Effect of plant roots on vane shearing resistance of two Fijian soils

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Abstract

Plant roots have been shown to significantly enhance soil stability and increase soil shearing resistance. Plants were selected on the basis of suitability for biological erosion control in the South Pacific region. Pot and plot treatments were established using soils from two sites in Fiji. Treatments were monitored for a period of 12 months and during this period, vane shearing resistance was measured at intervals of 2 months. Results showed that plant roots had a significantly positive effect on soil shearing resistance and on root-reinforcing effect (\(\Delta S\)). Plant root parameters which showed a highly positive correlation with \(\Delta S\) are root weight density, total cross-sectional area of roots, root length and root tensile strength at the shear plane.

1 Introduction

Plant roots have long been recognized as effective agents for protecting soil from soil erosion by impacting raindrops over land. However, the effect of plant roots on soil physical properties in these situations is less well understood. Gerard and Mehta (1971) reported that root crops increased bulk density, permeability and strength of soil.

Plant roots have also been shown to significantly enhance soil stability against downslope mass movement through the removal of soil water by transpiration and by mechanical reinforcement of the soil (Waldron and Dakessian, 1981, 1982). It was shown (Waldron, 1977; Waldron and Dakessian, 1982), that a range of plants (pine, oak, lucerne and grasses) increased shear resistance of soils and that this also depends on the type and age of plants. Woody plants are more effective than herbaceous plants in stabilizing soil against slips and slides over a long period of time (Waldron and Dakessian, 1982). Willatt and Saliyaningsih (1990) showed that rice roots increased both the bearing capacity and shearing resistance of soils and a linear relationship between these strength parameters was observed. Unpublished data (Willatt) shows that roots of vetiver grass and dadap have a positive effect on the shear strength of Fijian soils.

Measurement of soil shear strength is compounded by the fact that this soil mechanical property changes during the very process of measurement and is related to soil texture, soil structure and its water content. However, soil shear strength, \(\tau\) can be divided into two parts, given by Coulomb's equation:

\[ \tau = c + \sigma \tan \phi, \]

where \(c\) is the apparent cohesion, \(\sigma\) the stress normal to shear plane and \(\phi\) the angle of shearing resistance.


3 Experimental Methodology

3.1 Description of soils

Table 1 shows texture and mechanical analysis results of the two soils used.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Sample</th>
<th>Particle size distribution, percent sand, silt, clay and soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Soil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SAND</td>
</tr>
<tr>
<td>Waibau</td>
<td>38</td>
<td>2</td>
</tr>
<tr>
<td>USP Campus</td>
<td>40</td>
<td>11</td>
</tr>
</tbody>
</table>

3.2 Design of pot experiment

Pot experiments were established using soils collected from the Waibau Catchment of the Rewa River watershed and from The University of the South Pacific Suva Campus. The collected soils were air-dried and passed through a 5.0 mm sieve. The pot experiments were conducted in 200 mm diameter pots, with sixteen replications for each soil type giving 32 pots with approximately 3 kg of soil per pot. The plant treatments used for pots were Vetiver grass (\textit{Vetiveria zizanioides}), Turf grass (\textit{Axonopus compressus}) and Calliandra (\textit{Calliandra calothyrsus}). Four replications of each plant treatment for two soils were set up. The remaining 8

pots were used as control with no plant species. The soils which were free draining, were saturated and left overnight before planting. Vane shear resistance was measured at two depths (30 mm and 50 mm) prior to planting, and the following treatments were established:

Treatment I: Waibau soils with no plant species, (control pots).

Treatment II: Waibau soils planted with vetiver grass with 3 plants per pot.

Treatment III: Waibau soils planted with turf grass with 3 plants per pot.

Treatment IV: Waibau soils planted with calliandra plants with 3 plants per pot.

Treatment V: USP Campus soils with no plant species, (control pots).

Treatment VI: USP Campus soils planted with vetiver grass with 3 plants per pot.

Treatment VII: USP Campus soils planted with turf grass with 3 plants per pot.

Treatment VIII: USP Campus soils planted with calliandra plants with 3 plants per pot.

During the growing stages plants were kept in an open area and were exposed to natural weather conditions. Plants were saturated once every week and free drainage was permitted from the pots.

3.3 Design of plot experiments/location

Dalo (Colocasia esculenta) and Ginger (Zingiber officinale) plots were established in the Waibau catchment by The Fiji Ministry of Agriculture, Forestry and Fisheries in collaboration with The University of the South Pacific, to study the erodibility of Fiji soils on steep slopes (PACIFICLAND*). Waibau is located in the southeastern part of Viti Levu near the coast, at an altitude of about 200 metres. The valley of the Waibau Creek passes to the low countryside in the broad valley of the lower Waidina River.

Six plots, three each consisting of dalo and ginger, set up on the sloping land in the upper areas of Waibau, were monitored in this project. To study the relationship between plant roots and soil shearing resistance, two plots each of dalo and ginger were planted with biological barriers as soil stabilizers. The stabilizers, vetiver grass and pineapple were planted in four rows at 1, 8, 16 and 24 metre displacements across the length of the plots. For Waibau plots the treatments sampled were:

Treatment I: Dalo plot with no stabilizers (control plot).

Treatment 2: Dalo plot with pineapple used as stabilizer.

Treatment 3: Dalo plot with vetiver grass used as stabilizer.

Treatment 4: Ginger plot with no stabilizers (control plot).

Treatment 5: Ginger plot with pineapple used as stabilizer.

Treatment 6: Ginger plot with vetiver grass used as stabilizer.

Plots were monitored for one growing season for dalo and ginger, and during the growth stages vane shearing resistance was measured at intervals of two months.

At the USP Suva Campus, another plot was planted to study the effect of plant roots on soil shearing resistance for this soil. The plot consisted of two rows of vetiver grass two metres apart. This plot was monitored for a period of 12 months. Vane shearing resistance measurements were conducted at intervals of three months during the growing stages of vetiver grass, to determine the effect of vetiver grass on campus soil.

3.4 Shear measurement techniques

3.4.1 Pot experiments

To study the effect of plant roots on soil shearing resistance in the pot experiments; plants were grown for a period of 12 months. During the growing stages, shearing resistance was measured using the Eijkelkamp, self-recording, light weight vane shear tester, at intervals of 3 months for all treatments. The vane shear tester consists of exchangeable vanes attached to a torque meter. Shear measurements were taken by pushing the vanes into the soil to the required depth, and a slowly increasing torque was applied through the handles until the soil failed. Torque meter reading at yield point was recorded and converted to equivalent shearing resistance, in (kPa), depending on the size of vane used. About 30 hours prior to shearing resistance measurements, all pots were saturated with water. The object of wetting was to bring the water content of soils to field capacity. This was done for two reasons; that is, at field capacity the soil is near its weakest and most prone to mass movements, and shearing resistance is water content dependent. Two measurements of shearing resistance were taken at two depths (30 mm and 50 mm) per pot and water contents were determined using the gravimetric method.

At the end of 12 month experimental period, plants were uprooted and the roots of each species of plants were washed and dry weights at 65-70°C were determined to enable the calculation of root weight density (RWD), root length and root tensile strength (RTS). Root length was measured using the line intersect method formulated by Newman (1966).

* An Internal Board of Soil Research and Management (PACIFICLAND) funded project
Root weight density (RWD) was calculated as:
\[
\text{RWD} = \frac{\text{Dry weight of roots at (65-70°C) per pot}}{\text{Volume of soil per pot}}
\]

Root tensile strength was determined using "Griffins Tensiometer Testing Machine". Root specimens were held tightly between the two jaws of the machine, and a slowly increasing tensile force was applied until the root specimen failed. RTS was calculated as:
\[
\text{RTS} = \frac{\text{Maximum force at failure of root specimen}}{\text{Original cross-sectional area of roots}}
\]

3.4.2 Plot experiments
For the plot experiments, the shear measurement techniques described above were followed. The field soils were free draining, and attempt was made to determine the shearing resistance close to field capacity. Measurements were conducted, if the rainfall for one-week period exceeded 100 mm. Soil shearing resistance for the Waibau plots were measured at one metre intervals along three transects at a depth of 50 mm. At any one measuring time, 72 measurements (24 data points per transect) per plot were taken. Measured torque’s at yield point, at a particular displacement along the three transects were averaged and converted to equivalent shearing resistance (kPa).

For the USP Campus plot, vane shear measurements were taken at intervals of 200 mm along three transects across the plot at a depth of 50 mm. Measured torque’s at a particular displacement along the three transects were averaged and converted to equivalent shearing resistance (kPa).

4 Results
4.1 Pot experiments

Tables 2 and 3 show average shearing resistances (kPa) at 12 months and \( \Delta S \) (kPa) values at two depths (30 mm and 50 mm) for pot treatments. Table 2 is for USP campus soil and Table 3 for Waibau soil. \( \Delta S \) has been calculated as the difference between (shearing resistance for control bare pot at 0 month) and (shearing resistance for rooted treatments at 12 months), that is \( \Delta S = S_{12(12)} - S_{0(0)} \). Table 4 presents various root data such as average root cross-sectional area, root weight density, average root length and average root tensile strength for the plant treatments used for pot experiments. Table 5 is for bulk densities of pot treatments at 12 months. Tables 6 and 7 present summary of mathematical analysis on results (correlation coefficients and variance respectively).
Table 6: Average correlation coefficients ($r^2$) between plant root parameters (PRP) and shearing resistance, and (PRP) and $\Delta S$.

<table>
<thead>
<tr>
<th>PLANT ROOT PARAMETERS</th>
<th>CORRELATION COEFFICIENT ($r^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SHEARING RESISTANCE</td>
</tr>
<tr>
<td>Root Weight Density</td>
<td>0.89</td>
</tr>
<tr>
<td>Root Length</td>
<td>0.78</td>
</tr>
<tr>
<td>Root Tensile Strength</td>
<td>0.84</td>
</tr>
<tr>
<td>Root Cross-sectional Area</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Table 7: Analysis of Variance results for mean $\Delta S$ values for treatments at 5% level of significance

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Critical Region</th>
<th>Computed $f$</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalo Plots (Dalo/ Pineapple/ Vetiver)</td>
<td>$f &gt; 3.15$</td>
<td>$f = 91.62$</td>
<td>$\Delta S$ significantly different</td>
</tr>
<tr>
<td>Ginger Plots (Ginger/ Pineapple/ Vetiver)</td>
<td>$f &gt; 4.98$</td>
<td>$f = 80.61$</td>
<td>$\Delta S$ significantly different</td>
</tr>
<tr>
<td>Campus Pot (Turf/ Calliandra/ Vetiver)</td>
<td>$f &gt; 19$</td>
<td>$f = 38.46$</td>
<td>$\Delta S$ significantly different</td>
</tr>
<tr>
<td>Waibau Pot (Turf/ Calliandra/ Vetiver)</td>
<td>$f &gt; 19$</td>
<td>$f = 174.33$</td>
<td>$\Delta S$ significantly different</td>
</tr>
</tbody>
</table>

4.2 Plot experiments

In figures 1 to 6, shearing resistance (kPa) at 50 mm depth is plotted against distance (m), from the leading edge of the plots for 6 treatments at Waibau. Each point on the graph represents an average of three measurements. Figure 1 is for dalo control plot with no stabilizer, and shows that shearing resistance increases with time along the entire plot and peaks to a maximum average of 23 kPa.

Figure 2 shows results for the dalo plot with pineapple used as stabilizer. Shearing resistance increases with time and peaked to a maximum average of 56 kPa at 8 months resulting in $\Delta S$ value of 46 kPa. Particularly interesting is the effect of pineapple roots, resulting in higher shearing resistance at each sampling time around the pineapple rows at 1, 8, 16 and 24 metres.

Figure 3 shows results for dalo plot with vetiver grass used as stabilizer. Analyses of the graphs show that shearing resistance increases almost exponentially with time around vetiver rows to a maximum of 100 kPa at 8 months. This represents a tenfold increase compared with areas across the plot without vetiver grass. Presences of well-defined peaks around vetiver rows are clearly evident resulting in average $\Delta S$ value of 74 kPa.

Figure 4 shows results for ginger plot with no stabilizer. The graphs show that shearing resistance increases uniformly with time to a maximum of of 30 kPa.

Figure 5 shows results for ginger plot with pineapple used as stabilizer. Shearing resistance increases to a maximum of 54 kPa at 8 months resulting in a $\Delta S$ value of 38 kPa.

Effects of pineapple roots are more pronounced around pineapple rows, which represents a five-fold increase in shearing resistance.

Figure 6 shows results for ginger plot with vetiver grass used as stabilizer. Analyses of the graphs show that average shearing resistance increases almost exponentially around vetiver rows and peaks to a maximum of 95 kPa at 8 months. Effect of vetiver grass in stabilizing soil is again noticeable resulting in high $\Delta S$ value of 66 kPa.

Figure 7 shows shearing resistance (kPa) at 50 mm depth versus distance (m) along USP Campus plot, with vetiver as stabilizer. Results show that average shearing resistance increases with time around vetiver rows to a maximum of 80 kPa resulting in $\Delta S$ value of 65 kPa.

Figure 1: Shearing resistance (kPa) at 50 mm depth Vs distance (m) along Waibau dalo plot with no stabilizer.

Figure 2: Shearing resistance (kPa) at 50 mm depth Vs distance (m) along Waibau dalo/ pineapple plot.
5 Discussion

5.1 Campus pot experiments

Table 2 shows that vetiver grass treatment has a greater $\Delta S$ value at both depths compared with other treatments, and that shearing resistance also increases with depth for all treatments. Analysis of variance test for treatments suggest that mean $\Delta S$ values for the 3 treatments are significantly different at 5% level of significance. The differences in mean $\Delta S$ values can be accounted by a number of factors; such as root weight density, average root length, total average cross-sectional area of roots and root tensile strength (Table 4). Hence higher $\Delta S$ values for both vetiver grass and calliandra plant treatments at the shear plane should be regarded as a function of plant root parameters mentioned above. This is consistent with root-soil model developed by (Waldron, 1977; Endo, 1980), which showed $\Delta S$ to be directly proportional to total root cross-sectional area.
5.2 Waibau pot experiments
Comparison of average ΔS values at two depths (Table 3) show existence of a positive relation between ΔS and depth for all treatments. The increase in mean ΔS values with depth can be explained in terms of higher bulk densities observed at greater depths (Table 5). Analysis of variance tests show that mean ΔS values with treatments are significantly different at 5% level of significance. The difference in mean ΔS values can be attributed to plant root parameters as mentioned for campus soil (Table 4). High root weight density for vetiver grass may lead to formation of aggregates with increased aggregate strength and correspondingly high ΔS values (Materechera et al., 1991).

The slight increase in average shearing resistances for both USP and Waibau control experiments at 12 months may be attributed to age hardening (Utomo and Dexter, 1981) by particle reorientation and cementing between particles.

5.3 Waibau dalo plots
Analysis of variance test for treatments show that mean ΔS values for 3 treatments are significantly different at 5% level of significance. The differences in mean ΔS values can be attributed to plant root parameters listed for pot experiments (Table 4). Vetiver grass and pineapple roots with root tensile strength of (9.8 x 10^7 N/m²) and (4.1 x 10^7 N/m²) respectively, seem to have the capacity to increase shearing resistance not only around the roots but in the near neighborhood resulting in increased shearing resistance along the entire plot. The response of these roots is that they bind particles of soil into aggregates with increased strength.

Duncan’s multiple range test on mean ΔS values for 3 treatments, confirms that they are significantly different and that mean:

\[ ΔS_{(Dalo/Vetiver)} > ΔS_{(Dalo/Pineapple)} > ΔS_{(Dalo only)} \]

The significant increase in shearing resistance for dalo/plot without any stabilizer may be considered as a function of one or both of the two factors; effect of dalo roots, and age hardening of soil.

5.4 Waibau ginger plots
Analysis of variance test for treatments suggest that mean ΔS values for 3 treatments are significantly different at the 5% level of significance. The differences in mean ΔS values can be accounted for in terms of plant root parameters listed for Waibau dalo plots. Roots of vetiver grass and pineapple result in the formation of aggregates with increased strength.

Duncan’s multiple range test on mean ΔS confirms that mean:

\[ ΔS_{(Ginger/Vetiver)} > ΔS_{(Ginger/Pineapple)} > ΔS_{(Ginger only)} \]

The significant increase in shearing resistance for ginger with no stabilizer may be considered as a function of either the effect of ginger roots, or age hardening, (particle reorientation and cementing between particles), or both of these factors. Another factor which could contribute to high ΔS values for all treatments is the water content at sampling time. However, this effect should be minimum since all shearing resistance measurements were conducted near to field capacity.

6 Conclusion
Vane shear test data indicate that plant roots have a significantly positive effect on soil shearing resistance and root-reinforcement (ΔS). For both pot and plot experiments, vetiver grass has significantly greater root reinforcing effect (ΔS) compared with other plants. Plant root parameters which correlate most strongly with ΔS values are total cross-sectional area of roots, root weight density, root length and root tensile strength at the shear plane.

7 References