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Evaluation of equivalent peak load for a plant species using Root Perpendicular Model and Fibre Bundle Model

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Abstract. Vegetation cover has a significant role in holding soil mass and preventing rainfall-induced slope failures. Earlier researchers have studied the root characteristics for different vegetation species and correlated them to obtain various parameters for quantifying root reinforcement. Among them, the apparent root cohesion parameter has been adopted widely to study root reinforcement for soil erosion and shallow failures. Two different models i.e., Root Perpendicular Model and Fibre Bundle Model (FBM) have been proposed, in the literature to quantify the mechanical reinforcement by roots in the soil mass. The root perpendicular model assumes catastrophic failure of roots of a species whereas the Fiber bundle model assumes progressive failure. The present study compares the maximum equivalent load for *Prunus Cerasoides* species using both the models and the result was compared. The study concludes that the progressive failure assumption of the fiber bundle model resembles the precise nature of root failure when the soil is subjected to shear stresses whereas the individual root failure occurs according to the root tensile strength capacity and root diameter. However, to compensate for the over-estimation from both the models, the study highlights the significance of several roots and soil characteristics while adopting different models for root cohesion estimation.

Keywords: Root Perpendicular model, Fibre Bundle Model, Root Reinforcement, Slope Failure, Apparent Root Cohesion

1 Introduction

Slope instability in hilly regions has been a major concern in the civil engineering practice. The slope failures are attributed to several natural and man-made causes such as un-engineered cuts, blasting, poor drainage facility, overgrazing, under felling of trees, and economic decisions in the infrastructure development. Along with these activities, the removal of vegetation from the slope leaves the topsoil loose and vulnerable to storm events that allow water infiltration into the soil mass. Subsequently, the development of pore water pressure destabilizes the soil mass leading to land- slides.

In light of the above, several methods in the past have been adopted in civil engineering practices to mitigate slope failures such as rockfall barriers, retaining walls, soil nailing, and the application of geosynthetics [1]. However, the large extent, steep slopes, terrain, and the ecosystem of ranges such as the Himalayas pose challenges to the existence and maintenance of such ground engineering solutions. Therefore, alternate reinforcement strategies by prioritizing sustainability and economy are being researched globally and adopted such as eco-technical solutions, and the application of vegetation for improving slope stability in several earlier practices [2, 3, 4, 5, 6].

The vegetation augments slope stability through the mechanical and hydrological characteristics of its roots [7, 8, 9]. The shear strength of soil mass transfers to the roots through the soil-root interface and mobilizes root tensile strength that develops resistance to soil failure [10, 11]. Similarly, several other factors were investigated in the past, including the pull-out capacity of roots, root architecture, root morphology, root anatomy, and root biomass concentration [12, 13, 14, 15, 16]. The above parameters were interlinked to define and quantify root reinforcement for different vegetation species in terms of Root Length Density, Root Density, Root Area Ratio, and Root Cohesion by several researchers [17, 18].

The mechanism for root reinforcement to soil has been explained using two well-established reinforcement models [11, 19]. Herein the load transfer from soil mass to roots, load distribution to individual roots of a plant structure, and the breakage of roots for final contribution to soil reinforcement have been explained. The Root Perpendicular Model (RPM) assumes the simultaneous failure of roots [11] whereas the Fiber Bundle Model (FBM) assumes the progressive failure of roots under shear stress in the soil mass [19]. Both the models have several limitations associated and therefore modifications related to load distribution among the root structure using root reinforcement models were studied and suggested by researchers in the past [10, 20, 21, 22, 23].

This study investigates the load distribution in the roots of *Prunus cerasoides sp.* and evaluates the maximum load that could be sustained by the root structure employ-ing RPM and FBM models. The root architecture of the plant species was analyzed using image analysis and the tensile strength of the individual root specimens was obtained from tensile testing. This study critically compared the equivalent maximum load obtained from the models and highlighted the significance of several features to be included further in future studies.

2 Methodology

2.1 Root Architectural Characteristics

The tree species *Prunus cerasoides* growing in the plant nursery of IIT Mandi under controlled environmental conditions were selected for the study due to their VH-type root structure [18]. The root structure was washed and extracted carefully from the soil by soaking it in water (Fig. 1). The root images were taken with a high-resolution camera and analyzed using the open-access SmartRoot tool. The information such as root diameter, root length, and branching was obtained using the tool. Further, the root specimens were separated from the structure for the root tensile testing.

Fig. 1 Root architecture of *Prunus Cerasoides*

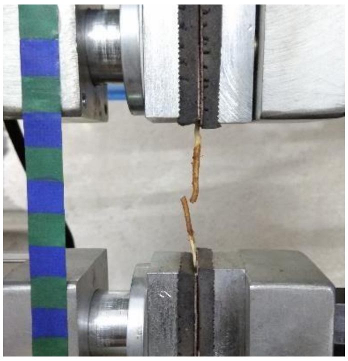

Fig. 2 Tensile testing set-up in UTM

2.2 Root Mechanical Testing

The mechanical testing for studying load-deformation of different specimens was carried out using the Universal Testing Machine, UTM (specimen set-up is depicted in Fig. 2). The root specimens were prepared by cutting individual roots of similar root lengths across the specimens and the tensile strength testing was carried out un- der the constant strain rate according to the previous studies [8]. The peak load for all the specimens including primary and secondary roots was obtained. The equivalent load depicting the contribution of root structure was obtained using the peak load of individual specimens using different reinforcement models as described in the following section.

2.3 Root Reinforcement

Root Perpendicular Model (RPM). The quantification of root reinforcement to the soil was first proposed in the study, [11]. It was observed that the root reinforcement to the shearing soil mass is a function of root tensile strength and the area occupied by individual roots in the unit area of soil mass. However, the major assumptions of the model were: (i) the full tensile strength mobilizes for all the roots and there would be a simultaneous failure upon soil shearing, and (ii) all the roots were parallel to each other and perpendicular to the shear plane. Therefore, the equivalent load carried by the whole root structure to fail simultaneously was evaluated as the total load carried by individual root specimens in the root structure.

Fiber Bundle Model (FBM). In a modification to the assumption of simultaneous root failure, the fiber bundle model assumes that the total load (due to shear stress in soil) is distributed equally to individual roots in the structure. Therefore, for an in- stance under a certain load, a root would break if the load exceeds its peak load capac-ity. In this process, the weakest root fails first, and the total load would be further distributed to the remaining roots. With reference to this model, the equivalent load carried by the root structure was evaluated as per the study [24]. However, the major assumption in this model was that the roots were considered parallel to each other as well as the shear plane, which could not ideally be possible either for all roots. Therefore, the application of different models for estimating equivalent load using different models has been discussed in the context of soil stability.

3 Results

3.1 Root Characteristics

The root architectural characteristics of the *Prunus cerasoides sp.* computed from the SmartRoot tool have been shown in Table 1. The root characteristics obtained fromthe analysis indicated that the root structure consists of a primary root and several lateral roots connected to it at different points, this could also be realized in Fig. 1.The distribution and variation of root diameter and root length were depicted in Table 1. The primary root was the thickest and longest with root diameter and length of 0.53 cm and 20.15 cm respectively. The root surface area and volume were also computed based on the root diameter and length.

Table 1 Root architectural characteristics of *Prunus Cerasoides* sp. computed from SmartRoot

Root ontology	Parent name	Root diameter (cm)	Root length (cm)	Root surface area (cm^2)	Root volume (cm^3)
Primary		0.53	20.15	36.28	5.55
Lateral	Primary	0.25	16.27	12.51	0.77
Lateral	Primary	0.16	5.58	2.95	0.13
Lateral	Primary	0.23	1.86	1.37	0.08
Lateral	Primary	0.06	6.90	1.53	0.03
Lateral	Primary	0.06	2.67	0.50	0.01
Lateral	Primary	0.04	4.10	0.56	0.01
Lateral	Primary	0.03	4.69	0.55	0.01
Lateral	Primary	0.05	3.35	0.61	0.01
Lateral	Primary	0.04	3.35	0.51	0.01

3.2 Equivalent Load Contribution from Different Reinforcement Models

The load corresponding to the failure of each root specimen as observed from the tensile strength testing has been reported in Table 2. It was observed from the load-deformation studies that the tensile strength was inversely proportional to the root diameter, which is in accordance with the previous studies [8].

Table 2 Root reinforcement by *Prunus Cerasoides* sp.

Diameter (cm)	Force (kgf)	Weight assigned (w)	Weighted force (w X force) (kgf)	Tensile strength (kgf/cm^2)	Stress distribution (kgf/cm^2) (FBM calculations)				
					I1	I2	I3	I4	I5
0.53	18.49	1	**18.49**	82.99	8.29	20.75	27.66	41.49	82.99
0.25	6.19	2	12.38	130.61	39.03	97.57	130.09	195.14	
0.23	5.77	3	17.33	134.38	43.01	107.52	143.37		
0.16	3.44	4	13.79	166.42	89.24	223.10			

0.06	0.94	5	4.74	284.21	554.57				
0.06	0.83	6	4.99	299.92	666.43				
0.05	0.66	7	4.66	329.02	914.14				
0.04	0.59	8	4.79	343.60	1059.96				
0.04	0.50	9	4.55	368.73	1348.79				
0.03	0.39	10	3.93	409.27	1925.58				
Total	**37.86**								

According to FBM, for evaluating the root reinforcement by whole root structure, the force required for the failure of each root specimen was arranged and the corresponding weights were assigned according to the study [24]. Here, the peak force of 18.49 kgf/cm^2 could be considered as the total load capacity by the root structure showing the individual roots failing progressively. This outcome was supported by iterations in the stress distribution among the individual roots considering the total load as 18.49 kgf/cm^2. According to Table 2, the first iteration (I1) observed failure ofsix roots where the stress exceeds the tensile strength of the corresponding root. Therefore, in the second iteration (I2), the total load of 18.49 kgf/cm^2 was distributed among the remaining roots of the structure, and the process iterated till the failure of the last root was observed under this load. Hence the total load of 18.49 kgf/cm^2 couldbe considered as the contribution of root structure according to the FBM.

Similarly, the total load for simultaneous breaking of roots in the root structure (according to RPM) would be 185 kgf/cm^2 (i.e., 10 times that of FBM's) and could even be observed as much greater than the summation of individual peak load carried by the individual root specimens (i.e., 37.86 kgf/cm^2).

4 Discussion

In this study, the equivalent tensile load contribution by the plant of *Prunus cera- soides sp.* was evaluated using two different root reinforcement models. A difference of 10-fold was observed between the equivalent load obtained from RPM and FBM. The RPM was developed assuming the catastrophic failure of roots perpendicular to the failure plane of a root structure while soil shearing. Similarly, the FBM proposed the progressive failure of different roots in a root structure that resembles a more real- istic failure approach in nature. However, the RPM explains a more realistic stress transfer mechanism between soil mass and perpendicular roots. Therefore, both the models have a major limitation associated with the natural root architecture of the vegetation.

The *Prunus cerasoides sp.* has a VH-type of root structure that contains secondary roots inclined to different angles with respect to the vertical (see Fig. 1). Similarly, from Table 1, it could be observed that the root structure was comprised of roots of different diameter range i.e., above 2 mm, below 2 mm including several finer roots ($d < 0.1$ cm) [8]. The straight and coarse roots such as the primary root (Table 1)might undergo stress mobilization under lower strain when compared to fine rootsthat might observe straightening of roots and stress mobilization at higher strain [10]. Therefore, the root orientation and structure could affect the stress distribution on roots and contribute to the shear strength of reinforced soil differently.

The earlier researchers had also observed that upon shearing of soil mass, the stress transfers via root-soil interface where fine roots break in tension whereas coarse root might overcome soil friction and slips out of the matrix [10]. Hence further stress redistribution takes place until the whole effective length of root for friction exceeds the total root length or root breaks, whichever takes place earlier [10]. Further, the study [12] observed through the large direct shear that the root morphology i.e., whereroots inclined to the vertical in direction of shear and that opposite to shear behave differently while shearing. It implies the significance of root morphology while eval- uating the shear strength of vegetation species. However, the factor for accounting for the effect of root inclination on apparent root cohesion has been considered 1.2 [11] which remains valid for the angle of internal friction greater than 35° [23]. This signi- fies the importance of including soil characteristics in the root reinforcement models.

Furthermore, the overall root's contribution to the soil shear strength depends upon mechanical as well as hydrological characteristics of roots [7]. This highlights that the effect of matric suction developed by the roots needs to be considered in the root reinforcement models. Similarly, the development and release of pore water pressure and its effect on soil density and angle of internal friction affect the root-soil stress transfer mechanism. Therefore, the effects of spatial and temporal variation must be considered in soil bio-engineering works. This signifies the further scope of modification of root reinforcement models including hydro-mechanical aspects of soil and roots.

5 Conclusion

In this study, the roots of *Prunus Cerasoides sp.* were analyzed for equivalent maximum load that a root structure could bear as a whole while shearing soil mass. Two different root reinforcement models were utilized to study the significance of root characteristics and load distribution of vegetation species. The following conclusions could be drawn from the study:

1) The equivalent load predicted using RPM was 10 times than that predicted from FBM and this was attributed to the assumptions in the models.
2) Root reinforcement has been observed as a factor of root morphology, and soil properties, and therefore parameters other than root diameter need to be included for equivalent load evaluation. Therefore, the reinforcement models need further modifications.
3) In the root-soil matrix anchorage mechanism plays a vital role in stress transfer. Therefore, coarse roots or the primary roots in trees contribute much via friction than the tension, and the failure mechanism, in that case, would be slippage only. The reinforcement models consider the breakage of all the roots present in the structure that need to be re-consider.
4) The progressive failure of roots as in the case of FBM observed to present a more realistic approach to stress distribution and root failure. Therefore, the assumptions could be further extended to study the propagation of failure surface in case of soil erosion and shallow failures where multiple or mixed species of vegetation are present on a slope.

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