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Wave Transmission at Detached Breakwaters for Shoreline Response Modeling

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PURPOSE: The Coastal and Hydraulics Engineering Technical Note (CHETN) herein evaluates selected available formulas for predicting wave transmission at reef breakwaters and more conventional multilayer structures, leading to recommendations for the most appropriate formulas for shoreline-response modeling. The GENESIS shoreline response numerical model is modified to allow for automated time-dependent calculation of the wave transmission coefficient, and a case study is presented to illustrate the new predictive capability.

BACKGROUND: Detached breakwaters, reef breakwaters, and spurs attached to jetties are shore-parallel structures constructed to serve as a shore-protection measure or to intercept sediment moving alongshore before arrival at inlet entrance channels and harbors. Reef breakwaters are rubble mounds of rock size similar to that found in the armor and first underlayer of conventional detached breakwaters, and they are designed to adjust in cross section in response to the waves and currents at the site. Reef breakwaters are broad crested in comparison to conventional detached breakwaters. Detached breakwaters (hereafter also referred to as reef breakwaters unless otherwise stated) can be either emergent or submergent, depending on the depth of placement, crest elevation of the structure, and tidal range. Often, detached breakwaters are designed with crest elevation close to mean sea level to reduce construction cost and allow waves to pass over them to prevent accretion of the beach that reaches the structure, called a tombolo. Detached structures built of prefabricated units are typically porous and likewise allow transmittal of wave energy. Attached breakwaters (hereafter spurs) can also be submergent or emergent and may be designed to protect the beach adjacent to an inlet and/or reduce sediment bypassing and shoaling of the entrance channel. Thus, wave transmission properties can vary significantly depending on structure configuration and composition. Wave transmission properties also vary over different time scales as controlled by tidal variations, change in the incident waves, and possibly longer-term change in water level such as occurs in the Great Lakes.

The response of the shoreline to placement of a detached breakwater must be considered in the design process. The transmission coefficient is a leading parameter in controlling beach response to detached breakwaters (Hanson and Kraus 1990). GENESIS (Hanson and Kraus 1989) has been applied to model shoreline change both in the field and in movable-bed physical model experiments based on its capability of representing combined wave diffraction, refraction, and transmission at multiple detached breakwaters (e.g., Hanson and Kraus 1989, 1990, 1991a, 1991b; Hanson, Kraus, and Nakashima 1989; Rosati, Gravers, and Chasten 1992; Gravens and Rosati 1994; Herbich et al. 1996). Previously the GENESIS model only represented a constant transmission coefficient (K_t) for detached breakwaters. It is desirable to have the capability of predicting shoreline response to detached breakwaters for a wide range of engineering conditions. To achieve this goal, an expression for the wave transmission coefficient must be

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valid over a broad range of environmental forcing conditions and breakwater designs. To improve the predictive capability of the GENESIS model, several published empirical formulae for the wave transmission coefficient were evaluated. Sensitivity tests were performed to determine the most suitable predictive formula for a given structure configuration and properties, water level, and wave condition. The selected formulae are incorporated in GENESIS to calculate time-dependent wave transmission and shoreline response for multiple detached breakwaters of possible different types.

COMPARISON OF PREDICTIVE EQUATIONS FOR TRANSMISSION: Wave transmission at structures has been studied extensively with 2-D physical models, most concerning narrow-crested, emergent structures with little variation in experiment parameters for a given study. Less data are available for submerged structures with a broad crest width. The exception is the work of Tanaka (1976), who performed monochromatic wave tests that included both submerged and emergent crests as well as a broad range of crest widths. Based on his results, Tanaka established design curves that give the transmission coefficient (defined as $K_t = H_t/H_o$, where H_t = transmitted wave; and H_o = unreflected deepwater wave height) as a function of the relative submergence (R/H_o, where R = structure freeboard) and the relative crest width (B/L_o, where B = crest width of the structure; and L_o = deepwater wavelength). Note that this definition for K_t allows for values greater than unity if waves shoal on a submerged structure. Notation is shown in Figure 1.

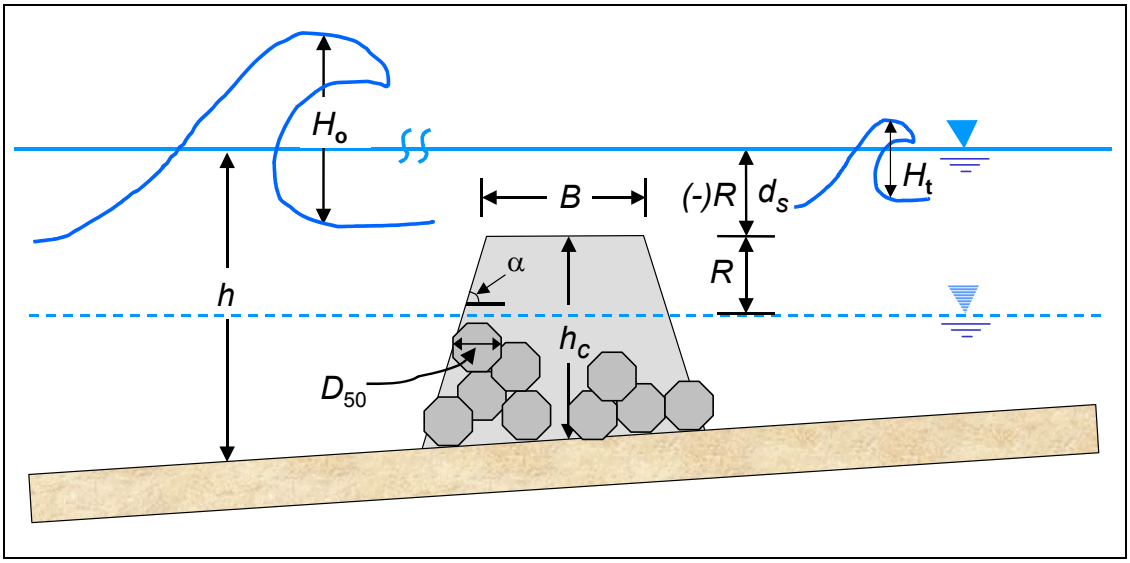

Figure 1. Notation for wave transmission predictive formulas

Tanaka's work forms the basis of the Japan Ministry of Construction official guidelines on breakwater design. Adams and Sonu (1986) examined wave transmission across a submerged breakwater at Santa Monica, CA, through 3-D model tests using random waves. The tests corroborated the trends of Tanaka's findings within the range of the test parameters in their study. Adams and Sonu concluded that the curves based on Tanaka's results could serve as a design tool, but should be applied with caution as they underpredicted the transmission coefficients based on the random wave tests for Santa Monica.

At present, the Tanaka (1976) curves provide the most comprehensive standard with which to compare predictive equations empirically derived from a limited set of data. To be considered reliable, a generalized predictive equation is expected to demonstrate qualitative trends similar to the Tanaka curves over a wide range of values in representing the physical processes adequately over a wide range of conditions. However, because Tanaka's experiments were carried out with monochromatic waves, quantitative agreement cannot be expected for transmission of irregular waves.

The design curves developed by Tanaka based on monochromatic waves are presented in Figure 2. The Tanaka curves clearly illustrate the decisive roles of both relative submergence and relative crest width on wave transmission. Relative submergence has long been recognized as a primary factor and is incorporated in all design equations. Other researches have also recognized relative crest width as a pivotal parameter (e.g., van der Meer (1991), d'Angremond, van der Meer, and De Jong (1996), Seabrook and Hall (1998), and Ahrens (2001)), but have not always adequately accounted for it in design equations, likely due to limited range in their tests. Values calculated by the predictive equations proposed by van der Meer (1991), d'Angremond, van der Meer, and De Jong (1996), Seabrook and Hall (1998), and Ahrens (2001) were compared to the trends of the Tanaka (1976) design curves to assess their predictive capability. Reference is given to three fundamental transmission modes as introduced by Ahrens (2001): transmission through the breakwater for both surface-piercing and submerged structures, transmission by overtopping of surface-piercing structures, and transmission over the crest of submerged structures.

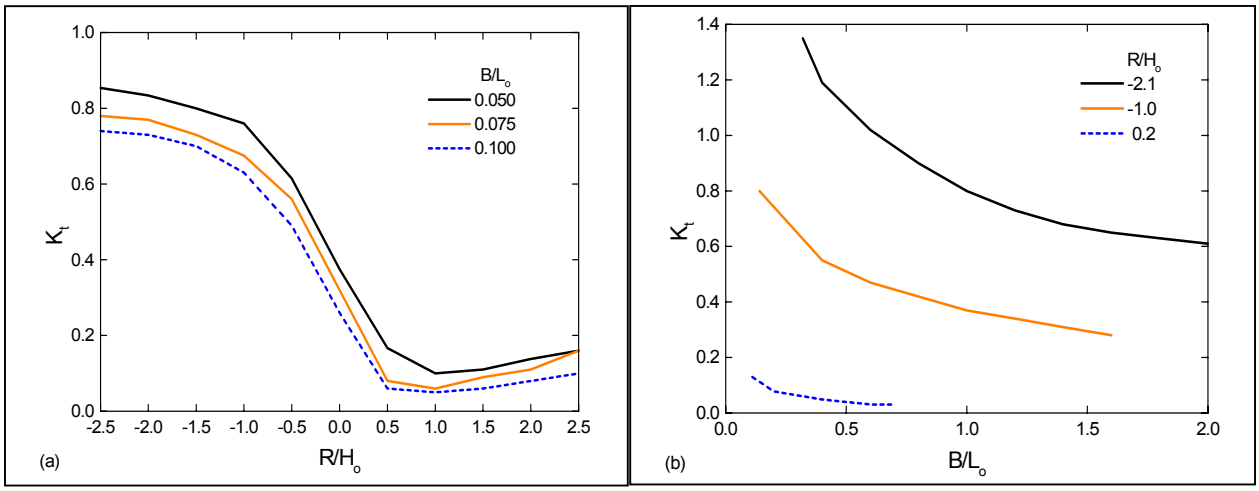

Figure 2. Wave transmission design curves (redrawn from Tanaka 1976)

The Tanaka transmission curve has an inverted S-shape as a function of relative submergence. Ahrens (1987) and van der Meer (1991) also found that the transmission coefficient varied as an S-curve if plotted against relative submergence. With the Tanaka (1976) results accepted as a guide, a general predictive formula should also describe an S-curve in plotting K_t versus R/H_o. Figure 3 plots K_t versus relative submergence for relative crest width $B/L_o \approx 0.075$. In Figures 3-5 and Figures 7-8, the following abbreviations appear: vdMc = van der Meer-conventional equation; vdMr = van der Meer-reef equation; dA = d'Angremond equation; SH = Seabrook and

Hall equation; and A = Ahrens equation. The van der Meer (1991) and d'Angremond, van der Meer, and De Jong (1996) equations produce straight lines and are only qualitatively similar to the Tanaka curve for values of approximately $0.1 < K_t < 0.7$ and relative submergence values between about –1.0 and 0.5. Limited predictability for these equations is expected because they were developed based upon a restricted range of variables. Transmission values for relatively high and low structures were deemed to be independent of incident conditions and not included in the formulation.

The formulation put forth by Seabrook and Hall (1998) is qualitatively similar to the Tanaka curve for relative submergence values less than zero (i.e., submerged structures), which is expected because the Seabrook and Hall tests dealt exclusively with submerged structures. The similarity to the Tanaka curve indicates that this equation may be representing transmission processes well over a wide range of submerged structures. The Ahrens equations produce an S-curve that is qualitatively similar to the Tanaka curve, suggesting that the dominant-mode approach has potential for producing an acceptable general predictive equation. Note that the equations developed based upon data on reef breakwaters, the Ahrens and van der Meer reef equations, are shifted to the right in Figure 3. This shift supports an assertion by Daemen (1991) that reef structures should be considered separate from conventional structures, requiring a distinct predictive equation.

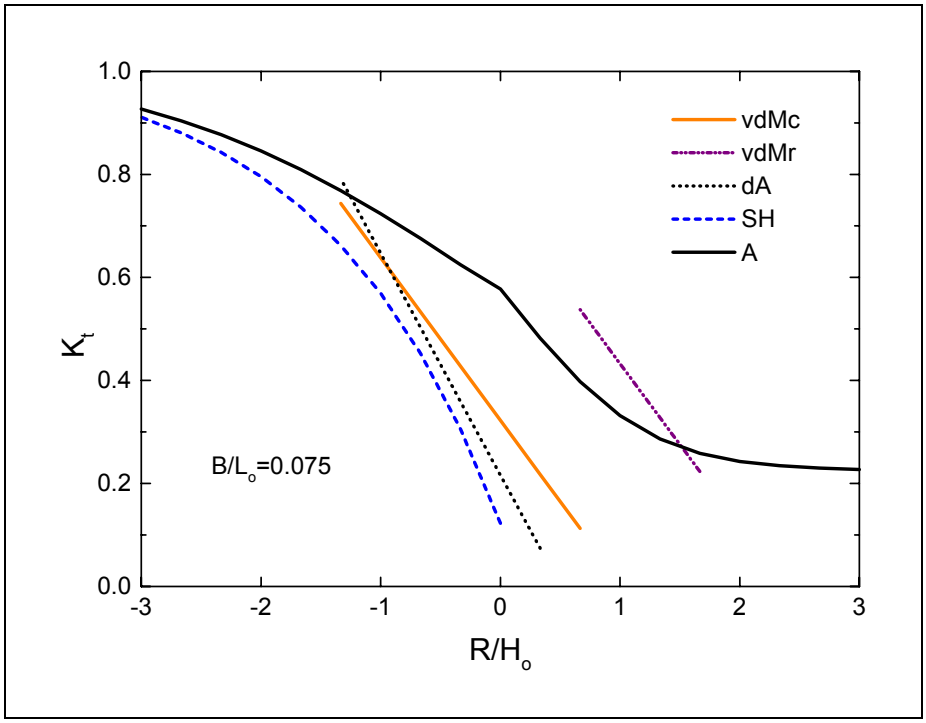

Figure 3. Transmission coefficient versus relative submergence

Figures 4-5 plot K_t versus B/L_o for submergent ($R/H_o < 0$) and surface-piercing ($0 < R/H_o < 2$) structures, respectively. The Tanaka curves in Figure 2(b) are similar, indicating a steep gradient in K_t versus B/L_o which decreases with increasing B/L_o until there is little change in K_t for $B/L_o >$ 1.5 for submerged structures and $B/L_o > 0.6$ for surface-piercing structures. An acceptable

predictive equation should demonstrate a similar trend of decrease. Van der Meer's (1991) reef equation does not include a crest-width term and is, therefore, independent of B/L_o for all three modes of transmission. For relative submergence of –1.0 (Figure 4), the van der Meer (1991) conventional breakwater equation is similar to the Tanaka curve only for values of $B/L_o \leq 0.1$. The Ahrens equation for submerged structures only includes a cross-sectional area term and does not follow the Tanaka curve form. The equations proposed by Seabrook and Hall (1998) and by d'Angremond, van der Meer, and De Jong (1996) are similar to the form of the Tanaka curve, indicating that they may adequately capture the influence of relative crest width.

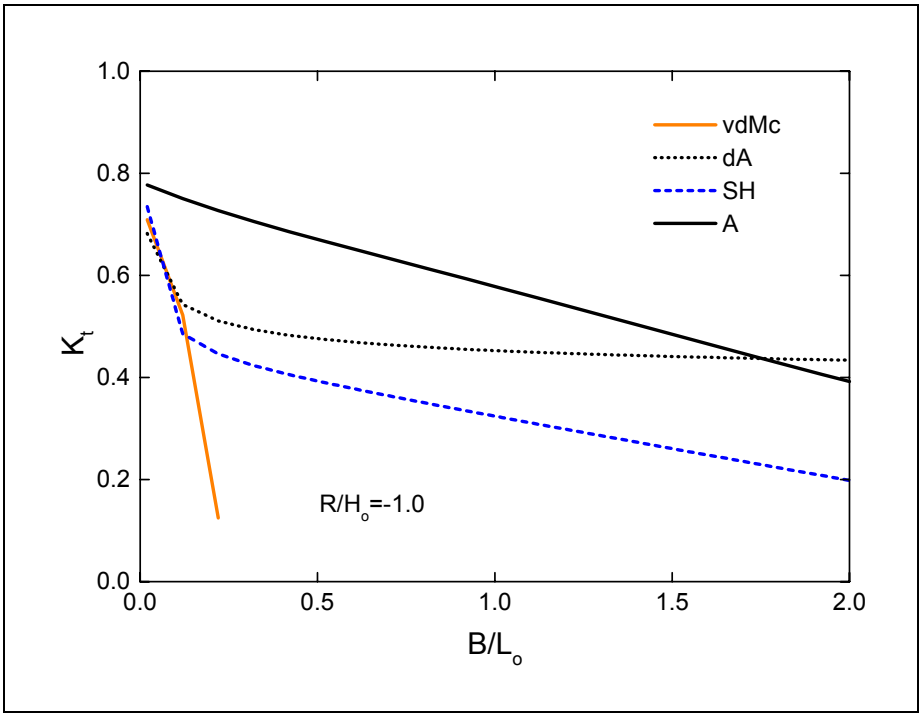

Figure 4. Transmission coefficient versus relative crest width of submerged structure

Figure 5 shows K_t versus B/L_o for surface-piercing structures with a dominant transmission mode of overtopping. The Seabrook and Hall (1998) results are not included for this and the transmission-through modes because their work was intended to be applicable only to submerged structures. Again, the conventional van der Meer equation does not produce a decaying curve and is similar to the Tanaka curve for very narrow-crested structures only. The decaying curves resulting from the d'Angremond and Ahrens equations suggest they have adequately represented relative crest width. The Ahrens equation also demonstrates a decaying trend for high structures in which the dominant mode is transmission through the structure. The other equations gave negative values of K_t for the high structure.

In summary, the Tanaka (1976) curves are referenced here as a qualitative guide for assessing the validity of predictive equations. Most of the equations investigated follow the Tanaka curve trends over a narrow range of design conditions. Van der Meer's (1991) equations are best suited for narrow-crested structures with a crest height near the water surface (i.e., $R \approx 0$). Based on this analysis, general application of van der Meer's equations is not recommended. Seabrook

and Hall (1998) derived a formula that appears to capture transmission processes associated with submerged structures. Their work specifically concerned submerged structures and should not be transferred to surface-piercing structures. d'Angremond, van der Meer, and De Jong (1996) produced an equation that can be applied to rubble mounds and solid structures, and it appears to work well for structures with relative submergence between about -0.75 and 0.5. For deeply submerged and relatively high structures, the d'Angremond formulation is not recommended. Both the Seabrook and Hall and d'Angremond formulations were developed primarily with conventional structure data and, therefore, care should be taken in applying them to reef structures. The most promising work from a general predictive equation prospective appears to be the Ahrens (2001) dominant-mode approach. The Ahrens equation was the only one to render an S-curve in plotting K_t versus R/H_o and to give reasonable results for high structures. Also, the Ahrens equation does not impose applicability limits. The Ahrens equation, however, was developed based primarily upon reef breakwater data and may overpredict transmission for a conventional structure. Additionally, the Ahrens equation for submerged structures may not adequately account for the influence of relative crest width.

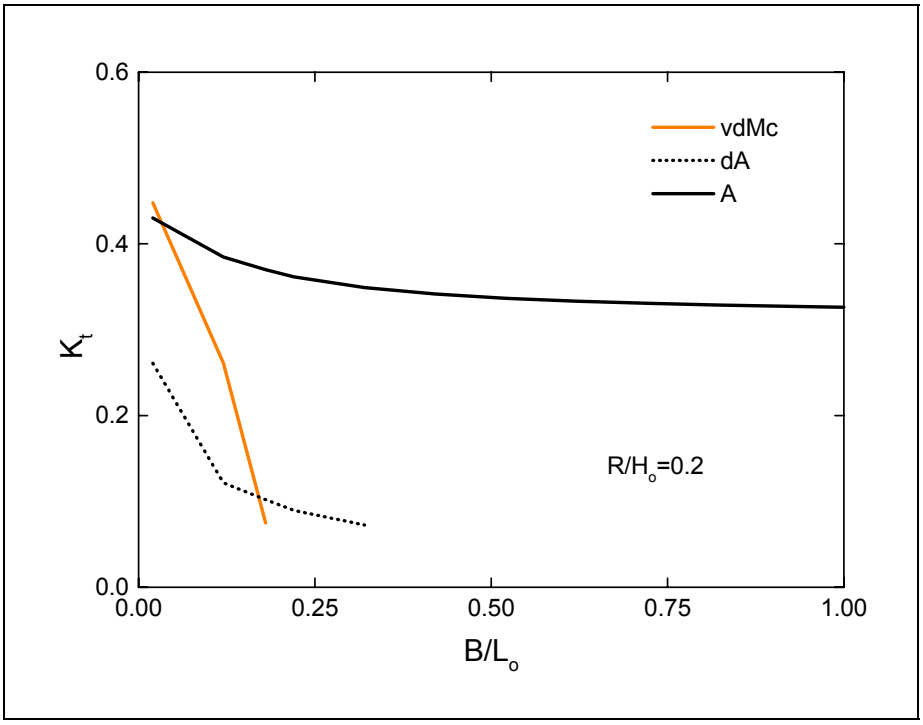

Figure 5. Transmission coefficient versus relative crest width of surface-piercing structure

IMPLEMENTATION IN GENESIS: In GENESIS, wave transformation from deep water to the location of the structure may be calculated by selecting either an external 2-D wave transformation model, e.g., STWAVE (Smith, Resio, and Zendel 1999), or the internal wave module within GENESIS (Hanson and Kraus 1989). In the revised GENESIS, the user may choose either a constant value of K_t for each structure or allow the model to calculate appropriate values based on time-varying water level and wave height, and structure characteristics. If the variable-K_t option is selected, water level is read from an input file at a specified input time interval. For each structure, the user specifies geometric properties (crest height and width,

slopes on seaward and landward sides, and median rock size) and can select between the calculation methods of Ahrens (2001), Seabrook and Hall (1998), and d'Angremond, van der Meer, and De Jong (1996). The method selected should be based upon structure type and configuration.

Based on the input values describing the structure, water level, and calculated wave properties, a corresponding K_t is calculated for each structure at each time-step. The calculated K_t will have a strong influence on the wave field behind and adjacent to the structure as it influences wave transmission and diffraction. Through an iterative procedure for calculating wave breaking, K_t also influences the breaking wave height and direction alongshore, thereby determining the associated shoreline response to the structure (Hanson and Kraus 1989, 1990, 1991a, 1991b).

CASE STUDY – GRAYS HARBOR, WA: The wave transmission predictive capabilities implemented into GENESIS were applied in a study for Grays Harbor, WA. Grays Harbor, located on the Pacific Ocean coast, is one of the largest estuaries in the continental United States. The tide is semidiurnal with 2- to 3-m neap to spring typical range. The adjacent beaches have a slope of approximately 1 on 60 and median sand grain size of 0.25 mm. A high-energy wave climate produces average annual significant wave heights of 2 m and peak periods of 10 sec. Winter storms generate waves greater than 6 m high and 17 sec period.

The entrance to Grays Harbor is bounded on both sides by rubble-mound jetties. The north jetty (Figure 6) was constructed to block southward transport of sediment and to protect and maintain the entrance navigation channel (U.S. Army Engineer District, Seattle, 1973). The effectiveness of the north jetty has decreased as a result of subsidence and deterioration, resulting in sediment being transported into the inlet, potentially increasing the need for maintenance dredging. The beach north of the jetty, Ocean Shores, has recently exhibited a tendency to erode, reversing a historic trend of advancement. Construction of a submerged spur off the north jetty has been proposed as a potential alternative for trapping and retaining sand and for promoting a morphological response that will reduce the southward transport of sediment, while protecting the jetty from scour. The GENESIS model is being applied to determine if the proposed spur will produce beneficial changes in shoreline orientation and reduction in longshore sand transport without causing updrift erosion.

The spur was represented as a detached breakwater in GENESIS. It is a reef-type rubble-mound structure with a median rock size of 0.9 m. The toe depth is approximately 8.1 m relative to mean tide level (mtl). Initially considered spur dimensions are crest height of 3.6 m, crest width of 10 m, seaward facing slope of 0.2, and a landward facing slope of 0.3.

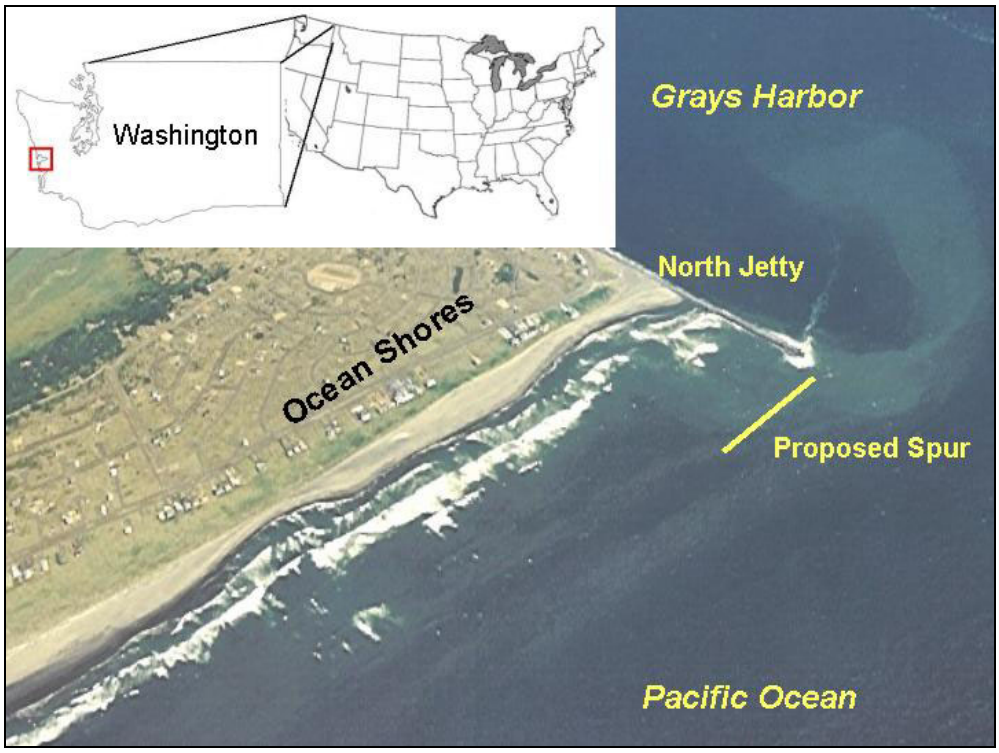

Figure 6. Study site, Grays Harbor, WA, looking SE

Comparisons to Numerical and Physical Model Data. Comparisons of predictions of wave transmission to data from numerical and physical models of the Grays Harbor spur further assessed their applicability as implemented in GENESIS for the case study. Wave transformation over the proposed spur was simulated with the fully nonlinear 1-D Boussinesq wave model of Wei et al. (1995)[1]. Simulations were run for nine storm wave conditions (H_s = 4, 6, 8 m; T_p = 10, 15, 20 sec; shape of offshore spectrum approximated using Jonswap, γ = 3.3) at mean lower low water (mllw) and mean higher high water (mhhw). Predictions of K_t were compared to wave transmission values computed from the numerical model results (Figure 7) for the d'Angremond, Seabrook and Hall, and Ahrens equations. The root-mean-square error (RMSE) between the calculated and predicted values are also given in Figure 7. The Ahrens equation provides the best prediction, indicating the central role of structure type and that relative submergence is a primary factor, with relative crest width playing a secondary role for these conditions. As expected, the Seabrook and Hall equation also compares well with the numerical predictions. The upper limit on the d'Angremond equation was invoked for each wave simulation.

[1] These simulation results were provided by Dr. Philip D. Osborne of Pacific International Engineering, Seattle, WA.

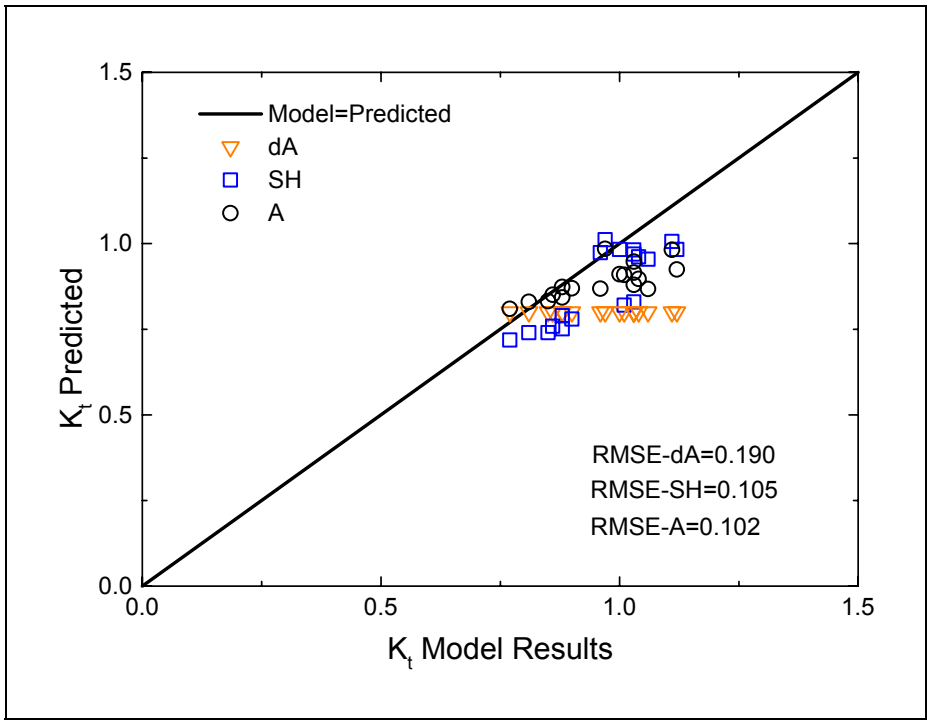

Figure 7. Transmission coefficient predictions and Boussinesq model results

Wave transmission data were also collected at three locations along the spur for three different offshore wave conditions in a 3-D physical model being operated at the U.S. Army Engineer Waterways Experiment Station of the Grays Harbor site with the spur in place. Waves were created in the 1:75 scale model with a 24-m-long plunger-type wave generator. The generator was programmed with actual prototype wave spectrum information to recreate the scaled waves. Each wave condition was run at mllw, mtl, and mean high water (mhw). The transmission data collected at the three measurement locations along the spur were averaged and are compared to the d'Angremond, Seabrook and Hall, and Ahrens formulations in Figure 8. The Ahrens equation again gives best agreement. The Seabrook and Hall equation also compares well to the physical model data, whereas the d'Angremond results again invoked the upper limit for many wave conditions. The d'Angremond equation is not applicable for this situation of high relative submergence.

The high submergence, large incident wave heights, and small stone size for the Grays Harbor spur place it close to the stated variable range limits for the Seabrook and Hall equation. In this situation, applicability of this equation is questionable for the larger wave heights. Predicted transmission coefficients from the Ahrens and the Seabrook and Hall equations are plotted in Figure 9 versus wave height for constant water level. The Ahrens formulation indicates a reduction in K_t with increasing wave height. The smaller waves shoal on the submerged spur, yielding a $K_t > 1$. As the wave height increases, a decrease in K_t is expected through dissipation. The Seabrook and Hall formulation also displays a decreasing K_t with increase in incident wave height for $H_s < 4$m. The Seabrook and Hall formulation then yields K_t values that increase with increase in wave height. The unexpected results begin to occur if the Seabrook and Hall equation is applied outside the range of their stated test parameters. Based on these results, it

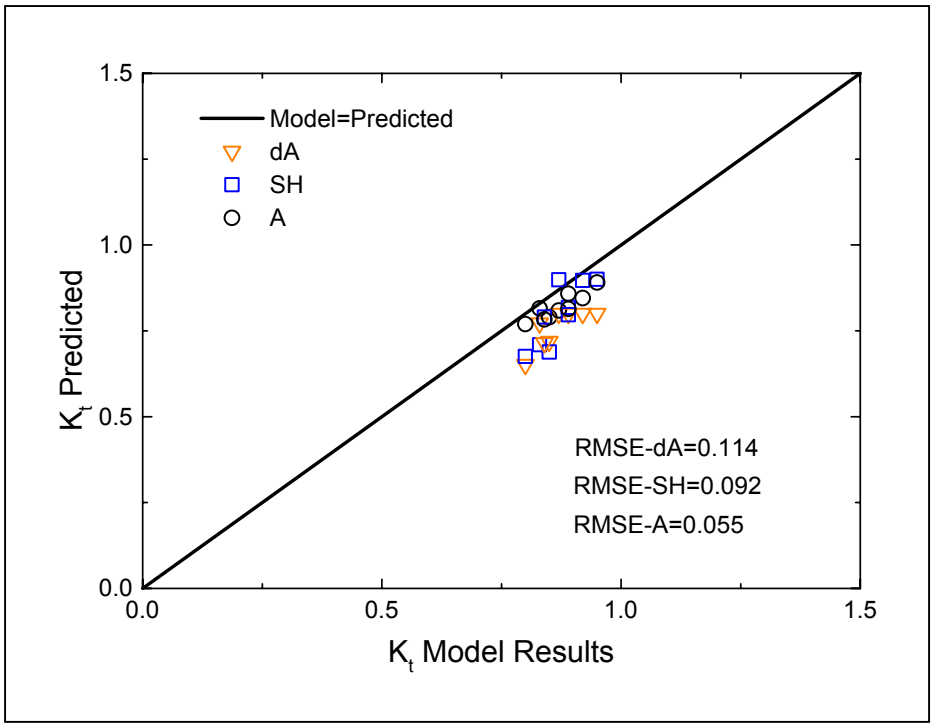

Figure 8. Transmission coefficient predictions and 3-D physical model data

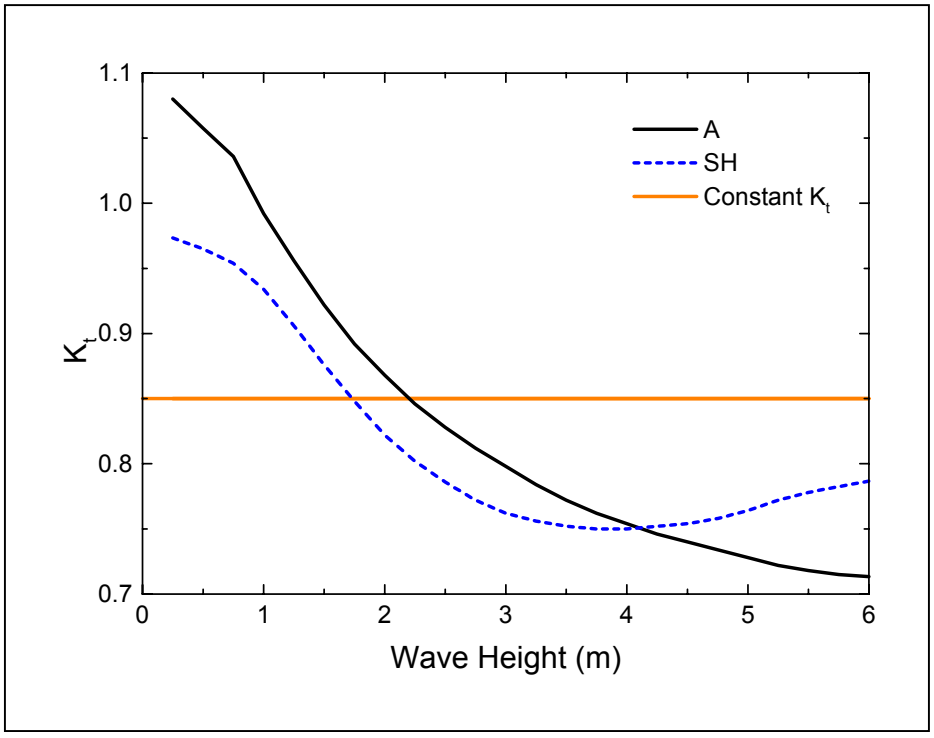

Figure 9. Transmission coefficient versus wave height, constant water level

appears that the Grays Harbor spur design is outside the applicable range of the Seabrook and Hall equation for certain environmental conditions.

Although the Ahrens formulation may not adequately account for the crest width of some submerged structures, it performs well for the Grays Harbor spur. This result suggests that the relative submergence of a structure is the primary variable determining transmission. The effectiveness of the Ahrens equation also supports Daemen's (1991) conclusion that reef breakwaters should be treated separately from conventional structures. The Ahrens formulation is applied to model shoreline response to the spur at Grays Harbor.

Simulation Results. The GENESIS model for Grays Harbor was calibrated to reproduce shoreline change observed between September 1976 and August 1985 and verified for the time period September 1985 through August 1995 (Wamsley and Hanson, in preparation). The spur was then modeled as a 500-m long detached breakwater in GENESIS. The time-varying water level file required for computing the transmission coefficient was created by input of local tide data. The year 2000 shoreline served as the initial shoreline and a 4-year simulation was run using the Ahrens transmission formulation. A 4-year simulation with constant K_t was also run to assess the significance of varying K_t with the waves and water level. The average $K_t = 0.85$ computed by the Ahrens formula for the 4-year record was assigned for the constant-K_t simulation.

The predicted shorelines, together with the 4-year simulated shoreline without the spur, are plotted in Figure 10. Both the Ahrens formulation and the constant K_t predict accretion behind the spur with 10 m or less of updrift recession compared to the no-spur simulation. Presence of the spur also alters the shoreline orientation within 1 km of the jetty. Without the spur, the shoreline orientation near the jetty is approximately 2 deg west of north. A variable K_t reorients the shoreline to 4 deg east of north, whereas a constant K_t predicts a shoreline orientation near the jetty of due north.

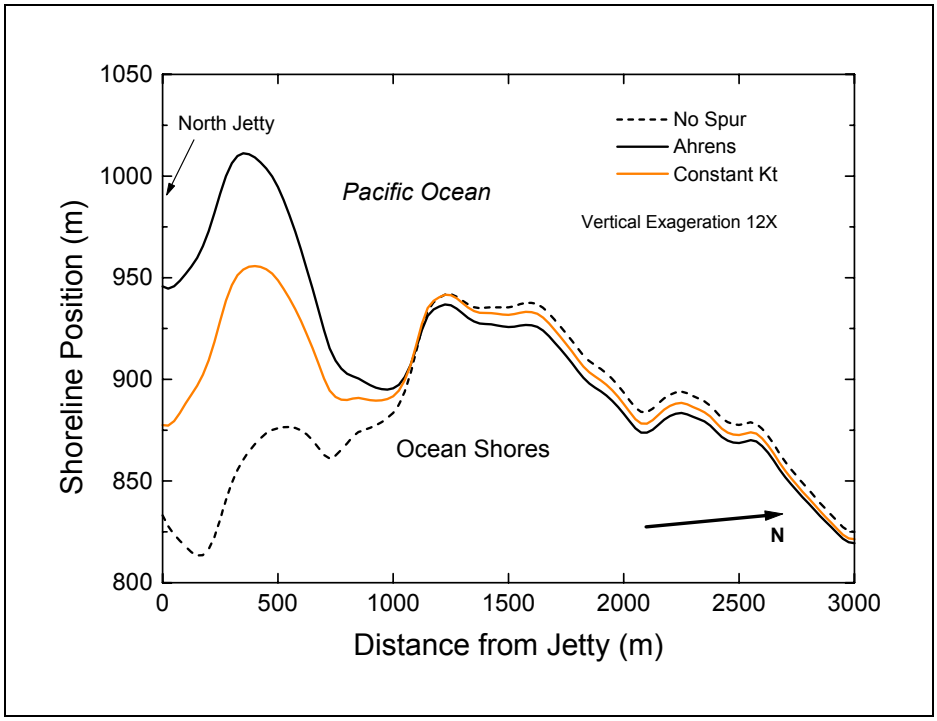

Figure 10. Predicted shoreline positions

The difference in calculated shoreline planforms demonstrates the improved reliability of a variable K_t prediction. The variable K_t formulation produced as much as 70 m more shoreline advance behind the spur than predicted with constant K_t. The primary reason for the difference is the sensitivity of the prediction to water level and incident wave height, acting together with directionality of the wave climate. Figure 9 plots the change in K_t versus wave height for constant water level. As compared to K_t =0.85, the Ahrens formulation predicts higher K_t-values for waves less than 2.25 m in height. That trend then switches, and the Ahrens method predicts smaller K_t-values for higher waves. The Grays Harbor wave climate is characterized by higher winter waves that approach from the WSW and drive sand to the north, in contrast to the more prevalent smaller summer waves that approach from the WNW and drive sand to the south. The large winter waves tend to erode the beach near the jetty as they transport sediment northward with no supply possible through bypassing the inlet. Waves from the WNW transport sand toward the inlet where it is impounded at the jetty and widens the beach or bypasses the jetty and enters the inlet. Because longshore transport is approximately proportional to $H^{5/2}$, an increase in higher waves results in much greater change in transport than does a similar height differential for smaller waves. The reduced transmitted wave heights predicted by the Ahrens formulation for the large waves decreases the predicted erosion, not only maintaining beach width but also promoting a shoreline orientation that reduces the southbound transport induced by the WNW waves. The result is a wider beach in the lee of the spur.

CONCLUSIONS: Wave transmission at a detached breakwater is a leading parameter among many variables controlling the response of the shoreline to the structure. Wave transmission depends on the configuration and composition of the structure, wave height and period, and water depth, and the forcing parameters are time dependent. In this study, predictive formulas for wave transmission at detached breakwaters were critically evaluated, and the new Ahrens (2001) formulation proved to provide reliable predictions for reef-type structures over a wide range of geometric, water level, and wave conditions. The predictions of the Ahrens formulas were confirmed for a case study through comparison to results from a numerical model and a physical model.

Variable wave transmission was incorporated in the GENESIS shoreline change numerical model, which was calibrated to represent shoreline change at Grays Harbor, WA. Predicted shoreline response to a proposed submerged shore-parallel spur on the north jetty differed considerably between the constant and the time-dependent wave transmission cases. Sensitivity tests indicated that seasonal directionality and energy of the incident waves, combined with the variable wave transmission, contributed to a significant difference in predictions between constant- and variable-wave transmission. The combined working of wave direction and wave transmission was unanticipated and demonstrates the functional utility of numerical simulation models of shoreline change that can automatically account for a wide range of contributing variables determining longshore sediment transport and shoreline response to structures.

ADDITIONAL INFORMATION: This CHETN is a product of the Inlet Geomorphology and Channel Evolution and Inlet Channels and Adjacent Shorelines Work Units of the Coastal Inlets Research Program (CIRP) being conducted at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Much of the original research upon which it is based was conducted under the support of the U.S. Army Engineer District, Seattle.

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