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Modeling Attenuation of Storm Surgeover Deformable Vegetation: Methodology and Verification

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ABSTRACT: Thisstudyextendedandunifiedresistanceformulationsforrigidanddeformableplantsunderbothemergentandsubmergedcon-ditions.Threeapproacheswereexaminedindetailandimplementedintoanumericalmodel.First,theflowresistanceformulationsforrigidplants were critically reviewed. By introducing plant deformation relations with a given vegetal stress and vegetation properties, the formulationfor rigid plants was extended to flexural rigid plants. Second, a flow resistance formulation directly derived from submerged, flexible plants wasexaminedandextended.Bothapproachestosimulatingdeformablevegetationsolveasetoftwoequations,avegetationdeformationrelationandaresistancelaw,iteratively.Themethodologyandnumericalalgorithmforrigidanddeformableplantswereimplementedintoanoper-ationalstormsurgemodelandtested againstlaboratorydata.Goodagreementhasbeenfound.Theverifiedmodelcan beusedtostudy the spatial and temporal variations of deflected vegetation heights and equivalent Manning's coefficient under realistic hurricane and wetlandconditions.

Authorkeywords: Stormsurge;Wetlands;Vegetation;Flowresistance;Numericalmodeling.

I. INTRODUCTION

Coastalwetlandsplayanimportantroleinprotectingcoastalcom-munitiesandstabilizingshorelines(Costanza etal.2008; Gedanet al.2011;Shepardetal.2011).Itiscommonlyacceptedthatvegetationcanattenuatenotonlyshortwaves(e.g.,Mendezetal.1999;ChenandZhao2012;Jadhavetal.2013)butalsolongwavessuchastsunamiwaves.Forinstance,itwasobservedthatmangroveswampseffec-tively attenuated tsunami waves and protected a sheltered communitywhilecommunitieswithouttheprotectionofmangrovesweredam-agedseverely(LatiefandHadi2007;Alongi2008;Teoet al.2009).However,whethercoastalwetlandscaneffectivelyattenuateforcedlong waves such as storm surges remains under debate (Resio andWesterink2008;Feaginetal.2010).SinceHurricane KatrinastruckNewOrleans,Louisiana,in2005,moreattentionhasbeendrawntothepotentialbenefitsofcoastalwetlandsforreducingstormsurge.Fieldmeasurementsandnumericalsimulationsinrecentyearsarein supportofvegetation'sroleinstormsurgereduction(e.g., Loderetal.2009;Wamsleyetal.2009;Shengetal.2012).Wetlandrestorationisadvocatedfrombooththeecologicalandflood-reductionperspec-tives(Waltonetal.2006;Dayetal.2007).

Typically, surface waves that may cause damages to coastalcommunitiesincludeshortwaves(wind-orboat-generated),tsunamis,andstormsurges.Shortwavesaregeneratedbywindsormovingboatswithwaveperiodsofseconds.Tsunamisoftenresultfromseismic

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activity or landslides on the ocean floor, and consist of a series ofwaveswiththeperiodrangingfromminutestohours.Stormsurgesasagradualriseofwaterlastingfromhourstodays arebuiltupasaresultofacombinationofwindsetup,lowatmosphericpressure,wavesetup,andinteractionwithtidal conditions.Tropical cyclones and extra-tropicalstormsproducestormsurgeswithsurgeheightsranging1–9mdependingonthewindintensity,thesizeofthestorm,proximitytothelandfalllocation,aswellaslocalbathymetry andgeometry(e.g.,Chen etal.2008).Smallstripsofcoastalwetlandsandforeststhat effectivelyattenuatewindwavesandtsunamiwavesaretypicallyinsufficientforreducingstormsurge.Potentialbenefitsofcoastalwetlandsforre-ducingstormsurgeheightsdependonthewetlandsizeandvegetationproperties.Withtheurgentneedofcoastalrestorationandhurricaneprotection along the Louisiana coast, a number of science-basedprograms have been launched to sustain a coastal ecosystem thatprovidessupportandprotectiontotheenvironmentandeconomyofsouthernLouisianaandbeyond[LouisianaCoastalAreaScience&Technology Program (LCASTO) 2010; Louisiana Applied CoastalEngineering and Science Division (LACES) 2012; Louisiana CoastalProtection and Restoration Authority (CPRA) 2012]. Both numericalmodelsandfieldmeasurementsareprimarytoolstoinvestigatetheroleof coastal wetlands in storm surge and wave reduction. Numericalsimulations using increased bottom friction resulting from vegetationhave shown that coastal wetlands together with other landscapefeaturesareabletoattenuatestormsurgeand wavestosomeextent(Suhayda1997;Loderetal.2009; Wamsleyetal.2009,2010).Thedominantvegetativeresistancetotheflowinvariouscirculationorstormsurgemodelsisparameterizedasananalogofthebottomfriction usinganenhanced,staticManning'scoefficient(n),which maynotbeadequatelyaccurateaccording torecentstudies(e.g.,KouwenandLi1980;Wuetal.1999;Freemanetal.2000;WilsonandHorritt2002; Carolloetal.2005;Wilson2007).

Vegetation-induced drag force, as an extra force exerted on theflow, was originally explored in the literature primarily for deter-mining the discharge capacity of an open channel with submergedor emergent vegetation. For a given energy slope, the vegetativeflowresistancebecomesdominantasvegetationdensityincreases.LopezandGarcia(1998)showed thatthebedshearstressof a vegetation field, with a 0.3 ratio of the stem frontal area to thesubstrateareawherethestemshootsarerooted,isonly20%ofthevalue experienced by a bare bed. The diminished bed shear stressentrainsfewerbottomsediments(LopezandGarcia1998)becausethe rooting soil has been strengthened physically and biologically byvegetation (Micheli and Kirchner 2002). Therefore, the bed stressresulting from the bottom friction is often neglected (Fenzl andDavis 1964; Carollo et al. 2005). The drag force caused by vege-tation is composed of the form drag, inertial force, and skin friction,while the latter two are often neglected in a time-averaged model.Therefore, the vegetation-induced drag force is simply considered astheformdrag.

The vegetative drag force is commonly computed using thequadratic friction law, where the hydraulic relationship is utilized todeterminethe flowresistancecoefficientgiven a value of theManning's roughness coefficient, n, and a hydraulic radius (Chow1959).Thisrelationshipiswidelyadoptedforfloodplains,coastal plains, and other aquatic environments with the hydraulic radiusreplacedbyaflowdepth(e.g.,GuardoandTomasello1995;Copeland 2000; Kouwen and Fathi-Maghadam 2000; Doncker et al.2009;Bunyaetal.2010;Dietrichetal.2011).Areliableestimationof n-values for a given type of vegetation is critical for investigatingthe hydrodynamics and ecology of a wetland environment (Lee et al.2000, 2004; Schaffranek 2004). The USGS had a guide for selectingn-values(ArcementandSchneider1989)andsuggestedaddingaconstantntoabasevalueforachannelbottomwithacertaintypeof growing plants in addition to other adjustments resulting fromthe channel irregularity, variation of cross section area, and so on.Nevertheless, it was also stated that the effects of vegetation on ndependontheflowdepth,thepopulationdensityofvegetation,thedegree to which the vegetation is flattened by strong currents, and thealignment of vegetation relative to the flow. As those influencingfactorswereidentified,variouslaboratoryexperimentsandfield measurements have been undertaken to quantify the relationshipswith n. Manning's n was found to vary seasonally as a result ofthe seasonal variation of vegetation biomechanical properties andabovegroundbiomass(e.g.,ShihandRahi1982;Donckeretal. 2009). More importantly, n varies with the flow stage. Typically, aswater depth increases, n increases for emergent plants and decreasesfor submerged plants (Wu et al. 1999; Wilson and Horritt 2002;Wilson 2007). When considering the flexibility of vegetation, ndecreases as the flow velocity increases because a fast flow wouldbend the flexible vegetation and reduce the effective roughnessheight (Kouwen and Fathi-Maghadam 2000; Lee et al. 2000). Thevariation of n with the flow depth and flow velocity leads to a re-lationship between n and the product of flow velocity and flow depthproposed in Palmer (1945) and denoted as the n-VR curve. However,becauseofthelargediscrepancyinn-VRcurves(e.g.,KouwenandLi 1980;Wilson and Horritt 2002; Carollo et al. 2005), this re-lationship is physically meaningful yet not practical owing to theabsenceofthevegetationbiomechanicalproperties. Ontheotherhand,adragcoefficientisoftenused,especiallywhentheunderlyingphysicsofflow-vegetationinteractionareconcerned.Alargenumberoflaboratoryexperimentshavebeenperformedtoinvestigate the drag coefficient of an individual plant shoot withinagroupofthesamekindandthecorrespondingdragforceresultingfrom both rigid and flexible vegetation (live or artificial) under eitheremergentorsubmergedconditions(e.g.,Tsujimoto et al.1996;Lopezand Garcia 1997; Nepf 1999; Stone and Shen 2002; Wilson et al.2003).Notethatdragcoefficientsweredefinedwithrespecttodif-ferentreferenceflowvelocities.Inadditiontothewell-knowndragcoefficientofaninfinitelylongisolatedcircularcylinder,astemlayerdragcoefficientwasintroducedinStoneandShen(2002)withrespecttoaspatiallyaveragedvelocitywithinthestemlayer;abulkdrag coefficientwasintroducedinNepf(1999)withaporevelocityaveragedovertheentirewatercolumnforaflowthroughanemergentcanopyfield;andabulkdragcoefficient withrespecttothedepth-averageddischargevelocityisusefulforhorizontaltwo-dimensional(2D)models.Thesedragcoefficientsaredifferentintheirreferencevelocitiesbutsimilarlyrepresentanarrayofrigidcircularcylinders,wheretheflowisaffectedbyadjacentcylinders.Nepf(1999)conductedaseriesofexperimentsinaflumecov-eredwithemergentcylinders.Adimensionlessparameterofpop-ulationdensitywasusedtorepresentthevolumeconcentrationofemergentstems.Itwasfoundthatthebulkdragcoefficientdecreasesasthepopulationdensityincreasesforastem Reynoldsnumber(R_d)larger than 200. The reduction of the drag coefficient is caused by thevelocityreductionintheaffectedwakestructureandbythedelayedpointofseparationatthedownstreamstemresultingfromtheup-streamwakeinducedturbulence(Nepf2004).However,theshel-teringeffectsoftheupstreamcylindersondownstreamelementsarelesssignificantforalowerstemdensity.Experimentaldatashowedthatthebulk dragcoefficientremainsnearlyconstantuptoapop-ulationdensityof0.01(Nepf1999)andthebulkdragcoefficientcanbeapproximatedfromthatofasinglecylinder(StoneandShen2002;Nepf2004).Thedragcoefficientofasinglecylinderdependsonthestem Reynoldsnumber,R_d,foralaminarregime,andisvirtuallyequalto1uptoR_d533 10^5(Naotetal.1996;Nepf2004;Wilsonetal.2006;Zhangetal.2010).StoneandShen(2002)conductedanextensivesetofflumeexperimentsonflowsthroughboth emergentand submergedrigid cylinders and showed that thedrag coefficient of a single cylinder equals 1.05 with a small standarddeviationforawiderangeofpopulationdensity,stemdiameter, andR_d.

The drag for a submerged, flexible canopy field is likely to beoverestimatedifplantsareassumedtoberigid(WilsonandHorritt2002),becausealowerdragisexpectedasaresultofthebendingandstreamlining of deformable plants. In reality, flexible plants arecommon, although they may act like rigid cylinders under weak flowconditions. A stiffness parameter, EI, which is the product of themodulus of elasticity and the second moment of the stem crosssection,wasintroducedasameasureoftheplantflexibilityandcanbe related to the deflected vegetation height and flow resistance(Kouwen and Unny 1973; Kouwen and Li 1980; Tsujimoto et al.1996)forsubmergedplants.Fathi-MaghadamandKouwen(1997)presented more evidence showing the reduction of the flow re-sistance resulting from vegetation flexibility under emergent con-ditions. Wilson et al. (2003, 2006) emphasized the importance ofvegetation deformation in determining the mean velocity of flowthroughsubmergedvegetation.

In addition to plant flexibility, the degree of submergence isanotherkeyparameterthathasacloserelationwiththevegetationdragforce,especiallyduringahurricaneeventwhenthetotalwaterdepth changes with the rising and falling surge water level at dif-ferent stages of the event. Submergence is defined as the ratio of flowdepthtothevegetationheight.Theflowthroughacanopyfieldcanbe classified as emergent, submerged, and deeply submerged, as thedominant driving forces of the canopy flow vary with the sub-mergence(Nepf2004).Theflowoveradeeplysubmergedcanopyconsists of three layers including a logarithmic velocity profile up tothe water surface, a stem flow layer inside the canopy, and a mixinglayer in between. The logarithmic layer becomes dominant as thesubmergenceincreases(- 10)andthedeeplysubmergedflow eventuallyresemblestheunconfinedflow(Nepf2004). Asthesub-mergence decreases, the logarithmic layer becomes less importantwhile the mixing layer persists. When the submergence decreasesbelow1.5,themixinglayertakesupthenonvegetationlayeruptothewatersurface(NepfandVivoni2000)untiltheplantsare

emergent with the water column occupied simply by the canopy.With different degrees of submergence, the drag force varies. Thedependencies of the vegetative flow resistance on vegetation pro-perties, flow depth, flow velocity, and the combination have beenwidely revealed in laboratory scale experiments, yet less recognizedin numerical modeling. A vegetative flow resistance module con-sidering these dependencies is desirable for a horizontal 2D stormsurgemodelto(1)takeintoaccounteffectsofvegetationonstormsurge reduction by wetlands, (2) quantify the flood risk reductionbenefits, and (3) provide guidance for restoration project design. Thepurpose of this study is threefold: (1) to review different flow re-sistancerelationshipsresultingfromrigidandflexiblevegetation;
(2)toextendtheexistingformulatoaccountforboththerigidityofvegetationandvaryingdegreesofsubmergence;and(3)todevelopa vegetation-surge dynamically coupled model for predicting theeffect of vegetation on the mean flow, surge levels, and wind waves.Theresultsfromthestudyarepresentedinthispa
data.Afuturepaperwilldocumentthestudyusingsimplifiedfield 2 v
conditionsandhurricaneforcing,whichrevealsthespat
temporal variability of the equivalent Manning's coefficient incoastal wetlands during a hurricane and provides insight into surge-vegetation-waveinteractions.

The paper is organized as follows. After the introduction, the"Methodology" section reviews the flow resistance laws proposedby Stone and Shen (2002) and Kouwen and Unny (1973), and in-tegrates them for a full range of submergence and a variety
ofvegetationrigidity.Next,theintegratedformulations areimple-
mented into a storm surge model and the numerical algorithm isexplained. Then the vegetative flow resistance module is testedagainst three sets of laboratory experimental data for emergentvegetation, submerged rigid vegetation, and submerged
deformablevegetation.Thefindingsaresummarizedinthe"Summaryand
Conclusions"section.

wheret_v5vegetalstress;ČD5bulkdragcoefficientwithr
bulkdragcoefficientC^pcanberelatedtothe$C_D$underem

Methodology

FlowResistance
conditions(H^w5h)byapplyingthecorrespondingveloc
Considerableeffortshavebeenmadeintheliteraturetounderstand
theflowstructureandturbulencecharacteristicsindeeplysub-

per.Thispaperisfocusedonmodeldevelopmentandverificationusinglaboratory
vegetativeflowresistance,eitheradragcoefficientoran equivalentManning's coefficient needs to be determined. Both coefficients canbe related to a dimensionless friction factor that is commonly used inthequadraticlaw[Eq.(1)]

t_v¼$\frac{1}{2}$r$f_v$$V^2$ (1)

wheret_v5 vegetal stress; r 5 water density; f_v5 vegetal frictionfactor; and V 5 depth-averaged velocity (discharge over the grosscross-sectionalarea).

Thedragcoefficientofasinglerodwithinanarrayvaries as
a result of the upstream wake structure and vortex shedding (Nepf1999; Barkdoll et al. 2004). Therefore, a drag coefficient repre-senting the array is defined as a bulk drag coefficient and the vegetalstressisexpressedbasedontheMorison-typeequation

t_v¼$\frac{1}{2}$rČDN$B_v$$H^w$$\check{V}^2$ (2)

ialand

espectto
areferencevelocity,V̌;N5numberofstemspersquaremeter,
known as the stem density (N 5 1=d^2); $d^2$5 average rooting areaof a single rod; d 5 average distance between two adjacent stems; B_v5stemdiameter;andH^w_v5wettederectstemheightthat isequaltothe water depth for emergent conditions or equal to the vegetationheight for submerged conditions. Fig.1 illustrates an array of cy-linder rods and corresponding parameters. Table 1 lists referencevelocitiesandthecorrespondingbulkdragcoefficients.

ItwasfoundbyStoneandShen(2002)thatifthemaximum
depth-averaged velocity at a constricted section in the stem layer (V_c)is used, the drag coefficient $C_D$approximates the value of a singlecylinder, which is nearly constant with a relative standard deviationof7.6%forawiderangeofexperimentalconditions.InTable1,the

ergent D
ity,$V_p$and v
V_c,inEq.(2).Therelationshipisexpressedas
12NB^2 2

D
mergedoremergentvegetationcanopies(e.g.,Shietal.1995;Lopez

Cp¼CD
v

and Garcia 1997; Nepf 1999; Järvelä 2005; Ghisalberti and Nepf2006). However, a low-submergence flow (submergence is largerthanbutcloseto1)withaturbulencemixinglayerextendedtothe surfaceofthewatercolumnislessstudied.Duringahurricane,thevegetationexperiencesconditionsthatareemergent(submergence
D p
islessthanone),nearemergent(submergenceisclose to 1),and
submerged (submergence is larger than one) as the storm surge waterintrudes and retreats. The near emergent stage may be critical forunderstanding not only the surge reduction but also the vegetationmortality as the drag force is significant under near emergentconditions (Nepf and Vivoni 2000; Nikora et al. 2001). In this study,flow resistance formulations within a wide range of submergence arecritically reviewed, extended, and integrated into a new algorithm tomodelthevegetativeflowresistanceforbothrigidand

1 2Bv piii2
(3)
InNepf(1999),apopulationdensitywasdefinedasNB2. Given
apopulationdensitysmallerthan0.01,Cpvariesaround 1.2andislessaffectedbythepopulationdensity.However,ifthepopulationdensity becomes large, CDdecreases as the effects of wake structurebecomesignificant.Consequently,Cpdecreasesaswell.Applying

deformableplants.Anotationtableisprovidedforallsymbolsusedinthetext.

RigidCylinderFormulation
Formulationsforrigidcylindersarediscussedfirstbecause notonlyisunderstandingtheflowresistanceofrigid,cylindricalrodsinachannelfundamentalforstudiesonflexibleplants,butalso
Eq.(3)andthepopulationdensityof0.01yieldsCD51:21CD.
Thus,theauthorshaveCp51:2byassumingCD51:0forasparse

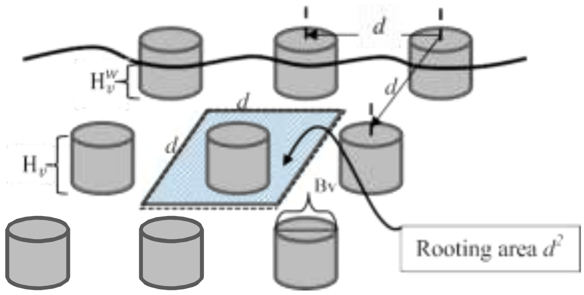


Fig.1.Schematicarrayofemergentcylinderrods

emergentflexibleplantsmayactlikerigidcylinders.Toquantify

Table1.VariousDragCoefficientsandDefinitionsofCorrespondingReferenceVelocities

^ V	^ Definition	Formulation	C_D	Reference
V_p	Emergentcanopyporevelocity			
V_l	Apparentstemlayervelocity			

Vp5 Bhð1V5Ql

l $\overline{BH^w}$

v

Q_l

NB2Þ

2 *v*

Nepf(1999,2004);Wu(2008) C_D

l

StoneandShen(2002) C_D

V_c Maximumdepth-averagedvelocityat

V5 V_l

c

C_D StoneandShen(2002)

aconstrictedsectioninthestemlayer

ð12Bv pffiffi NÞ

$\overline{V}$ Apparentdischargevelocity V5Q

Bh

C_D Wuetal.(1999);Struveetal.(2003)

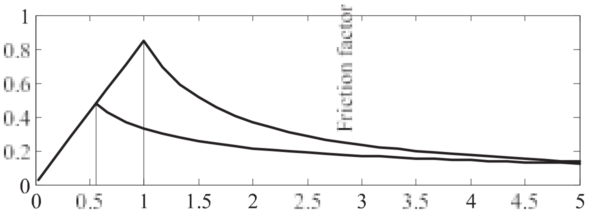
Note:Q, B, andh5volumedischarge,channelwidth,andwaterdepth,respectively; Q_l5volumedischargein the canopyfield,whichistypicalinanaturalmarshfieldofJuncusroemarianusandSpartinaalternaflora. Inahorizontal2Dnumericalmodel,itismorecommonthatthe depth-averagedapparentdischargevelocity(V)iscomputed.Itwould be beneficial to determine the bulk drag coefficient $C_D$correspondingtoVfromC_D.StoneandShen(2002)c

stemlayer;definitionsof othersymbols aregiveninEq.(2).

onducteda series of laboratory experiments with various stem density anddiameters, and found that the apparent discharge velocity, V , can bedefinedasafunctionof$V_c$withotherparameters,such as,N,H^w,h,andB_v,seeninEq.(4)

$$V \,¼\, \frac{h^p \text{ pffiffi}}{\;}\, V_c \quad (4)$$

v



h/Hv

Fig.2.Frictionfactorversussubmergenceforrigidplants(solidline)andflexuralplants(dashedline);verticaldottedlinesindicatethenear-emergentconditionsforflexuralplants(*s*,1)andrigidplants(*s*51)

12Bvh pffiffi N

whereh^{p}5ratioofthewettedstemheighttotheflowdepth(H ^{w}=h).Replacing(V̌,C̃D)inEq.(2)with(V,CD)and(Vc,CD ^{v}),re-
spectively,andinvokingEq.(4)yields

hp

Thedependenceofthefrictionfactoronthesubmergenceoffersa way to determine the surge-dependent drag force. Nikora et al.(2001) studied the flow over a rough permeable or impermeable bedandshowedthreeflowtypeswithhighsubmergence,nearemergent

f_v¼ $\frac{C_D N B_v H_v}{}$ 1, submergeds.1;H^w¼H_v (7b)

C_D¼C_D 1

2hpBv

p N 2 (5)

andrelativelysmallsubmergence.TheyfoundthattheDarcy-Weisbachfrictioncoefficient[one-fourthofthefrictionfactorinEqs.(1),(6),and(7)]increasesasthedegreeofsubmergence(s)

Eq. (5) suggests that the bulk drag coefficient, C_D, is positivelyrelated to the stem density, the stem diameter, and the vegetationheight, and is inversely affected by the water depth for a given C_D. Ifthepopulationdensityincreasesremarkably,$C_D$itself willreduce,andsowillC_D,asaresultoftheeffectsofenhancedwakestructureandvortexsheddingwithahighReynoldsnumber.

By combining Eqs.(1), (2), and (5), the vegetal friction factor canbeexpressedas

increases for the emergent condition (s , 1), and then decreases asthesubmergenceapproaches1andcontinuestoincrease(s.1).

Because Manning's coefficient is widely used in operationalnumerical models, it is worth noting that an equivalent Manning'scoefficient (n_e) can be derived by employing the hydraulic re-lationshipbetweentheManning'scoefficientandthefrictionfactorforuniformflow[n_e5f_v=2$g^{1=2}h^{1=6}$].Eq.(8)definesn$_e$ asafunctionoftheflowdepthandvariousvegetationproperties

$C_D N B_v H^w$ H^w

12 h $H^w_v B_v$ h p N

C NB w

fv¼ 2

(6)

n¼ D v v p N

(8)

Eq.(6)canberewrittenfortheemergentandsubmergedconditions

whereg5accelerationduetogravityandallothersymbolsweredefinedinpreviousequations.

$C_D N B_v H_v$

12B_vp N 2

s,emergents#1;H^w¼h (7a)

It is observed from Eq. (8) that $n_e$increases as the populationdensity and vegetation height increase, which is consisent withpreviousstudies(e.g.,LopezandGarcia2001;Wu2008).Forgiven

12 B_v p 2s

whereH$_v$5 erect vegetation stem height; and s 5 degree ofsubmergencedefinedass 5 h=H$_v$.Therefore,thevegetalfrictionfactorbecomesafunctionofsubmergenceinadditiontovegetationproperties.

Fixingallparametersbutthesubmergence,thevegetalfrictionfac-torincreaseswithswhens,1,andthendecreasesasthesubmergenceincreaseswhens.1,asshownbythesolidcurveinFig.2.

vegetationproperties,n$_e$wouldincreaseasthewaterdepthincreasesforemergentvegetation,whichhasbeenobservedinlaboratorystudies(e.g.,Wu2008).Whenthevegetationissubmergedandthewaterdepthissufficientlylarge(s 1),n$_e$approaches a constant.NotethattheequivalentManning'scoefficientinEq.(8)isnot

afunctionoftheflowvelocity,whichcontradictsthen-VRcurvesin previous studies of flexible vegetation (e.g., Wilson and Horritt2002; Carollo et al. 2005). This is because the derivation is based onrelationships for rigid cylinders. Rigid plants do not adjust them-selvestotheflowandresultindragcoefficientsindependentvarying velocities for large Reynolds numbers. When the plantflexibility is considered, $H^w$is expected to change with the velocity,whichisalsothecaseforn$_e$.Ithasbeendocumentedthateitherthebulkdragcoefficientortheequivalent Manning'scoefficientreducesastheflowvelocityincreases(Freemanetal.2000;Kouwen

2g $h^{1=3}$ 12 $H^w_v B_v$ h

andFathi-Maghadam 2000). The next section provides a detaileddiscussionondeformableplants.

ExtendedFormulationforDeformablePlants

Natural grasses are flexible and adjust themselves to a water flow.Fig.3 illustrates a flexible plant bent by the drag force and notesthe vegetation dimensions. Because of the inclination of stems, asthevegetationcanopyheightdecreasessodoesthefor mdragorthevegetative flow resistance (Kouwen and Li 1980; Tsujimoto et al.1996; Freeman et al. 2000). The vegetal resistance may reducefurther to skin friction as highly bent flexible vegetation becomesastreamlined,thinlayersimilartoasmoothpla tethatexertsaminimumformdragontheflow(LiandXi e2011).

A relationship between the deflected vegetation height and theflow drag exerted on vegetation elements is needed to iterativelydetermine the changing drag force and vegetation deformation. Thestudy on submerged flexible plants by Kouwen and Unny (1973) ex-pressedthedeflectedvegetationheightasafunctionofth eratioofa stiffness parameter to the vegetal shear stress. Kouwen and Li(1980) reanalyzed the experimental data in Kouwen and Unny(1973)andproposedthedeformationrelationass eeninEq.(9)

0:25 1:59 2 3

MEI= t

For given parameters of EI, H_v, N, and t_v, $H_s$can be determinedfrom one of the deformation relations defined by Eqs. (9)–(10).Uponknowingthedeformationrelationforaspecific

Hs ¼0:144 6 v

H_v H_v

where H_s5 deflected vegetation stem height; MEI 5 stiffness pa-rameter (EI) multiplied by the number of stems per square meter(M); t_v5 vegetal stress, also known as the stress exerted onvegetationelements;E5modulusofelasticity($N^x m^2$) ;andI 5secondmomentofthecrosssection(m^4).NotethatMis definedinthesamewayasthestempopulationdensity,N ,exceptthatMis

effects of deformable plants on hydrodynamics, the treatedasdimensionless.ThisequationiscappedbyHs=Hv 51

whentheplantrigidityissufficientlylargerthantheimp osingload.

SubstitutingH^wforH^winEq.(6)andtreatingemergenta nd

planttypeanda flow resistance law, one can determine the deflected vegetationheightandthereducedvegetativeflowresistan cesimultaneouslyby

solving the twoformulations iteratively.

A logarithmic formula of the flow resistance law was proposedby Kouwen and Unny (1973) and further examined by Kouwen andLi(1980)forsubmergedconditions.

$\frac{1}{f}$¼C_1log$\frac{h}{H_s}$þC_0 (11)

wheref5 friction factor including both the bed friction (f_b) and thevegetal friction (f_v); f fvif the bed friction is omitted; C_0 and $C_1$5 empirical coefficients that may be obtained from regression ofmeasurement data, which are dependent on vegetation propertiesandflowconditions.

Different coefficients were reported in previous studies (e.g.,KouwenandUnny1973;Carolloetal.2005).Carolloetal.(2005)proposedanotherflowresistanceformul ationwithmorefittingco-efficients involved under submerged conditions. To apply theseformulations, laboratory experiments are desired to determine co-efficientsforthetypeofvegetationthatistargetedinthefi eld.

It has been demonstrated by Kutija and Hong (1996) that for-mulasdevelopedforrigidvegetationcouldbeextended toflexibleones by using the cantilever theory. The cantilever beam is defined asapolewithoneendrigidlyfixedtoasupportandtheothere ndfreetomove.Itisusedtomimicthelessrigidvegetatio nstem.Thestem maybebentastheflowloadincreases;inreturn,theresistan cedueto

(9)

bending decreases. The balance position between the resistance andtheflowdragloadisachieveddynamicallyandtheso lutioncanbefounditeratively.Todemonstratetheproce dureandillustratethe formulationproposedinStoneandShen(2002)isadopted herebecauseitemploysless regression coefficients and it is valid for both submerged andemergent conditions. However, to apply the formulation, the wetvegetation height (H^w) needs to be replaced by the wet deflectedvegetationheight(H^w).Thedescriptorwetis mainlyusedfordis-criminatingbetweenemergentandsubmergedconditio ns;thus,H^w 5H_s forsubmergedconditionsandH^w5h s foremergentconditions.

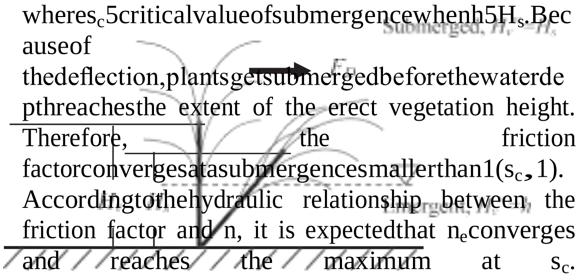
Usingadifferentapproach,Tsujimotoetal.(1996)applied finite s v deformationtheoryofacantileverbeamandsuggesteda similarrelationoftheplantdeformationasseeninEq.(10)

$\frac{H_s}{H_v}$ $\frac{NH^2EI}{}$ ¼1:020:89exp 24:66 $t_v H^4$ (10)

whereallsymbolsweredefinedinpreviousequations.

f_v¼

Fig.3.Sketchofflexibleplantfromerecttoprone
$H_v s$



wheres$_c$5criticalvalueofsubmergencewhenh5H$_s$.Becauseof thedeflection,plantsgetsubmergedbeforethewaterdepthreachesthe extent of the erect vegetation height. Therefore, the friction factorconvergesatasubmergencesmallerthan1(s$_c$,1). Accordingtothehydraulic relationship between the friction factor and n, it is expectedthat n$_e$converges and reaches the maximum at s$_c$. Experimentalstudieshaveshownthatempiricalformulationsofn$_e$ofdeformableshrubs and woody vegetation for emergent and submerged con-ditions converge when the water depth is 80% of the erect vegetationheight(Freemanetal.2000;Copeland2000). Taking Eq. (9) as an example of the deformation relation, thefrictionfactorandthedeflectedvegetationheightcanbesolved

submergedconditionsseparately,anewrelationshipof thefrictionfactorforflexibleplantsisexpressedas

f¼ s, $\frac{C_D NBH_v}{12B_v}$ emergentðs#sÞ (12a)

$\frac{HB \quad ^2 H_v \; C_D N B_v H_v \quad H_s^2 1}{12}$ s' submergedðs.s$_c$Þ(12b)

$s \quad v \quad N$

iteratively using Eqs. (9) and (12). A reduced friction factor is shownasthedashedcurveinFig.2.Thereductionbecomes negligiblewhenthedegreeofsubmergenceisfairlylarge.Foremergentconditions,thevalue of the friction factor overlaps with that of emergent rigid plantsbecause no deflection formulation for emergent plants is considered.NotethatbothEqs.(9)and(10)weredeformationrelationsderivedfor submerged, flexible vegetation. Fathi-Maghadam and Kouwen(1997) and Kouwen and Fathi-Maghadam (2000) studied the de-formationofcedartreesanddemonstratedthereductionofthefrictionfactorwithincreasingvelocity;however,noconvergencebetweenthedeflectionsofsubmergedplantsandemergentplantshasbeenfoundyet.Therefore,inthisstudy,onlythedeflectionofsubmergedveg-etationisconsideredandemergentvegetationisassumedtoactlikerigidplants.

NumericalImplementation

The resistance force induced by vegetation has been included inthe momentum equation as an extra term in many numerical studies(e.g.,LopezandGarcia 2001; Stoesseret al.2003;Li andYan2007).
Inthecurrentstudy,thebarotropic(horizontal2D)modeofan existingcoastaloceancirculationmodel,ECOMSED(HydroQual 2002),isadopted,andaseparatesubroutineisdevelopedtocalcu-latethevegetalshearstress.Thegoverningequationsofthedepth-integratedcontinuityequationandmomentumequationswiththeextratermofvegetationshearstressarewrittenas

$$\frac{\partial h}{\partial t} þ \frac{\partial v_x h}{\partial x} þ \frac{\partial v_y h}{\partial y} ¼ 0 \quad (13a)$$

$$\partial y \quad ¼ F_c v_y h 2gh \partial x þ F_{dif,x}$$

ofiterationsisusuallylessthan10.
TherequiredinputparametersforthevegetalshearstressmoduleincludeH_v,B_v,EI,N,andC_D,(orC_0,C_1iftheKL-extendedap-

only for submerged conditions. Therefore, during the transition fromthe submerged to emergent conditions, a linear interpolation isintroduced for the continuity of the formulation and completeness ofthe approach. The KL-extended approach is applied for s $
s_d(givensufficientsubmergence,e.g.,s_d51:5),whilethefrictionfactorats 5 $s_c$is computed using the SS-extended approach. In the transi-tionzone (s_c,s , 1:5), the frictionfactor isobtained by linearinterpolation.
Although different equations are implemented for deformableplants, the procedure of solving each set of equations is similar.Fig.4 illustrates the iteration process using Eqs. (9) and(11) þ whereEq.(1)andthedefinitionofthefrictionvelocity[V_p5t_v=$r^{0:5}$]areintroduced to rewrite those equations in terms of V_p and H_s, asEqs. (14a) and (14b). The deflected vegetation height and the frictionvelocityaresolvediteratively.

$$\frac{H}{H} ¼ 0:144 \left(\frac{MEI}{rV_s^2} \right)^{0:25\, 1:59} \quad (14a)$$

$$\frac{V}{V_p} ¼ C_1 \log \frac{H_s}{H_v} þ C_0 \quad (14b)$$

InFig.4,theintersectionofthetwocurvesisthesolution,whilethe circlesconnectedbythethin,straightlinesarequasi-solutionsatiterativestepsthatgraduallyapproachthefinal solution.Thenumber

∂ðvxhÞ ∂hvv
∂hv2 ∂x Þ
∂hvxvy ∂h
proachisused).ThevalueofC$_D$forasinglecylinderwithina narray
isused.Otherparametersaredeterminedbylaboratoryorfield

y yx ∂vh ∂t Þ
∂hv2
∂t Þ ∂x Þ
t0,x
Þr0
t0,y y ∂y ¼2FcVxh2gh ∂y ÞFdif,y
Þr0
2tb,x
r0
2tb,y
r0
2tv,x
r0
∂h
2tv,y
r0
(13b)

(13c)

measurements of the vegetation. The numerical model incorporatingthe vegetation module is tested against three laboratory measure-ments. Specific boundary conditions are given in accordance withthelaboratoryexperimentalsetup.
ModelTesting

wheret5time;h5watersurfaceelevationabove thestillwaterdatum;$v_x$and v_y5 depth-averaged velocities in the x- and y-directions,respectively;h5totalwaterdepth;F_c5Coriolisforcecoefficient;g5 acceleration due to gravity; $F_{dif,x}$, and $F_{dif,y}$are the horizontaldiffusiontermsinthex-andy-directions,respectively;t_0,t_b,andt_v5 wind stress, bottom shear stress, and the vegetal shear stress,respectively;andtheirsubscriptsrepresentthecomponentsinthex-andy-directions.Thevegetalshearstressiscalculatedinaseparatemoduleusingthemethodologyandalgorithmdescribedintheprevioussection.Itisthenpassedtothemomentumequationsateachtimestepwherethevelocitycomponentsandsurfaceelevationaresolved.Threeapproachesareimplementedtoaccountforrigidplants,unyieldinglydeformableplants,andyieldinglydeformableplants.
InApproach1,Eq.(6)isutilizedtocalculate the frictionfactorforrigidplants.InApproach2,Eq.(12)extendedfromtheformulaforrigidvegetationandEq.(9),theplantdeformationrelationshipare employed for deformable plants with a certain degree of rigidity.Thisprocedureisvalidforawiderrangeofsubmergence,hereafterknownastheSS-extended(StoneandShenextended)approach.InApproach 3, Eq. (11) developed for highly flexible plants and theplantdeformationrelationshipofEq.(9)areemployedforflexibleplants, hereafter known as the KL-extended (Kouwen and Li ex-tended)approach.BecauseEq.(11)wasdevelopedfromexperi-
EmergentVegetation
TsujimotoandKitamura(1995)designedaflumethatimitatesacompoundchannelbycoveringthebedpartiallywithemergent

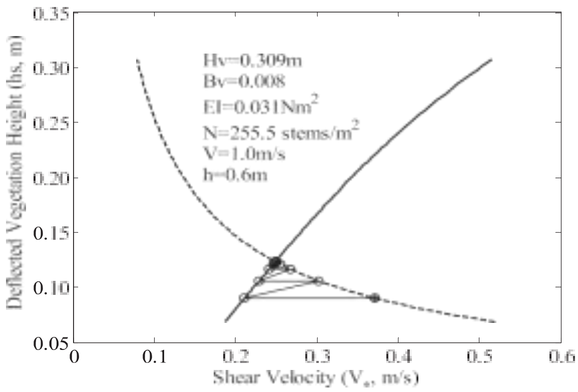
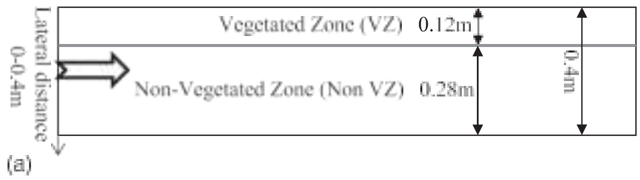


Fig.4.Iterativesolutionofshearvelocityanddeflectedvegetationheightforflexibleplants[dashedline,usingEq.(14a);th

icksolidline,
usingEq.(14b);thinlinewithcircles,iterationsteps]

mentsofsubmergedvegetation,theKL-extendedapproachisvalid cylindrical rods (bamboo, vinyl chloride, and nylon). Quasi-uniformflows over the channel were studied through five sets of experiments(A through E), among which there were three experimental data sets(A1, B1, and C1) presented in Tsujimoto and Kitamura (1995). Inthis study, only the data sets from experiments with bamboo areutilized, thatis,A1 andB1.Theflumewas12mlongand0.4mwidewith emergent bamboo covering a 0.12-m-wide vegetation zone(Fig. 5). Bamboo plants with a diameter of 0.15 cm were distributedinaparallelpatternandthespacingofvegetationelementswas 2.8cmforA1and2.0cmforB1.Forbothexperiments,themeanbedslopewas1:7310[23].Themeanchannel-averageflowvelocity,themean flow depth, and the friction factor in the main course weregiven as control parameters of the experiments. The cross-sectionaldepth-averagedvelocitywasmeasured40cmdownstreamusingaseriesofelectromagneticanemometers.Thestemdensityandthedrag coefficient (C_D) as two of the vegetation-property input pa-rameters are calculated according to the information provided inTsujimotoandKitamura(1995)andlistedinTable2. Approach 1 for rigid plants is used in this test. The drag co-efficient $C_D$input to the model is related to the bulk drag coeffi-cient(C_D)fortheemergentconditionusingEq.(5a),whe re$C_D$iscomputedusingthegivenvaluesofthefrictionco efficient(V5 1=2$C_D B_v$Nh) over the vegetation bank in Tsujimoto and Kitamura(1995).Thevalueofthefrictioncoefficient(C_f)forthemaincourseofthe channel was given in Tsujimoto and Kitamura (1995) and used tocalculatet$_b$5r$C_f V^2$. Themodeldomaincoverstheentireflumerangewithdx52: 5cm,dy5 2 cm, and dt5 0:005 s. It takes 218 s to reach a steady statewhen model results are output and compared with experimentaldata. The bottom panel in Fig.5 shows good agreement betweenthe modeled and experimental results. The numerical model showsthatthebamboofieldconsiderablyreducestheflowvelocityinthevegetationzone,consistentwiththemeasurements.Theslight



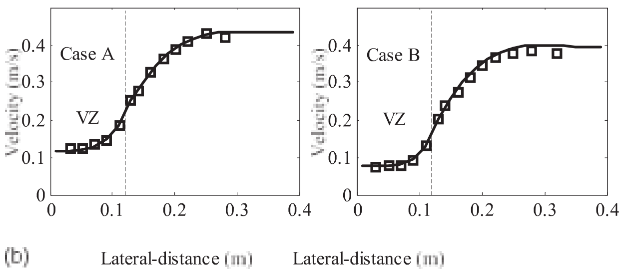


Fig.5.(a) Plan view of the experiment setup adapted from TsujimotoandKitamura(1995);(b)comparisonofmeasured(squares)andmodeled(solidlines)depth-averagedvelocities

overestimate of velocity in the main course of the channel is causedby the lack of wall friction in the numerical model. In the veg-etation zone, the agreement is better as the effect of the wallfriction is negligible compared with the flow resistance due to thebamboo.

SubmergedRigidVegetation

Lopez and Garcia (1997) conducted a series of laboratory experi-ments under uniform flow conditions in a 19.5-m-long, 0.91-m-wide, and 0.61-m-deep tilting flume. The first approach for rigidvegetation implemented in the storm surge model is applied andtested against the experiments with submerged rigid cylinders (#1through #12). Table 3 lists the experimental conditions and modelresults. The drag coefficient, C_D, is set to 1.05 according to

StoneandShen(2002).Thestemdensity,N,iscompute dusingthestemdiameter (B_v5 0:64 cm) and the plant population density (a 5 N3B_v)providedinLopezandGarcia(1997).Anaverage valueofbedfrictioncoefficientisestimatedfollowingt heprocedureintroducedin Stone and Shen (2002) (see Appendix) because no bottom frictionparameters were provided in Lopez and Garcia (1997). The openchannel flow is modeled using a grid with resolution of dx 5 20cmanddy515cm. Thetime stepisset todt50:001sand the steadystateisreachedafter73s. Themodelresultsagreewellwiththelaboratorymeasur ements.

The square of correlation coefficient (R^2) for the average depth,depth-averaged velocity and average surface slope against labora-tory measurements are 0.994, 0.995, and 0.995, respectively, asshowninTable3.TheRMSerrorforeachoutputpara meterisalsolistedinTable3.

SubmergedFlexibleVegetation

Flow resistance of a deformable vegetation field is different fromthat of rigid plants, as the deformable plants are bent by the dragforce of the flow. In return, the bent plants reduce the vegetation-induced resistance to the flow. A dynamic balance exists betweenthe deflected vegetation and the flow. Järvelä (2005) conductedflumestudiesandprovidedadatasetofmean velocityofflowoverflexible vegetation. The flume was 50 m long and 1.1 m wide.Naturalwheat(H_v50:28mandB_v50:28cm)waspl antedintheflumewithanaveragedensityof12,000 stems=m^2andcovereda 6-m-wide zone in the middle of the flume. An adjustable overflowweir was used to achieve desired water depth. Four flow depths wereused and total nine tests were carried out with three discharges. Thedeformation relation, Eq. (9), was adopted to calculate the flexibility,MEI5 1:2N$\cdot$$m^2$.Fordetailedinformationabo utthelaboratory experiment,thereaderisreferredtoJärvelä(2005). ByapplyingtheKL-extendedapproachthatsolvesEqs.(9)and (11) iteratively, the vegetal stress and the deflected vegetation heightwere obtained. Note that two coefficients (C_0 and C_1) are requiredby this method in the logarithmic formulation of a flow resistancelaw, which need to be calibrated for the different types of vegeta-tion(KouwenandLi1980;Kouwen1992;Carolloetal.2 005).

Table2.InputParametersforNumericalSimulationswithEmergentVegetation

	Flowdepth (cm)	Crosssection averagevelocity(cm/s)	Channel frictioncoefficient(310^{2} ^{3})	Elementsspacing(m)	Stem density(number =m^2)	Vegetation bankfriction coefficient	Characteristicdrag coefficient
Tests	h	V	C_f	d	N	V	C_D
CaseA	4.57	32.0	3.8	0.028	1,275.5	0.050	1.054
CaseB	4.28	27.6	4.0	0.020	2,500.0	0.116	1.239

Laboratory or field experiments are desirable for determining thevegetationspecificcoefficientsofC_0andC_1. Inthenumericalsimulation,C_0(0.494)andC_1(7.315)w ere predetermined by fitting the experimental data to the logarithmicformula, Eq. (11), with $R^2$5 0:92. The numerical model was setupaccording to the laboratory conditions and the downstream watersurface level is adjusted to achieve the measured flow depths withRMSerror55:9310^{25}m.Allsimulationsusethesa memeshwithdx520cm,dy522cm,andrunwithdt50:0 1s.Slightlydifferenttime spans are required to reach the steady state for various cases,ranging from 548 to 903 s. Table 4 lists the laboratory data (dis-charge,flowdepth,watersurfaceslope,anddeflectedpl antheight)and model results. Good agreement is seen for cases of large relativesubmergence,whereasunderestimationofthes urfaceslopeoccursforcasesofsmallrelativesubmerge nce(#1and#2).Thissuggeststhat the KL-extended method is valid for a large submergence butgiveslargeerrorfornear-emergentcases. TheSS-extendedmethodisnotappliedtothistestcasebecause nodragcoefficientwasprovidedinJärvelä(2005)andth e$C_D$of 1.05 used previously may not be applicable for the experimentalmaterial (wheat seedlings) of a fairly flexible form, and further-more, the experimental plants field of a fairly large stem density,N512,000=m^2.

II. SUMMARY AND CONCLUSIONS

The paper has extended and unified resistance formulations for rigid,flexural rigid, and flexible plants under both emergent and sub-

mergedconditions.Threeapproacheswereexaminedi ndetailandimplementedintoa stormsurge model.
First,theflowresistanceformulationsforrigidplantswe recrit-ically reviewed. By introducing the plant deformation relations, theformulation for rigid plants developed by Stone and Shen (2002)was extended to flexural rigid (or unyieldingly flexible) plants,namely the SS-extended approach, in which the deflected vegetationheight substitutes the erect height of rigid vegetation. Both the rigidformulation and the SS-extended approach are valid continuouslyfor a wide range of submergence from emergent to submergedconditions. The formula for rigid plants was tested against laboratorymeasurements while the SS-extended approach was only checkedanalyticallyowingtothelackofobservationda taforunyieldinglyflexible plants. As the plant stiffness parameter becomes sufficientlylarge,thesolutionconvergestothatoftherigidf ormula.InFig.2,thefrictionfactorfordeformableplants (dashedline)predictedbytheSS-extended will shift upward and approach the solution of rigidplants(solidline)forlargeplantrigidity.
Another flow resistance formulation directly derived from sub-merged,yieldinglyflexibleplantsbyKouwenandLi(1980)was

Table3.LaboratoryMeasurementsandNumericalModelResultsofUniformOpen-ChannelFlowoverRigidPlants

number	(a, m^{2} ^{1})	h(m)	Q(m^3=s)	V(m=s)	Averagedsurfaceslope	h(m)	V(m=s)	Averagedsurfaceslope
1	1.09	0.335	0.179	0.587	0.0036	0.334	0.589	0.0035
2	1.09	0.229	0.088	0.422	0.0036	0.230	0.421	0.0036
3	1.09	0.164	0.046	0.308	0.0036	0.165	0.306	0.0037
4	1.09	0.276	0.178	0.709	0.0076	0.274	0.715	0.0075
5	1.09	0.203	0.098	0.531	0.0076	0.202	0.534	0.0075
6	0.27	0.267	0.178	0.733	0.0036	0.262	0.746	0.0032
7	0.27	0.183	0.095	0.570	0.0036	0.182	0.575	0.0035
8	2.46	0.391	0.180	0.506	0.0036	0.393	0.503	0.0038
9	2.46	0.214	0.058	0.298	0.0036	0.220	0.289	0.0041
10	2.46	0.265	0.180	0.746	0.0160	0.273	0.723	0.0163
11	0.62	0.311	0.177	0.625	0.0036	0.305	0.638	0.0031
12	0.62	0.233	0.181	0.854	0.0110	0.223	0.894	0.0107
					R^2	0.994	0.995	0.995
					RMSerror	0.0050	0.0149	0.00027
					Percenterror	1.95%	2.60%	4.56%

Experiment

Plantdensity
Experimentalconditions Modelresults

Table4.Model Setupand Model Results

	Experimentalconditions				Modelresults	
Experiment number	Discharge(m^3=s)	Depth(m)	Surfaceslope(%)	Deflectedvegetationheight(m)	Surfaceslope(%)	Deflectedvegetationheight(m)
1	0.040	0.3060	0.15	0.205	0.12	0.191
2	0.100	0.3084	0.36	0.155	0.32	0.132

3	0.040	0.4065	0.05	0.230	0.05	0.248
4	0.100	0.4041	0.13	0.190	0.13	0.169
5	0.143	0.4070	0.20	0.160	0.19	0.145
6	0.040	0.5044	0.02	0.245	0.02	0.280
7	0.100	0.4950	0.06	0.220	0.06	0.204
8	0.100	0.7065	0.02	0.260	0.02	0.279
9	0.143	0.7037	0.03	0.215	0.03	0.235
				R^2	0.993	0.937
RMSerror					0.017	0.0210
Percenterror					15.00%	10.05%

alsoexaminedandextended,namely,theKL-extendedapproach.Thisapproachessentiallycoversonlysubmergedconditions.How-ever,toavoiddiscontinuityandnumericalinstability,nearemergent

• Step 7.Convert$f_b$to the bed friction coefficient $C_f$as in thequadraticlaw(t5r$C_f V^2$)byinvokingEqs.(16)and(17)

tofullysubmergedconditionswereconsideredusingthelinearinterpolationinthetransitionzone.Thedegreeoffullsubmergence (s_d)isrecommendedtobe1.5accordingtoNepfandVivoni(2000), C_f¼ f_bð12Iþ 2ð12Ihpþ

12B^{P}N ^{2}

pïïï$_2$ (18)

above which a logarithmic nonvegetation flow starts developingbeyond the mixing layer. Both the KL-extended and SS-extendedapproaches solve a set of two equations, that is, a deformation re-lation and a resistance law, iteratively, in a similar fashion. The threeapproaches have been implemented into a storm surge model as threeoptions. Good agreement with laboratory measurements has beenfound for the approach of rigid plants and the KL-extended ap-proach.TheSS-extendedapproachanalyticallytestedispromisingbecause it accounts for both the flexibility of natural plants and a fullrangeofsubmergence.However,furthertestsagainstobservationsaredesirableforfutureresearch.

Insummary,thisstudyhasdevelopedaphysics-basedproceduretoincorporatetheeffectsofdeformablevegetationintoanumericalstorm surge model and unified formulations for emergent, near-emergent,andfullysubmergedrigidorflexiblevegetation.Asub-modelofvegetalstressanddeflectedvegetationheightwas developedand tested against laboratory experiments. To improve the predictionofsurgereductionbywetlandvegetation,quantifyingthespatialand temporal variations of deflected vegetation heights and equivalentManning'scoefficientunderrealisticfieldconditionsisofsignificanceandwillbediscussedinanupcomingpaper.

Appendix.EstimateofBedFrictionCoefficient

The flow depth, depth-averaged velocity, and bed slope are availablein the experimental data sets. The bed friction factor is estimated byusingthe method providedinStone andShen(2002).

• Step1.Initiatethechannelbedfrictionfactorf_b .

• Step2.Calculate$C_v$using

Theaverage valueof$C_f$isestimatedtobe0.0072 ïïïï

hp

12$B_v$hp N

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