changes to the guidelines for improvement of its products. The validity of this document is therefore limited, but CLI will maintain accurate the version available online.

Please Contact us : cli@concretelayer.com

Website : www.concretelayer.com

CLI

01/02/2012 - CLI - ACCROPODE™ II - ECOPODE™ Design Guide Table - En

Figure 7: Technical specification of Accropode^{TM} II armour units

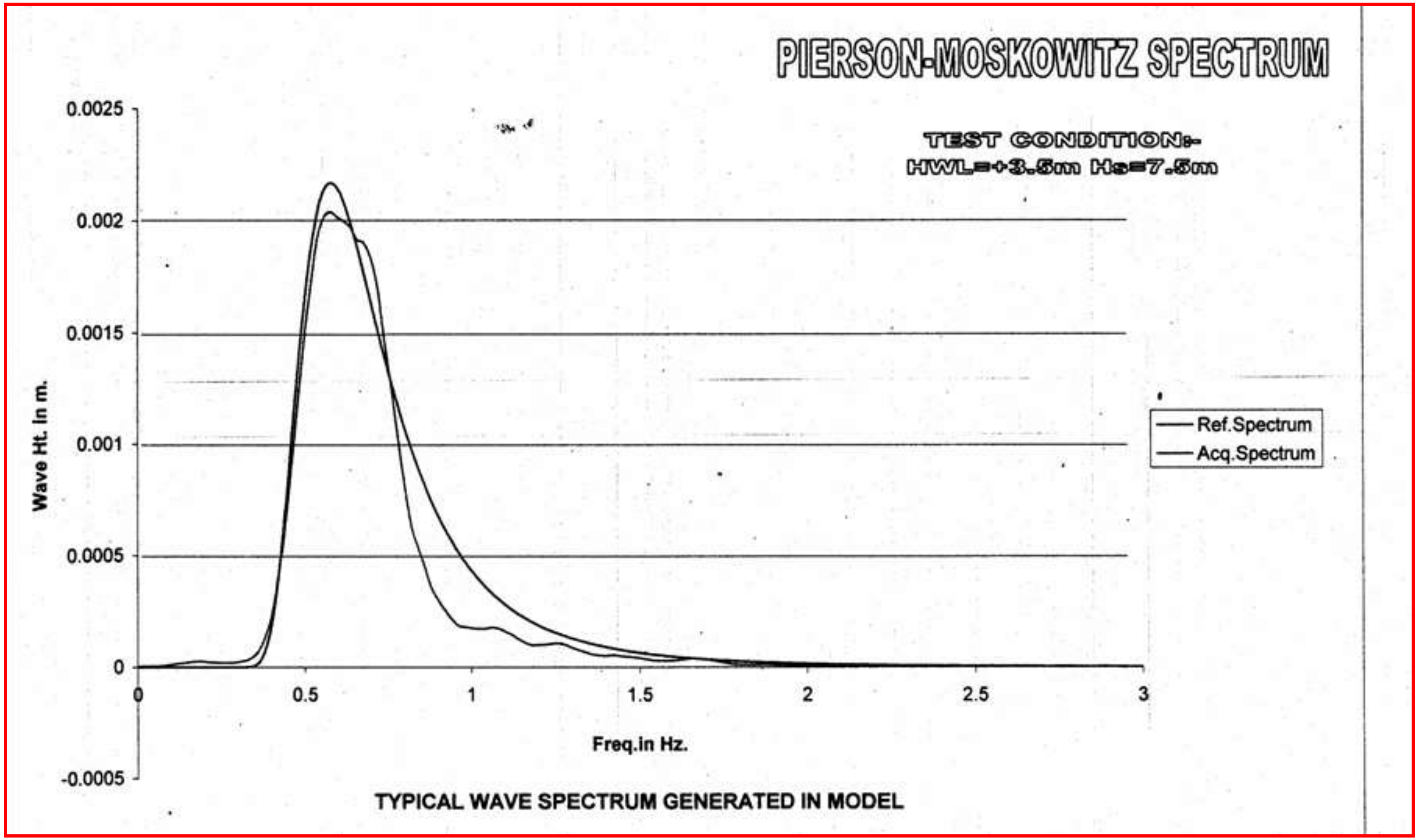


Figure 8: Typical Wave Spectrum

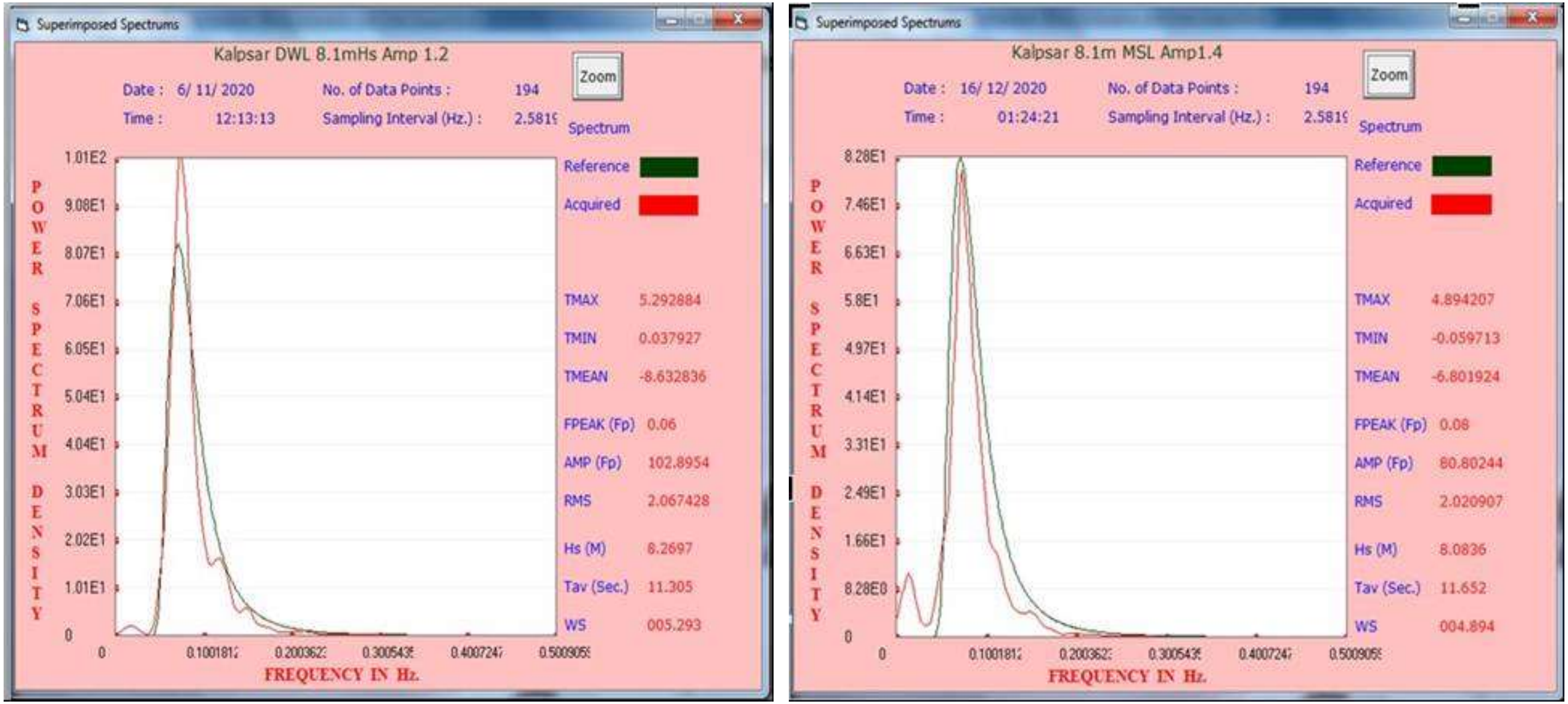


Figure 9 : Typical Wave Spectrum Generated in the Model

Photo-1 : Wave flume Laboratory facilities at CWPRS

Photo-2 : RSWG with Servo Actuator

Photo-3 : Wave basin (45 m x 11 m x 1.1 m)

Photo-4 : Control room with wave data acquisition System

Photo-5 : Placement of Accropode™ II model units in the wave flume at -25 m bed level

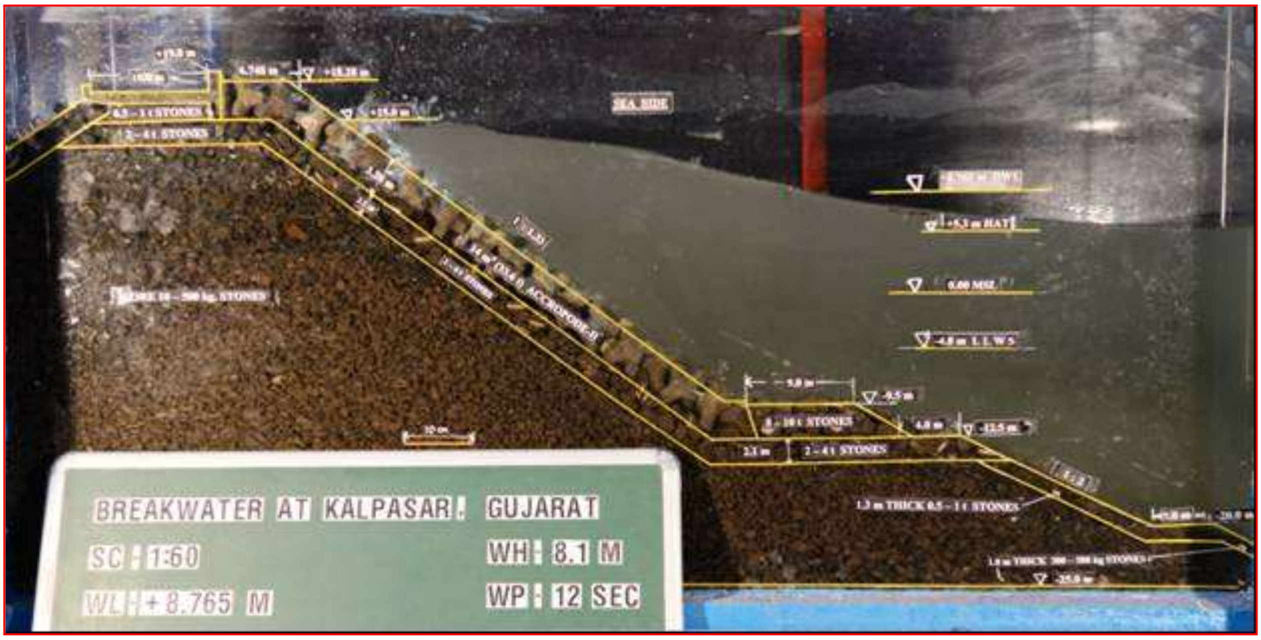


Photo-6 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during significant wave height (Hs) of 8.1 m at Design Water Level (DWL) of +8.765 m

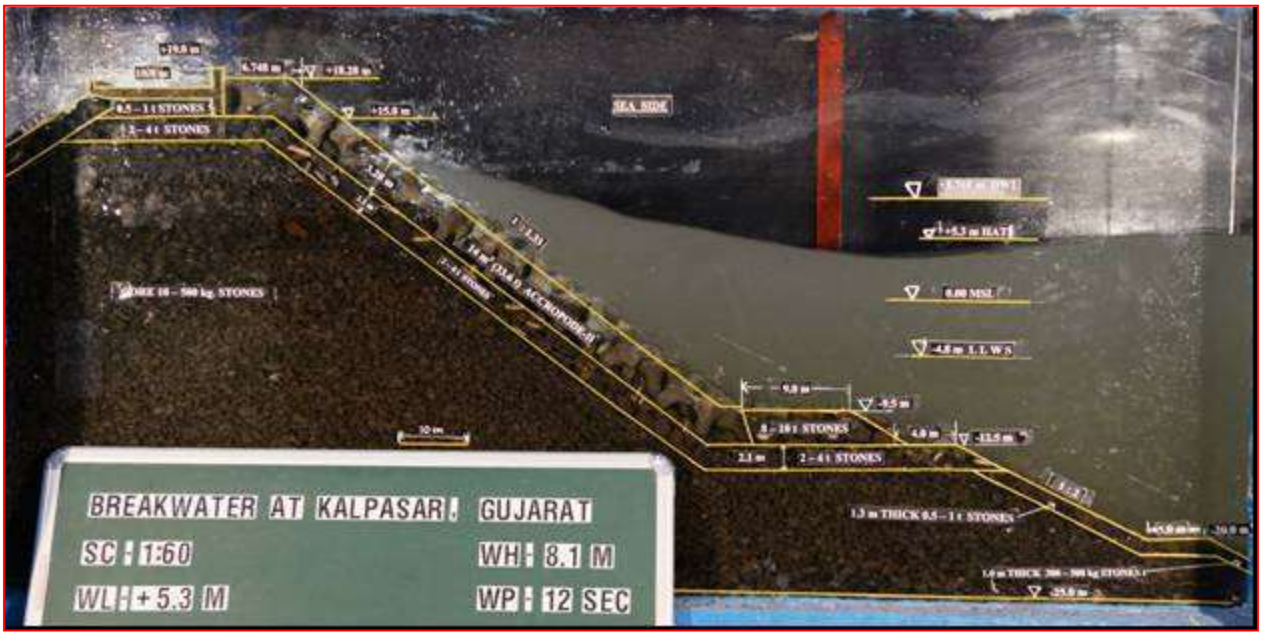


Photo-7 : Wave action on the armour of breakwater cross-section at -25.0 m bed Level during significant wave height (Hs) of 8.1 m at Highest Austronomical Tide (HAT) Level of +5.3 m

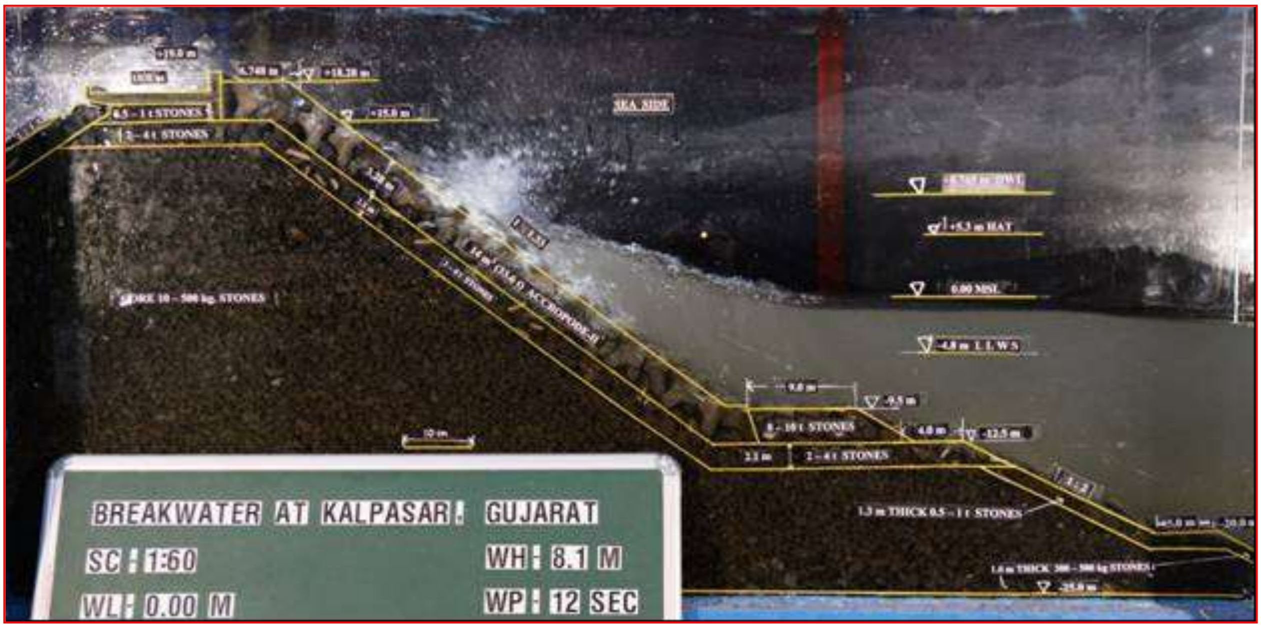


Photo-8 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during significant wave height (Hs) of 8.1 m at Mean Sea Level (MSL) Level of 0.0 m

Photo-9 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during significant wave height (Hs) of 8.1 m at Lowest Low Water Level (LLWL) of -4.8 m

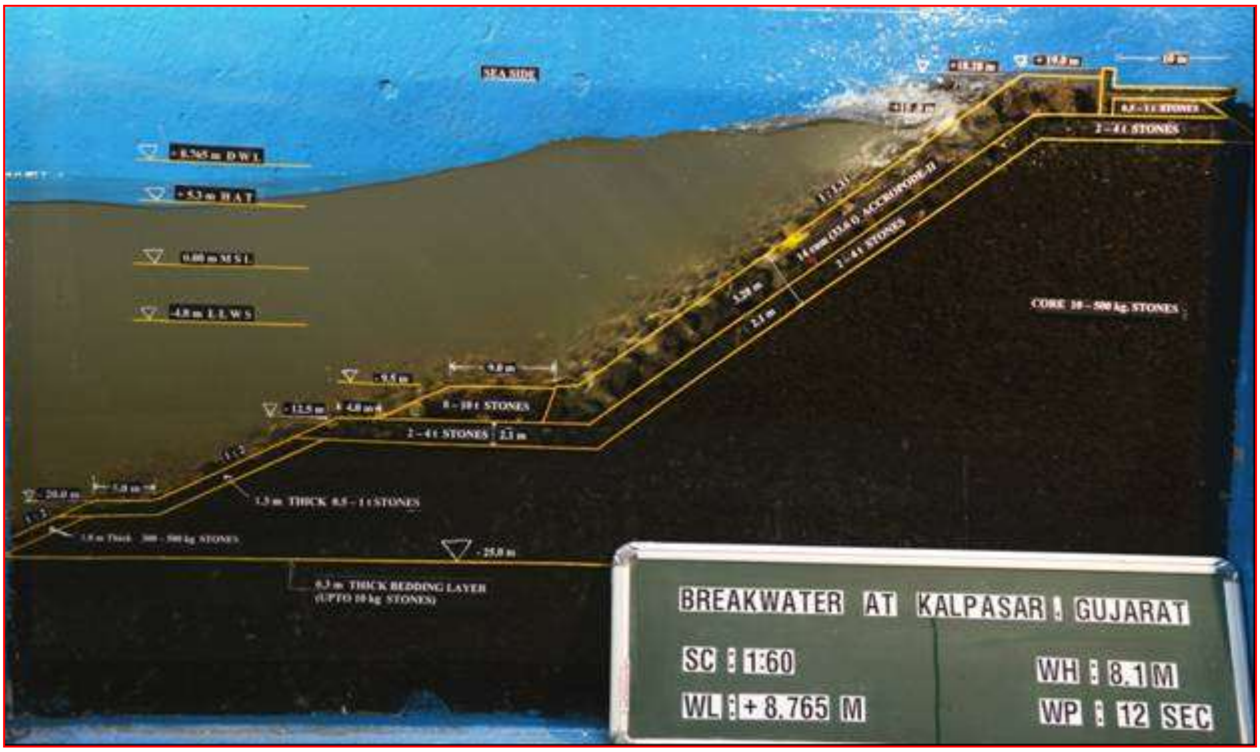


Photo-10 : Wave action on the armour of breakwater cross-section at -25.0 m bed Level during significant wave height (Hs) of 8.1 m at Design Water Level (DWL) of +8.765 m

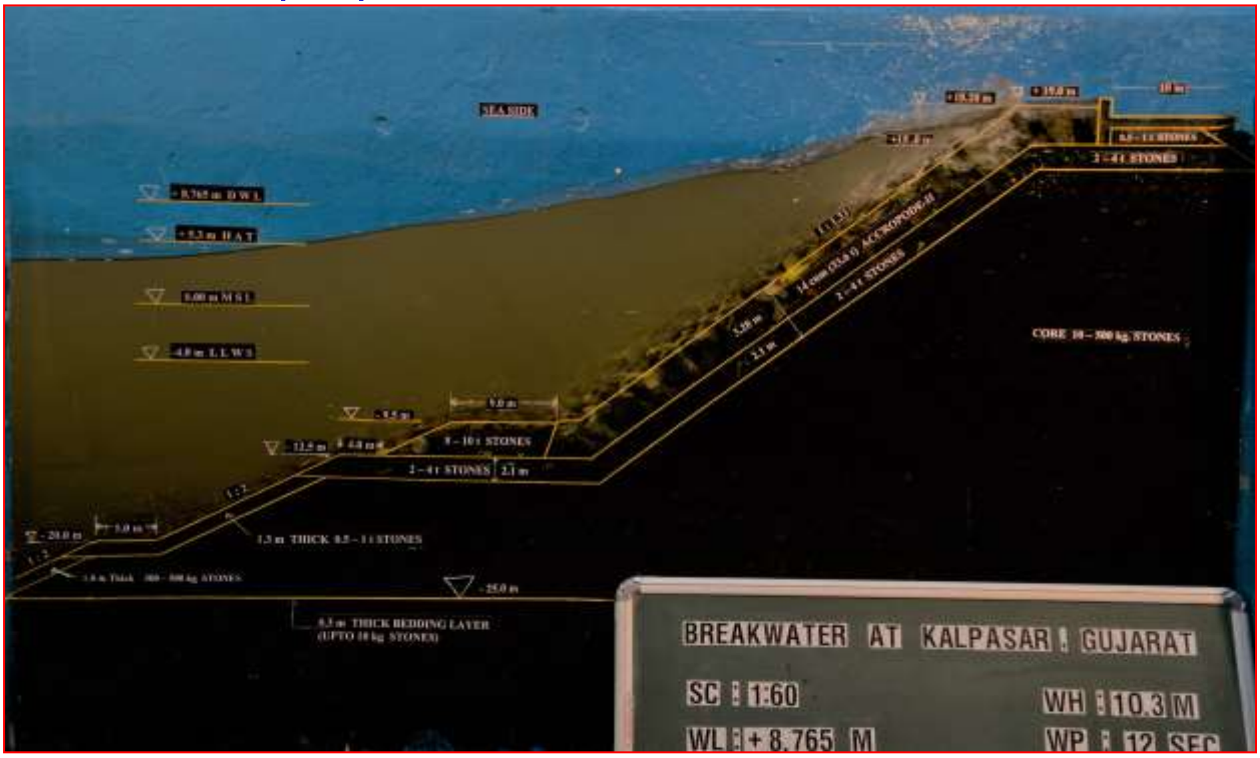


Photo-11 : Wave action on the armour of breakwater cross-section at -25.00 m bed level during maximum breaking wave height ($H_{1/10}$) of 10.3 m at Design Water Level (DWL) of +8.765 m

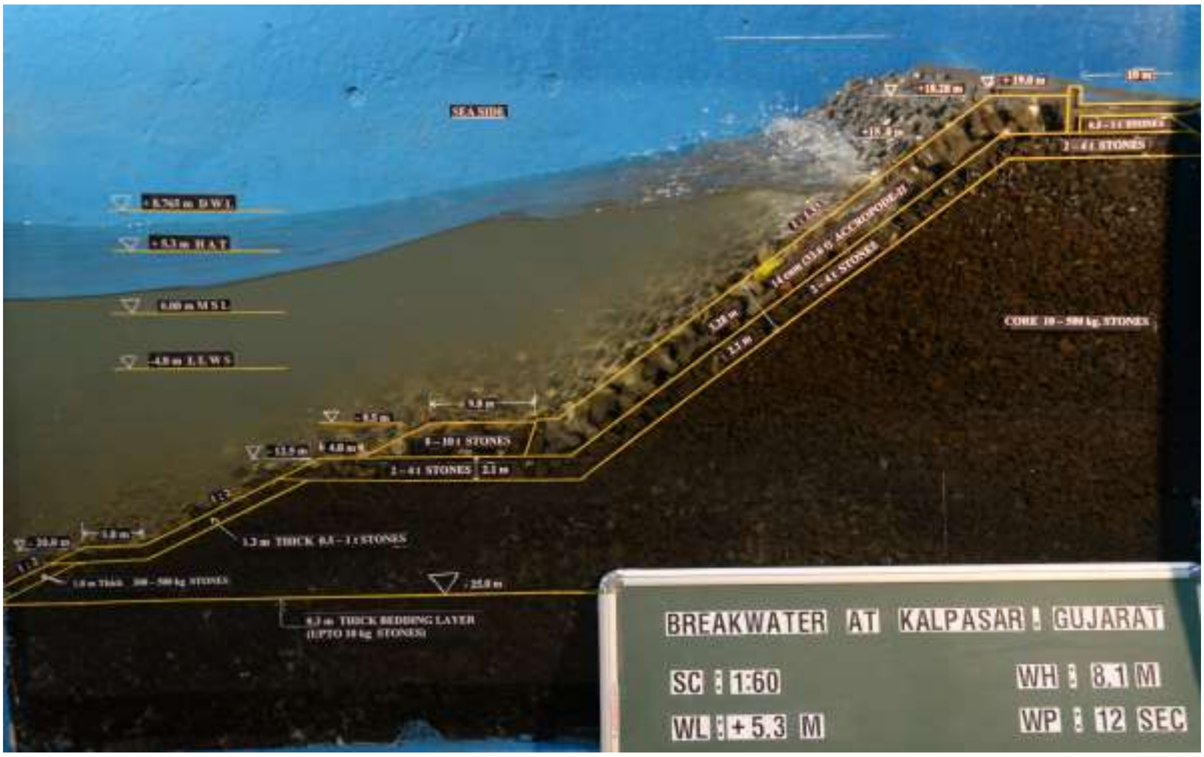


Photo-12 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during significant wave height (Hs) of 8.1 m at Highest Austronomical Tide (HAT) Level of +5.3 m

Photo-13 : Wave action on the armour of breakwater cross-section at -25.00 m bed level during maximum breaking wave height ($H_{1/10}$) of 10.3 m at Highest Austronomical Tide (HAT) Level of +5.3 m

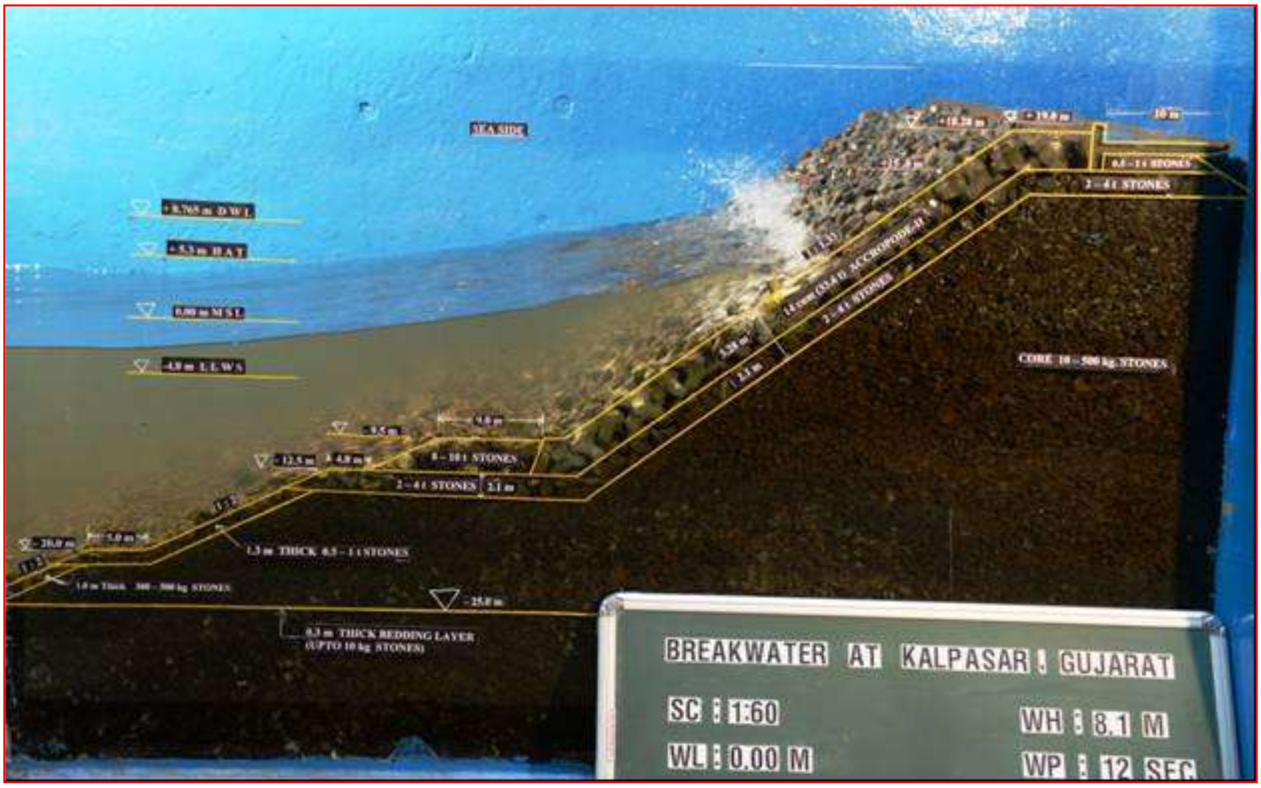


Photo-14 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during significant wave height (Hs) of 8.1 m at Mean Sea Level (MSL) Level of 0.0 m

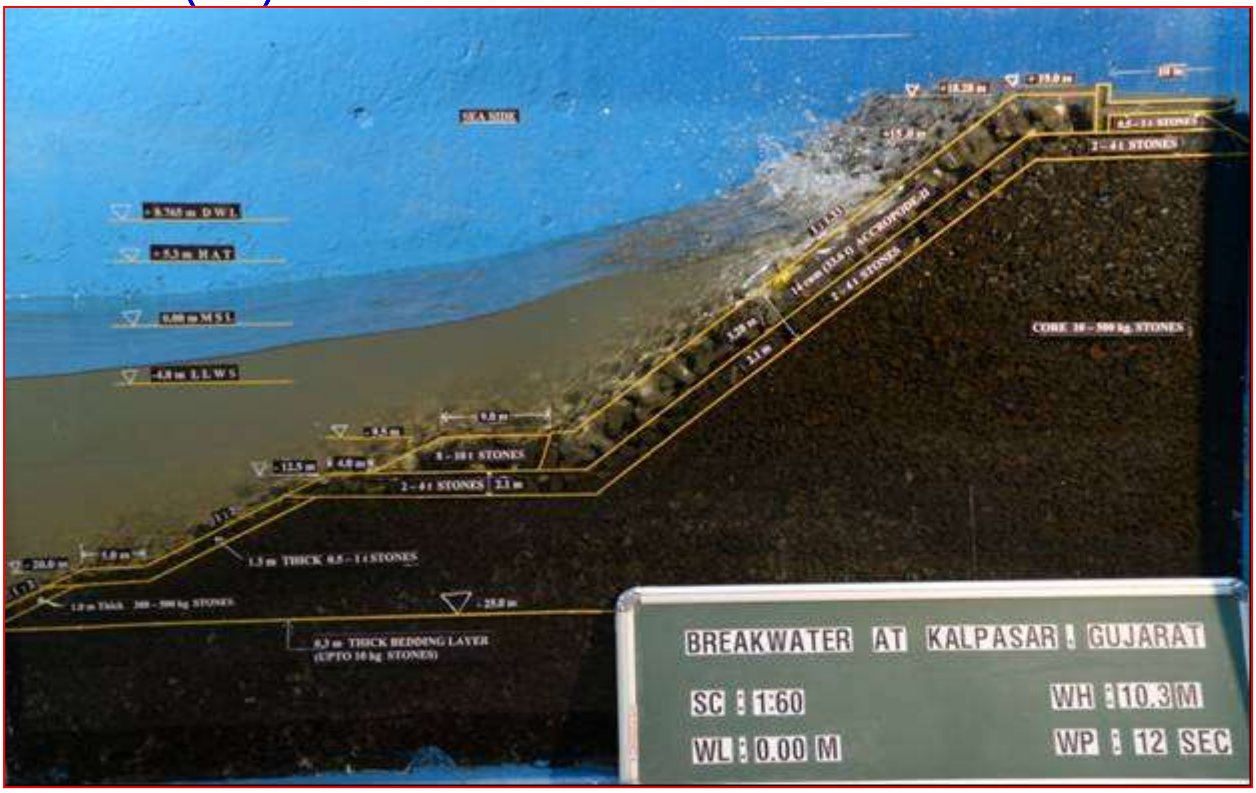


Photo-15 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during maximum breaking wave height ($H_{1/10}$) of 10.3 m at Mean Sea Level (MSL) of 0.0 m

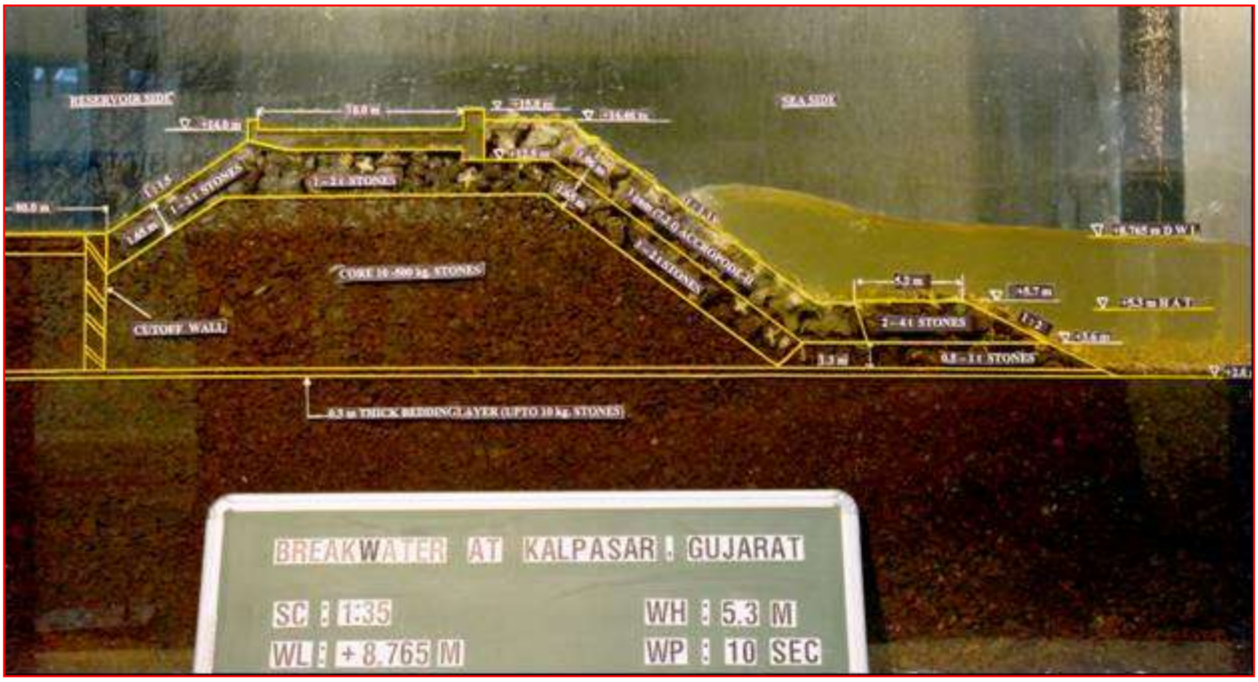
Photo-16 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during significant wave height (Hs) of 8.1 m at Lowest Low Water Level (LLWL) of -4.8 m

Photo-17 : Wave action on the armour of breakwater cross-section at -25.0 m bed level during maximum breaking wave height ($H_{1/10}$) of 10.3 m at Lowest Low Water Level (LLWL) of -4.8 m

Photo-18 : Placement of Accropode^{TM} II model units in the wave flume at 0.0 m bed level

Photo-19 : Wave action on the armour of breakwater cross-section at 0.0 m bed level during breaking wave height (Hs) of 6.8 m at Design Water Level (DWL) of +8.765 m

Photo-20 : Wave action on the armour of breakwater cross-section at 0.0 m bed Level during significant wave height (Hs) of 4.1 m at Highest Austronomical Tide (HAT) Level of +5.3 m



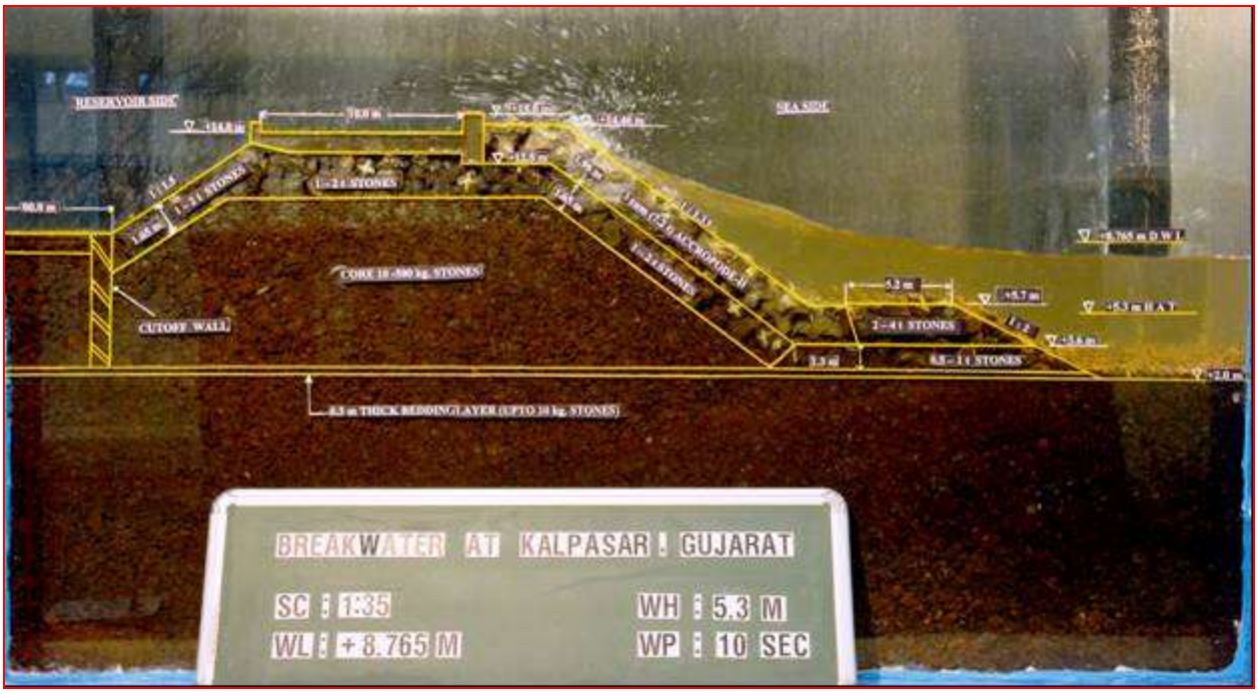


Photo-21 : Wave action on the armour of breakwater cross-section at +2.0 m bed level during breaking wave height (Hs) of 5.3 m at Design Water Level (DWL) of +8.765 m