Lodging Velocity for an Emergent Aquatic Plant in Open Channels

Jennifer G. Duan[1]; Brian Barkdoll[2]; and Richard French[3]

Abstract: Vegetation can impede flow in open channels. The control of vegetation by hydraulic means is a nonchemical approach that can be attractive. To control the vegetation, the calculation of the lodging velocity (velocity at which the plant stem breaks) is an important parameter. A theoretical method is developed here for a single stem fully exposed to the flow, assuming that the drag force is the sole failure-inducing force. Results are compared to field results and the trends analyzed. The comparison and field visual observations may indicate that vortex shedding (not accounted for in the model) could be the dominant failure-inducing force, and not the drag force, as assumed.

Introduction

The encroachment of vegetation (*Scirpus acutus*, or tule, for example) is a severe water resources management problem in unlined canals, streams, and rivers in western America. For example, within the Owens Valley, Calif., tule has occluded much of the Lower Owens River channel where flow has been diverted since 1912 to supply the city of Los Angeles. In the portion of the Owens River above the diversion to the Los Angeles Aqueduct, tule is also encroaching into the channel and adversely impacting the hydraulic efficiency and the recreational value of the river. Wade (1990) reviewed physical control techniques, and concluded that physical removal of tule will temporarily establish a channel free of obstruction. Unfortunately, the scale of most western water supply and irrigation systems precludes the use of such treatment in all but special habitats of limited extent. Further, the treatment only results in a temporary improvement and will have to be periodically repeated. Chemical control of aquatic plants (Murphy and Barrett 1990) is often not acceptable if the end use of the water is human consumption or irrigation of crops for human consumption. Aquatic vegetation can also be controlled by physical factors through (1) reduction of photosynthesis in flowing water (Westlake 1967; Madsen and Sondergaard 1983); (2) reduction of photosynthesis or plant respiration with depth (Lieffers and Shay 1981; McKee and Mendelssohn 1989; Van

Vierrsen 1990); and (3) physical removal or constraint in high-energy environments such as zones of high wave exposure (Keddy 1982; Coops et al. 1991) or channels with sufficient velocity (Madsen and Warncke 1983; Nilsson 1987; Chambers et al. 1991; Groeneveld and French 1995).

Hydrodynamic control of emerging aquatic plants has the advantages of minimizing capital and annual costs and being environmentally neutral. Hydraulic engineers have traditionally viewed and analyzed aquatic vegetation as a roughness component (Kouwen and Unny 1973; Kouwen and Li 1980; Masterman and Thorne 1992; Fischenich 1996; Flippin-Dudley et al. 1997) that affects hydraulic efficiency. Literature that examines the control of emergent aquatic vegetation by manipulating the water resources system is very limited. Duan et al. (2002) derived an analytical equation to calculate the critical lodging velocity based on the assumption of the small linear elastic deflection of aquatic plants. However, because the deflection of aquatic plants under high-speed flow is nonlinear, this paper derives a set of differential equations for the analysis of the lodging velocity of aquatic plants.

This issue of lodging velocity differs from most previous studies in that it does not focus on velocity structure (Carollo et al. 2002; Velasco et al. 2003; Wilson et al. 2003; Ohmoto et al. 2002) or roughness (Kirby et al. 2005; Stone and Shen 2002; Velasco et al. 2003; James et al. 2004; Righetti and Armanini 2002; Kouwen 1992; Niklas and O'Rourke 1987; Wu et al. 1999), but rather on the hydraulic conditions necessary to induce plant stem failure. One previous study exists (Duan et al. 2002) that also develops a theoretical model for lodging velocity, but assumes linear elastic plant stem behavior rather than nonlinear behavior as in the present study.

In this paper, the lodging flow condition, the flow required to bend and rupture the stem, was analyzed by relaxing the linear elastic assumption. In an attempt to verify the model results with field conditions, the model results were compared with the field results of Groeneveld and French (1995).

[1]Assistant Professor, Division of Civil Engineering and Engineering Mechanics, Univ. of Arizona, Tucson, AZ 85721.

[2]Associate Professor, Dept. of Civil and Environmental Engineering, Michigan Tech Univ., Houghton, MI 49931.

[3]Professor, Dept. of Civil and Environmental Engineering, Univ. of Texas at San Antonio, San Antonio, TX 89119.

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Tule Plant Physiology

Tule (genus *Scirpus*) is a common species existing in the waters of the western United States. This study analyzes tule, but there is nothing in the analysis that precludes the use of the proposed model from use on other plant stems as well. Tule is a colonial species and has numerous stems that originate from interconnected, buried horizontal stems, or rhizomes. The emergent and buried organs are interdependent. Tule colonies survive the winter as rhizomes, which are buried in bottom sediments that are extremely low in oxygen. Stems transit between the buried rhizome and the atmosphere and serve as snorkels to provide for rapid downward diffusion of oxygen through intercellular air-filled spaces. It has been hypothesized (Darcey 1980; Raskin and Kende 1985) that as rhizomes respire, the resultant, highly soluble CO_2 dissolves into the water and saturates the sediments that jacket the rhizome and roots. This process creates a negative pressure in the rhizome that draws air downward to oxygenate the tissues.

To maintain colonial growth and expansion, the metabolic energy for producing and maintaining leaves requires a return in the form of carbohydrates produced through photosynthesis. The stems transport carbohydrates from the leaves for rhizome maintenance, growth, and storage to reinitiate stem growth after the winter dormancy.

Tule stems are round cylinders that taper upward from their point of attachment. The center of a tule stem is mostly air space within a matrix of longitudinally running elongated fibers. Discontinuous transverse fibers connect these longitudinal fibers and impart resistance to bending deformation. The tule stem structure is optimized for a minimum of material to provide for maximum upright structural support, transmission of air to the rhizome, and photosynthesis (McMahon and Kronauer 1976). Although the round cross section of tule stems provides considerable resistance to deformation in flowing water, sufficient velocity and depth will cause the stem to bend and rupture. This deformation, called lodging, is permanent. Once lodged, tule stems no longer provide support for the rhizome. Because the loss of each stem represents a concomitant loss of carbohydrate resources, lodging constrains rhizome vigor and expansion and may lead to the death of the plant.

Theoretical Analysis

Tule is a composite material whose properties, like any other structural material, vary among samples and species (Kouwen and Li 1980). The cross-section geometry of the plant influences rigidity and the bending mechanism (Niklas and O'Rourke 1982; Niklas and Moon 1988). In the following analysis, tule is assumed to be a composite elastic material that bends or breaks under stress. According to classical mechanics of materials theory, the maximum bending moment and shear stress is located at the bottom of the tule stem, assuming the stem acts as a cantilever element attached at the base but without support elsewhere and having a load applied above the base. If it is assumed that the cross section does not vary vertically, lodging of a tule stem is expected to occur at the bottom where the maximum bending moment and shear stress occur.

The most widely accepted criteria of elastic failure (Roark and Young 1975) are (1) the maximum normal stress theory, which states that elastic failure occurs when the maximum normal stress at any point reaches the axial failure stress, σ_u; and (2) the maxi-
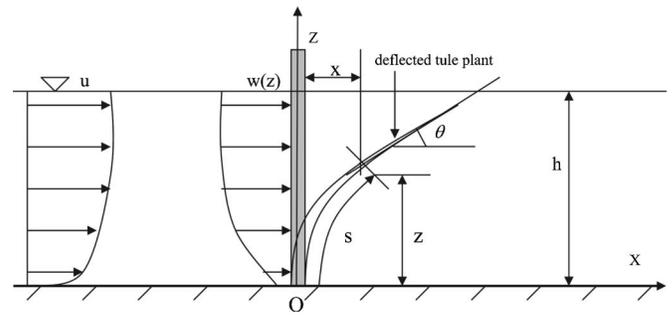

Fig. 1. Schematic and free-body diagrams of a plant stem

mum shear stress theory, which predicts failure of a specimen when the maximum shear stress at any point reaches the failure stress, σ_{max}, which equals $(1/2)\sigma_u$. Since shear stress failure was not observed in preliminary lodging experiments (Groeneveld and French 1995), it is assumed that tensile flexural stress dominates. It is also assumed that, in the case of emergent aquatic plants, the primary load acting on the plant stems is the flow-induced drag force and not oscillations due to vortex shedding. The relevance of this assumption will be discussed later.

The vertical velocity profile in a gradually varied open channel flow is assumed to satisfy the power law adopted in Odgaard (1989)

$$\frac{u}{\bar{u}} = \frac{m+1}{m}\left(\frac{z}{h}\right)^{1/m} \tag{1}$$

where $\bar{u}$=depth-averaged velocity; h=depth of flow; z=vertical distance from the bed; m=roughness factor, whose relationship to the shear velocity u, the Darcy–Weisbach friction factor f, and the Chezy coefficient c is $m=\kappa\bar{u}/u_*=\kappa\sqrt{8/f}=\kappa c/\sqrt{g}$; and κ=von-Karman constant. This equation can handle uniformly and logarithmically varying vertical velocity distributions depending on the coefficient, m. Assuming a single stem fully exposed to the flow and no other stems around it to alter the vertical velocity profile, the drag force acting on a single stem is

$$F_D = \tfrac{1}{2}\rho u(z)^2 C_D A \tag{2}$$

where F_D=turbulent fluid drag force on the submerged portion of the stem; C_D=drag coefficient; ρ=density of water; and A=area of the submerged stem projected perpendicular to the flow. The governing differential equations for the deflection of structural members, such as the cantilever beam (Fig. 1) are written as

$$\frac{d\theta}{ds} = \frac{M}{EI} \tag{3}$$

$$\frac{dz}{ds} = \cos\theta \tag{4}$$

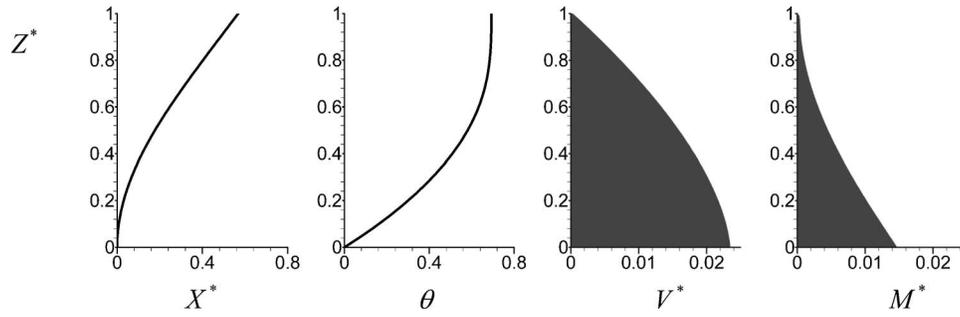$$\frac{dx}{ds} = \sin\theta \tag{5}$$

$$\frac{dM}{ds} = V\cos\theta \tag{6}$$

Fig. 2. Bending curve, rotation angle, shear, and bending moment of plant stem ($EI=15.94$ N cm^2, $u=0.3$ m/s, $D=0.0119$ m, $H=0.81$, $m=3.156$, and $C_D=1.2$)

$$\frac{dV}{ds} = w(z)\cos\theta \qquad (7)$$

where θ=angle of rotation of the deflection curve; s=distance along the curve; M=moment at a section; I=moment of inertia; E=modulus of elasticity; V=shear force acting on a section of the stem; $w(z)$=loading force induced by flow; and x and z represent the horizontal and vertical distances between any section and the bottom of this plant.

As the deflection of a tule plant could be substantial when it is about to rupture due to flow-induced drag force, the small deflection assumption (i.e., $\tan\theta \approx \theta$) cannot be used. Therefore, Eqs. (3)–(7) should be solved simultaneously to obtain the shear stress and moment distribution. As the solution is for the submerged portion of the plant stem ranging from $z^*=0$ to $z^*=1.0$, where $z^*=z/h$, the governing equations were transformed with respect to the dimensionless vertical coordinate rather than the dimensionless plant length to easily apply the boundary conditions. The dimensionless forms of Eqs. (3)–(7) can be obtained through mathematical manipulation and are as follows:

$$\frac{d\theta}{dz^*} = \frac{M^*}{E^*I^*}\frac{1}{\cos\theta} \qquad (8)$$

$$\frac{ds^*}{dz^*} = \frac{1}{\cos\theta} \qquad (9)$$

$$\frac{dx^*}{dz^*} = \tan\theta \qquad (10)$$

$$\frac{dM^*}{dz^*} = V^* \qquad (11)$$

$$\frac{dV^*}{dz^*} = w(z^*) \qquad (12)$$

where $x^*=x/h$; $z^*=z/h$; $s^*=s/h$; $V^*=V/(1/2)\rho h^2\bar{u}^2$; $M^*=M/(1/2)\rho h^3\bar{u}^2$; and $E^*I^*=EI/(1/2)\rho h^4\bar{u}^2$.

The dimensionless horizontal loading forces are obtained as follows by substituting Eq. (1) into Eq. (2), and divided by $(1/2)\rho\bar{u}^2h^2$

$$w(z) = \frac{dV^*}{ds^*\cos\theta} = C_D\frac{D}{h}\left(\frac{m+1}{m}\right)^2\left(\frac{z}{h}\right)^{2/m} \qquad (13)$$

where D=mean diameter of the tule stem. Substituting the dimensionless horizontal loading force Eq. (13) into Eq. (12) results in

$$\frac{dV^*}{dz^*} = C_D\frac{D}{h}\left(\frac{m+1}{m}\right)^2(z^*)^{2/m} \qquad (14)$$

Therefore, Eqs. (8)–(12) are the governing equations for the solution of the deflection curve, shear stress, and bending moment for tule plants. Five boundary conditions are required to solve these equations. The bottom of a tule plant is fixed and has negligible rotation, which indicates $x^*=0$, $z^*=0$, and $\theta=0$ at $s^*=0$. The bending momentum should be zero at the top of the tule plant, that is, $M=0$ and $V=0$ at $z^*=y_n/h$, in which y_n=length of the plant. For emergent aquatic plants there is no fluid drag force acting on the plant stem above the water surface. Only the submerged section with $0\leqslant z^*\leqslant 1.0$ experiences turbulent drag force, and thus the other two boundary conditions are $M=0$ and $V=0$ when $z^*\geqslant 1.0$.

Additionally it is assumed that the aquatic plants remain emergent when they are bent so that the vertical coordinate of the deflection curve at the water surface where $z^*=1(z=h)$ always equals unity. It should be pointed out that this may not always be the case, i.e., when a plant is strongly deflected, it can be submerged. The submergence assumption is a limitation, therefore, to the present model. Shear stress and bending moment at the bottom of the plant are calculated according to Eqs. (11) and (14). From the static equilibrium equation, $\Sigma F_x=0$, the dimensionless shear force at the bottom section is obtained as follows:

$$V_0^* = C_D\frac{D}{h}\frac{(m+1)^2}{m(2+m)} \qquad (15)$$

From the static equilibrium equation, $\Sigma M_0=0$, the dimensionless bending moment at the bottom section is written as

$$M_0^* = \frac{1}{2}C_D\frac{D}{h}\frac{m+1}{m} \qquad (16)$$

where V_0^* and M_0^*=dimensionless shear stress and bending moment at the bottom section, respectively. The solutions of Eqs. (8)–(12) can then be obtained for the deflection angle θ, x coordinate, length h of the deflection beam, shear stress, and bending momentum, all at any vertical location, z. The solutions of shear stress and bending momentum are (Fig. 2)

$$V_z^* = V_0^* - \frac{m}{m+2}C_D\frac{D}{h}\left(\frac{m+1}{m}\right)^2(z^*)^{1+2/m}, \quad M_z^* = M_0^* - V_z^*z^* \quad (17)$$

In addition, the maximum tensile flexural stress at a cross section is

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$$\sigma_{\max} = \frac{MC}{I} \tag{18}$$

where $\sigma_{\max}$=maximum tensile flexural stress at any cross section; I=second moment of the area of the cross section; and C=distance between the edge of the cross section and the neutral axis. For a circular cross section, $I=(\pi/64)D^4$, and $C=D/2$, then $I/C=(\pi/32)D^3$. Substituting Eq. (16) into Eq. (18), then, the maximum flexural tensile stress becomes

$$\sigma_{\max} = \frac{8\rho C_D}{\pi}\frac{h^2\bar{u}^2}{D^2}\left(\frac{m+1}{m}\right) \tag{19}$$

When the maximum flexural tensile stress becomes equal to or greater than the axial failure stress, which is $\sigma_{\max} \geq \sigma_u$, the tule plant will lodge. The flow condition for the lodging of aquatic plants can be derived from Eq. (19)

$$\frac{h\bar{u}}{D} = \sqrt{\frac{\pi}{8\rho C_D}\frac{m}{m+1}\sigma_u} \tag{20}$$

Substituting $\pi=3.14$ and $\rho=1000.0\,\text{kg/m}^3$ into Eq. (20), the following is obtained:

$$\frac{h\bar{u}}{D} = 0.0198\sqrt{\frac{1}{C_D}\frac{m}{m+1}\delta_u} \tag{21}$$

Eq. (20) indicates that the lodging flow for emergent aquatic plants is a function of plant diameter, flow roughness, and the axial failure stress.

Model Comparison with Field Data

Growing and testing aquatic plants in the laboratory is difficult. Most studies use wooden dowels (Bennet et al. 2002) which will not bend or lodge at all, thereby negating their utility in verification of the present model.

The only available data set for the lodging of aquatic plants is a field experiment conducted on the Owens River in California (Groeneveld and French (1995). The field study investigated lodging of tule stems during the middle of the growing season (mid-July) in 1994 during several days of steady flow. Tule plant stems were both observed in a group of plants during a reconnaissance study and also placed in a holder with flexible shims to provide a tight fit and to reduce any effects of sharp holder boundary on the plant stem during an induced-lodging study. The holder, with plant inserted, was then place in flowing water and the failure conditions noted. The plant was placed alone and not in a group of plants. It was noted that failure occurred at the bottom of the plant stem, as assumed in the theoretical model presented earlier. Just prior to failure an intense vibration of the stem was noted, however. Bending stresses from measured velocity profiles, flow depths, and surface slopes when bending occurred were determined based on assumptions of drag-induced forces, failure at stem base, linear elastic material behavior, and linearly varying stem diameter. Measurements were taken in both uniformly and logarithmically varying vertical velocity distribution flow regions and samples taken from both types of velocity distribution statistically deemed to come from the same sample. The conclusions were as follows. For no lodging of any stems, the base bending stress must be less than 241,000 N/m². For complete lodging of all stems, the base bending stress must be at least 842,000 N/m². These measurements, result in an overlap region such that for $241,000 < S_c < 842,000\,\text{N/m}^2$, partial lodging oc-

curred and S_c=critical bending stress at the point of attachment resulting in lodging. From these data and results, and assuming a logarithmic velocity profile, Groeneveld and French (1995) concluded that when $\bar{u}h/D > 12.8$, 95% of the emerging tule stems were lodged. The flow depth was equal to 0.81 m, the average base diameter was 0.012 m, and the average drag force was 1.36 N.

To compare model results with these field results some additional calculations are necessary and are presented next. Under the condition of emerged plants, the length of the submerged portion projected perpendicular to the flow is equal to the flow depth. Therefore, the average shear stress can be calculated as

$$\tau_0 = \frac{F_D}{A} = \frac{F_D}{Dh} = \frac{0.36}{0.012 \times 0.81} = 140\,\text{N/m}^2 \tag{22}$$

The equivalent roughness height in grass channels is calculated as (Kouwen 1988)

$$k_s = 0.14y_n\left[\frac{\left(\frac{NEI}{\tau_0}\right)^{0.25}}{y_n}\right]^{1.59} \tag{23}$$

where τ_0=shear stress exerted on the tule plant and y_n=length of the tule plant. According to Kouwen (1988), EI is the flexural rigidity in bending, in which E=modulus of elasticity and I=second moment of the cross-sectional area; N=density of plants, and its influence on flow resistance is similar to that of plant diameter (Temple 1982). The value of NEI is calculated empirically as follows:

$$NEI = 319y_n^{3.3} = 160\,\text{N m}^2 \tag{24}$$

Substituting the values of τ_0, NEI, and y_n into Eq. (24) results in k_s=0.020 m.

Also, the relation of Darcy's coefficient to roughness height is

$$\frac{1}{\sqrt{f}} = a + b\log\left(\frac{h}{k_s}\right) \tag{25}$$

If $a=0.290$ and $b=3.50$ (Kouwen 1988) are used in Eq. (25), then $f=0.029$; and the roughness factor is given by $m=\kappa\sqrt{8/f}=6.82$.

C_D, the remaining parameter that is undefined in Eq. (21), is the drag coefficient for the flow around a circular cylinder and ranges from 0.25 to 1.5 depending on the flow Reynolds number. The flow Reynolds number was over 100,000 during the field study. The value of C_D was taken as 1.2 in the field experiment when Reynolds number $\bar{u}h/v=4.46\times10^5$ (Groeneveld and French 1995). Base stem diameters ranged in the field study from 7.1 to 30.5 mm. Tule plants started to lodge at a shear stress of 241,000 N/m², and when shear stress reached 842,000 N/m², all stems were lodged. In addition, when 95% of the tule plants were lodged, $\bar{u}h/D=12.8$, which was obtained by assuming a log-normal distribution of bending stresses and from their Eq. (7), repeated here as: $\bar{u}h/D=(S_c/6,088)^{1/2}$.

Provided that the axial failure stress is defined as the axial stress at which tule plants begin to fail, the critical lodging flow condition can be obtained by substituting σ_u values into Eq. (21). Fig. 3 shows $\bar{u}h/D$ values for a wide range of σ_u values for both the field method of Groeneveld and French (1995) and the present model. It can be seen that the present model always overpredicts the $\bar{u}h/D$ value by about 32%. This result suggests that nonlinear material behavior results in higher values of $\bar{u}h/D$ required for lodging, which is perhaps due to the ability of the flexible plant stems to endure more stress than rigid, linear-elastic elements.
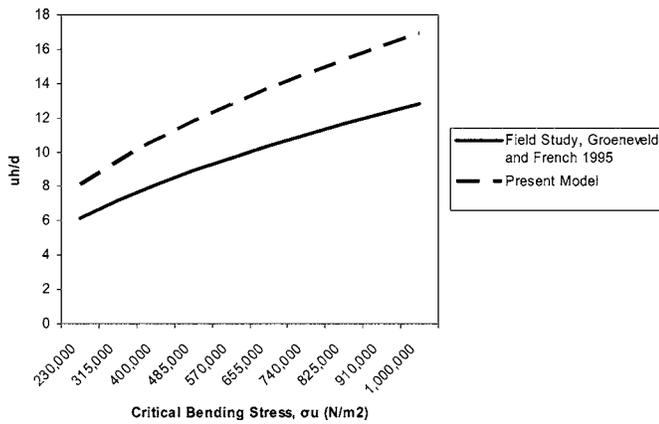
Fig. 3. Comparison of present model with field study of Groeneveld and French (1995)

In the field experiments it was noticed that the stems vibrated before failure. This observation may suggest a failure mode induced by vortex shedding. Therefore, the current model could overpredict $\bar{u}h/D$ values for lodging and that vortex shedding may be a primary failure mode. Future work on vortex-shedding-induced failure of flexible, emergent plant stems would be valuable.

Conclusions

A theoretical model for plant stem lodging based on the assumptions of failure due to bending stress at stem base and nonlinear material behavior overpredicts the value of $\bar{u}h/D$ for initiation of lodging from that of linear elastic theory. This result is perhaps due to the stems' ability to bend and not fail. This model is general and can be used for a wide variety of conditions. However, a new model formulated on vortex-shedding-induced failure might provide better agreement with the field results of Groeneveld and French (1995). In addition, a detailed laboratory experiment investigating the effects of flow conditions on flexible, emergent vegetation in a group of stems is warranted for validation of models of this kind.

Notation

The following symbols are used in this paper:

A = area of the submerged stem projected perpendicular to the flow;
a,b = coefficients in Eq. (25);
C_D = drag coefficient;
c = Chezy coefficient;
D = diameter of tule plants at any section;
E = modulus of elasticity;
E^* = dimensionless modulus of elasticity;
F_D = turbulent fluid drag force;
f = Darcy–Weisbach friction factor;
f_m = a function of roughness;
f_u = a function for the calculation of a and b coefficients;
g = gravity acceleration;
h = flow depth;
I = second moment of the cross-sectional area;
I^* = dimensionless second moment of the cross-sectional area;
k_s = equivalent roughness height in grassed channels;
M = bending moment;
M^* = dimensionless bending moment;
m = roughness factor;
N = density of plant;
S_c = critical bending stress at the point of attachment resulting in lodging;
s = distance from a cross section of tule plant to the bottom;
s^* = dimensionless distance from a cross section of tule plant to the bottom;
t = subscript or superscript to identify time in numerical calculation;
u = flow velocity;
$\bar{u}$ = depth-averaged velocity;
u_* = shear velocity;
V = shear force;
V_0 = dimensionless shear force at the bottom section;
V^* = dimensionless shear force;
$w(z)$ = loading force induced by flow;
x = horizontal distance between any section and the bottom of this plant;
x^* = dimensionless horizontal distance between any section and the bottom of this plant;
y_n = length of plant;
z = vertical distance from the bed;
z^* = dimensionless vertical distance from the bed;
θ = angle of rotation of the deflection curve;
κ = von-Karman constant;
π = 3.14=constant;
ρ = density of water;
$\sigma_{\max}$ = maximum shear stress;
σ_u = axial failure stress; and
τ_0 = averaged shear stress.

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