

Subareal wave pressures, layer thicknesses, run-up and run-down velocity on sea walls

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Wave pressures, layer thickness, run-up and run-down velocities were measured on the splash/subareal zone (the part of the seawall which is partially in water during run up and partially in the air during run down) of plane seawalls for a wide range of hydrodynamic parameters and seawall slopes. The complete wave breaking range (spilling, plunging, collapsing and surging) is covered in the study. The maximum wave pressure in the subareal region can be as high as 1.2 times the static pressure due to water column equal to the incident wave height. The maximum wave pressure at any point is higher than the water pressure induced by the layer thickness due to the dynamic contribution of the flowing water on the seawall. The maximum run up and run down velocity can be as high as 25 times the maximum horizontal water particle velocity in deep water. The run-down velocity is found to be higher than the run-up velocity for the same input condition. Using the measured data, empirical formulae are proposed to predict the subareal wave pressures, layer thicknesses, and run-up and run-down velocities. The proposed formulae incorporate the surf similarity parameter and relative elevation of the location on the subareal region of the seawall. The empirical equations are simple, reliable and hence can be used for the optimal design of plane seawalls.

[Key words: Sea wall, wave pressures, layer thickness, run-up and run-down velocity, surf similarity parameter, subareal region]

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Introduction

Seawalls are built to protect coasts from erosion and to reduce overtopping. The design of cheap and safe seawall requires reliable methods of estimating the maximum pressures and other flow variables on such structures. These variables are not studied in detail as on date in the splash/subareal zone. Figure 1 (ref. 1,2) shows what we mean by subareal zone (in Fig. 1, the region AC, which is the region between the mean water level (point A) to the maximum run up point (point C) which is exposed for partial wave action and partial exposure to atmosphere).

Experiments on wave pressures on the seawalls closer to the free water surface and well inside the water have been carried out by many investigators³⁻⁹. Wave interaction on sea walls with energy dissipating blocks is investigated by Neelamani & Sandhya¹⁰. The benefit of introducing the energy dissipaters on the seawall surface is brought out by them. The wave pressures and layer thickness on the sub areal region on a plane seawall for random waves was investigated by Neelamani¹¹. Seawall with slopes of 1:3, 1:4 and 1: 6

were used. JONSWAP spectrum with significant wave height, H_s from 0.08 m to 0.2 m and peak periods, T_p from 1.5 to 6.0 s and a constant water depth of 0.7 m is used. Based on extensive measurements, empirical formulas for practical applications are proposed by Neelamani¹¹ to predict the maximum, significant and mean sub aerial random wave pressure and layer thickness (thickness of water layer perpendicular to the still water level on the run-up zone) by using the surf similarity parameter, significant wave height and elevation on the sub aerial region as inputs. It is found that the maximum layer thicknesses is 1.11 times the significant layer thickness and maximum sub Aerial wave pressure is 1.06 times the significant wave pressures. The predictive equations based on extensive

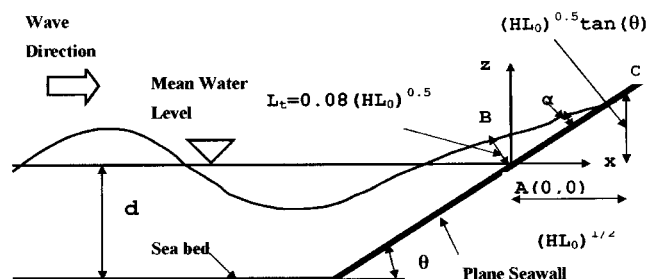


Fig. 1—Geometric interpretation of Hunt¹ for run-up and Battjes & Roos² for layer thickness²

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measurements can be used for the design of non-overtopping seawalls.

Battjes & Roos² investigated the layer thicknesses on impermeable sloped seawalls. Their study focused on breaking wave conditions for surf similarity in the range of 0.5 to 2.0 only. Prominent studies on run-up velocity have been undertaken by Zitscher¹², Shore Protection Manual¹³ (SPM, which is now called as Coastal Engineering manual, CEM), Battjes & Roos², Führböter & Witte¹⁴ and van der Meer & Breteler⁵. Figure 2 shows the comparison of run-up velocity at different vertical elevations from the shoreline ($z = 0.0$) by the different authors for a typical incident wave height of 1.0 m, wave period of 5.0 sec, seawall slope of 1:6 and water depth of 5.0 m. The results of the present study are also provided. The proposed maximum predicted run-up velocity at SWL is less than the predicted result by the SPM. It is due to the fact that SPM assumes the shallow water celerity as the run-up velocity at $z = 0$. In practice, the wave dissipates part of its energy due to breaking and turbulence on the seawall slope before it reaches the still water line. Hence one can expect a smaller run-up velocity than the shallow water wave celerity value of $(gd)^{0.5}$ at $z=0.0$. Some of the works on rundown velocities were by Battjes & Roos², van der Meer & Breteler⁵ and Mani *et al*¹⁵. The available literature is limited to one seawall slope with investigations closer to the still water line and for a limited range of input waves. The results for layer thicknesses are available over a limited wave breaking conditions ($\xi_o < 2.0$, where ξ_o is called the surf similarity parameter, $\xi_o = \tan \theta / (H/L_0)^{1/2}$, where $\tan \theta$ is the seawall slope, H is the incident wave height and L_0 is the deep water wave length). But, the magnitude of

layer thickness is significant for the higher values of ξ_o ($\xi_o > 3.3$) due to the existence of higher momentum, especially for the surging waves. Most of the published studies on run-up velocities are based either on the derivation of the measured water surface elevation or on direct velocity measurements on a single slope. The present investigation is carried out for a wide range of surf similarity parameters, covering spilling, plunging, collapsing and surging breakers. There are no simple predictive equations for estimating the wave pressures, layer thickness, run-up and run-down velocity in the subareal region of sloped plane seawalls, hence the investigation was attempted. Based on planned measurements, empirical equations have been developed for which the following criteria are considered:

- The equations should be simple for use by field Engineers
- The equations should not include input variables of marginal influence.
- The equations should be consistent with data from a wide range of wave and structure conditions.
- The equations should be consistent with the current understanding of the physics of the problem.
- The equations should approach the logical limiting values.

Analysis of the problem

The present development of predictive methods for wave pressures, layer thickness, and run-up and run-down velocities on sloped impermeable seawalls can be visualised by analysing the fundamental physics of wave transformation on sloped structures. Waves

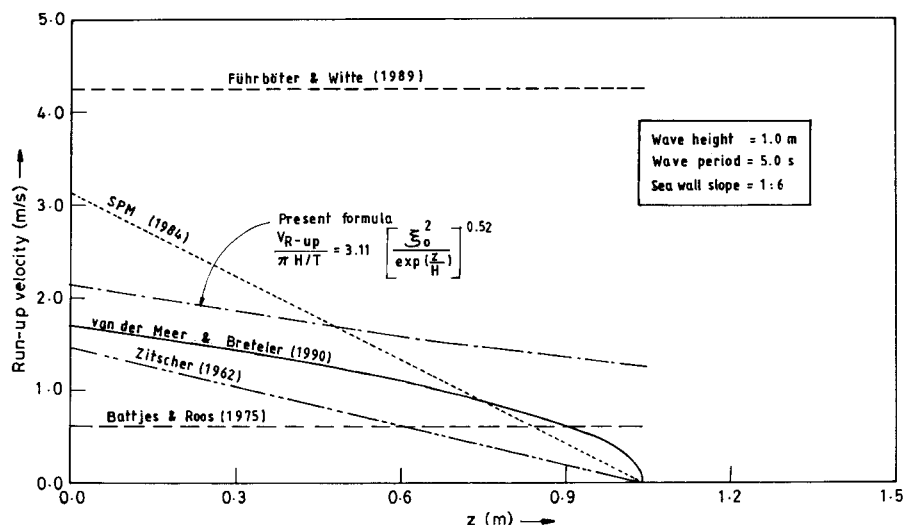


Fig. 2—Comparison of different formulae for run-up velocity on sloped sea walls

undergo significant transformation during their propagation on a sloped structure. On breaking, the wave becomes one or more of the following types: spilling, plunging, collapsing or surging (depending on the seawall slope and the incident wave steepness). Energy dissipation is very significant for spilling waves compared to surging waves (Führböter¹⁶). In other words, the wave energy availability at $z = 0$ increases with increased surf similarity parameter, which is the main input for run-up on the subareal region (Hunt¹). Hence it is expected that layer thickness, wave pressures and run-up and run down velocities on a point in the subareal region increase with increased ξ_0 .

According to Battjes & Roos², the layer thickness on a plane impermeable seawall at $z = 0$ is given as

$$L_t = 0.08 (H L_0)^{0.5} \quad \dots(1)$$

where H is the incident wave height at the toe of the sea wall and L_0 is the deep water wave length. According to Hunt¹, the run-up, R_{up} on a smooth impermeable structure due to regular monochromatic waves is given as

$$R_{up} = (H L_0)^{0.5} \tan \theta \quad \dots(2)$$

where $\tan \theta$ is the slope of the seawall. The horizontal distance between the water line ($z = 0$) to the point of maximum run-up, S is

$$S = (H L_0)^{0.5} \quad \dots(3)$$

Assume that the line joining the layer thickness at water line and the point of maximum run-up is linear (line BC in Fig.1). The mass of water in the run-up zone per unit width, M_1 is equal to the area of the triangle ABC in Fig.1, and is given as:

$$M_1 = \rho \frac{1}{2} (H L_0)^{1/2} (0.08 (H L_0)^{1/2}) \quad \dots(4)$$

where ρ is the mass density of water. The mass of water in a sinusoidal wave per unit width, M above the SWL is

$$M = \rho (H/2) (L_0/2)(2/\pi) \quad \dots(5)$$

The ratio of water mass in the run-up zone to the water mass in the crest part of the incident wave, M_1/M is equal to 0.08π . i.e. 0.25. It means that about 25% of the water mass in the crest part of wave is approximately participating in the run-up process to formulate the layer thickness.

From Fig.1, the angle α between line AC and BC is given as

$$\tan(\alpha) = [0.08 \cos(\theta) (H L_0)^{1/2}] / [(H L_0)^{1/2} (1 + \tan^2(\theta))^{1/2}] \quad \dots(6)$$

which is exactly the same as

$$\tan(\alpha) = 0.08 \cos^2(\theta) \quad \dots(7)$$

For the practical range of θ ($\theta = 10^\circ$ to 45°) the value of α range from 2.29° to 4.44° . The above derivations are based on Battjes & Roos² works on layer thickness and Hunt¹ on run-up.

Materials and Methods

Experimental set-up

The experimental investigations were carried out in a wave flume. The experimental set up is shown in Fig. 3. The dimensions of the flume facility and the characteristics of the waves used for the study are:

Flume Length	=	90 m
Flume Width	=	2 m
Flume Depth	=	1.2 m
Water Depth, d	=	0.6, 0.7 and 0.8 m
Type of wave generator	=	flap type
Waves used	=	monochromatic
Incident wave heights, H	=	8 to 20 cm
Wave periods, T	=	1.5 to 6.0 sec
Slope of the sea wall	=	1:3, 1:4 and 1:6
Type of sea wall	=	impermeable and non-overtopping

Elevations of wave gauge for measuring layer thicknesses = 0.60 to 1.03 m from the flume bed at 9 different locations.

Elevations of pressure transducers for measuring wave pressures = 0.60 to 0.90 m from the flume bed at 5 different locations.

Elevations of miniature type propellers for measuring run-up and run-down velocities = 0.6 to 1.03 m from the flume bed at six different locations.

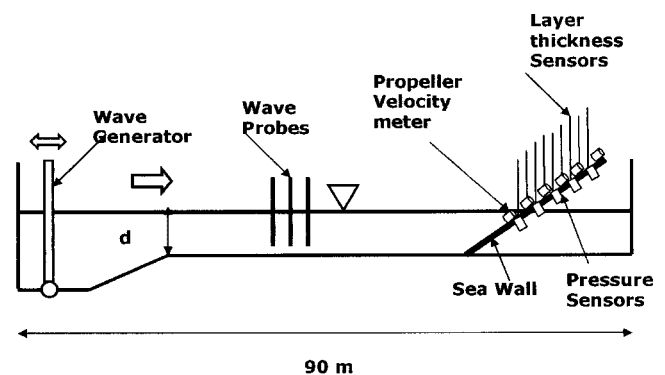


Fig. 3—Experimental set up

The different ranges of normalised hydrodynamic parameters obtained are:

Incident wave steepness, H/L	= 0.003 to 0.065
Relative water depth, d/L	= 0.04 to 0.26
Surf similarity parameter, ξ_0	= 0.6 to 7.0
Relative wave height, H/d	= 0.06 to 0.42
Ursell Parameter, $H L^2/d^3$	= 0.01 to 80.0
Relative elevation, z/H	= 0.0 to 3.2
Normalised parameter, $\xi_0 \exp(-z/H)$	= 0.2 to 3.0
Normalised parameter, $\xi_0^2 \exp(-z/H)$	= 0.5 to 30.0

Regular waves were generated for 100 sec and the data were collected for 200 sec at a sampling rate of 40 samples per second. The time series corresponding to the clear repetition of the regular occurrences of the events were used for the analysis.

Instrumentation and data collection

The incident waves were measured by using capacitance type wave probes fixed at a distance of 30 m from the seawall. Five pressure transducers of type PDCR 830, each 5 bar capacity and accuracy of $\pm 0.06\%$ were used for wave pressure measurements. Nine capacitance type wave probes were used for measuring the layer thickness. The uncertainty in the measurement of waves of 5 cm height is about 2%. Six number of miniature propeller type velocity meters were used for measuring the run-up and run-down velocity. The pitch diameter of the propeller is 8 mm and was fixed inside a hollow cylinder of 10 mm dia. The propeller rotates in the clockwise direction during run-up and in the anti clockwise direction during rundown. A computer records the time histories of wave heights, wave pressures, and run-up and run-down velocities. A total of 200 runs with different combinations of water depths, wave periods, wave heights and three different sea wall slopes were used. About 1800 measurements of layer thickness, 1000 measurements of wave pressure and 1200 measurements of run-up and run-down time series were made. All these time series were analysed to get the normalised dependant variables like $P_{\max}/\rho gH$, L_t/H , $V_{\text{Run-up}}/(\pi H/T)$ and $V_{\text{Run-down}}/(\pi H/T)$, where

$P_{\max}$	= Maximum wave pressure
L_t	= Maximum layer thickness
$V_{\text{Run-up}}$	= Maximum value of the run up velocity
$V_{\text{Run-down}}$	= Maximum run down velocity
$\pi H/T$	= Max. horizontal or vertical water particle velocity at SWL in deep water
g	= Acceleration due to gravity.

Predictive equations

At first a correlation analysis between the normalised independent and normalised dependant variables were carried out. The results are shown in Table 1.

It is seen from the above table that wave pressure coefficients, layer thickness coefficient, run-up and run-down velocity coefficients are negatively correlated with H/L , d/L , H/d , $\cot \theta$ and z/H and positively correlated with ξ_0 , $\xi_0 \exp(-z/H)$ and $\xi_0^2 \exp(-z/H)$. The interpretations are as follows:

- Increase in wave steepness results in better energy dissipation and hence reduces the coefficients of pressures, layer thicknesses and run up and run down velocity. Similar concept applies for d/L and H/d .
- Increase in $\cot \theta$ or reduction of slope of the structure results in spilling breaking and significant loss of energy on the sloped structure, before waves reach the still water line.
- With increased z/H , the water mass has to travel against the gravitational force and also overcome the frictional resistance on the seawall and hence all the coefficients must reduce.
- Increase in ξ_0 results in the transformation of type of wave breaking from spilling to surging breaking, which means increase of available energy at still water line.

It is noted from Table 1 that pressure and layer thickness coefficients are correlated strongly with $\xi_0 \exp(-z/H)$ and run-up and run-down velocity coefficients are correlated strongly with $\xi_0^2 \exp(-z/H)$. It is to be noticed that the selection of the normalised independent variables $\xi_0 \exp(-z/H)$ and $\xi_0^2 \exp(-z/H)$ were made after carrying out many numbers of multiple regression analysis and permutations and combinations with the basic normalised independent variables H/L , d/L , ξ_0 , H/d , $\cot \theta$ and z/H .

Various forms of predictive equations were investigated. Both linear polynomial and power equations were explored. It is found that the correlation coefficients (R) of linear polynomial equations were as

Table.1—Correlation coefficients between the normalised independent and dependent variables

Parameter	$P_{\max}/\rho gH$	L_t/H	$V_{\text{Run-up}}/(\pi H/T)$	$V_{\text{Run-down}}/(\pi H/T)$
H/L	-0.26	-0.27	-0.64	-0.62
d/L	-0.21	-0.30	-0.58	-0.58
ξ_0	0.49	0.45	0.72	0.75
H/d	-0.22	-0.12	-0.46	-0.44
$\cot \theta$	-0.19	-0.13	-0.12	-0.08
z/H	-0.19	-0.12	-0.18	-0.20
$\xi_0 \exp(-z/H)$	0.92	0.83	0.70	0.71
$\xi_0^2 \exp(-z/H)$	0.75	0.68	0.86	0.89

good as power equations. But the problem with the linear polynomial predictive equations is that they have an intercept and hence they do not approach the logical limiting values. Hence linear polynomial predictive equations are not proposed.

Surf similarity parameter and relative elevation, z/H were found to be the very prominent independent parameters. It is found that addition of other normalised independent parameters has insignificant effects on improving the accuracy of the predictions.

The following predictive equations are obtained:

Subareal wave pressures

$$P_{\max}(z)/\rho gH = 0.32 [\xi_0 e^{(-z/H)}]^{1.03} R=0.94 \quad \dots(8)$$

Layer thicknesses

$$Lt(z)/H = 0.32 [\xi_0 e^{(-z/H)}]^{0.93} R=0.86 \quad \dots(9)$$

Run-up velocity

$$V_{\text{Run-up}}(z)/(\pi H/T) = 3.11 [\xi_0^2 e^{(-z/H)}]^{0.52} R=0.88 \quad \dots(10)$$

Run-down velocity

$$V_{\text{Run-down}}(z)/(\pi H/T) = 3.66 [\xi_0^2 e^{(-z/H)}]^{0.61} R=0.92 \quad \dots(11)$$

The predictive equations are applicable for $0.2 < \xi_0 e^{(-z/H)} < 3.0$, $0.5 < \xi_0^2 e^{(-z/H)} < 30$ for $0.6 < \xi_0 < 7$ and $0 < z/H < 3.2$. It is interesting to note that the range of z/H covers the complete run-up height zone, since the maximum run-up height is about 3 times the incident wave height (van der Meer & Janssen¹⁷). Hence the upper limit of run-up is 3.2 times of the incident wave height and the above formula can be applied up to this upper limit.

It may be logical to have run-up height as an upper boundary, where the wave pressure, layer thickness and velocities will be zero. However, the wave run-up on the seawall is an unknown. It is required to measure the run-up for the various input parameters studied in this paper and obtain a predictive equation, which gives a good regression equation. Then the predicted run-up equation needs to be linked with the predictive equation for wave pressures, layer thickness, run-up and run-down velocity. Unfortunately, the run-up height was not measured and it is proposed to provide the predictive equation as simple as possible (as a function of direct inputs like wave height, period, seawall slope and elevation of the point of interest on the seawall) so that the practical engineer can use it without much complication.

Results and Discussion

Subareal wave pressures

A comparison of the proposed (Eq.8) and measured subareal wave pressure coefficients on the smooth impermeable sea wall is presented in Fig. 4. In general, the comparison is found to be satisfactory. It is intended to bring it to the notice of the reader that the measured output time series of pressures and other output parameters (layer thickness, run-up and run-down) are not purely regular even though the input wave is regular. This is one reason for the scatter of data. Also, a single empirical formula is tried for each output parameter (Eqs 8 to 11) for the whole range of surf similarity parameter, which is in the range of 0.6 to 7.0. The physical and kinematic character of each type of wave breaking is different. This may be another possible reason for the scatter. It is recommended to carryout more investigations and obtain the empirical formula for each type of breaker type.

Figure 5 is presented to visualise the effect of type of wave breaking on the subareal wave pressures. Typical trends of the predicted pressure coefficients as a function of z/H are presented for $\xi_0 = 1, 3$ and 5 , which indicates breaking, transitional and non breaking wave action respectively on sloped structures (Seelig & Ahrens¹⁸). The measured wave pressure data points are also grouped according to the type of wave action into three zones; Breaking waves ($\xi_0 < 2.0$), Intermediate waves ($2.0 < \xi_0 < 4.0$) and non-breaking waves ($\xi_0 > 4.0$) as recommended by Seelig & Ahrens¹⁸. It is seen in general that the comparison between the proposed predictive equation and the measured pressure coefficients are satisfactory.

Layer thicknesses

A comparison of the proposed (Eq.9) and measured layer thickness coefficients on the sea wall is provided in Fig. 6. The comparisons in general are acceptable. Figure 7 is presented to understand the type of wave breaking on the layer thickness coefficient, which is similar to Fig. 5. Normalised layer thickness Lt/H of about 1.0 to 1.2 is possible closer to $z = 0.0$.

The present experimental data at $z = 0.0$ is compared with Battjes & Roos² in Fig. 8. According to Battjes & Roos², the layer thickness is given as $Lt/(HL_0)^{0.5} = 0.08$. For the present study, from Eq. 9, at $z = 0.0$

$$Lt = 0.32 H \xi_0^{0.93} \quad (12)$$

The above equation can be approximated as

$$Lt/H = 0.32 \xi_0 \quad (13)$$

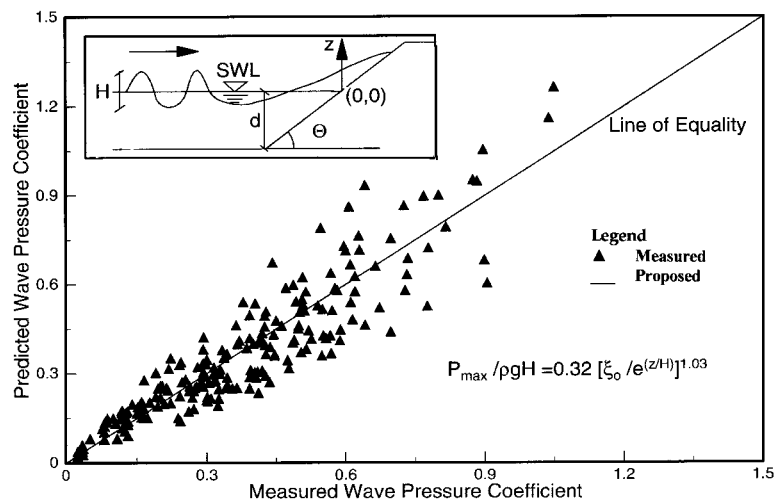


Fig. 4—Comparison of proposed and measured wave pressure coefficients in the run-up zone on plane impermeable sea walls

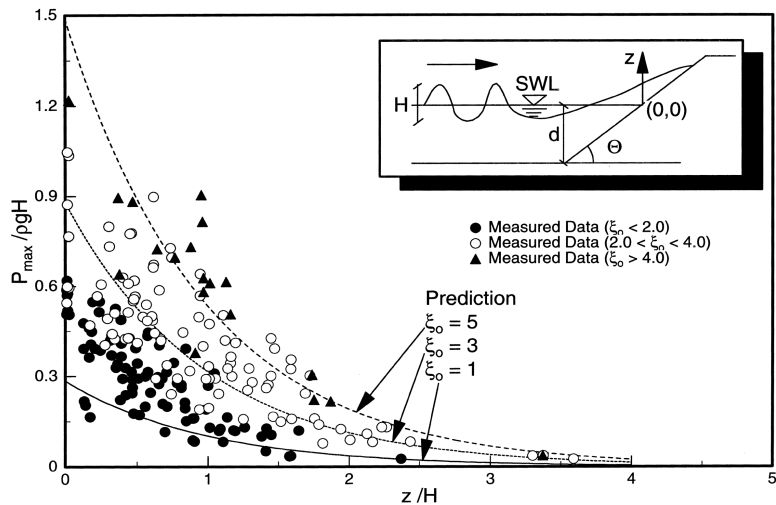


Fig. 5—Comparison of proposed and measured wave pressure coefficients for different ξ_{s0} values on plane impermeable sea walls

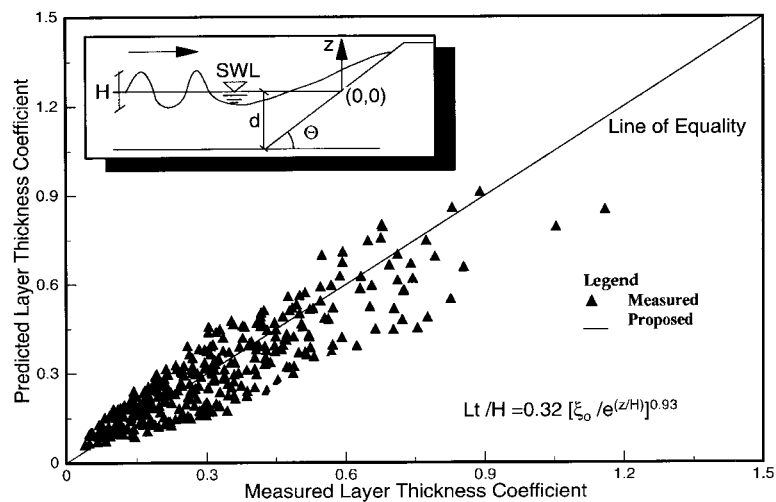


Fig. 6—Comparison of proposed and measured layer thickness coefficients in the run up zone on plane impermeable sea walls

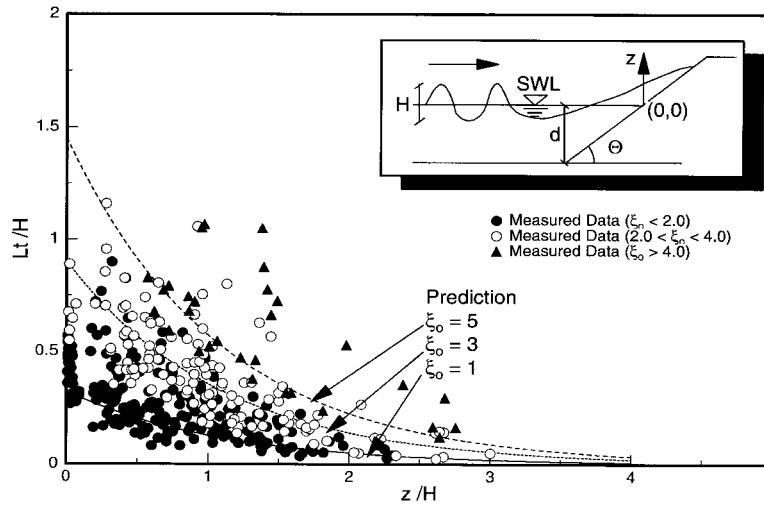


Fig. 7—Comparison of proposed and measured layer thickness coefficients for different ξ_0 values on plane impermeable sea walls

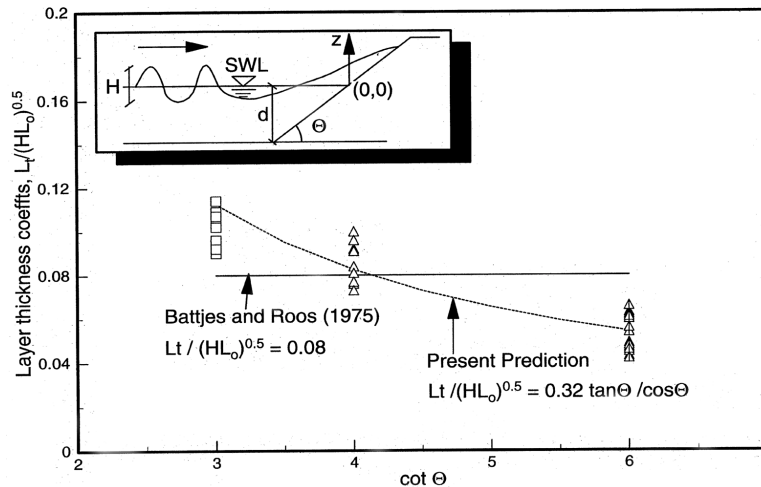


Fig. 8—Comparison of measured layer thickness coefficients around the still water line with the present proposed formula and with Battjes & Roos² on the sea wall

This equation can be written as

$$Lt/(HL_0)^{0.5} = 0.32 \tan \theta \quad (14)$$

Equation 1 by Battjes & Roos² is independent of the slope of the seawall, whereas from Fig.8, it can be seen that the prediction is improved when the seawall slope is considered.

Comparison of subareal wave pressures and layer thickness

Figure 9 shows the comparison of subareal wave pressure and layer thickness as a function of $\xi_0 e^{(-z/H)}$. It is seen that the magnitude of wave pressure coefficient is slightly more than that of layer thickness coefficients. Wave pressure on the seawall has a component of impact, whereas the layer thickness measurement is like measuring the height of water column, even

though it is a dynamic process. Since wave pressure has both static (due to layer thickness) and impact component, the predictive equation for wave pressures gives higher values than the predictive equation for layer thicknesses.

Run-up velocity

A comparison of the proposed (Eq.10) and measured run-up velocity coefficients on the sea wall is presented in Fig. 10. The comparison is satisfactory. The maximum value of the run up velocity recorded is about 25 times the horizontal water particle velocity in deep water. Figure 11 is provided to understand the effect of type of wave action on the run-up velocity coefficients. Typical predictive trends as a function of z/H are presented for breaking ($\xi_0 = 1$), transitional ($\xi_0 = 3$) and non breaking ($\xi_0 = 5$ and 7) wave actions respectively. It

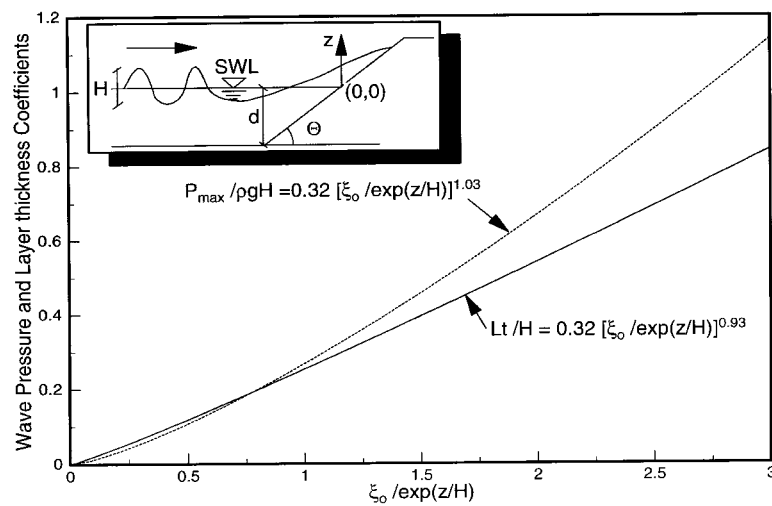


Fig. 9—Comparison of proposed wave pressure and layer thickness coefficients in the run-up zone on plane impermeable sea walls

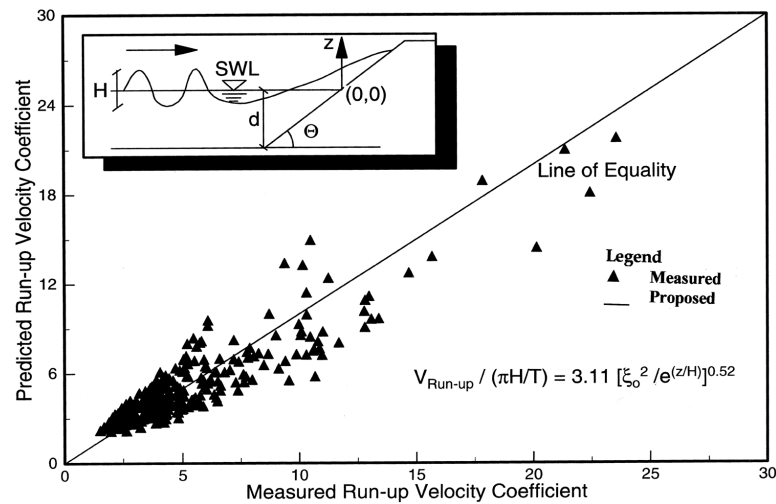
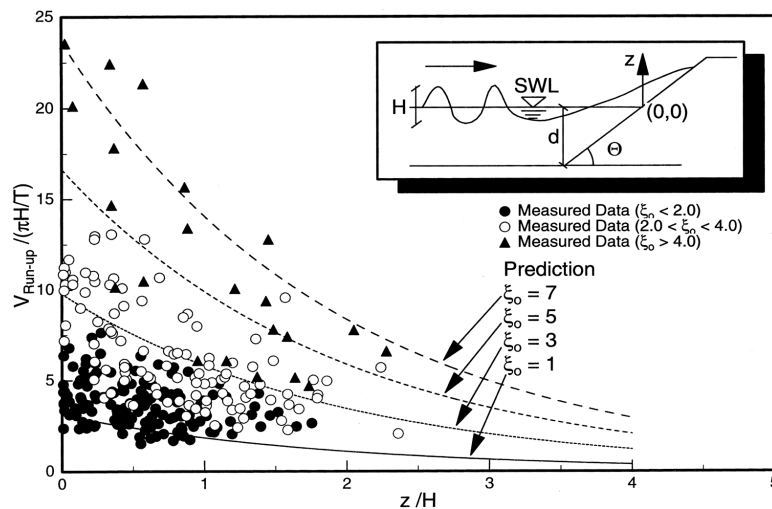


Fig. 10—Comparison of proposed and measured run-up velocity coefficients on plane impermeable sea walls

Fig. 11—Comparison of proposed and measured run-up velocity coefficients for different ξ_0 values on plane impermeable sea walls

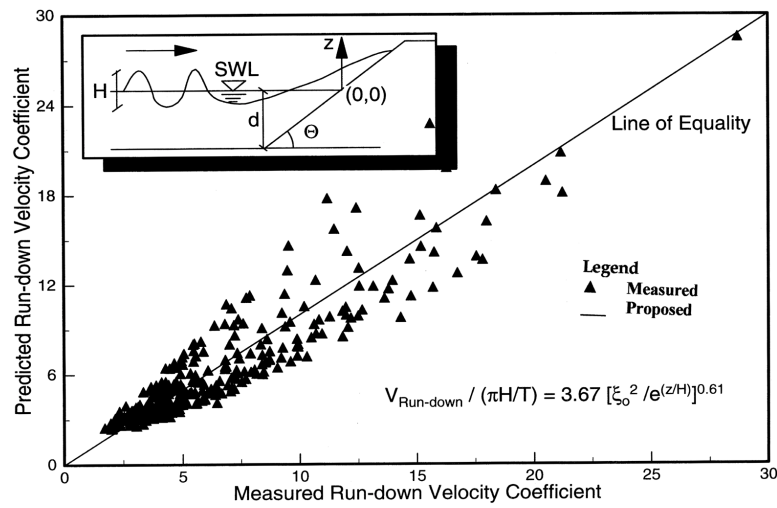


Fig. 12—Comparison of proposed and measured run down velocity coefficients on plane impermeable sea walls

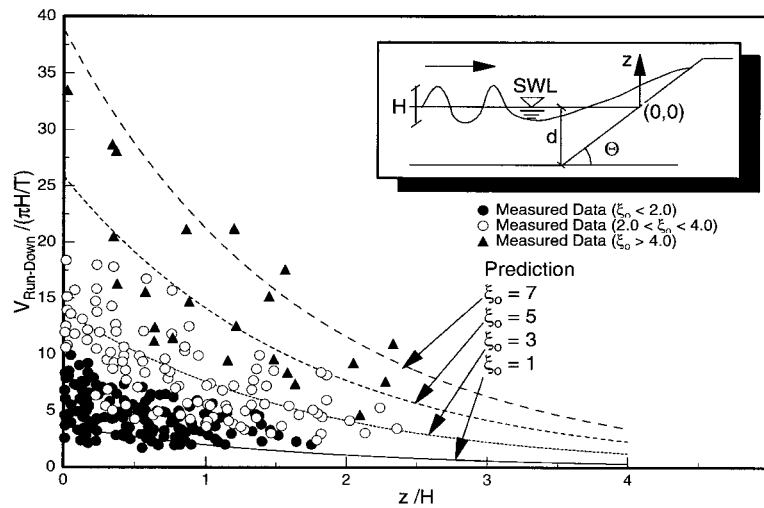


Fig. 13—Comparison of proposed and measured run down velocity coefficients for different ξ_0 values on plane impermeable sea walls

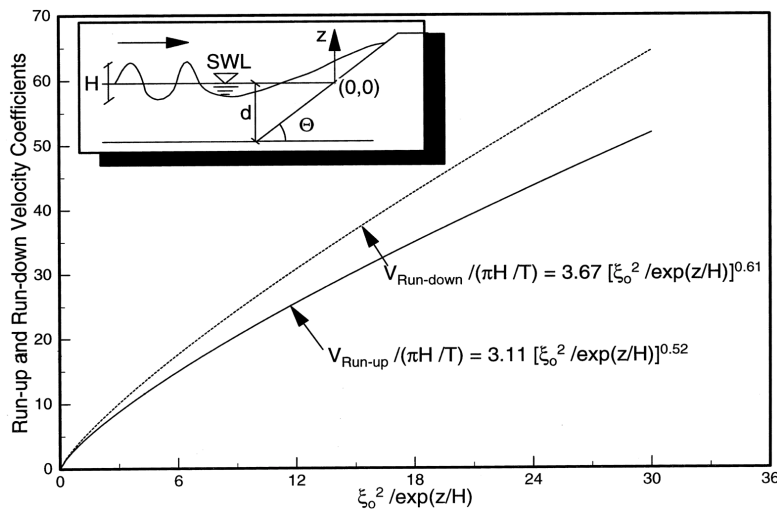


Fig. 14—Comparison of proposed run up and run down velocity coefficients on plane impermeable sea walls

can be concluded that the spilling breaker offers relatively smaller normalised run-up velocity compared to surging breakers. At still water line, the magnitude of run-up velocity coefficient for spilling wave is about 3, whereas the surging waves yield the run-up velocity coefficients as high as 25. Such high order of magnitude was also registered by Führböter¹⁶ on 1:4 sloped seawall. Hence due attention for surging waves must be given during the design.

Run-down velocity

A comparison of the proposed (Eq.11) and measured run-down velocity coefficients is presented in Fig. 12. The comparison is acceptable for practical applications. The effect of type of wave breaking on the normalised subareal run down velocity is given in Fig. 13. The information is similar to run up velocity. At still water line, the magnitude of run-down velocity coefficient for spilling wave is about 5, whereas the surging waves yield the run-down velocity coefficients as high as 35. Such high order of magnitude is also registered by Führböter¹⁶ also.

Comparison of run-up and run-down velocities

Figure 14 provides a comparison of run-up and run-down velocity coefficients as a function of $\xi_0^2 e^{(-z/H)}$. It is found that the run-down velocity is higher than the run-up velocity. It is due to the fact that the run-down velocity is aided by the pull of the gravity force, whereas the run-up velocity is against the gravity force. Also, during running up of the water on the seawall, still a thin sheet of water was observed flowing down, which is expected to oppose the free run-up of water, which could be the reason to reduce the run-up velocity compared to the run down velocity for the same input conditions.

Application of the present work

The sloped seawalls and dikes are designed to withstand the wave pressures induced by different types of waves breaking on it. The design of a stable toe against the possible toe scour is very important. The run-down velocity is the key input causing the toe scour. Hence the present results will be a useful information for the coastal engineering community involved in the seawall design. The overtopping aspect of the wave is also important for the estimate of flooding on the land side. This topic is not studied in the present paper.

Conclusion

Based on extensive experimental investigations, empirical equations are proposed to predict the wave pressures, layer thicknesses, run-up and run-down velocities in the subareal region (above the still water line) of plane impermeable seawalls. The study covers the spilling, plunging, collapsing and surging waves. The maximum wave pressure in the subareal region can be as high as 1.2 times the static pressure due to a water column equal to the incident wave height and the maximum run up and run down velocity can be as high as 25 times the maximum horizontal water particle velocity in deep water. The proposed predictive equations are:

$$\begin{aligned} P_{\max}(z)/\rho gH &= 0.32 [\xi_0 \exp(-z/H)]^{1.03} \\ Lt(z)/H &= 0.32 [\xi_0 \exp(-z/H)]^{0.93} \\ V_{\text{Run-up}}(z)/(\pi H/T) &= 3.11 [\xi_0^2 \exp(-z/H)]^{0.52} \\ V_{\text{Run-down}}(z)/(\pi H/T) &= 3.66 [\xi_0^2 \exp(-z/H)]^{0.61} \end{aligned}$$

These predictive equations can be used for $0.2 < \xi_0 \exp(-z/H) < 3.0$, $0.5 < \xi_0^2 \exp(-z/H) < 30$, $3 < \cot \theta < 6$ and $0.0 < z/H < 3.2$, which covers almost the practical ranges encountered in the field. These formulae are simple and easy for field Engineers.

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