研究報告

四種原生殼斗科樹種之苗木根系功能性狀及生物力學特性

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摘　要

在臺灣，颱風及季風暴雨常引發高山及丘陵地區嚴重的崩塌災害。崩塌地復育為當前林業經營之重要課題。卡氏櫧(*Castanopsis carlesii*)、青剛櫟(*Cyclobalanopsis glauca*)、三斗石櫟(*Pasania hancei*)及川上氏櫧(*Pasania kawakamii*)為崩塌地次級演替常見的原生殼斗科樹種，具有崩塌地復育之潛力，然其根系性狀及生物力學特性仍未被探討。本研究利用WinRHIZO分析系統、拉拔試驗及單根拉伸試驗等方法，調查此四樹種二年生苗木之根系性狀及根生物力學特性，以作為選擇植生復育樹種之參考。研究結果顯示，四種殼斗科樹種之根系結構均屬於垂直水平型(VH-type)。青剛櫟之生長表現、根系功能性狀均顯著優於川上氏櫧、三斗石櫟及卡氏櫧者；青剛櫟根系之最大拉拔抗力也顯著高於川上氏櫧、卡氏櫧及三斗石櫟者；青剛櫟、川上氏櫧及卡氏櫧之單根抗拉強度顯著高於三斗石櫟者；青剛櫟之單根抗拉力為四樹種中最高者；而青剛櫟、川上氏櫧及卡氏櫧之單根抗拉強度亦顯著高於三斗石櫟者。綜合以上結果證實，青剛櫟之生長表現、根系功能性狀、拉拔抗力及單根抗拉強度優於川上氏櫧、卡氏櫧及三斗石櫟者。因此，依據本研究結果建議造林樹種的選擇順序可考慮為青剛櫟＞川上氏櫧＞卡氏櫧＞三斗石櫟。

關鍵詞：殼斗科樹種、根系結構、根功能性狀、生物力學特性。

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Research paper

Root Functional Traits and Biomechanical Properties of Four Endemic Fagaceae Species

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【Summary】

In Taiwan, typhoons and monsoonal torrential rains often induce serious landslide hazards in mountains and hilly regions, and thus landslide restoration has become a pressing issue for forest management. *Castanopsis carlesii*, *Cyclobalanopsis glauca*, *Pasania hancei,* and *P. kawakamii* are endemic Fagaceae species that often occur during secondary succession on scars after a landslide. They have high potential for enhancing restoration of landslide scars. However, their root characteristics and biomechanical properties have not been explored. In this research, root traits and biomechanical properties were investigated with the WinRHIZO system, vertical uprooting, and tensile tests using 2-yr-old seedlings in order to provide criteria for species selection in landslide restoration. The results show that the root systems of these 4 species belong to the vertical and horizontal (VH)-type. *Cyclobalanopsis glauca* had remarkably higher root traits and functional traits than those of *P. kawakamii*, *P. hancei*, and *Cas. carlesii*. Additionally, the maximum pullout resistance for *Cyc. glauca* was notably higher than for *P. kawakamii*, *Cas. carlesii*, and *P. hancei*. Root tensile resistance for *Cyc. glauca* was significantly higher than for *P. kawakamii*, *P. hancei,* and *Cas. carlesii*. Root tensile strengths of *Cyc. glauca*, *P. kawakamii,* and *Cas. carlesii* were notably higher than that for *P. hancei*. Taken together, these results clearly demonstrate that *Cyc. glauca* has superior growth performance, functional traits, anchorage capability, and root tensile strength than *P. kawakamii*, *Cas. carlesii,* and *P. hancei*. Thus, it is suggested that the species priority ranking for these 4 species should be *Cyc. glauca* > *P. kawakamii* > *Cas. carlesii* > *P. hancei*.

Key words: Fagaceae species, root system architecture, root functional traits, root biomechanical properties.

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緒 言

臺灣多山地形陡峭且地質脆弱，颱風及季風暴雨常引發高山及丘陵地區嚴重的崩塌及土石流等天然災害(Chang 1996, Tsou et al. 2011)。Huang (2010)指出，臺灣國有林崩塌以淺層崩塌(2 m以下)的分布範圍最廣且頻率最高，而且臺灣的淺層崩塌主要發生於海拔500~2000 m的山區，崩塌坡度則是集中於25°~40°之間。崩塌地復育為當前林業經營之重要課題。由於崩塌地土層淺薄、土質貧瘠且乾旱，植生復育樹種的選擇相當重要。近年來的生態工法應用植物根系的特性，將植生導入於邊坡防護工程中，不僅可增強土壤的穩定度，防止崩塌，更可使地貌恢復自然樣貌，減少對環境的衝擊，並增加生態多樣性(Ngugi et al.

2015, Lin 2016)。原生樹種能適應本土生態環境，在崩塌地復育及水土保持上扮演著重要的角色。臺灣原生殼斗科樹種為次級演替樹種，分布在海拔500~2000 m山區，具有復育崩塌地之潛力(Liao 1996)。

植物的根系分布結構與性狀及力學性質對植物之固土能力有很大的影響(Chen et al. 2014)。根系的結構及型態隨土壤性質及生長環境而異，Yen (1987)將根系分類為橫走型(parallel and horizontal (PH)-type)、直角型(right (R)-type)、垂直水平型(vertical and horizontal (VH)-type)、垂直型(vertical (V)-type)以及團網型(massive (M)-type)等5種類型。植物根系類型會影響植物根系的錨錠作用。良好的根系結構可以有效控制淺層崩塌的風險(Shen and Tsao 2009)。Stokes et al. (2009)指出，植物根系結構及性狀對根系之拉拔抗力具有顯著之影響。Saifuddin et al. (2015)研究證實銀合歡(*Leucaena leucocephala*)之根生物量、根長及根抗拉強度較高，所以比盾柱木(*Peltophorum pterocarpum*)具有較佳之固土能力。許多研究探討崩塌地復育用樹種如臺灣山芙蓉、血桐、白匏仔及構樹等之根系結構性狀及力學性質(Lee et al. 2020, 2021)。

殼斗科(Fagaceae)樹種為臺灣原生具有造林潛力之復舊造林樹種，在海拔500~2000m的山區與樟科的樹種組成楠櫧林帶，並在海拔1500~2500 m的山區形成櫟林帶(Cheng 2009)。Yang (2017)研究指出，殼斗科有多種是臺灣中低海拔之主優勢木具良好之逆境抗壓性及天然更新之能力，有利於森林生態系之穩定發展與演替。因原生殼斗科樹種常分布於次級演替階段之崩塌地，可良好的適應臺灣山區環境，十分適合應用於崩塌地植生工程。雖然殼斗科為崩塌地演替中常見之樹種，但是有關其應用在植生工程方面之研究卻相當少見。所以，本研究以卡氏櫧、青剛櫟、三斗石櫟及川上氏櫧等四種臺灣中低海拔常見的原生殼斗科樹種作為研究對象，調查其根系結構、根系功能性狀及生物力學特性，以作為山區崩塌地復舊造林及邊坡植生防護工程之參考資料。

材料與方法

一、試驗材料

本次試驗選用四種殼斗科(Fagaceae)樹種卡氏櫧(*Castanopsis carlesii* (Hemsl.) Hay. var. *carlesii*)、青剛櫟(*Cyclobalanopsis glauca* (Thunb.) Oerst)、三斗石櫟(*Pasania hancei* (Benth.) Schottky)及川上氏櫧(*Pasania kawakamii* (Hay.) Schottky)之原因係因其為中低海拔800~1900 m崩塌地常見之樹種。所使用之四種殼斗科樹種之小苗係於2018年6月取自林務局東勢林區管理處出雲山苗圃(120°910′230″E, 24°235′110″N)，苗高平均為17.2±0.3, 19.3±0.6, 16.5±0.4, 及20.6±0.5 cm。取回之各樹種苗木分別移植至30個試驗木箱(60×60×100 cm, l×w×h) 中，每箱1株。木箱中以取自嘉義山區崩塌地之土壤填充之。土壤為砂質壤土(含72.1%砂、20.4%坋土及7.5%黏土；比重2.62；土壤容積密度1.53%；孔隙度41%)。土壤之化學性質為pH 7.85；電導度0.12 ds m^{-1}；有機質0.06 g kg^{-1}；全氮量0.03%；磷20 mg kg^{-1}；鉀149 mg kg^{-1}；鈣3512 mg kg^{-1}；鎂315 mg kg^{-1}；鋅4.6 ppm；錳158 ppm；鐵345 ppm；銅1.6 ppm；鎘0.01 ppm；鉻0.68 ppm；鎳1.4 ppm及鉛4.2 ppm。移植後將苗木逢機排列於嘉義大學森林苗圃中(120°29′06.67″E, 23°01.69″N)，並有14個未種植之木箱作為對照組，且每五天澆水一次。所有木箱每二週輪流移動一次，以減少遮陰的影響，並保持木箱的方位不變。苗木培養2年後，分別進行根系性狀調查、垂直拉拔試驗及單根拉伸試驗，以探討各樹種根系結構型態、性狀及力學特性。

二、根系結構型態與性狀調查

根系結構與分布之調查係採用全根開挖法(Böhm 1979)，逢機選擇各樹種14個樣木之地下根部全面挖開，沖洗根系並拍照其全貌觀察紀錄後，利用照片製成根系側視圖，應用WinRHIZO (Regent Instruments, Quebec, Canada)軟體分析其總根長(total root length, TRL)、根表面積(root surface area, RSA)及根尖數(tips) (Bouma et al. 2000)。隨後，收集根系以75℃烘乾至恆重，稱取乾重。另外，以排水法(water displacement method)測定根體積(root volume, RV) (Pang et al. 2011)。將所得到的根系性狀參數，計算根密度(root density, RD)、根長密度(root length density, RLD)及根組織密度(root tissue density, RTD)，並將所得之數值與拉拔抗力，進行皮爾森積差相關分析，分析四個樹種拉拔抗力與根系性狀間的相關性。根系性狀參數：根質量密度(root density, RD, kg m^{-3})、根長密度(root length density, RLD, km m^{-3})、根組織密度(root tissue density, RTD, g cm^{-3})及比根長(specific root length, SRL, m g^{-1})之計算如式1、2、3、4 (Burylo et al. 2014)。

$RD = \frac{RM}{V}$ RM =根乾重 V =單位體積土壤 .... (式1)

$RLD = \frac{RL}{V}$ RL =總根長 V =單位體積土壤 .... (式2)

$RTD = \frac{RM}{V}$ RM =根乾重 V =根體積 .... (式3)

$SRL = \frac{RL}{RM}$ RM =根長 V =根乾重 .... (式 4)

根面積比(root area ratio, RAR)之調查與計算係將挖開樣木之表土，以每10 cm為一個級距，依土壤深度進行分類，1: 0~10 cm; 2: 10~20 cm; 3: 20~30 cm; 4: 30~40 cm; 5: 40~50 cm; 6: 50~60 cm; 7: 60~70 cm; 8: 70~80 cm; 9: 80~90 cm; 10: 90~100 cm共分為10類。使用游標尺測量每類根橫斷面直徑並計算其斷面積及加總，將根的總斷面積除以木箱斷面積，即得樣木的根面積比(式 5) (Bischetti et al. 2005)。

$RAR = \frac{\Sigma\pi r^2}{A}$ .... (式 5)

$\Sigma\pi r^2$ =每層土壤中根段面積和

A =每層土壤面積

二、植生力學試驗

逢機選取四樹種各14株苗木，進行垂直拉拔試驗及單根拉伸試驗，並將數據進行統計分析後，比較四個樹種根系拉拔抗力及單根抗拉強度之差異。

(一)垂直拉拔試驗(Vertical pullout test)

試驗前，先控制木箱之土壤水分，以土壤水分計量植株根系30 cm處之土壤含水率，調節至25%。隨後測量其植株高度，在距離根基10 cm處截斷，並秤取其地上部鮮重，根基直徑則以游標尺(精度0.01 mm)量測紀錄。再以自行設計的夾具鎖緊根基，套上鋼索接上荷重計(最大容量 5000 kg)，以垂直拉拔試驗機(U-Soft USPA-003，U-Soft Technology, Taipei, Taiwan)進行垂直拉拔試驗。拉拔試驗機之最大拉力容量為3000 kg，最大位移量為200 mm。隨後，將拉拔力以2 mm min^{-1}的速度緩慢施加，直至植株根系被拉拔出為止，並記錄位移與強度變化及最大拉拔抗力(maximum pullout resistance force, kN)。拉拔完成後，挖掘土壤中的根系並秤取其鮮重。再將各株苗木之根、莖、葉攜回實驗室，分別置入70℃烘箱中，烘至恆重後供計算其生物量。

(二)單根拉伸試驗

試驗中所使用的根段樣本是採自垂直拉拔試驗樣株之根系。將植株單根由地徑位置處依次分為上、中、下等三個部分進行剪裁，並將樣木根系分成不同直徑級(0~1, 1~2, 2~5,及5~10 mm) (Sudmeyer et al. 2004, Genet et al. 2008)，每株每徑級各剪30根，每段根試樣長度為8~10 cm。而後保存於內盛15%酒精之塑膠袋中，以保存其含水量並防止微生物分解，接著攜回實驗室儲存於4℃冰箱中，以保留其新鮮度(Bischetti et al. 2005, Mattia et al. 2005)。進行單根拉力試驗時，將長度8~10 cm的根段夾在單根拉伸試驗機(U-Soft USPT-003，精度0.01 kg，最大拉力500 kg)之上下夾具中，儀器設定拉伸速率為4.7 mm min^{-1}，拉距為5 cm。隨即進行根段拉伸試驗，記錄根段的最大拉力值(maximum tensile resistance force, Fmax)，並使用游標尺(精度0.01 mm)量測記錄根段中點的直徑，以計算根段之抗拉強度(tensile strength, Ts)(式6) (De Baets et al. 2008)，並分析單根抗拉強度與直徑之關係(式7) (Burylo et al. 2011)。

$T_s = \frac{4F_{max}}{\pi d_i^2}$ .... (式6)

T_s =抗拉強度
F_{max} =最大拉力(N)
d_i =根段中點的直徑
$Ts = \alpha \cdot d^{-\beta}$ .... (式7)
α與β為實驗值

三、統計分析

四樹種間根系性狀、垂直拉拔抗力及單根抗拉強度之差異係以單因子變異數分析及杜凱確實差異檢定法(Tukey’s honest significant difference test)分析。樹種間單根抗拉力、單根抗拉強度及根徑之關係則以迴歸分析法(Excel 2013 regression analysis, Microsoft Redmond, WA, USA)分析之。

結 果

一、根系結構分布與性狀

(一)根系結構分布

調查結果顯示，四樹種之根系結構型態均屬於垂直與水平(VH)型。二年生青剛櫟苗木之根系發育較川上氏櫧、卡氏櫧及三斗石櫟者為佳。二年生青剛櫟、卡氏櫧及川上氏櫧苗木之根系均可達80 cm之土壤深度，而三斗石櫟者較淺僅達70 cm (Fig. 1)。青剛櫟苗木之根系生長較茂密，而川上氏櫧、卡氏櫧及三斗石櫟者較稀疏。根面積比之分析結果顯示，四樹種大部分的根系分布於土壤上層30 cm處，根密度隨土壤深度而下降，而且四樹種間在0~40 cm之根面積比有顯著差異，以青剛櫟之根面積比為最高，川上氏櫧者次之，卡氏櫧者又次之，三斗石櫟者為最低(Fig. 2)。由四樹種垂直與水平型根系結構可知，其根系對土體之錨定力及穩定度均較水平型者為佳。此外，根面積比愈高者其根與土體之接觸面積愈大，對土體穩定度之貢獻亦愈大。

(二)生長表現

數據統計分析結果顯示，樹種間之高生長、基徑生長、主根長、總根長、根生物量及地上部生物量均呈現顯著差異(Table 1)。二年生青剛櫟苗木之生長表現顯著優於川上氏櫧、三斗石櫟及卡氏櫧者。綜合言之，青剛櫟之生長表現為最佳，川上氏櫧者次之，三斗石櫟與卡氏櫧者為最差。

(三)根系功能性狀

四樹種根系功能性狀之分析結果顯示，樹種間之根密度、根長密度、根表面積、根組織密度及根體積均呈現顯著差異(Table 2)。青剛櫟苗木之根系功能性狀顯著優於川上氏櫧、卡氏櫧及三斗石櫟者。整體而言，四樹種中以青剛櫟之根系功能性狀為最佳，川上氏櫧者次之，卡氏櫧者又次之，三斗石櫟者為最差。

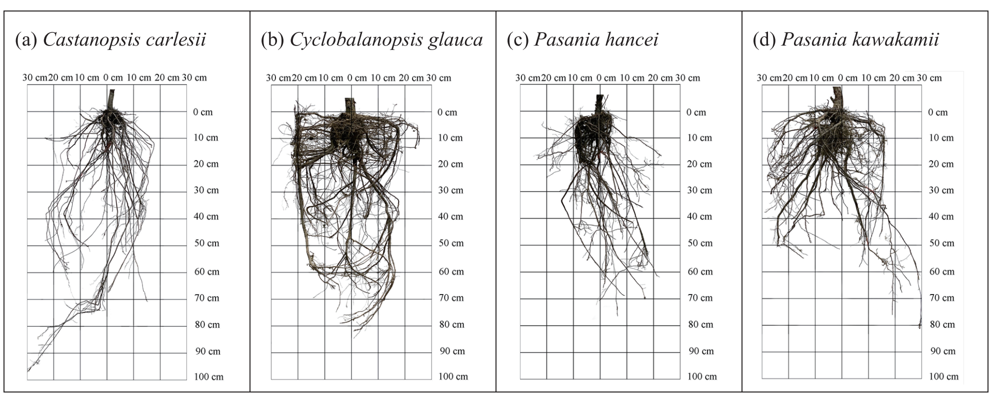

Fig. 1. Representative root system configuration of 2-yr-old *Castanopsis carlesii* (a), *Cyclobalanopsis glauca* (b), *Pasania hancei* (c), and *Pasania kawakamii* (d) seedlings.

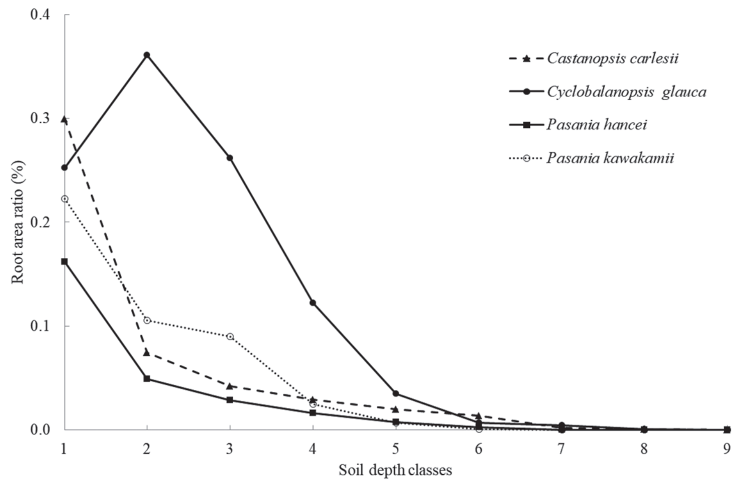

Fig. 2. Root area ratio (RAR) distribution with soil depth classes for 4 Fagaceae species. RAR = total root area (Ar) / area of soil profile (A). Class 1 (0~10 cm), class 2 (10~20 cm), class 3 (20~30 cm), class 4 (30~40 cm), class 5 (40~50 cm), class 6 (50~60 cm), and class 7 (60~70 cm).

Table 1. Means±standard errors of growth performance for 4 Fagaceae species and a 1-way analysis of variance (ANOVA)

Growth parameters	*Cas. carlesii*	*Cyc. glauca*	*P. hancei*	*P. kawakamii*	ANOVA
H (cm)	78.25±13.16[b]	186.17±15.61[a]	82.60±13.98[b]	109.8±6.18[b]	15.454***
RCD (mm)	14.06±1.67[c]	28.93±1.25[a]	14.06±2.38[c]	22.51±1.24[b]	19.484***
TL (cm)	57.50±7.5[a]	56.67±4.22[a]	38±87[b]	38±3.74[b]	3.481*
Tips	1010.25±214.7[a]	1737.33±161.46[a]	1196.40±327.76[a]	1457.2±163.43[a]	2.393 ns
TRL (cm)	1567.65±307.84[b]	3384.41±647.44[a]	1648.13±369.94[b]	2446.83±313.36[b]	7.649**
RB (kg)	0.04±0.02[c]	0.31±0.03[a]	0.05±0.01[c]	0.14±0.03[B]	31.099***
SB (kg)	0.04±0.01[c]	0.46±0.06[a]	0.07±0.02[c]	0.18±0.03b	22.777***

Cas., *Castanopsis*; *Cyc*., *Cyclobalanopsis*; *P*., *Pasania*; H, shoot height; RCD, root collar diameter; TL, taproot length; Tips, number of root tips; TRL, total root length; RB, root biomass; SB, shoot biomass. Different letters in the same row signify a significant difference (by Tukey's test) among species. $N = 14$. Levels of significance: ns, non-significant, * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

二、根系力學特性

(一) 根系之拉拔抗力

垂直拉拔試驗顯示，四樹種之拉拔抗力隨拉拔力之升高而上升，直至根系斷裂後下降(Fig. 3)。ANOVA統計分析結果顯示，四樹種間之根系最大拉拔抗力有顯著之差異。其中以青剛櫟根系之最大拉拔抗力(4.79±0.42 kN)為最高 ，川上氏櫧者(1.34±0.17 kN)次之，卡氏櫧者(0.70±0.26 kN)又次之，三斗石櫟者(0.61±0.18 kN)為最低。青剛櫟之平均最大拉拔抗力顯著大於其他三樹種者(Table 3)。研究結果證實，二年生青剛櫟之根系錨定力顯著高於川上氏櫧、卡氏櫧及三斗石櫟者。造成拉拔抗力差異之原因與根系性狀參數有密切關係，根系性狀分析結果亦顯示，青剛櫟之根系功能性狀根密度、根長密度、根面積比、根組織密度、及根體積均顯著優於川上氏櫧、卡氏櫧及三斗石櫟者。

Table 2. Means±standard errors for root functional traits of the 4 species studied and 1-way analysis of variance (ANOVA)

Root traits	*Cas. carlesii*	*Cyc. glauca*	*P. hancei*	*P. kawakamii*	ANOVA
RD (kg m^{-3})	0.75±0.31[c]	5.69±0.49[a]	1.01±0.27[c]	2.6±0.48[b]	31.097***
RLD (km m^{-3})	0.29±0.06[b]	0.63±0.12[a]	0.31±0.07[b]	0.45±0.06[b]	7.652**
RSA (cm^2)	932.87±204.97[b]	2779.85±533.99[a]	1053.96±188.23[b]	1553.18±196.83[b]	18.015***
RTD (g cm^{-3})	0.32±0.08[a]	0.61±0.03[a]	0.46±0.05[ab]	0.47±0.06[ab]	4.474**
RV (cm^3)	115±20.21[c]	511.67±50.56[a]	137±47.32[c]	302±38.26[b]	18.326***
SRL (m g^{-1})	0.56±0.16[a]	0.11±0.02[a]	0.38±0.12[a]	0.2±0.05[a]	4.846**

Cas., *Castanopsis*; *Cyc*., *Cyclobalanopsis*; *P*., *Pasania*; RD, root density; RLD, root length density; RM, root mass; RSA, root surface area; RTD, root tissue density; RV, root volume; SRL, specific root length. Different letters in the same row signify a significant difference (by Tukey's test) among species. $N = 14$. Levels of significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

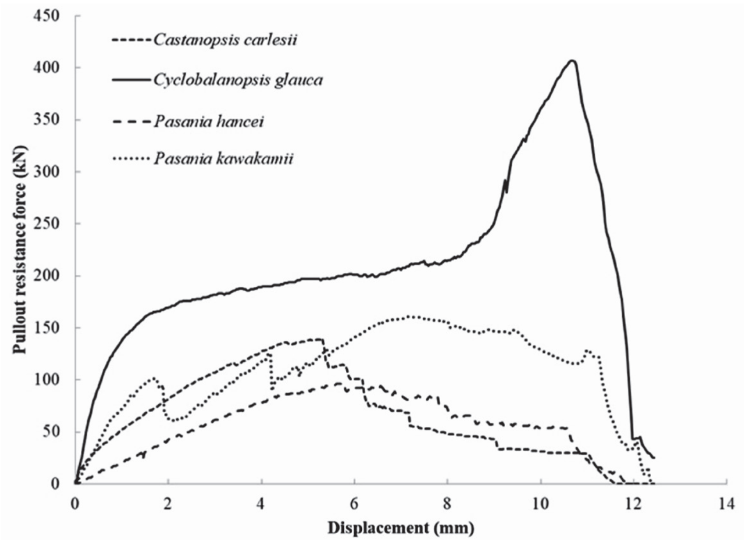

Fig. 3. Typical pullout force-displacement curves for 4 Fagaceae species.

(二)單根抗拉強度

分析結果顯示，四樹種之單根直徑、單根抗拉力及單根抗拉強度間均呈顯著差異。青剛櫟之平均單根直徑(4.38±0.21 mm) 顯著大於川上氏櫧(4.38±0.21 mm)、三斗石櫟(2.29±0.13 mm)及卡氏櫧(2.00±0.13 mm)。青剛櫟之單根抗拉力(383.41±34.47 N)顯著高於川上氏櫧(146.57±16.34 N)、三斗石櫟(70.70±6.89 N)及卡氏櫧(69.59±9.55 N)者；而青剛櫟之單根抗拉強度(218.41±6.40 MPa)、川上氏櫧(213.95±7.26 MPa)、卡氏櫧(201.91±8.08 MPa)顯著高於三斗石櫟(168.02±10.97 MPa) (Table 4)。迴歸分析結果顯示，四樹種之單根抗拉力與根徑呈顯著正相關(Fig. 4)，而其單根抗拉強度在根直徑0~1.5 mm部分，從分布狀況可見負相關，抗拉強度隨直徑增加而降低，在直徑1.5~9 mm部分則沒有相關(Fig. 5)。

討 論

本研究結果顯示，卡氏櫧、青剛櫟、三斗石櫟及川上氏櫧之根系結構型態均屬於垂直水平型(Yen 1987)。林地現場勘查發現，青剛櫟、川上氏櫧、卡氏櫧及三斗石櫟大多分布於崩塌

Table 3. Means±standard errors of maximum pullout resistance force for 4 Fagaceae species and a 1-way analysis of variance (ANOVA)

Biomechanical property	*Cas. carlesii*	*Cyc. glauca*	*P. hancei*	*P. kawakamii*	ANOVA (*F*)
Maximum pullout resistance force (kN)	0.70±0.26[b]	4.79±0.42[a]	0.61±0.18[b]	1.34±0.17[b]	6.612***

Cas., *Castanopsis*; *Cyc*., *Cyclobalanopsis*; *P*., *Pasania*. Different letters in the same row indicate a significant difference (by an ANOVA and Tukey's test) among species (N = 14). Level of significance: *** $p < 0.001$.

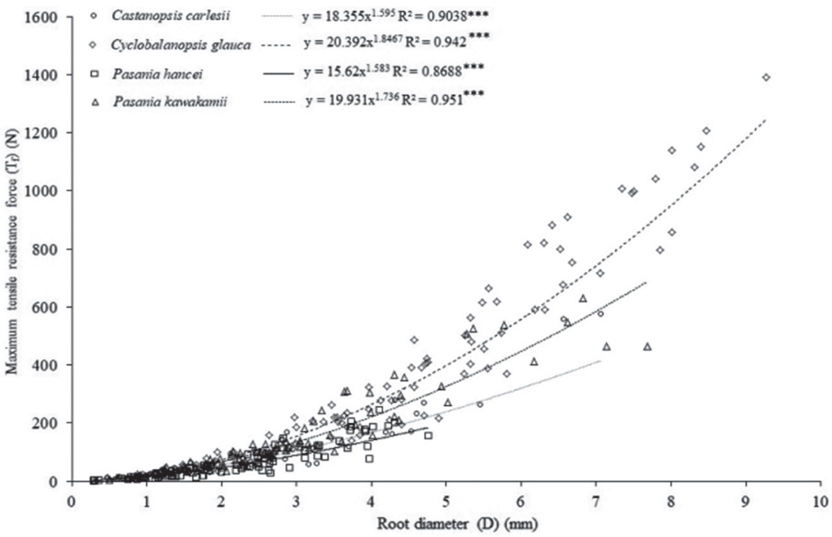

Fig. 4. Relationships between root tensile resistance force and root diameter for 4 Fagaceae species.

Table 4. Means±standard errors of root diameter, root tensile resistance force, and root tensile strength for 4 Fagaceae species and a 1-way analysis of variance (ANOVA)

Parameters	*Cas. carlesii*	*Cyc. glauca*	*P. hancei*	*P. kawakamii*	ANOVA (*F*)
Root diameter (mm)	2.00±0.13[bc]	4.38±0.21[a]	2.29±0.13[bc]	2.77±0.18[b]	43.209***
Tensile resistance force (N)	69.59±9.55[c]	383.41±34.47[a]	70.70±6.89[c]	146.57±16.34[b]	52.247***
Tensile strength (MPa)	201.91±8.08[a]	218.41±6.40[a]	168.02±10.97[b]	213.95±7.26[a]	7.229***

Cas., *Castanopsis*; *Cyc*., *Cyclobalanopsis*; *P*., *Pasania*. Different letters in the same row signify a significant difference (by an ANOVA and Tukey's test) among species. Level of significance: *** $p < 0.001$.

地山坡之中段。因此，本研究建議青剛櫟、川上氏櫧、卡氏櫧及三斗石櫟可應用於山坡中段之植生護坡工程。前人研究亦證實，具有茂密且深根系之樹種較具穩定土壤之能力(Danjon and Reubens 2008, Ghestem et al. 2014)。Fan and Chen (2010)指出垂直水平型根系有利於邊坡之穩定。Saifuddin and Normaniza (2016)之研究亦顯示，垂直水平型根系之樹木適合於栽植在山坡中段。根面積比之分析結果顯示，四樹種之根系分布具顯著差異，根系大都分布在土壤上層30 cm處，且隨土層深度而下降，與其他研究結果相一致(Jobbágy and Jackson 2001, February and Higgins 2010)。此一結果顯示，植物根系分布在崩塌地淺層之貧瘠土壤上層以攝取水分及養分(Ford 2014, Kiba and Krapp 2016)，而且根系較深且密者較具獲取養分及水

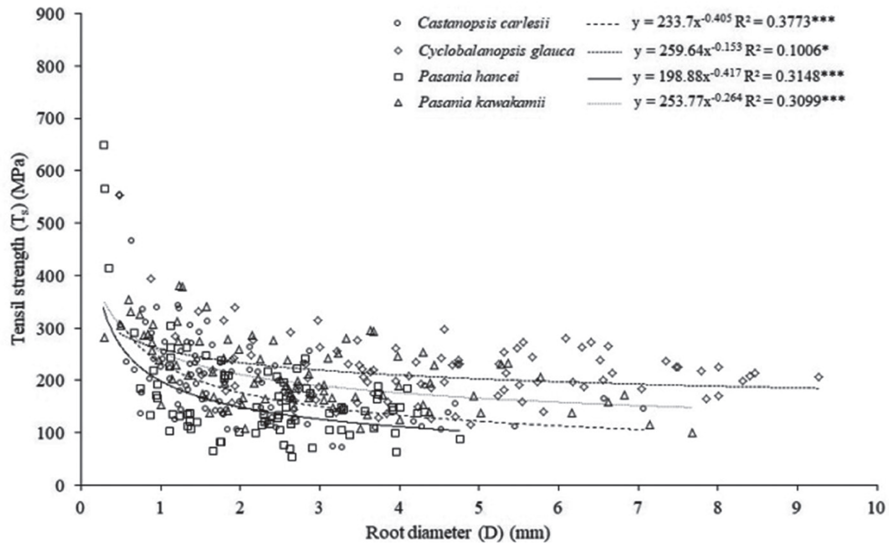

Fig. 5. Relationships between root tensile strength and root diameter for 4 Fagaceae species.

分之能力(Wasson et al. 2012)。青剛櫟之根系為四樹種中較密且深者，很適合於應用在崩塌地之植生復育工程。

在生長表現方面，青剛櫟苗木之生長為最佳，川上氏櫧者次，三斗石櫟與卡氏櫧者為最差。就根系功能性狀而論，青剛櫟苗木之根系功能性狀為最優，川上氏櫧者次之，卡氏櫧者又次之，三斗石櫟者為最差。此一結果亦證實，由於青剛櫟苗木之生長表現與根系功能性狀均顯著優於其他三樹種，所以很適合作為崩塌地植生復育樹種。

垂直拉拔試驗結果顯示，青剛櫟根系之最大拉拔抗力顯著大於其他三樹種者。青剛櫟根系之最大拉拔抗力為川上氏櫧者之3.5倍，為卡氏櫧與三斗石櫟者之7倍。此一結果證實，青剛櫟根系具有最佳之錨定力，有利於增進崩塌地邊坡之穩定度。

單根拉伸試驗結果顯示，青剛櫟之平均單根直徑顯著大於川上氏櫧、三斗石櫟及卡氏櫧者。青剛櫟之單根抗拉力顯著高於川上氏櫧、三斗石櫟及卡氏櫧者；而青剛櫟、川上氏櫧及卡氏櫧之單根抗拉強度亦顯著高於三斗石櫟者。迴歸分析結果顯示，單根抗拉力與根徑呈顯著正相關，而單根抗拉強度則與根徑呈顯著負相關。其他研究結果亦證實此一相關性(Genet et al. 2005, Capilleri et al. 2016, Lee et al. 2020)。Genet et al. (2005)指出，此一相關性與根纖維素含量有關；然Zhang et al. (2014)將其歸因於根木質素與根纖維素含量比。此外，林木根部內部組成是木材，木材的密度及強度也會影響根的抗拉強度。青剛櫟、三斗石櫟、卡氏櫧及川上氏櫧之木材密度及強度亦有差異。青剛櫟、三斗石櫟、卡氏櫧及川上氏櫧之木材密度分別為0.767、0.657、0.609及0.598；而其剪斷強度分別為292±29、201±27、253±47、170±34 kgf cm^{-2} (Wang 1983)。

實際在邊坡防護的植生工程上，植物根系之結構、功能性狀及力學性質對邊坡土壤之錨錠穩定作用影響甚大。青剛櫟之生長表現、與根系功能性狀、拉拔抗力及單根抗拉強度均顯著優於川上氏櫧、卡氏櫧及三斗石櫟者。因此，依據本研究結果建議四種殼斗科樹種在造林樹種的選擇順序可考慮為：青剛櫟＞川上氏櫧＞卡氏櫧＞三斗石櫟。此外，本研究證實根系性狀參數，如根密度、根長密度、根表面積、根組織密度及根體積，可配合根系力學數據如根系拉拔抗力及單根抗拉強度，實際應用於邊坡穩定分析。

結論

本研究結果顯示，二年生卡氏櫧、青剛櫟、三斗石櫟及川上氏櫧苗木之根系結構為垂直水平型。青剛櫟苗木之生長表現及根系功能性狀均顯著優於川上氏櫧、卡氏櫧及三斗石櫟者。青剛櫟苗木根系之最大拉拔抗力顯著大於川上氏櫧、卡氏櫧及三斗石櫟者。青剛櫟之單根抗拉力為四樹種中最高者；而青剛櫟、川上氏櫧及卡氏櫧之單根抗拉強度亦顯著高於三斗石櫟者。綜合以上所述及其他有關四樹種苗木之根系型態之研究，青剛櫟具有最佳之生長表現、根系功能性狀、拉拔抗力及抗拉強度，有利於增進崩塌地邊坡之穩定度，很適合作為崩塌地生態復育之樹種。依據本研究結果建議四種殼斗科樹種在造林樹種的選擇順序可考慮為：青剛櫟＞川上氏櫧＞卡氏櫧＞三斗石櫟。

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