FEMA

October 14, 2011

Operating Guidance No. 7-11
For use by FEMA staff and Flood Hazard Mapping Partners

Title: Application of TAW Runup Methodology to FEMA Needs

Effective Date: October 14, 2011

Approval: Luis Rodriguez
                Branch Chief, Engineering Management Branch
                Risk Analysis Division
                Federal Insurance and Mitigation Administration

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Operating guidance documents provide best practices for the Federal Emergency Management Agency's (FEMA's) Risk MAP program. These guidance documents are intended to support current FEMA standards and facilitate effective and efficient implementation of these standards. However, nothing in Operating Guidance is mandatory, other than program standards that are defined elsewhere and reiterated in the operating guidance document. Alternate approaches that comply with program standards that effectively and efficiently support program objectives are also acceptable.

Background: There has been an issue related to the wave setup inherently present in the runup methodology recommended in the TAW manual and the most appropriate method of accounting for this setup in wave runup calculations.

Dr. Robert G. Dean was consulted to provide recommendations for the application of the TAW runup methodology to FEMA problems, specifically whether wave setup should be calculated separately and added to the runup results obtained from the TAW runup calculation procedure. The TAW runup methodology is based on wave tank tests and includes wave setup in the runup measurements landward of the Toe of Slope (TOS) of the structure, thus requiring knowledge of wave and water levels at the TOS. There has been an issue related to the wave setup inherently present in the runup methodology recommended in the TAW manual and the most appropriate method of accounting for this setup in wave runup calculations.

Issues: The central issue in this study is related to the wave setup inherently present in the runup methodology recommended in the TAW manual and the most appropriate method of accounting for this setup in wave runup calculations. Thus, the focus in this study is landward of the toe of the steep feature on which runup will be calculated and it is considered that all hydrodynamic quantities at the toe of the slope (TOS) relevant to wave runup are quantified adequately.

Actions Taken: For all new detailed coastal study starts in Fiscal Year 2010 using the TAW method for computing runup, it is recommended that the combined storm surge, astronomical tide and any wave setup at the TOS be the water level to which the wave runup determined by the TAW methodology is added. Users of the TAW method should consult the technical report accompanying this document, in additional to the guidance presented in Appendix D of the Guidelines and Specifications for Flood Hazard Mapping Partners.

Supersedes/Amends: Section D.2.8.1.5 of the *Atlantic Ocean and Gulf of Mexico Coastal Guidelines Update, Final Draft,* February 2007 and Section D.4.5.1.5.2 of the *Final Draft Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States,* January 2005

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Operating Guidance 7-11

Application of TAW Runup Methodology to FEMA Needs

FINAL

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The following document is a memo prepared for FEMA by Dr. Robert G. Dean. This document was not prepared as a guidance document, and is a technical report detailing the application of TAW runup methodology to FEMA needs.

Application of TAW
Runup Methodology to FEMA Needs

June 25, 2010

Prepared For:

Department of Homeland Security
Federal Emergency Management Agency (FEMA)
Washington, DC

Prepared By;

Robert G. Dean
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Executive Summary

The purpose of this consulting study is to provide recommendations for the application of the TAW runup methodology to FEMA problems, specifically whether wave setup should be calculated separately and added to the runup results obtained from the TAW runup calculation procedure. The TAW runup methodology is based on wave tank tests and includes wave setup in the runup measurements landward of the Toe of Slope (TOS) of the structure, thus requiring knowledge of wave and water levels at the TOS.

Because the wave tank tests on which the TAW methodology is based includes wave setup in the measurements, wave setup should not be added explicitly to the runup calculations in the region between the TOS and the top of the wave runup. As an example, for the 1% (100 year) runup, it is recommended that the 1% water level and wave parameters at the TOS be calculated. These inputs should then be used to calculate the 1% runup elevation using the TAW method. The reference level for the computed 1% runup is the 1% water level which includes wave setup seaward of the TOS.

Although artificialities in the wave tank test results exist due to the finite tank length and the most probable vertical reference in the tank experiments being the still water level, calculations suggest that, at a maximum, the resulting runup underestimate is approximately 5%.

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Application of TAW
Runup Methodology to FEMA Needs

1.0 Introduction

The central issue in this study is related to the wave setup inherently present in the runup methodology recommended in the TAW manual and the most appropriate method of accounting for this setup in wave runup calculations. Thus, the focus in this study is landward of the toe of the steep feature on which runup will be calculated and it is considered that all hydrodynamic quantities at the toe of the slope (TOS) relevant to wave runup are quantified adequately.

2.0 Review of the TAW Wave Runup Methodology

The TAW methodology applies to the case of a structure for which the slope, roughness and other relevant characteristics are known. Application of the methodology requires that the significant wave height, peak wave period of the wave spectrum and water level are known at the toe of the slope (TOS), see Figure 1.
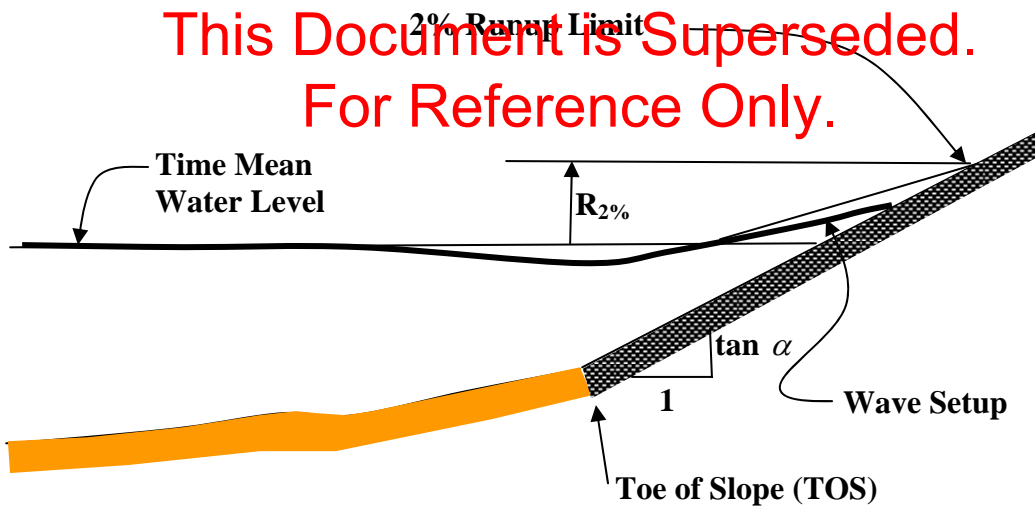

Figure 1. Definition Sketch for Runup Calculation Application.

The TAW equations for the 2% wave runup, $R_{2\%}$, are:

$$R_{2\%} = H_{mo} \begin{cases} 1.75\gamma_b\gamma_f\gamma_\beta\xi_o & 0.5 \leq \gamma_b\xi_o < 1.8 \\ \gamma_f\gamma_\beta\left(4.3 - \dfrac{1.6}{\sqrt{\xi_o}}\right) & \gamma_b\xi_o \geq 1.8 \end{cases} \qquad (1)$$

where:

ξ_o = Iribarren Number defined as:

$$\xi_o = \tan\alpha / \sqrt{s_o} \qquad (2)$$

$\tan\alpha$ = structure slope

s_o wave steepness, defined as:

$$s_o = H_{mo} / \left(gT_{m-1.0}^2 / 2\pi\right) \qquad (3)$$

H_{mo} = spectral significant wave height at the toe of the structure, defined as:

$H_{mo} = 4.0\sqrt{m_o}$, where m_o is the total wave energy (or equivalently the area under the spectrum,

γ_b = reduction factor for influence of a berm

γ_f = reduction factor for influence of surface roughness

γ_β = reduction factor for influence of angled wave attack

$T_{m-1.0} \approx \dfrac{T_p}{1.1}$ and T_p is the wave period associated with the peak of the wave spectrum.

Figure 2 presents the TAW runup relationship.
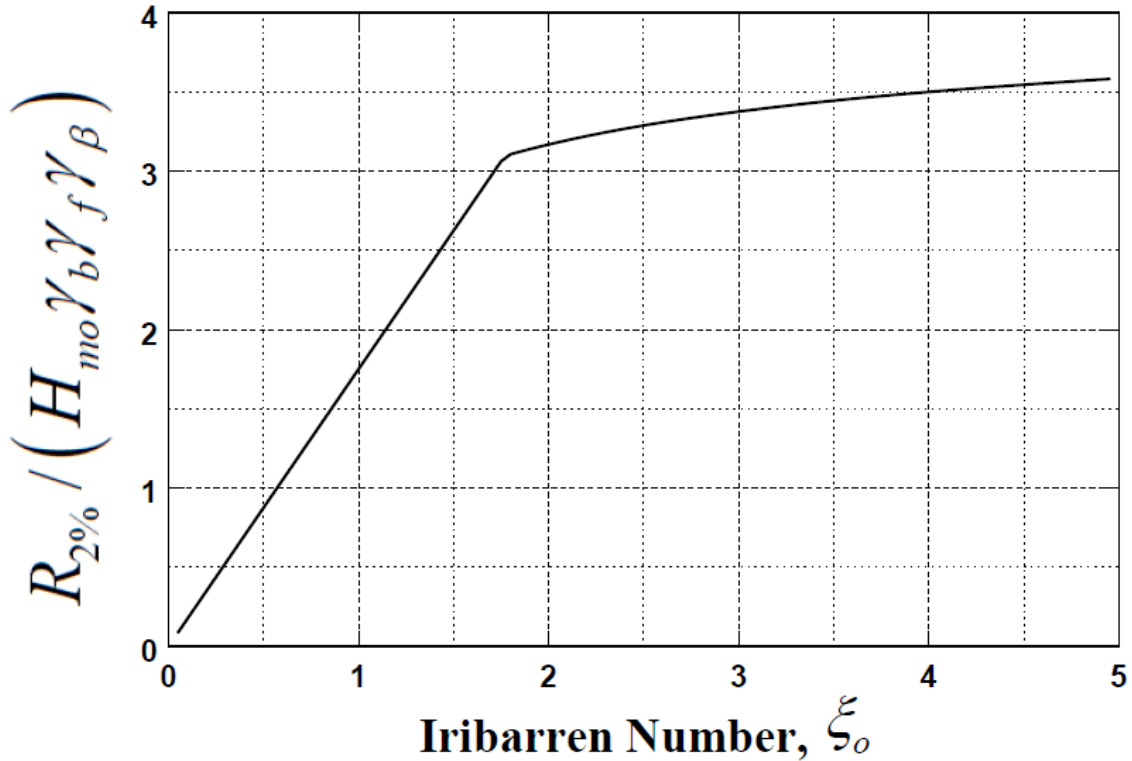
Figure 2. The TAW Relationship for Wave Runup

2.1 Basis for the TAW Methodology

Review of the development of the TAW methodology (Appendix A) establishes that the TAW methodology is based primarily on wave tank tests in which, as shown above, the runup is based on wave and water level conditions at the toe of the slope (TOS). Thus, it is clear that wave setup landward of the TOS is inherent in the wave tank measurements. Because the objective of the TAW methodology was application to design situations, there was no attempt to separate the wave setup from the wave runup. However, Hedges and Mase (2004) have reanalyzed the experimental runup measurements of Mase (1989) and have extracted the wave setup from the wave runup measurements. The Hedges and Mase paper is reviewed in Appendix B in which quite good agreement with the TAW methodology for smooth slopes is demonstrated. Because the objective of the TAW methodology is for design purposes, there does not appear to be an advantage in considering separately the wave setup in the runup calculations.

A question remains as to whether wave tank results are completely representative of conditions in nature. One issue that cannot be resolved completely is related to the wave conditions in the wave tank, specifically the wave setup or setdown at the toe of the slope. For conditions of interest in nature, it is likely that the waves will be breaking seaward of the toe of slope and thus a setup will be present. In a wave tank, because the steeper slope where runup occurs is usually preceded by a horizontal section, it is more likely that a wave setdown is present at the TOS. This is due, in part, to the limited water volume in the tank that results in an artificial setdown in the tank not present in nature.

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Appendix C investigates this possible difference and concludes that any effect is small, say less than 5%.

The conclusion herein is that the wave setup should be considered separately for two regions: (1) Seaward of the TOS on which runup is to be considered, and (2) Landward of the TOS. The latter is the focus of this study. Each of these is discussed briefly below.

2.2 Wave Setup Seaward of the Toe of Slope

Wave setup seaward of the TOS on which runup is to be determined should be calculated according to the governing relationships recognizing that breaking may occur under conditions other than shallow water conditions. In the intermediate depth region, breaking depends on both water depth and wave steepness. The usually mild slope in this region will influence the breaking wave conditions and will also tend to reduce wave setup. Thus, if the most simple shallow wave setup methodology is applied seaward of the TOS, the resulting wave setup will be overestimated.

2.3 Wave Setup Landward of Toe of Slope

The TAW methodology includes wave setup and accounts for the slope in this region. Thus there is no need to add wave setup as it is inherently included in the methodology.

3.0 Conclusion and Recommendation

The central issue in this study is the correct approach for representing wave setup when calculating wave runup based on the TAW methodology. The TAW methodology is based on wave and mean water level characteristics at the TOS and, in addressing this question, it is considered that these characteristics are available for calculation purposes and have accounted for any wave setup seaward of the TOS.

The TAW methodology is based on wave tank measurements in which wave setup is inherently included in the wave runup characteristics. Thus, it is clear that wave setup landward of the TOS should not be included separately in the wave runup calculations by the TAW methodology. To do so would be including this wave setup twice. Therefore it is recommended that the combined storm surge, astronomical tide and any wave setup at the TOS be the water level to which the wave runup determined by the TAW methodology is added.

Although the most probable vertical reference in the tank experiments was the still water level and some effects exist in the measurements due to finite tank length, the associated errors are estimated to result in a maximum runup underestimate of 5%.

4.0 Acknowledgements

Professor Jurjen Battjes, retired from Delft University, provided a constructive review of this report and valuable information regarding the conduct of the model tests leading to

the runup methodology in the TAW Manual. Dr. Alan Niedoroda of URS provided guidance during the project and also reviewed two report drafts.

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Appendix A

Brief Review of TAW Manual Background

Appendix A

Brief Review of TAW Manual Background

Wave runup and overtopping have been of concern for many years in the Netherlands. This concern has led to early efforts to develop and verify wave runup prediction methodologies. The early background of the TAW Manual runup methodology is described by Wassing (1957). A review of this and other related references establishes that the runup methodology is based primarily on wave tank model tests and, as such, the test results include wave setup. Where available, confirmation with the methodology has been obtained through limited measurements in nature.

All efforts to develop runup relationships appear to have focused on the highest 2% of the runup values, ie $R_{2\%}$.

The earliest methods (which commenced in 1936) and were based on wave tank tests in which the waves were generated only by wind. The 2% runup was correlated with the wind expressed in velocity head of water and the elevation at which the wind velocity head was based. The average wave steepness for these studies was 0.07.

Later studies commenced in 1942 with the waves apparently consisting of a combination of mechanical generated periodic water waves and wind generated waves. These investigations included smooth sloping surfaces with slopes ranging from 1:10 to 1:2.5 and wave steepnesses of 0.05 and 0.07. These studies led to Wassing's original equation:

$$\frac{R_{2\%}}{H_s} = 8\tan\alpha, \quad H_s/L = 0.05$$

which when the effect of wave steepness is incorporated in the above equation, results in

$$\frac{R_{2\%}}{H_s} = 1.79\frac{\tan\alpha}{\sqrt{H_s/L}} = 1.79\xi$$

The 1.79 constant in the above equation differs from the 1.75 in the TAW relationship by only 2.3%!

The earliest appearance of the <u>form</u> of the TAW runup expression appears to be due to Hunt (1959) which was developed for periodic waves in the form:

$$R = \sqrt{H/L_0}\,\tan\alpha$$

And was later cast into the more familiar following form by Battjes (1974)

$$\frac{R}{H} = \frac{\tan\alpha}{\sqrt{H/L_0}} = \xi$$

More recent laboratory investigations which have contributed to the TAW Manual include those of Sparboom, et al. (1990), van der Meer and de Wall (1990), de Wall and van der Meer (1992) among others.

Saville (1962) appears to be the first to apply random wave considerations to the Hunt equation to develop relationships for this more realistic case. Battjes (1974) developed and applied a very elegant treatment of probabilistic methods to transform the Hunt equation in terms of random variables, finding general relationships which were not inconsistent with Wassing's equation.

An earlier version of the TAW Manual (1972) was available only in Dutch and other TAW manuals also address wave runup, overtopping and safety issues (TAW 1989a and 1999b).

Appendix B

Explicit Identification of Wave Setup in Wave Runup Measurements

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Explicit Identification of Wave Setup in Wave Runup Measurements

Hedges and Mase (2004) reanalyzed the Mase (1989) wave runup data to quantify the portion of runup due to wave setup. The motivation for their reanalysis was the form of the original Hunt (1959) and later TAW relationship expressed as

$$\frac{R_{2\%}}{H_{mo}} = 1.75\gamma_b\gamma_f\gamma_\beta\xi_o$$

where, as noted previously

$$\xi_o = \tan\alpha / \sqrt{s_o}$$

which suggests that as the structure slope ($\tan\alpha$) approaches zero, the wave runup also approaches zero. However, they argue that wave setup would still be present in the runup and thus, based on a typical plot of the Mase data as shown in Figure B.1, the following form was examined[1]

$$\frac{R_{2\%}}{H_{mo}} = \frac{S_{2\%}}{H_{mo}} + c_{2\%}\xi_o$$

in which $\dfrac{S_{2\%}}{H_{mo}} = 0.37$ and $c_{2\%} = 1.38$

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[1] It is noted that because the wave breaking parameter, κ, (discussed later) decreases with slope, the wave setup would also decrease with slope, but would not approach zero as suggested by the Hunt and TAW relationships.
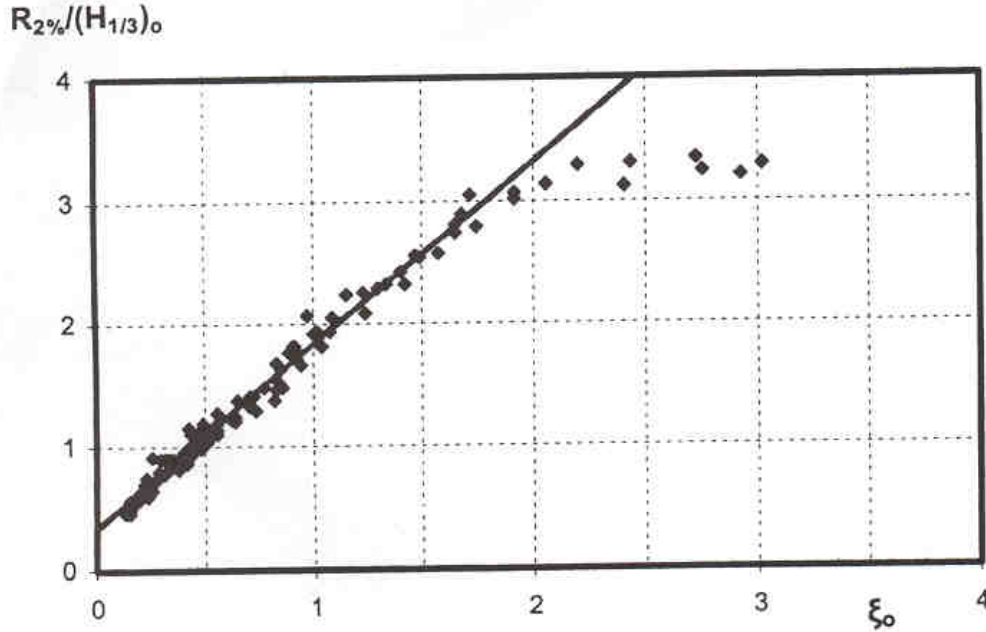
Figure B.1. Variation of non-dimensional runup with Iribarren Number (Hedges and Mase, 2003).

Both $\dfrac{S}{H_{mo}}$ and c increase with the percentage exceedance of interest and were found to be reasonably well represented by the Rayleigh probability distribution relationship. For $\xi_o > \approx 2.0$, the Mase data indicate that the ratio is constant with increasing ξ_o at approximately 3.2. The Hedges and Mase results are compared with the TAW relationships for a smooth slope in Figure B.2 and show quite good agreement.
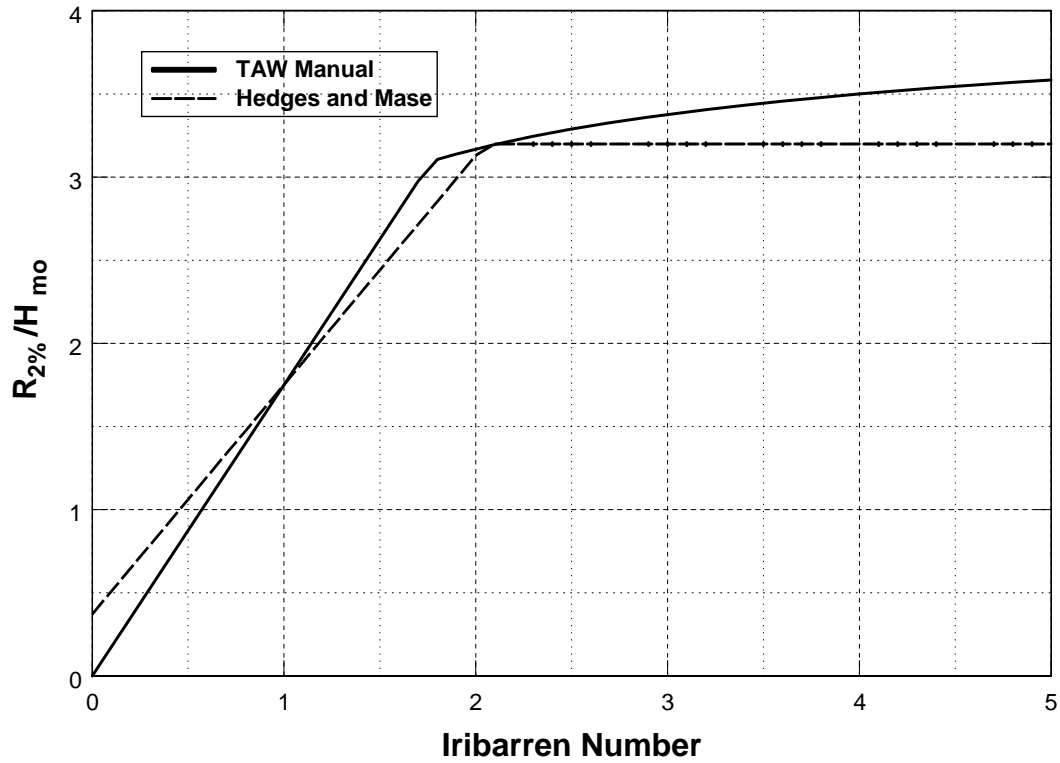
Figure B.2. Comparison of Runup Relationships: TAW Manual and Hedges and Mase (2004).

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Appendix C

Effect of Wave Setup on Mean Water Level in Wave Tank Tests

Appendix C

Effect of Wave Setup on Mean Water Level in Wave Tank Tests

C.1 Introduction

In contrast to nature, the water volume in wave tanks is limited. Thus, the setup in the surf zone will require a water volume that results in an artificial lowering of water in the wave tank which will result in a lower wave runup relative to the still water level[2], see Figure C.1. The purpose of this appendix is to evaluate the approximate magnitude of this artificial setdown and to evaluate its possible effect on maximum wave runup.
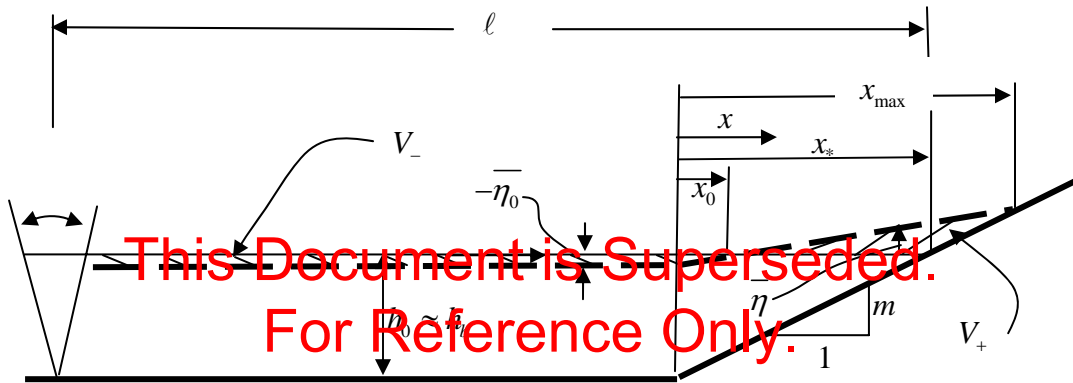

Figure C.1. Definition Sketch For Case in Which Waves Break at Toe of Slope.

C.2 Methodology

The method considers regular shallow water waves and the most simple approach in which the waves break at the toe of slope (x = 0) and wave setup, $\overline{\eta}(x)$ at any location in the breaking zone is given by:

$$\overline{\eta}(x) = \overline{\eta}_0 + K(h_b - h(x)) \qquad (C.1)$$

in which $\overline{\eta}_0$ is the wave setup (actually setdown) in the tank and at the toe of slope and and K is a parameter defined as

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[2] The <u>still water level</u> at the TOS is the most likely vertical reference in the wave tank tests on which the TAW procedure is based. This has been confirmed by Battjes in his review of this report.

$$K = \frac{3\kappa^2/8}{1+3\kappa^2/8} \qquad (C.2)$$

in which $\kappa = H/(h+\bar{\eta})$ within the breaker zone.

The positive water volume stored relative to the still water level, V_+, is given by:

$$V_+ = \int_{x_0}^{x_{max}} \bar{\eta}(x)dx - (x_{max} - h_0/m)\bar{\eta}_{max}/2 \qquad (C.3)$$

in which x_0 and x_{max} are the location of zero wave setup and maximum wave setup, respectively.

The negative volume is $V_- \approx \bar{\eta}_0 \ell$ recognizing that $\bar{\eta}_0$ is negative. Conservation of water requires

$$V_+ + V_- = 0 \qquad (C.4)$$

where the negative volume is given by

$$V_- \approx \bar{\eta}_0 \left[\ell - \frac{\bar{\eta}_0}{2mK} \right] \qquad (C.5)$$

C.3 Results

Integrating Eq. (C.3), The positive water volume stored in the setup, V_+, is:

$$V_+ = \int_{x_0}^{x_{max}} \bar{\eta}(x)dx - (x_{max} - h_0/m)\bar{\eta}_{max}/2 =$$
$$\bar{\eta}_0(x_{max} - x_0) + \frac{mK}{2}(x_{max}^2 - x_0^2) \qquad (C.6)$$
$$-\frac{\bar{\eta}_{max}}{2}(x_{max} - x_*)$$

where x_* is the distance to the still water intercept as shown in Figure C.1.

Conservation of water requires

$$\bar{\eta}_0\ell - \frac{\bar{\eta}_0^2}{2mK} + \bar{\eta}_0(x_{max} - x_0) + \frac{mK}{2}(x_{max}^2 - x_0^2) - \frac{\bar{\eta}_{max}}{2}(x_{max} - x_*) = 0 \quad (C.7)$$

Based on the geometry in Figure C.1,

$$\left(\bar{\eta}_{max} + h_0\right) = mx_{max}, \qquad (C.8)$$

and

$$\left(\bar{\eta}_{max} - \bar{\eta}_0\right) = Kmx_{max}$$

Eliminating $\bar{\eta}_{max}$ from these two equations yields

$$\left(\bar{\eta}_0 + h_0\right) = mx_{max}(1-K) \qquad (C.9)$$

or

Also, from geometry, $x_0 = -\dfrac{\bar{\eta}_0}{mK}$

The conservation of water equation can now be written as

$$\bar{\eta}_0^2\left(\frac{1}{2m(1-K)}\right) + \bar{\eta}_0\left(\frac{h_0}{m(1-K)} + \ell\right) + \frac{Kh_0^2}{2m(1-K)} = 0 \qquad (C.10)$$

which is in quadratic form and can be solved analytically

$$A\bar{\eta}_0^2 + B\bar{\eta}_0 + C = 0 \qquad (C.11)$$

Thus,

$$\bar{\eta}_0 = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \qquad (C.12)$$

in which

$$A = \left(\frac{1}{2m(1-K)}\right) \qquad (C.13)$$

$$B = \left(\frac{h_0}{m(1-K)} + \ell\right) \qquad (C.14)$$

$$C = \left(\frac{Kh_0^2}{2m(1-K)} \right) \qquad \text{(C.15)}$$

C.3 Example

The effect of the artificial lowering in the wave tank relative to the still water level is evaluated in the following example conditions:

$\kappa = 0.78, \; K = 0.186$
$m = 1:15 = 0.067$
$\ell = 30 \text{ m}$
$h_0 = 0.4 \text{ m}$
$H_b = 0.31 \text{ m}$
$T = 2 \text{ sec}$

With the above values, the wave setup at the TOS (actually setdown) in the tank, $\bar{\eta}_0 = $ -0.734 cm.

To compare with the calculated wave runup, we first calculate the Iribarren number,

$$\varsigma_o \equiv \frac{m}{\sqrt{\dfrac{H_b}{gT^2/2\pi}}} = 0.3 \qquad \text{(C.16)}$$

Thus the wave runup, $R_{2\%} = 1.75 H_b \xi_0 = 16.2$ cm.

Thus, the relative effect for this example would be an <u>under prediction</u> of wave runup by approximately 4.5%. It is appropriate to note that conditions for this example have been selected to represent a near upper limit for this effect.