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Wave Action on a Mild Sloped Offshore Breakwater for the Protection of a Promenade

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ABSTRACT

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Physical model study on a 1:25 scale model of an offshore rubble mound breakwater is carried out. The breakwater is to protect an artificially built sandy promenade in Al-Khiran, South of Kuwait in the Arabian Gulf. The wave transmission, reflection, energy dissipation, wave climate on the crest and seaside toe velocities were assessed based on measurements. Random waves of JONSWAP spectrum were used. The sea side slope of the breakwater is 1:4.9 and the lee side slope is 1:2. The physical model tests were carried out for different water levels to cover a wide range of astronomical tide, i.e. Low (LAT), High (HAT), Highest high (HHWL) and water level at the crest of the breakwater (CAT). The results indicate that at CAT condition the transmission coefficients can be on the order of 0.5. The water particle velocity at the seaside toe can reach a design value of about 2.5 m/sec. In general it has noted that normalised value of the significant wave height at the crest of the breakwater can be in the order of 5% to 18% when the incident wave height is increased from 80% to 120% of the design value without considering the CAT level. The range of average reflection coefficient is between 0.22-0.49 and the dissipation coefficients are well above 0.8.

ADDITIONAL INDEX WORDS: *Wave reflection, Transmission, Water particle velocity at the toe, Rubble mound breakwater*

INTRODUCTION

Kuwait is one of the coastal countries of the Arabian Gulf and is situated on the north-eastern corner of the Arabian Peninsula and covers a land area of about 17,800 km^2. La'ala Al-Kuwait Real Estate Company is developing a huge housing project in the southern part of Kuwait called Al-Khiran (Fig.1) to meet the housing demand of the developing population. It is an artificial lagoon making project. The project contains 5 phases which will be completed in 15 years. Phase A2 (Fig.2) of the project includes the construction of a detached offshore breakwater to protect the artificially nourished promontory beach at the entrance of the Northern inlet. The plan view of Al-Khiran lagoon project is shown in Fig.2.

The layout of the northern inlet can be seen on the top right hand side of Fig.2. One can see the plan features of the proposed promenade and the proposed layout of the offshore breakwater in Fig.3. The offshore breakwater has to protect the promenade against erosion.

The breakwater is designed by Buro Happold, UK. The breakwater has the shape of an arc. The details of the offshore breakwater and the input hydrodynamic conditions are as follows:-

The length of the offshore breakwater: 1100 m
The elevation of the bottom level of the breakwater: -4.3 m KLD.
The average sea bed slope from the breakwater: 1 in 700.
High Astronomical Tide (HAT): 2.7 m KLD
Low Astronomical Tide (LAT): 0.4 m KLD
The Highest High Water Level (HHWL): 3.1 m KLD
Design significant wave height: 3.7 m
Design peak wave period: 10.6 s
The recommended spectrum: JONSWAP
Predominant wave direction: South east
Storm duration: 12 hours
The armor material: Natural stone
The specific gravity of armor stone: 2.65 t/m3
Weight of the armour stone: 2.5 tones
South & North crest level of the offshore breakwater: 5.6 m KLD
South trunk seaward slope: 1V: 4.9 H
North trunk seaward slope: 1V: 3 H
Leeward side slope of the breakwater: 1V: 2H
Maximum aspect ratio of the armor unit: 2
In the above description, KLD is defined as Kuwait Land Datum.

Protection of coast from erosion due to waves using offshore breakwaters is a well known concept. Coastal structures have failed around the world by storms and such failures can be catastrophic in the absence of any defence structure like offshore breakwaters (OUMERACI, 1994). The promenades can be designed with rubble seawall protection and then its utility as a beach will not be available. From utility point of view a sandy promenade with an offshore breakwater is better. The area between the promenade and offshore breakwater can be used for swimming.

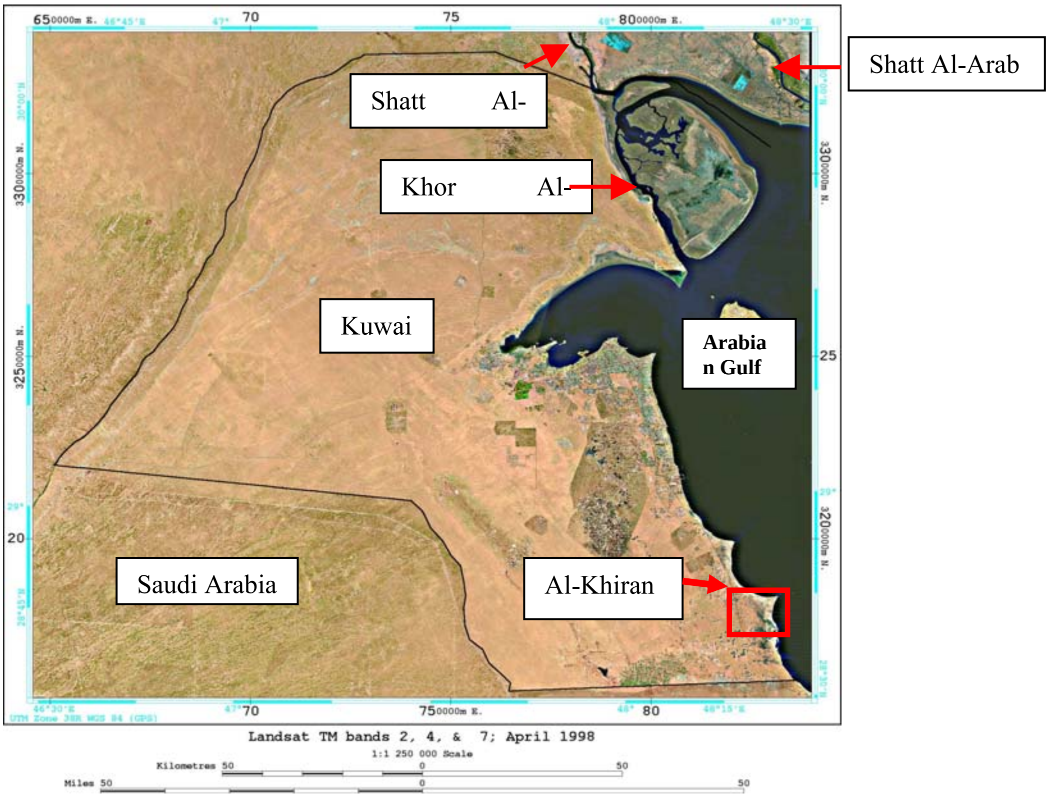

Figure 1. Location Map of Al-Khiran Area

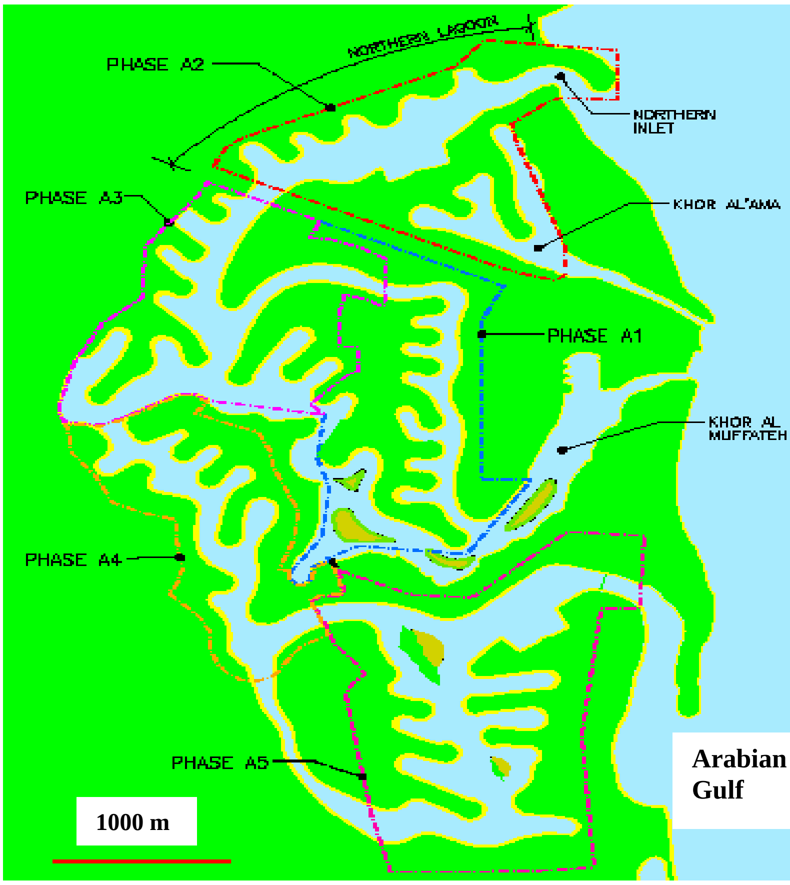

Figure 2. Project proposed by La'ala Al-Kuwait Real Estate Company, Kuwait

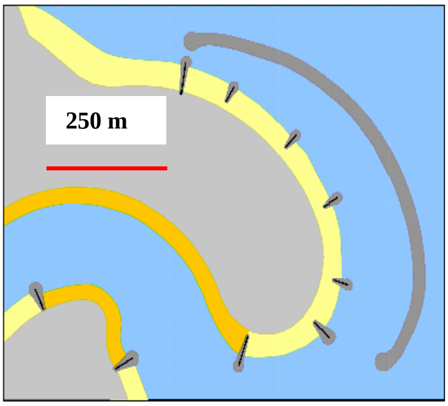

Figure 3. Proposed layout of the offshore breakwater

The need for reduction of water particle kinematics on the promenade to increase the stability and life span has resulted in the introduction of an offshore breakwater in this project. Literatures related to the hydrodynamic studies of offshore breakwaters are abundant. However, not much study on the present topic except the work by GONZELZ MADRIGAL and PRUD`HOME (1990) on the reduction of forces on vertical breakwater defenced by seaward submerged breakwater. Recently MUNIREDDY and NEELAMANI (2005) have studied the effect of an offshore breakwater on the hydrodynamic parameters of vertical seawalls and caissons. The advantage of having the offshore breakwater for reducing the hydrodynamic load on the seawall is clearly emphasised in this study based on detailed lab measurements.

PHYSICAL MODEL STUDY WITH 1:25 SCALE

General

A state of the art wave maker, supplied by DHI Water & Environment Denmark, which is capable of generating regular as well as random waves of many different spectra and waves up to 40.0 cm wave height for wave period range of 1.5 to 3.0 sec, was used for the study. All the lab parameters (Wave height, Wave period, Water depth, different dimensions of the breakwater etc.) for 1:25 scale were worked out based on the Froude law. Stones of 70% to 130% of 2500 kg were allowed for the construction in the field. In the 1:25 scale model, the armour stone weight was ranging from 112 gram to 208 gram. Only stones falling in this weight category and within the aspect ratio of 2 were used. The specific weight was estimated using standard technique. The average estimate based on 5 trials is 2.72 t/m^3. A false bottom was fabricated to suit the study for 1:25 scale. The height of the false bottom was 52 cm. It was used to transform the offshore deep water wave condition into the required water depth at the breakwater location. The physical model tests were carried out for different water levels to cover wide range of astronomical tide, i.e. Low Astronomical Tide (LAT), High Astronomical Tide (HAT), Highest High Water Level (HHWL) and Water level at the crest of the breakwater (CAT).The tests were carried out for 80%, 100% and 120% of the design wave conditions. The following combinations of significant wave height, Hs and peak period, Tp were used:

Hs=3.0 m and Tp=9.5 s (80% of the design condition).

Hs=3.7 m and Tp=10.6 s (100% of the design condition) and Hs=4.5 m and Tp=11.6 s (120% of the design condition).
80% corresponding to a particular developing sea state during a storm event. 120% of the design condition was used for testing the reserve strength of the proposed breakwater. JONSWAP spectrum was used. The calibration for the wave generation was carried out before building the breakwater.

Figure 4. The view of the breakwater after completion of the construction

The breakwater armour stones were painted with white, yellow, red and blue colors. The armor layers were arranged by using these stones in 17 numbers of portions covering the whole surface of the breakwater (Fig. 4).

Instrumentation and data acquisition details

For this study, six capacitance type wave probes were used. 3 probes were installed on the seaward side for obtaining the incident and reflected wave characteristics. One probe was located at the toe of the breakwater, one was placed at the crest of the breakwater to measure the thickness of the overtopping water and one was placed to measure the transmitted wave height. An electromagnetic current meter was placed at the seaward toe of the breakwater in line with the wave probe for measuring the water particle velocity at the toe. The wave synthesiser software supplied by DHI Water & Environment, Denmark was used for wave generation, data acquisition and analysis. All the wave probes were calibrated before, during and after the experiment. The factory calibration constant was used for the current meter. The data were collected at a sampling speed of 40 Hz and for duration of 600 sec.

RESULTS AND DISCUSSIONS

Wave Reflection Characteristics

The DHI reflection analysis module of the wave synthesiser package was used. The positions of the 3 probes were selected so as to avoid the singularities in the analysis. The distance between Probe 1 and Probe 2 was about 0.1 Lp, where Lp is the wave length corresponding to the peak period and the distance between Probe 2 and Probe 3 was about 0.3 Lp. The average reflection coefficient, C_r for the random wave test was obtained using the formula $C_r = (R/I)^{1/2,}$ where
max

$$R = \int_{min} S_R(f)\, df \;\&$$

$$I = \int_{min}^{max} S_I(f)\, df$$

$S_R(f)$ is the reflected spectrum and S_I (f) is the incident spectrum. Table 1 provides the average reflection coefficient for different runs. It is seen in general that the reflection coefficient reduces with increased water depth, which is due to the increased energy transmission. Overall the range of reflection coefficient is between 0.22 to 0.49, which indicates the good wave energy dissipation characteristics of the mild sloped rubble mound breakwater. Typical spectral density plot for the incident and reflected wave spectra is shown for the case of LAT-120% in Fig. 5. The energy level in the reflected wave is insignificant.

Wave Transmission Characteristics

The measured transmitted wave heights were analysed in frequency domain. Typical spectral density of the transmitted waves for different incident energy levels for CAT conditions is given in Fig. 6. Table 1 also provides the average coefficient of transmission, C_t for different input conditions. The average transmission coefficient, C_r for the random wave test is obtained using the formula

$C_t = (T/I)^{1/2,}$ where

$$T = \int_{min}^{max} S_t(f)\, df$$

$S_t(f)$ is the transmitted spectrum

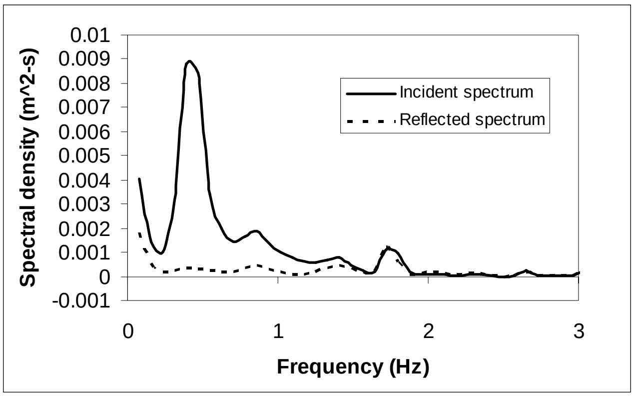

Figure 5. Incident and reflected spectrum for LAT-120%

The wave transmission is insignificant for LAT, HAT and HHWL conditions (Less than 5%). It is of the order of 0.5 for CAT condition, the probability of occurrence of such condition in reality is very rare. It is to be noted that the elevation difference between CAT (+5.6 m KLCD) and HHWL (+3.1 m KLCD) is 2.5 m. In the territorial waters of Kuwait, storms are very rare events and wind induced surges of more than 1.0 m is very rare. Hence CAT event is almost an impossible event.

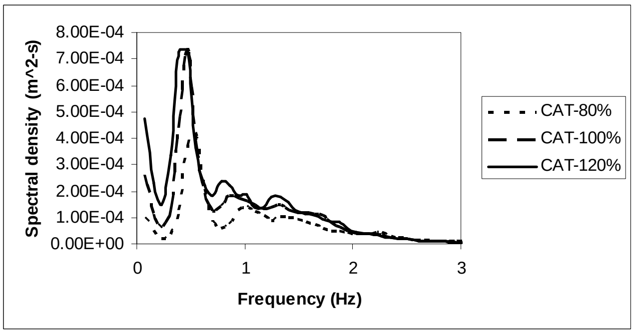

Figure 6. Spectral density of transmitted wave for CAT and for different input energy levels

However, the study for CAT condition was carried out, since the results can be used by the people for other open sea locations around the world.

Wave Energy Dissipation Characteristics of the Breakwater

Since the average wave energy reflection and wave energy transmission characteristics of the offshore breakwater is known, one can readily calculate the average wave energy dissipation coefficients. The dissipation coefficient C_l is obtained by using the equation $C_l = (1 - C_r - C_t)^{0.5}$. Table 1 also provides the value of C_l for different wave energy and tidal levels. It is found that the breakwater is dissipating the energy the most for HAT and HHWL conditions compared to CAT condition. It is found during HAT and HHWL conditions that most of the run-up and rundown was covering the seaward face of the breakwater and hence more cumulative energy dissipation is obtained compared to CAT condition during which the wave interaction on the breakwater armour has been reduced due 100% submergence of the breakwater.

Wave Climate on the Crest of the Breakwater

The significant wave height at the crest level of the breakwater is obtained from the spectral density plot of the wave time series collected by using the wave probe placed on the crest of the breakwater. This wave height is normalised by using the corresponding incident significant wave height and the result is called average normalised significant wave height at the crest level of the breakwater. Table. 1 also gives this normalised value for different test conditions.

It is seen that the average normalised value of the significant wave height at the crest level of the breakwater is 0.0 for all wave energy levels at LAT condition. However, for HAT the normalised value has reached from 4.6% to 12.8% when the energy level of the incident wave is increased from 80% to 120%. Similarly for HHWL, the normalised value is found to vary from 7.8% to 18.3% when the input energy level is varied from 80% to 120% of the design value. During CAT test, the wave sensor on the crest was not functioning properly and hence the results pertaining to CAT is not included in the table. However, it was observed from the scale marked on the flume wall that the magnitude of the wave on the crest is closer to the incident wave height.

Water Particle Velocity at the Seaside Toe of the Breakwater

The water particle velocity at the sea side toe is important for the safe and optimal design of the scour mat for the breakwater toe. The spectral density plots for the water particle velocity were obtained for different input conditions. Fig.7 shows the comparison of spectral density plot for different water depth conditions and for H_s = 100% of the design values. It is found that a significant part of the energy exists in the high frequency region for the case of CAT condition. Overall, CAT condition contributes higher order of spectral density, which may be due to lesser energy dissipation by the structure. Table 1 also provides the measured significant water particle velocity at the toe, u_{ms} as well as the estimated maximum water particle velocity (By using H_s and T_p as input) at the toe in the absence of the breakwater using liner wave theory, u_{ts}. The purpose of presenting this information is to understand the perturbation effect of the breakwater structure on the water particle velocity. It is to be noted that for LAT-120% and for CAT-120%, the significant water particle velocity is lower than those for LAT-100% and CAT-100% respectively, which could be due to the error in the averaging of spectral density plot to obtain the significant value of the water particle velocity.

The results also provided in the normalised form. The normalised significant water velocity at the seaward toe of the breakwater, u_{ns} was calculated using the formula $u_{ns} = u_{ms}/u_{ts}$. u_{ms} was obtained from the spectral density of the measured water particle velocity as

$u_{ms} = 2\,(m_{0u})^{0.5}$, where

$$m_{0u} = \int_{min}^{max} S_u(f)\,df$$

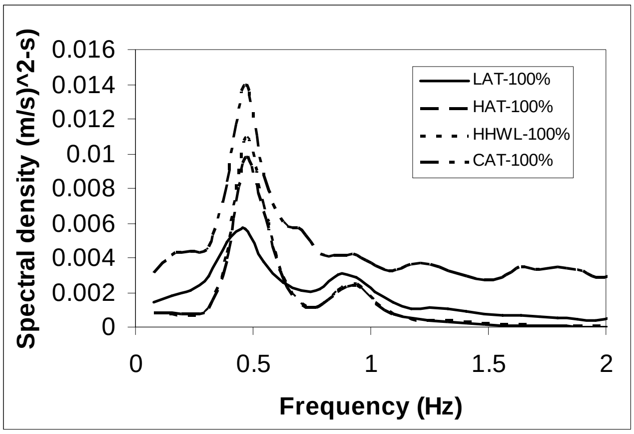

Figure 7. Spectral density of water particle velocity at the sea side toe for different water levels for H_s = 100% of the design value

$S_u(f)$ is the spectral density value of the water particle velocity. u_{ts} was obtained using the equation, $u_{ts} = (H_s\, g\, T_p)/(2\, L_p \cosh(k_p\, d))$, where H_s = Significant incident wave height, g = Acceleration due to gravity, T_p = Peak period, L_p = Wave length corresponding to the peak period, k_p = Wave number corresponds to the peak period and d = Local water depth at the breakwater location.

From the time domain analysis, the maximum water particle velocities ranging from 0.214 m/s to 1.025 m/s were recorded in the lab for the 1:25 scale model. From the time series, it is seen that velocity of the order of 1.025 m/sec exists for a fraction of a second. A total of about 300 to 360 waves were recorded over a period of 600 s in the lab for each input conditions. Hence the maximum value of the water particle velocity for the design purpose can be estimated as $u_{max} / u_s = \{(In[N])/2\}^{0.5}$,where u_{max} is the maximum value of the horizontal water particle velocity, u_s is the significant value of the water particle velocity and N is the number of waves in the time series

Table 1. The measured Reflection coefficient, Transmission coefficient, Dissipation coefficient, Normalised significant wave height at the crest level of the breakwater, Significant water particle velocity at the toe along with the liner theory based water particle velocity and the corresponding expected velocity in the field

Test condition	*Average Reflection Coefficient*	*Average Transmission Coefficient*	*Average Dissipation Coefficient*	*Average normalized significant wave height at the crest level of the breakwater*	*u_{ms} (m/sec)*	*u_{ts} (m/sec)*	*u_{ms}/u_{ts}*	*Estimated value for the field (m/sec)*
LAT-80%	0.456	0.029	0.889	0.000	0.115	0.408	0.281	0.573
LAT-100%	0.471	0.034	0.881	0.000	0.145	0.511	0.283	0.723
LAT-120%	0.490	0.040	0.871	0.000	0.124	0.629	0.196	0.618
HAT-80%	0.301	0.016	0.953	0.046	0.110	0.319	0.345	0.551
HAT-100%	0.349	0.018	0.937	0.061	0.111	0.403	0.275	0.554
HAT-120%	0.361	0.031	0.932	0.013	0.123	0.498	0.246	0.614
HHWL-80%	0.281	0.018	0.959	0.078	0.108	0.309	0.348	0.538
HHWL-100%	0.334	0.027	0.942	0.142	0.119	0.390	0.304	0.590
HHWL-120%	0.349	0.045	0.936	0.183	0.142	0.482	0.294	0.709
CAT-80%	0.220	0.524	0.823	-	0.283	0.256	1.108	1.421
CAT-100%	0.265	0.524	0.809	-	0.284	0.327	0.869	1.421
CAT-120%	0.299	0.483	0.823	-	0.252	0.406	0.619	1.260

From the above table, with u_s = 1.421 m/s and for N=355, the value of u_{max} was worked out as 2.43 m/s. Hence, it is recommended that the breakwater toe protection systems be designed for a velocity of 2.5 m/s.

CONCLUSIONS

Based on a detailed physical model study on a 1:25 scale model of an offshore mild sloped (1V:4.9H) rubble mound breakwater (to be used as a defence mechanism to protect an artificially nourished sand promenade) for different tidal conditions and for random waves of JONSWAP spectrum with different energy levels, the following conclusions are obtained:

a. The sea side toe mat, which prevents the scour at the sea side toe, need to be designed for a maximum wave induced flow velocity of 2.5 m/sec.
b. The wave transmission is insignificant for LAT, HAT and HHWL conditions. However, for CAT condition, transmission coefficients can be of the order of 0.5.
c. The range of average reflection coefficient is between 0.22 to 0.49 and the dissipation coefficients are well above 0.8. This indicates that the mild sloped breakwater with 1:4.9 sea side slopes is dissipating the wave energy very efficiently.
d. The average normalised value of the significant wave height at the crest level of the breakwater is 0.0 for all wave energy levels at LAT condition. For HAT condition, the normalised value of the significant wave height at the crest of the breakwater has reached from 4.6% to 12.8% when the energy level of the incident wave is increased from 80% to 120%. Similarly for HHWL, the normalised value has changed from 7.8% to 18.3% when the input energy level is varied from 80% to 120% of the design value.

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