age to water reticulation system from such events appears to be from pipe and connection breaks rather than structural failure of distribution reservoirs (as long as the reservoirs have been designed for lateral loading).

Most of the examples of storage tanks and distribution reservoirs impacted by the 1994 Northridge and 1995 Hyogo-ken Nanbu earthquakes appear to have been of steel construction rather than of reinforced concrete or prestressed concrete construction, which are predominant in New Zealand for water supply reservoirs. There appears to be a lack of evidence regarding the behavior of reinforced concrete and prestressed concrete reservoirs in large earthquake events. However, it is difficult to conceive that reservoirs of such construction could collapse catastrophically in an earthquake, particularly if they are designed for lateral loading (as they are in New Zealand). Concrete tanks are more likely to experience severe cracking (with the steel reinforcing or prestressing continuing to provide some residual structural integrity) or severed pipe connections. In the event of either scenario, the contents of the reservoir would tend to be released gradually over time rather than catastrophically.

For a large earthquake event, catastrophic failure of a water supply reservoir is, however, an appropriate failure scenario for ferro-cement tanks or wood stave tanks with wire rope wound round externally to provide circumferential strength. Similarly catastrophic failure is a realistic failure scenario for reservoirs of any type of construction where an earthquake-induced slope failure affects the platform on which the reservoir is sited.

In summary, before embarking on a detailed analysis of the dam break type flood event resulting from catastrophic collapse of a water supply reservoir, hazard assessments for such reservoirs need to consider the nature of reservoir construction, the potential extreme loading conditions on the reservoir, the behavior of the reservoir under those loading conditions, and potential failure scenarios.

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Closure by Christopher Zoppou[4] and Stephen Roberts[5]

The discussion suggests that a fundamental premise of the original paper is that water supply reservoirs, which form part of the water reticulation system for urban areas, could fail catastrophically. This is not the intention of the paper.

Although there is very little likelihood that a water supply reservoir would completely fail, ACTEW Corporation is acting as a responsible corporate citizen by ensuring that the assets it operates and owns do not endanger the public. The introduction of steel water supply reservoirs, replacing the prestressed reinforced concrete reservoirs, is one strategy for reducing the risk, albeit very small associated with the older concrete water supply reservoirs. Regular inspections of its assets further reduce the risk. The development of the model is another component of an asset management strategy.

A partial failure of a water supply reservoir due to a design fault has occurred in the Australian Capital Territory during its commissioning. Fortunately, it was in a greenfield development, posing no risk to property or life.

In the paper, the writers have demonstrated the model by simulating the complete failure of a water supply reservoir. The simulations of the complete collapse of a water supply reservoir represent a severe test for the model. We realize that this would not be the normal mode of failure, even during an earthquake event. The writers have developed a model that is capable of simulating rapidly varying flows in a variety of situations, including the catastrophic and partial collapse of a water supply reservoir. We have applied the model to a number of problems. The one reported in the paper involves the partial breach of a dam.

On a technical note, the writers do not solve the homogeneous but the nonhomogeneous two-dimensional shallow water wave equations.

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VARIATION OF ROUGHNESS COEFFICIENTS FOR UNSUBMERGED AND SUBMERGED VEGETATION[a]

Discussion by Vassilios A. Tsihrintzis,[4] Member, ASCE

The authors made commendable efforts to provide experimental data and explain phenomena of flow through vegetation, and particularly unsubmerged vegetation, which are not fully understood yet. The discusser presents additional experimental data from previous studies on unsubmerged vegetation in Fig. 10, a graph similar to the authors' Fig. 6. Fig. 10 uses data from the following studies: (1) Kadlec (1990), based on field data obtained from the Houghton Lake Wetland, for four different slopes, in the laminar and transitional state; (2) Chiew and Tan (1992), based on field data on a natural turfed slope of 14%, for two grass densities, in the transitional and turbulent state; (3) Hall and Freeman (1994), based on laboratory experiments with bulrush vegetation, for two vegetation densities (high 800 stems/m^2 and low 400 stems/m^2), in the turbulent state; (4) Fathi-Maghadam and Kouwen (1997), a laboratory study on emergent flexible vegetation, where pine and cedar tree samples, having stems and canopy, were used (transitional and turbulent state); and (5) Turner and Chanmeesri (1984), a laboratory study of shallow flow through emergent wheat crops in the transitional and turbulent state. Data provided by these studies were extracted and manipulated to produce drag coefficient C'_D versus Reynolds number R values. Fig. 10 is more comprehensive than Fig. 6 in terms of various vegetation types and covers a wider range of Reynolds numbers and drag coefficients.

In all studies considered, C'_D values are shown to decrease with increasing R. Similarly to the authors' conclusion, $C'_D \propto \mathsf{R}^{-k}$. Values for exponent k have been computed by fitting

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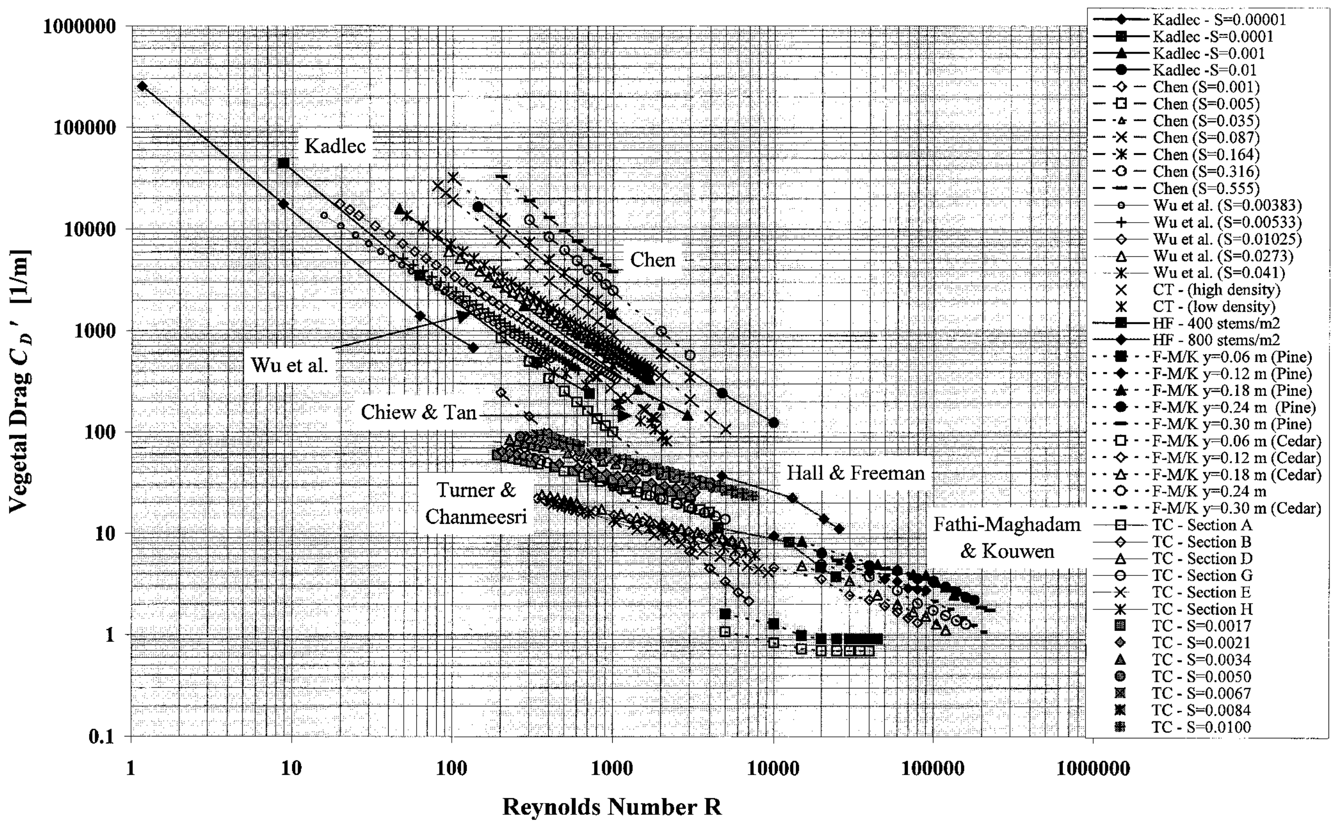

FIG. 10. Vegetal Drag Coefficient versus Reynolds Number for Unsubmerged Vegetation

through the data power regression equations of the following type:

$$C'_D = \gamma \mathsf{R}^{-k} = (\varepsilon S^x)\mathsf{R}^{-k} \quad (18)$$

where S = friction slope; and γ, ε, x, and k = regression coefficients specific to each study. Values for these coefficients are summarized in Table 2 for all studies used. The square of the correlation coefficient for (18) was excellent, approaching in almost all cases 1.0.

The following conclusions can be drawn from each specific study. Kadlec's (1990) data for emergent marsh vegetation (sedges) offer the highest roughness values, lying mostly in the laminar and transition zones. For Kadlec's data, k varies between 1.15 and 1.26 (Table 2). Similarly to the authors' data, Kadlec's (1990) data also show that C'_D values increase with increasing slope. The k values for Chen's (1976) data (Table 2) are 1.33 (the authors mention 1.5), indicating that the Chen (1976) curves are nearly parallel to the Kadlec (1990) curves. For the same slope S, Kadlec's C'_D values are about one order of magnitude higher than Chen's.

The Chiew and Tan (1992) study was similar to Chen (1996) but used a different grass. According to them, most data were in the transition and turbulent zones, and only one much steeper slope was tested. Fig. 10 shows that C'_D values are lower, even for the high density experiment, implying overall sparser vegetation. k values are 0.98 and 1.04 (Table 2) for the low and high density experiments, respectively. These k values are similar to those for the authors' data (Fig. 2). However, the C'_D values are quite lower than the authors', even though the slope is quite steeper. k values for both vegetation densities used are similar; therefore, it seems that vegetation density does not affect k values (as the authors state) but rather moves the curve up or down, i.e., affects the coefficients γ or ε.

The study by Hall and Freeman (1994) covered turbulent conditions (but not fully developed turbulence). Four flow rates were tested for each vegetation density. The lowest flow rate was not used in this analysis, because the resulting friction slope was quite different than that for the other three flow rates. k values were 1.16 and 1.03 (Table 2) for the two stem densities used, i.e., 400 and 800 stems/m^2, respectively. For both vegetation densities, the k values are similar, implying again that vegetation density affects the coefficients γ or ε.

The Fathi-Maghadam and Kouwen (1997) study covers turbulent flow conditions. Real vegetation samples (pine and cedar trees) were used as submerged flexible roughness elements, in an effort to simulate floodplain bush and brush vegetation with stems and canopy. The slope was 0.007 for the experiments with depths 0.06 and 0.12 m, and 0.004 for depths 0.18, 0.24, and 0.30 m. As shown in Fig. 10, pine resulted in higher C'_D values than cedar for all conditions. For a given flow depth, C'_D was found to decrease with R. For a given R, C'_D was found to increase with increasing flow depth. For the lowest flow depth (0.06 m), only the stems were submerged. For this case the roughness was overall the lowest, and actually fully developed turbulence seems to have been reached (C'_D became nearly constant for R greater than about 20,000). This condition was not reached for deeper flow, where either a portion or the entire canopy (0.30 m) was submerged. Therefore, resistance increased (by about one order of magnitude) with flow depth, because more and more vegetation area obstructed the flow area. For the experiments on slope 0.004 (deeper flow), k values were on the average 0.50 for pine and 0.72 for cedar (Table 2).

The study by Turner and Chanmeesri (1984) ranged mostly in the transition zone and employed flexible emergent wheat vegetation, a vegetation type different from all others considered previously. k values in this case are quite lower than all previous studies. Two sets of experiments are presented. The first set is on practically the same slope but for different vegetation densities. Actually, vegetation density reduces from experiments A to D to E or from B to G to H (Fig. 10), and the

TABLE 2. Values of Various Parameters Resulting from Data Studied

Study (1)	Conditions (2)	k (3)	γ (4)	ε (5)	x (6)
Kadlec (1990)	S = 0.00001	1.26	290,006	25,277,796	0.40
	S = 0.0001	1.20	547,701		
	S = 0.001	1.15	1,211,307		
	S = 0.01	1.16	4,894,030		
Chen (1976)	S = 0.001	1.33	286,502	60,523,602	0.77
	S = 0.005	1.33	997,763		
	S = 0.035	1.33	4,506,724		
	S = 0.087	1.33	9,124,987		
	S = 0.164	1.33	14,911,756		
	S = 0.316	1.33	24,785,363		
	S = 0.555	1.33	38,343,157		
Wu et al. (1999)	S = 0.00383	1.00	212,891	3,440,000	0.50
	S = 0.00533	1.00	251,144		
	S = 0.01025	1.00	348,273		
	S = 0.0273	1.00	568,381		
	S = 0.041	1.00	696,547		
Chiew and Tan (1992)	High density	1.04	354,655	n/a	n/a
	Low density	0.98	169,655		
Hall and Freeman (1994)	High density	1.03	371,747	n/a	n/a
	Low density	1.16	472,471		
Fathi-Maghadam and Kouwen (1997)	D = 0.06 m (pine)	0.26	13.1	n/a	n/a
	D = 0.12 m (pine)	0.58	1,966		
	D = 0.18 m (pine)	0.50	1,054		
	D = 0.24 m (pine)	0.48	775		
	D = 0.30 m (pine)	0.52	1,253		
	D = 0.06 m (cedar)	0.20	5.4		
	D = 0.12 m (cedar)	0.61	1,321		
	D = 0.18 m (cedar)	0.70	4,330		
	D = 0.24 m (cedar)	0.69	4,968		
	D = 0.30 m (cedar)	0.77	13,658		
Turner and Chanmeesri (1984)	Section A	0.45	666	n/a	n/a
	Section B	0.35	167		
	Section D	0.39	235		
	Section G	0.51	1,030		
	Section E	0.52	471		
	Section H	0.40	218		
	S = 0.0017	0.33	340	78,611	0.86
	S = 0.0021	0.33	377		
	S = 0.0034	0.36	592		
	S = 0.0050	0.39	780		
	S = 0.0067	0.44	1,107		
	S = 0.0084	0.46	1,376		
	S = 0.0100	0.46	1,424		

Note: n/a = not available.

set of experiments B, G, and H have, compared with A, D, and E, similar distances between stems, but denser stem arrangement. k values range from 0.35 to 0.52 (Table 2), without any obvious dependence on vegetation density. The second set of experiments is for a given vegetation density and for various slopes. In this case, k values seem to slightly increase with increasing slope in the range from 0.33 to 0.46 (Table 2). C'_D values also increase with increasing slope.

In an attempt to produce theoretical values for k and the other parameters, use was made of Kadlec's (1990) formula for flow through vegetation (called the power law), which reads

$$Q/W = q = VD = KD^{\beta}S^{\alpha} \tag{19}$$

where Q = flow rate; W = flow width; q = unit flow rate; V = mean velocity; D = flow depth; and K is a constant that is vegetation and site-specific. According to Kadlec (1990), the exponent α depends on flow state and assumes the values of 1 for laminar flow and 0.5 for turbulent flow. The exponent β depends on vegetation and other characteristics and, for marsh wetlands, assumes usually values between 2 (for vertically uniform wetland vegetation density and size) and 4 for decreasing vegetation frontal area with depth. Combining (18) and (19) with the authors' definition of C'_D [(5)], one gets the following expressions for exponents k and x:

$$k = 2(\beta - 1)/\beta \tag{20}$$

$$x = 1 - 2\alpha + k\alpha = 1 - 2(\alpha/\beta) \tag{21}$$

Characteristic values for k and x are computed in Table 3 for typical values of α and β, using (20) and (21). By comparing

TABLE 3. Values of k and x Computed Using Eqs. (20) and (21) for Typical Values of α and β

State of flow	α	β = 1.5		β = 2		β = 3		β = 4	
		k	x	k	x	k	x	k	x
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Laminar	1.00	0.67	−0.33	1.00	0.00	1.33	0.33	1.50	0.50
Turbulent	0.50	0.67	0.33	1.00	0.50	1.33	0.67	1.50	0.75

values of k and x in Tables 2 and 3, one can draw the following conclusions:

1. k and x values for Kadlec's (1990) and Chen's (1976) data fall within the range $2 \leq \beta \leq 4$ and are actually
close to $\beta = 3$. The x values indicate that Kadlec's data are in the laminar and Chen's data in the turbulent zone.
2. The authors' data correspond to $\beta = 2$, which seems correct, since their simulated vegetation was uniform with depth. The x value indicates turbulent flow.
3. Similarly, Chiew and Tan's (1992) k corresponds to $\beta = 2$. Since they only had one slope, an x value could not be extracted.
4. k values for the study by Hall and Freeman (1994) also correspond to β between 2 and 3, which is within the expected range $2 \leq \beta \leq 4$ for wetland vegetation. Again, x values could not be extracted.
5. k values for the study by Fathi-Maghadam and Kouwen (1997) correspond to about $\beta - 1.5$, a value probably expected for the kind of vegetation used. Again, x values could not be extracted.
6. k values for the data by Turner and Chanmeesri (1984) correspond to β values less than 1.5; however, the x values correspond to β values higher than 4.

In conclusion, a method was provided to estimate the authors' k value. Most of the experimental studies presented [except the one by Turner and Chanmeesri (1984)] are reasonably in agreement with (18)–(21). Therefore, these equations can be used with caution to predict values for k and the other parameters. Nevertheless, the data to draw this conclusion are limited and more studies are needed. k values seem to depend on vegetation characteristics (as the authors state) but not on vegetation density. Vegetation density seems rather to affect the coefficient ε in (18) (e.g., Chiew and Tan 1992; Hall and Freeman 1994). Fig. 10 can be useful in an analysis of a specific flow through a given vegetation, if a similarity can be established with some of the studies or with characteristics intermediate between two or more of them; in this case, an estimation of the drag coefficient C'_D can be made graphically from Fig. 10. The procedure will be by trial and error, which, for a given bed slope S and unit flow rate q, can lead to values of flow velocity and depth. This can be done by: (1) assuming a C'_D value; (2) reading from Fig. 10 an R value, for the given S; (3) computing from (5) the velocity V; (4) computing from R the depth D; and (5) checking if given q equals computed VD, and if not, repeating steps 1–4 with a new assumption for C'_D. The values obtained this way may give a sufficient degree of accuracy for preliminary analyses. A direct solution can also be obtained by combining (5) and (18) into the following equation:

$$Q/W = q = VD = [2g/(\varepsilon\nu^k)]^{1/(2-k)} D^{2/(2-k)} S^{(1-x)/(2-k)} \qquad (22)$$

where ν = kinematic viscosity. Values for k, x, and ε in (22) need then to be taken from Tables 2 and 3. This equation reduces to Kadlec's (1990) power law [(19)] if (20) and (21) are used.

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Closure by Fu-Chun Wu,[5] Hsieh Wen Shen,[6] Member, ASCE, and Yi-Ju Chou[7]

The writers would like to thank the discusser for his contributions. The discusser's Fig. 10 includes more comprehensive data and covers a wider range of R and C'_D. As the discusser points out, all the results coincide extremely well with the writers' conclusion that the variation of vegetal drag coefficient with Reynolds number can be represented by (13). The writers agree that the exponent k in (13) depends upon the biomechanical property of the plants. The additional data provided by the discusser (Turner and Chanmeesri 1984; Chiew and Tan 1992; Hall and Freeman 1994) appear to indicate that vegetation density affects the magnitude of C'_D, but not the value of k. The discusser raises several points related to the applicability of the proposed model that need to be clarified. First of all, the conclusions drawn from the writers' study are based on the data of subcritical flow conditions. As the writers mentioned in the paper, a previous experimental study (Wu 1994) has shown that the roughness coefficients for subcritical and supercritical flows have different trends of variation. This may provide a clue to the nearly constant C'_D values for the lowest flow depth (i.e., 0.06 m) of Fathi-Maghadam and Kouwen's data. For this case, the flow approached critical at $\mathsf{R} \cong 20{,}000$ and became supercritical when the mean flow velocity exceeded 0.77 m/s (or $\mathsf{R} > 40{,}000$). However, supercritical flow condition was not reached by the deeper flows, although their Reynolds numbers were much greater.

Secondly, for the vegetative roughness coefficient to decrease with increasing flow depth, the writers have shown a valid range of $0.8 < k < 2$ for the unsubmerged vegetation. The values of k for Turner and Chanmeesri's data are quite lower than 0.8, which implies that either the vegetative roughness coefficient increases with increasing flow depth or the writers' model is not applicable to their emergent wheat crops. Since Turner and Chanmeesri's data demonstrate very consistent trends of variation for the C'_D-R relationship, it is thus believed that the roughness coefficient of the emergent wheat crops increases with flow depth. In the writers' opinion, this type of flexible vegetation probably responds in the same manner as the row crops reported by Chow (1959) or the hypothesis proposed by Temple et al. (1987). For such partially submerged crops, the dependence of k on slope can be also attributed to the little change in the mean velocity with the increase of flow depth.

The discusser presents a theoretical expression of k as a function of β and shows that most of the experimental studies are in agreement with the proposed relationships. In essence, Kadlec's power law is compatible with the writers' model because his suggested range of β (i.e., $2 \leq \beta \leq 4$) corresponds to $1 \leq k \leq 1.5$, which is within the valid range proposed for

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the unsubmerged vegetation. In fact, for the proposed model, the lower bound of β should be 5/3. The experimental data with the values of $k < 0.8$ or $\beta < 5/3$ (e.g., Turner and Chanmeesri 1984; Fathi-Maghadam and Kouwen 1997) are not expected to coincide with the (18)–(21). However, as pointed out by the discusser, currently the available data are limited and thus more studies are desirable to examine the types of vegetation appropriate for the proposed framework. Nevertheless, the generality of the C_D'-R relationship holds for various types of vegetation under subcritical flow condition. Therefore, the trial-and-error procedures provided by the discusser may be very useful for preliminary flow analyses.