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模擬流場中植生抗流機制之研究
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（計畫名稱）

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一、 研究動機與目的

鑑於台灣本島河川先天上流短湍急的侷限，雖然已知水庫與攔水堰等水工構造對生態棲地的連續性會產生阻斷，有可能造成水生動植物物種的破壞與滅絕，然而在水資源分配不均衡的台灣，這些仍舊成為「必要之惡」，不過在設計與施工方式上卻開始有了不同面向的考量。

面對近年來頻頻發生的重大天災，許多關於生態工程之研究已在公私部門積極展開，然而研究重點多在河川護岸之型式、材質、工法，並以植栽之存活比率、綠覆速度做為適生植物種類之指標，對於曠日廢時的監測或實證研究較為少見，亦少有從植物之抗流能力（flow resistance）出發，針對植生對不同流速產生之抗流機制之探討，或者關於植生對不同流速之河床結構之適應性的實驗。

本研究擬從模擬流場之水工模型出發，探究不同水生植物對於不同流速之水道，在抗流力方面會產生如何之變化，並就植被之生長速率、莖葉組織強度的變化、抗流之耐度極限、抗沖刷反應、模擬河床粗糙係數之改變等加以分析，期能找出植物面對不同流速時在生理上的反應機制，除可進一步確認適性植生種類或先驅植物種外，亦可瞭解植物在生態工程上可扮演的角色與極限。

二、 文獻回顧

2.1 國外相關研究

關於植物抗流作用的研究，雖然有學者早在 1869 年即提出抗流平均值包括岩屑碎石與水中植物，認為水生植物主宰了其盤據的水道之水力（hydraulic）是不爭的事實，但對植被於河道的抗流作用之相關研究卻很少見。因此，非常缺乏對於植生河川流速之模式研究，特別是植生自由分佈的河道（Green, 2004）。根據目前的相關文獻回顧，大部分的研究是在模擬流場中以塑膠葉片或沉水性植物進行流速測試，少有操作於自然河道或者先行試種水生植物，再以不同流速之水流測試植物之生理反應機制者（Green, 2004; Järvelä, 2004）。

歷來的研究已證明植被的存在確實影響河流的流速，利用植物做為河岸緩衝帶的相關研究包括 Dabney 等人提出的論點，認為緩衝帶可降低沖蝕、攔截沉澱物，以及經由緩慢逕流移除污染物質，即使緩衝帶小於 1m 寬也能攔截許多沉澱物（Dabney, 2006）。而植被類型則在河道形態學上扮演關鍵的角色，研究指出，覆有河岸林緩衝帶的河川寬度要比單純草生帶的河川寬 2~2.5 倍；但相對的也有人指出河岸林河川較草岸林河川為窄。根據研究指出，重大的河岸侵蝕中，無河岸林河川的侵蝕為有河岸林的蜿蜒河川的 30 倍。在 1993 年 Kansas 洪氾後的研究中，Geyer *et al*.(2000)指出草岸緩衝帶的河岸一般平均形成 24m 的河岸侵蝕，至於河岸林緩衝帶則多為土壤沉積（Wynn, 2006）。

針對植被對河岸影響之研究，另有 Simon and Collison 提出河岸植被對河岸的穩定性有機械與水力兩種影響，有的改善河岸穩定性，有的卻相反（Simon and Collison, 2002），植物將其根錨定土壤中以支撐植物的地上部，因此對土壤基質產生強化作用（Greenway, 1987）。至於其產生的抗拉力究竟多大，在植物對抗水流的拉力測試中，發現不同物種對抗流速的潛力也有不同，Petryk 與 Bosmajian (1975)基於延滯力（drag force）即發展出一個植被抗力的理論模式，主要應用於洪氾平原的植被。而為測量植物因應流速產生之抗力，Haslam (1978)在引水槽中將植物附在彈簧秤上以記錄其在一組流速下產生的拉力，以測試各物種在流速上的相對衝擊與引起洪氾的潛力；Hanson 利用沉水式噴射器（submerged jet test device），計算基地內細粒物質對水力的抗力（Hanson, 1990, 1991; Handson and Simon, 2001）。Simon 等人則以兩種植物分析其對河岸穩定性之影響，發現檸檬柳提供較海灘松更重要的根部加強作用，提出物種造成的水文影響因空間而改變，且一般影響要比機械影響為小（Simon e*t al*., 2006）。

植被的根系型態也對河道之沖蝕作用有影響（Anderson *et al*., 2004），但是植物是如何影響河道抗力？其機制為何？卻仍有很大的研究空間。真正形成植被抗力的是什麼？Lewis 提出河道抗力係由兩種因素組成：經由摩擦力產生的能量損失與河道內流速的變化作用（Lewis, 1997），後者在植被河道中特別明顯，此由流速在密植植被中很小而在植被周圍則加速可見。植物莖的尺寸形成的抗力會導致植株內的低速與植株外的高速這種大幅度的流速變化，不同莖葉尺寸將形成不同的流速。就葉片的尺度而言，抗力依莖葉之結構與水力特性而異，例如其分枝的程度、個體的厚度、每株植物的芽的密度（Manz and Westhoff, 1988），個別枝芽的彈性是很重要的，因為其決定枝芽彎曲，以及植株受水流壓縮的程度（Sand-Jensen, 2003）。枝芽愈長彈性愈大，但枝芽愈厚彈性愈差（Manz and Westhoff, 1988）。

由於水力會破壞或移動生物體，使得流動水流中之生物棲息受到機械性的限制（Schutten, 2000），對於植物在形態上的因應，根據研究，淡水水生植物在流動水流中遭遇潛在的拖曳力時，必須在形態上加以適應以避免機械性的傷害與連根拔起，部分物種自短莖上長出小而硬的簇葉狀（rosette），以便抵抗強的拖曳力與加強裸露湖岸的力量。其他物種則遺傳了流線型的長線狀葉與莖，大部分的物種反應並無關乎生長的形式，而是會形成很具彈性的枝芽以讓其順著水流並降低直接暴露於水流的表面積（Sand-Jensen, 2003）。

從國外相關研究中可以得知，對於植物在抗流上的研究已開始受到重視，但因為侷限於開放河道複雜的不可確定因素，研究仍多以實驗室操作為主，而且不乏以塑膠葉片為實驗材

料者，實驗的方式則多以模擬河道中植被如何影響流速為重點，對於植物因應流速變化的生理反應機制如莖葉分歧、細胞壁之變化等之研究較少，也因此可預見此領域的研究價值。

2.2 國內相關研究

2.2.1 植生對邊坡穩定性的相關研究

關於植生對邊坡生態穩定性的研究，國內拱祥生、林宏達曾利用植生材料的特性，結合不飽和土壤理論，進行邊坡生態工法穩定機制的探討，以釐清植生對邊坡穩定性的影響。其提出植生根系的強度及錨定至岩層中的厚度，為邊坡植生工程的重點，而草本植物的高地表覆蓋率是防止邊坡沖蝕的重要因素；木本植物的高根系強度及土壤含根比則是抑制邊坡淺層崩塌的有效方法。（拱祥生、林宏達，2003）。林信輝等（2005）九芎植生木樁之生長與根系力學之研究，針對九芎植生木樁之生長特性與根力進行研究，探討不同生長地點與處理方式之萌芽樁成活率；吳瑞賢的研究團隊則利用根系力學模式，計算百喜草的植根對土壤強度之增量，並建立分析模型（陳秀婷等，2006）；另外尚有吳正雄（1990）針對植生根力與坡面穩定關係之研究、游新旺等（2006）提出「根力模式對含根土壤剪力強度評估之影響」，以及朱榮華等(2005)對於「根系變形模式與含根土壤剪力強度之研究」等，均是針對植物根系對土壤強度影響之研究，至於植物如何因應流速變化而產生抗流反應的相關研究則闕如。

2.2.2 生態渠道之相關研究

關於生態渠道之研究包括楊紹洋等（2006）針對植生護岸和粗糙渠床之渠槽試驗，以人造草皮模擬護岸植生，分析渠道在不同植物種類和高度時的水理特性；林鎮洋等（2006）以實驗水槽養殖指標魚種，嘗試建立本土性的水理參數（如雷諾數與福祿數等），據以模擬變遷的水域生態環境，以預測溪流完工後的生態環境變化趨勢。至於以真實水生植物進行生理機制變化的研究則尚未見到，因此在國內的研究有待開發的潛力。

三、 實驗設備與研究方法

3.1 研究方法

從國內外相關文獻回顧中可以得知，對於植物在抗流上的研究已開始受到重視，但因為侷限於開放河道複雜的不可確定因素，研究仍多以實驗室操作為主，部分水工實驗模型並以塑膠片做為植栽模擬材料，至於實驗的方式多以模擬河道中植被如何影響流速為重點，對於從植物生理學及植物解剖學的角度，探討植物因應流速變化而產生的生理反應機制如莖葉分歧狀況、維管束之變化、生物量之增減等之研究在國內外均很罕見，也意謂本研究領域發展之潛力。

基於前述相關文獻之剖析，本研究將以水生植物為實驗材料，實驗前期以實驗室內之模擬流場為操作場所，俟建立初步抗流模式後，後期實驗將選擇目前人為干擾低的河川中上游區段為實驗場，以便據以重覆修正抗流模式。

3.1.1 模擬流場設計

影響抗流之作用包括：植栽大小與其結構特性、在河道中的區位、當地的流動條件（Green, 2004），以及流場的結構、水文、水理的條件。因此實驗場設計應該包括三個部分：流場模型設計、植栽物種選定與環境營造（日照長度、日照強度、栽培介質及空氣流動等）。

在模擬流場設計部分，首先就流場之特性加以分類，選擇一個代表性類型為模擬流場模型設計依據。初步以大屯溪流場的流速為模擬對象，植栽之培養基亦將以大屯溪的河床周邊土壤為栽培介質，以便儘可能將栽培介質之變數降低。

3.1.2 植生流場環境型態

水生植物環境類型可依流動水域分為三種型態：

- 激流河岸：坡度 4%以上，僅適合挺水植物生長。
- 中流河岸：坡度 2%~4%中間，可生長木賊、帚馬蘭、台灣天胡荽與挺水植物。
- 緩流河岸：坡度 2%以下，適合大部分水生植物生長。（環保署，1995）

本計畫因係以模擬流場操作，所以模擬之水域環境鎖定中流河岸與緩流河岸，至於激流河岸因坡度大，能生長之植物極為有限，暫不納入實驗考量。

3.1.3 水生植物選種

植物影響河道流速已有相關研究確認，而不同莖葉尺寸形成的流速亦各有差異，所以實驗選用的物種會成為重要關鍵。

一般植物的分佈依河道剖面可以分為河床、河岸邊坡及高灘地，本研究鎖定的適生植物範圍以河床與河岸邊坡為主，至於高灘地部分，因需較大的操作空間，可能以實際河域為研究對象較宜，故不納入本研究範疇。

植物材料選種依據：為配合水槽尺寸，植物材料之尺寸需低於 30 cm，植物生長勢強、易於繁殖、多年生草本、分佈範圍廣；屬本土或馴化種，對本土生態環境無威脅性，根系以鬚根性為佳，以便比較生長速度並測試固土定砂能力。

3.1.4 材料選定：

水芹菜：繖形科 Apiaceae

學名：*Oenanthe javanica* DC.

- 植物分佈：全台灣水溝邊、田畦及溪岸頗常見。
- 植物生理特性：多年生草本，植物體多分枝，高可達 30 cm，全株具芹菜之香味。莖中空，表面有稜脊，無毛。葉互生，一至三回羽狀複葉，小葉卵形、橢圓形至線形，鋸齒緣。複繖形花序，花白色；萼片三角狀披針形，宿存；花瓣倒卵形，長約 2.5 mm。離果，脈隆起。分布於熱帶亞洲。（資料來源：http://content.edu.tw/primary/country/tc_ua/n012/html/5-4.htm，950409）

3.1.5 採土原則：

採土場址為大屯溪龜子山植生綠美化工程段下游 50 m 處，本區為生態工法河溪整治工程之示範河段，迄今完工三年，河岸與河床目前植生狀況良好，河床有泥沙堆積，有水生動植物存在，昆蟲部分有水蠆，植物則以次生林先驅植物五節芒(*Miscanthus floridulus (Labill.)* Warb. ex Schum, 又名 Japanese silvergrass)與入侵種大花咸豐草(Bidens pilosa)為優勢草種，採土區土壤質地表土 10 cm 處以砂質土壤為主，大於 10 cm 深則以黏土為主，有腐臭味，故僅採取表層土壤。以圓鍬採土，儘可能濾掉溪水。

在土壤質地選取部分，先清除較大石粒，使栽培土過篩尺寸均在 4.76 mm 以下(如圖 1)。

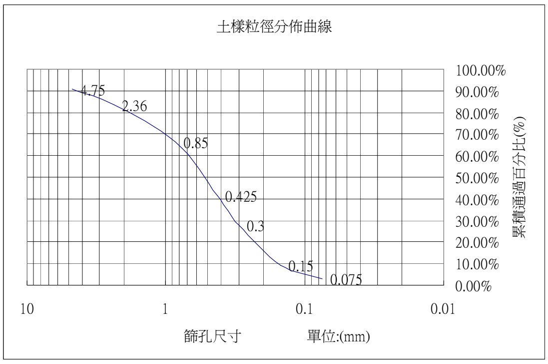

圖 1 大屯溪土樣粒徑分析

3.2 實驗設備：

- 水槽設計：透明壓克力水槽，長 200 cm，寬 30 cm 雙拼水道，高 40 cm。
- 可調式馬達 2 個。
- 植栽槽木箱長 90 cm，寬 29 cm，高 5 cm，板厚 10 mm，以樹脂與鐵釘膠著固定。
- 照明設備：4 支三尺長雙管 30 瓦植物燈管。
- 水生植物生長環境營造：包括水質、日照、水深、流速、土壤、坡度等。
- 對照組：環境條件相同，流速不同
- 其他周邊設備需求：溫度計、土壤、pH 值檢測分析設備、Timer〈設定照光時間 6:30 am~ 17:30 pm)、秤。

植栽槽覆土深度維持 4 cm 厚。

3.3 實驗步驟

- 於栽種前先測量水芹菜之高度、濕重、根長。
- 每組植栽箱槽種植 48 株水芹菜，初期兩槽固定相同流速讓水芹菜生長。
- 栽種生長四周後，實驗組流速不變；對照組每四周調高流速一次。
- 記錄頻率為每周一次，記錄項目為綠芽數、黃葉數、匍匐莖、匍匐芽及其它生理現象。
- 實驗二十周為一期，最終採收植栽並測量植栽乾重、濕重、根系長度、株高。
- 於最終採收完另取中間莖部做斷面切片 (Free hand section)，利用顯微鏡觀察，及 CCD 鏡頭即時拍攝，應用 Image J 電腦軟體計算斷面面積及人工計算微管束數量。

3.4 植物組織切片

3.4.1 埋蠟切片法（Paraffin method）

利用埋蠟切片技術針對實驗後採集之植物材料進行維管束與切片組織分析，埋蠟切片之過程概略為：固定→洗滌→脫水→浸蠟→埋蠟→切成薄片→貼於載玻片上→乾燥→溶蠟→脫水及染色→封片（蔡淑華，2000）。埋蠟之目的在於做成永久片後可以清楚比較在不同實驗條件下（如栽培密度或流速）植物在生理結構上產生的細微變化，是從植物解剖學的角度對「抗

流機制」做分析。

3.4.2 徒手切片法（Free hand section）

由於埋蠟手續繁複，僅能選取部分植栽抽樣分析，為取得更完整之資料，所有實驗後採集之植株均以徒手切片法留下新鮮的莖部組織，分別以 F.A.A.固定液（福馬林 5 ml，冰醋酸 5 ml 以及 50%~70%酒精 90 ml）暫時保存，留待記錄斷面積與植物組織。

四、 結果與討論

4.1 不同流速梯度影響水生植物之生長速度

實驗一操作最初，對照組植栽槽 AB 平均綠芽數為 2.92；實驗組植栽槽 CD 之平均綠芽數為 3.00，約高出對照組 2.7%（圖 2）。

當 CD 槽流速調整於 40 cm/sec 時，實驗組之平均綠芽數增加，大於對照組之平均綠芽數，但當實驗組之流速調整至 60 cm/sec 時，其綠芽數開始降低，黃葉數持續增加，至栽種 20 周後採收計算，實驗組之綠芽數降至 3.01，對照組則增加至 4.99，反高出實驗組 65.8%，而黃葉數亦呈現實驗組（高流速）多於對照組（低流速）之現象。此現象能約略推估水芹菜適應生長的流速範圍在 60 cm/sec 的流速以下，如超過則其生長可能開始衰退（圖 2、3）。

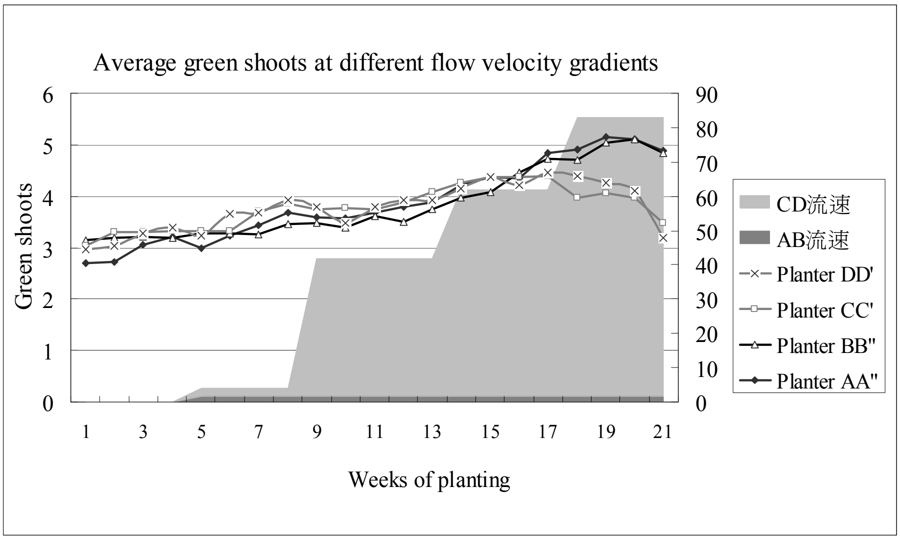

圖 2 實驗一平均綠芽數與流速對照圖

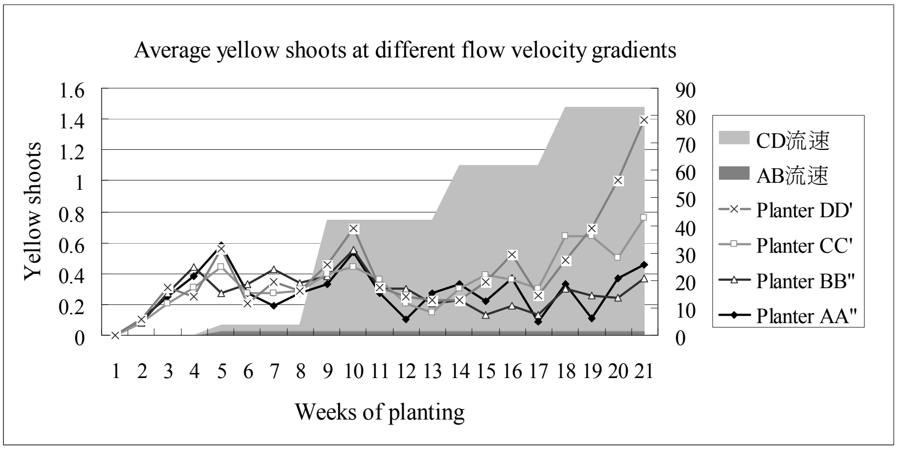

圖 3 實驗一平均黃葉數與流速對照圖

4.2 不同流速梯度影響水生植物之生物量

實驗一操作最初，對照組 AB 總鮮重為 120.26 gm，實驗組 CD 總鮮重為 131.36 gm，實驗組 CD 總重量高出對照組 AB 9.2%，但在栽種 20 周採收後，控制組 AB 之總鮮重為 148.70 gm，實驗組之總鮮重則為 80.03 gm，此時實驗組之總鮮重僅為對照組之 53.8%。

當以攝氏 100 ℃、26 小時烘乾後，實驗組 CD 之乾重為 5.82 gm，對照組 AB 為 13.42 gm，

實驗組之總乾重僅為對照組之 43.4%。

在實驗二中，當流速梯度縮小，水芹菜的鮮重在實驗初控制組 AB 為 152.65 gm，實驗組 CD 為 174.52 gm，實驗組高出控制組 14.3%，但在 20 周栽種採收後，實驗組 AB 鮮重為 46.81 gm，乾重為 6.09 gm，實驗組 CD 鮮重為 34.50 gm，乾重為 4.13 gm，差異雖不及實驗一明顯，但鮮重與乾重的變化仍然說明流速確實影響植物的生物量（圖 4）。

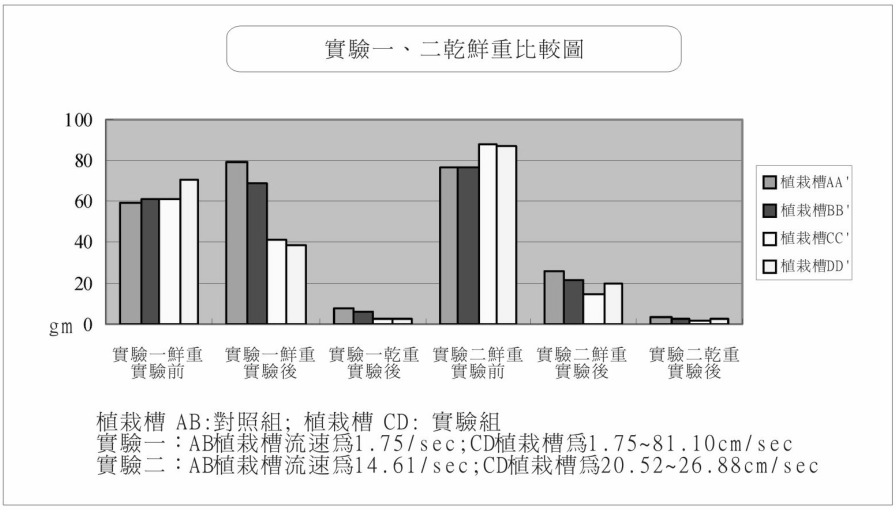

圖 4 實驗一、二乾鮮重比較圖

4-3. 水生植物面對不同流速梯度在型態上之變化

兩次實驗中均顯示，流速持續增加的實驗組 CD 在平均株高上比控制組 AB 要低矮，在流速梯度大的實驗一中，明顯呈現株高的差異，採收後實驗組的株高僅為控制組的 54.3%，直徑尺寸上實驗組 CD 為控制組 AB 的 84%，此外，控制組的徒長莖明顯多於實驗組（32:5），矮化莖數量則以實驗組為多（1:3），匍伏莖的變化則不顯著（因為埋在土裡，受水流梯度影響較小）呈現植物在流速增加時有降低植株高度與尺寸的傾向。在實驗二中，雖然流速梯度範圍較小，在株高與直徑的差異不及實驗一清楚，但卻發現其實驗組的平均根長僅有控制組的平均根長 73.8%（圖 5、6），是否意謂植物在惡劣的環境下以降低錨定作用以增加尋求更適宜生長環境的機制？值得進一步實驗證實。

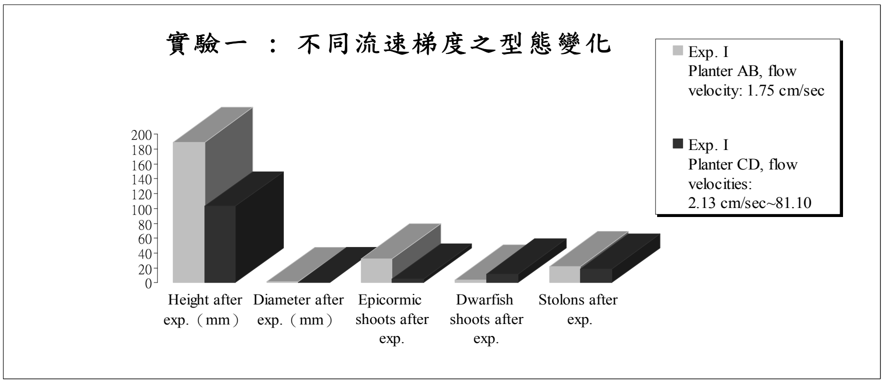

圖 5 實驗一不同流速梯度之型態變化

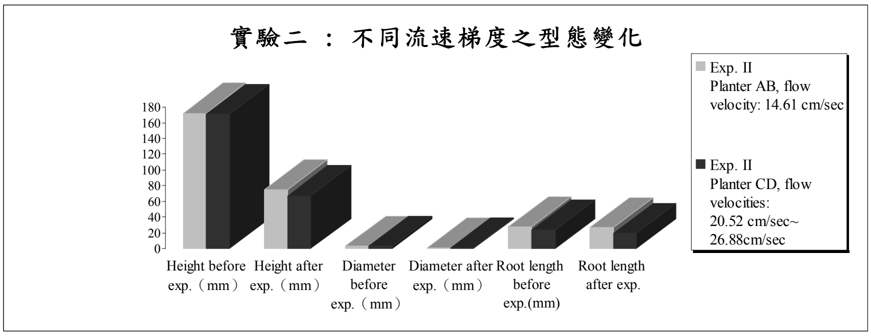

圖 6 實驗二不同流速梯度之型態變化

4.4 植物面對不同流速梯度在解剖上的變化

對實驗一與實驗二採收後的植株進行解剖分析，發現實驗組之新生枝芽除了高度有矮化現象外，其維管束的數量與陸域栽植之水芹菜相比也有降低的情形，一般陸域栽植的水芹菜其植株直徑較大，維管束多在 5 以上，但在水域中新生長的綠芽，在長成後解剖，其維管束多在 5 以下，並以 3 居多，說明植栽在水域環境時會調整自己的生理機制以適應水域中流動的水流環境。

五、 結論與建議

實驗發現，水芹菜在面對較大的流速梯度時，其反應機制為降低株高、根長，採收後計算株高/根長之比值，實驗組 CD 槽比值要大於對照組 AB，意謂流速增加會抑制植物根部的生長速度。根據 Sand-Jensen 的研究，淡水水生植物在流動水流中遭遇潛在的阻力 (拖曳力)時，必須在形態上加以適應以避免機械性的傷害與連根拔起（Sand-Jensen, K., 2003），而水芹菜用以避免機械傷害的反應機制乃是降低植株的高度與直徑，以便有較彈性柔軟的莖部對抗拖曳力，至於其根部變短，推測乃是為使植株降低錨定作用，以便有機會尋找更適當的生長環境。

針對實驗二於蟲害後新生綠芽之切片，發現其維管束較一般陸域生長之植株明顯減少，原因初步推斷為：水流加速，植株吸水容易，不需太多維管束吸收水份，而維管束外層伴隨之厚角細胞，與維管束同為機械支持作用，但流速增加時，如果機械支持（抗脫曳作用）愈大，被水流機械傷害的機會愈大，反而容易被折斷，所以維管束數量減少，厚角組織連帶減少，可降低其抗流反應。而實驗二與實驗一相較，實驗組與控制組並無明顯的水平葉、矮化莖、徒長莖之差異反應，應是流速梯度範圍過小緣故。

本實驗過程中另外發現，栽植第五周開始，逐漸會在植栽槽內形成「藻墊」，顯微鏡分析結果主要為矽藻、念珠藻、顫藻與舟型藻等，其產生原因乃是由於水芹菜提供藻類附著的支持與保護功能，而因為有水芹菜降低流速，亦使藻類可以停留於定點而不被沖走，實驗並發現，這種藻墊之形成對坋土等細粒土壤有保護作用，一旦植株死亡，藻墊隨之破裂，表層細粒土壤接著即會被水流沖刷，至於保護的作用有多大，則是可進一步實驗研究者。

鑑於適性植物種類可能是多元化的組成，因此未來擬進一步研究簇群植生之組成架構，以便做為河道植生工程之設計依據。

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七、計畫成果自評

本研究進行期間，曾赴夏威夷參加 2008 世界環境與水資源國際研討會，在會議中將現階段的研究成果向與會的人員報告（研討會論文如附錄），會場上多數為土木工程的學者或工程師，在聽罷本人的報告後，對於植物的抗流反應表示非常有興趣，也認為是很有意義的研究。

由於近年來，「生態工法」儼然已成為河川環境規劃設計的主流，但卻時見工程部門與生

態學界對此一工法的質疑，問題的根本在於缺乏對水生動植物於流場中之生理反應與耐度的深入實證研究。由於生物實驗曠日廢時，往往需數年方可見到研究成果，因此相關的研究寥寥可數，即使在國外的研究領域，相關文獻亦很有限。在推動「生態工程」多年後的今天，由於缺乏基礎研究資料，雖然各界對於營造合乎生態原則的環境已有共識，卻無法進一步證明「適生物種」或「適性工法」是那些，進行河岸植被復育時對栽植的方式或工程完工驗收亦難有標準。本計畫即在彌補前述實證研究之不足，擬從模擬流場出發，探討植物對於不同流場條件的反應機制，可以科學實驗的方式分析植物的抗流特性與耐度，有助於釐清長期存在於工程與生態學界間的質疑，也可更確定植物在河川環境穩定作用上的角色與功能。雖然目前為止對大部分植栽的抗流反應尚無法全盤瞭解，但是這個研究的出發點絕對有一定的生態意義與價值！

八、附錄：2008 世界環境與水資源國際研討會論文

Flow Resistance Mechanism of Aquatic Macrophytes in a Simulated Channel

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Abstract

The present study described in this paper was carried out in a simulated channel. The first part of the study examined how aquatic macrophytes respond to different channel flow velocities, in terms of changes in their flow resistance mechanisms, in order to confirm the suitability of local plants. The second part of the study examined the growth rate of the macrophytes, the growth rate and shape of macrophyte shoots, tissue strength of the shoots and roots, tolerance of the plants, and erosion-resistance response at various velocities. Study results show that *Oenanthe javanica* (Blume) DC. (water celery) experienced morphological variations at different flow velocities. In particular, as flow velocity increased, growth rate slowed and plant shoots became shorter and softer, which increased plant flexibility. Root length and root anchorage decreased. In addition, root, stem, and shoot mass also decreased.

Key words: flow resistance, simulated channel, aquatic macrophytes, river/streambank protection.

1. Introduction

In Taiwan, natural disasters, such as landslides and floods, have occurred more frequently and more severely in recent decades. The use of ecological engineering methods to mitigate the impact of such disasters has therefore gained much attention. However, most recent research studies have focused on the types, materials and construction methods of riverbank protection works, or on the survival rates of selected vegetation. There has been relatively little field monitoring work for verifying mitigation approaches and specifically for studying the effects of vegetation on channel and flow resistance mechanisms.

This study was carried out in a simulated channel. The first part of the study examined how aquatic macrophytes respond to different channel flow velocities, in terms of changes in their flow resistance mechanisms, in order to confirm the suitability of local plants. The second part of the study examined the growth rate of the macrophytes, the growth rate and shape of macrophyte shoots, tissue strength of the shoots and roots, tolerance of the plants; and erosion-resistance response at various velocities.

The purpose of this research was to investigate and clarify the roles and limitations of using aquatic macrophytes in ecological engineering applications as well as in design work.

2. Literature review

Aquatic macrophytes are often the dominant factor influencing flow conditions within the channels they occupy. However, the effects of vegetation on flow resistance are still not fully understood (Green, 2004; Järvelä, 2004). Most related empirical research studies were conducted in simulated channels with plastic leaves or submerged vegetation, and focused on addressing hydraulic effects such as drag and vegetation configuration (Järvelä, 2004; Sand-Jensen, 2003).

Many prior studies have verified that the presence of plants affects flow velocities. According to Dabney's study, plants used as buffers reduce erosion, trap sediment, and remove contaminants by slowing runoff, increasing infiltration, and facilitating the uptake and transformation of contaminants. (Dabney *et al.*, 2006; Wynn and Mostaghimi, 2006). Some recent studies have shown that riparian vegetation has both mechanical and hydrologic effects on streambank stability, some of which improve bank stability and some of which reduce bank stability (Simon and Collison, 2002). Roots anchor themselves into the soil to support the above ground component of the plant (Greenway, 1987); however, root type (variation in rooting depth and rooting density) also affects channel erosion (Anderson *et al.*, 2004).

Plant stem/leaf scales, the density of vegetation, as well as the length, stiffness, and diameter of the plants also cause variations in flow velocity (Green.2004; Manz and Westhoff, 1988). Individual shoot flexibility is also important. Flexibility increases with shoot length, but decreases with an increase in shoot thickness (Manz and Westhoff, 1988).

Mechanical constraints limit plant survival and growth in environments with flowing water because the hydraulic forces engendered tend to dislodge or break them (Schutten and Davy, 2000). The environmental effects cause morphological adaptation; some species develop a rosette of small, stiff leaves from a short stem which can resist strong drag and accelerational forces on wave-exposed lake shores. Other species develop an inherently streamlined morphology composed of long linear leaves or stems (Sculthorpe, 1967; Sand-Jensen, 2003). Most species develop very flexible shoots which allow them bend and twist in water flow to reduce the surface area which is directly exposed to flow current (Koehl, 1984; Sand-Jensen, 2003).

Literature review shows that few prior studies exist related to flow resistance mechanisms of aquatic macrophytes at different flow velocities. Studies related to how aquatic macrophytes modify their physical characteristics, such as vascular bundles and branching, to adapt to flow velocities are also scarce.

3. Materials and methods

3-1. Experimental design

Factors that affect flow resistance include size of plants, their structural properties, their location in the channel, and local flow conditions (Green, 2004). Structure of the channel, hydrology, and flow conditions should also be considered. This experiment included three parts: designing a simulated channel model, choosing plant species, and building a simulated plant environment.

3-1-1. Simulated channel model

First, existing channels were classified with respect to environmental conditions. Second, one of the channels was chosen for the simulation. Tatun Creek was chosen because it demonstrates channel dredging using ecological engineering methods and because it is well planted two years after construction. The culture media used to control experimental variables also came from Tatun Creek.

Characteristics of the simulated channel which was constructed include:

- Dimensions: 200 cm long x 30 cm wide x 40 cm deep.
- Materials: 1 cm thick transparent acrylic panels.
- Water flow: two adjustable water pumps.
- Lighting facilities: four 40-watt plant lights, 100 cm in length. Illumination time was set to be from 6.30 hr to17.30 hr). Average illuminance was set to be 843 Luxes.
- Planters: four planters, 90 cm long x 29 cm wide x 5 cm deep, made from 1 cm thick wooden panels.
- Experimental design: control group vs. experimental group with the same environmental conditions and different flow rates.

- Other facilities: thermometer, pH meter, lux meter, timer and weighing scale.

3-1-2. Plant species

Studies of how different plant structures, such as stem scale and leaf morphology, affect flow rate have been presented in many papers. Plant materials in this research study were chosen with respect to the following considerations:

- Native aquatic macrophytes or domestic species that pose no threat to native species.
- Lower than 30 cm height.
- Easy to cultivate.
- Perennial herb with fibrous roots, which are easy to check for sand stability.
- Spread widely.
- Short life cycle.

Based upon the above requirements, water celery, *Oenanthe javanica* (Blume) DC. was chosen for the study. In Taiwan, water celery can be found in ditches, ponds, paddy fields and wet places at low to medium altitudes throughout the island (Huang *et al.*, 1998).

3-1-3. Simulated plant environment

Natural riverbanks can be classified by environment, topography and slope. There are three types of planting environments for aquatic macrophytes: rapid flow, middle flow and streaming flow.

- Rapid flow: slope over 4%, only a few emerging plants can survive.
- Middle flow: slope 2%~4%, suitable for emerging plants.
- Streaming flow: slope below 2%, suitable for most aquatic macrophytes (EPA, 1995).

This study was designed for a simulated channel with slope below 4% for the sake of the plant materials.

The culture media came from the Tatun Creek. The site chosen for collecting the cultivated soil was covered with native plants, such as *Miscanthus floridulus (Labill.)* Warb. ex Schum (Japanese silvergrass) and invasive species such as Bidens pilosa. Dobsons were found under the gravel in the river.

Results of grain size analysis showed that 60% of particle-size was under 0.85 mm diameter and 90% of particle-size was under 4.75mm diameter.

3-2. Experimental steps

Step I:

Analyze and record culture media properties, plant weights, slope of the channel, water depth, flow velocity, water quality, pH value and lighting duration, for both the experimental group and the control group. The differences between plants, such as dimensions and weight, were not over 20%.

Since the time required for the water celery plants to grow stable in the planters was about three to four weeks, channel flow velocity was kept constant during the first four weeks and changed thereafter.

Step II:

Every 4 weeks, change the flow velocity for the experimental group. Record the number of green shoots, yellow shoots, horizontal shoots, epicormic shoots and shoots from the stolons. Finally, 20 weeks after planting, record height, root length, diameter, fresh weight for each plant and total dry weight.

3-3. Plant tissue sectioning

3-3-1. Paraffin method

After harvesting, plant material was analyzed for vascular bundles using the paraffin method. The purpose of making plant sections was to compare physical anatomical structure changes of the water celery plants at different flow velocities.

3-3-2. Free hand section

A second analysis method was also used: free hand sectioning. The process used was sectioning the fresh shoots and fixing temporarily with F.A.A. (formalin 5ml, glacial acetic acid 5ml and 50%~70% alcohol 90ml) (Tsai, 2000) and observing and recording the number of vascular bundles and plant tissue properties.

4. Results

The experimental study started in Nov. 2005 and two experimental trials have been completed so far, experiment I, with various velocity gradients from 2.13 cm/sec to 81.10 cm/sec, and experiment II, with velocity gradients from 20.52 cm/sec to 26.88 cm/sec. The duration of each experiment was 20 weeks. When experiment II had progressed to the second week, more than 80% of shoots were eaten by *Spodoptera litura* Fabicius. New shoots sprouted at the fifth week, after an application of pesticide.

Since most average flow velocities of dredged rivers in Taiwan are between 4.0~90.0 cm/s (5.0~13.0 cm/s for Dago Stream; 2.0~52.0 cm/s for Fungaue River) (Lin, 2003; Lin *et al.*, 2005), the first experiment was applied to find the flow velocity tolerance limit for water celery. Twenty weeks after planting, the survival rate of the experimental group was reduced to 75%, while the survival rate of the control group was higher at 95%. Suitable flow velocities were found to be between 2.0~60.0 cm/s.

4-1. Growth rate varied at different flow velocities

Before experiment I began, the average number of green shoots was 2.92 in the control group (planters A and B) and 3.00 in the experimental group (planters C and D). When flow velocity was increased to 40.0 cm/sec, the average number of green shoots in the experimental group increased continuously and plant growth rate was also higher than in the control group. However, when flow velocity was increased to 60.0 cm/sec, the quantity of green shoots in the experimental group declined, while the number of yellow shoots increased and stayed higher than the control group. After harvesting, the average number of green shoots in the control group was 4.99 in the control group vs. 3.01 in the experimental group. The growth rate in the control group was 65.8% higher than in the experimental group. In addition, the average number of yellow shoots in the experimental group increased more quickly than in the control group (see Fig.1, Fig.2).

For experiment II, at the beginning of the first week, the average number of green shoots in the control group was 4.62 vs. 4.67 in the experimental group. The difference in number of green shoots between the two groups was only 1.0%. After harvesting, the number of green shoots in the control group was 6.48 and in the experimental group was 5.68. The difference in the number of green shoots increased to 14.1%. The results show that flow velocities affected growth rate of the aquatic macrophytes studied and that plant growth adapted over the given flow velocity range.

4-2. Biomass varied at different flow velocities

At the beginning of experiment I, the total fresh weight of the control group was 120.26 gm and of the experimental group was 131.36 gm. Twenty weeks after planting, the total fresh weight of the control group was 148.70 gm vs. 80.03 gm for the experimental group. The total fresh weight of the experimental group was only 53.8% of the fresh weight of the control group. After harvesting, when dried for 26 hours at 100 ˚C, the dry weight of the control group was 13.42 gm vs. 5.82 gm for the experimental group.

For experiment II, flow velocity gradients were set from 20.52cm/sec to 26.88cm/sec. At the beginning of experiment II, the total fresh weight of the control group was 152.65 gm vs. 174.52gm for the experimental group. Twenty weeks after planting, the fresh weight of control group was 46.81 gm, and dry weight was 6.09 gm, vs. 34.50 gm fresh weight and 4.13 gm dry weight for the experimental group. The difference for experiment II was not as clear as for experiment I. However, both experiments showed that biomass varied at different flow velocities.

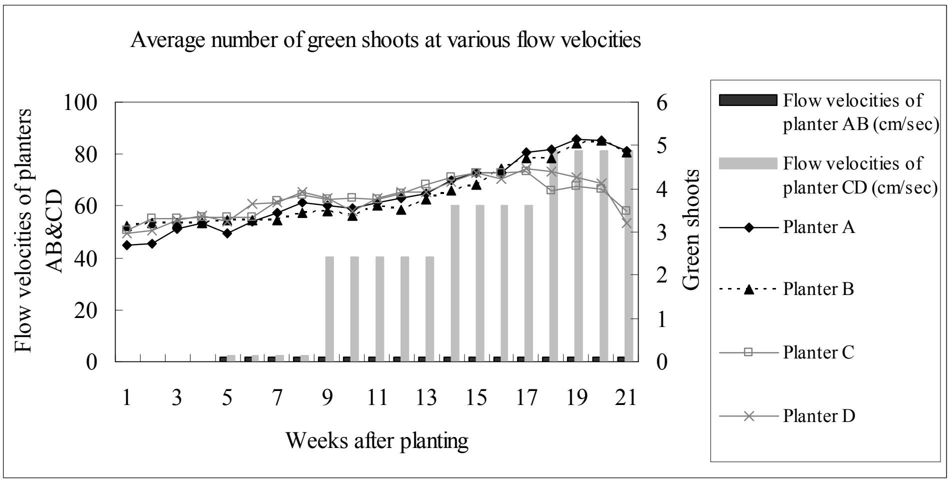

Figure 1. Average number of green shoots at various water velocities for experiment I.

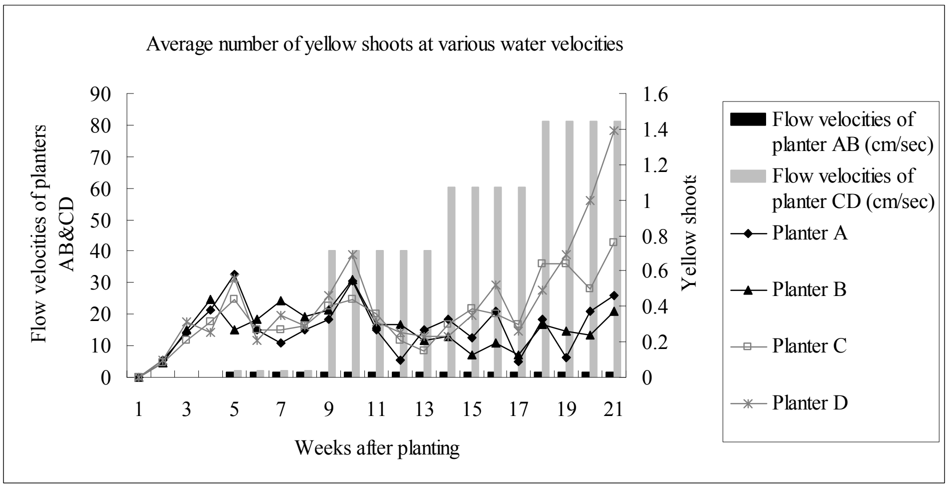

Figure 2. Average number of yellow shoots at various water velocities for experiment I.

4-3. Morphology varied at different flow velocities

The two experiments showed that average heights in the experimental groups were lower than in the control groups. For the faster flow velocities in experiment I, the average height of the experimental group water celery specima was only 54.3% of that of the control group specima. Average diameter of shoots in the experimental group was 84% of that in the control group. The number of epicormic shoots in the control group was greater than that in the experimental group by a ratio of 32:5.

However, the number of dwarfish shoots in the experimental group was more than that in the control group with a ratio of 3:1. The difference was not clear for stolons, since they were buried in the culture media. The results show that morphology of aquatic macrophytes varied at different flow velocities.

Experiment II results as show that plant height varied inversely with flow velocity. Although the difference between the two groups was not as clear as in experiment I, average length of the roots in the experimental group was 73.8% of average length in the control group. Apparently, plant root length decreased to reduce root anchorage as a modified mechanism for seeking a more suitable propagating environment.

4-4. Plant tissue sections changed at different flow velocities

Section analyses for the two experiments showed that not only was average new shoot height in the experimental group lower than that of the control group, but also that number of vascular bundles in the experimental group was less than that of the terraneous water celery. In this study, the terraneous water celery had larger diameters and more vascular bundles (usually above 5) than that of the water planted water celery (usually under 5). The results reveal that water celery plants adjusted their physical characteristics to adapt to changing conditions in the flowing water environment.

5. Discussion

Results of the two experiments show that water celery, when faced with higher flow velocities, reacted to decrease plant height and root length. After harvesting, the ratio of plant height to root length in the experimental group was higher than that in the control group. Flow velocity apparently restrained growth rate of the plants. According to Sand-Jensen, macrophytic freshwater plants encounter substantial drag forces in flowing water, must undergo morphological adaptations to prevent mechanical damage and uprooting (Sand-Jensen, 2003). The manner by which water celery apparently avoids mechanical stresses, when encountering drag forces at higher flow velocities, is to reduce both height and diameter and thereby to form softer and more flexible shoots. Plants in the experimental group also underwent a morphological adaptation to reduce root length and thereby to reduce root anchorage strength. According to research by Puijalon *et al.*, such a strategy may increase dispersal capability of the species in high flow habitats (Puijalon *et al.*, 2005).

Plant sections from experiment II, showed that number of vascular bundles in new shoots was less in flowing water environments than in terraneous planting environments. Apparently, plants could more easily absorb water in the experimental channels than in the terraneous environment. As a result, the plants in the flowing water environments did not need as many vascular bundles to absorb water. The number of collenchyma cells, which have a similar supporting function as the vessels also decreased as flow velocity increased. Plant response to modify morphology was apparently due to reduce breaking that could take place with more vascular bundles. It is apparently safer for aquatic macrophytes such as *Oenanthe javanica* (Blume) DC. to adapt and produce fewer vascular bundles at higher flow velocities.

For experiment II, the difference between the experimental group and control group with respect to numbers of parallel shoots, dwarfish shoots and epicormic shoots was not as clear as in experiment I, apparently due to the smaller flow velocity gradients used in experiment II.

Since suitable streambank vegetation may include a variety of several different plants, in future work it would be useful to study the flow-resistance mechanisms of a cluster of selected plants and to further investigate and clarify the roles and limitations of using aquatic macrophytes in ecological engineering applications.

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