Vegetation-induced soil stabilization in coastal area: An example from a natural mangrove forest

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Abstract

Mangrove forests provide essential ecosystem services in tropical and semitropical regions by supporting their natural regeneration and other biosystem processes, offering livelihood for local communities, and contributing significantly to the natural resources. A systematic analysis on the protective role of mangrove forests and its effect on reducing coastal erosion is rare. Mangroves form a complex ecosystem that increases substrate stabilization and dissipates wave energy favouring the deposition of fine material. This study focuses on assessing the role of the roots of the white mangrove (*Avicennia marina* (Forssk.) Vierh.) in stabilizing the coastline. In a study site located in Southern Iran, a series of field and laboratory measurements of root systems collected from transects perpendicular to the coastline were conduceted. Root samples were collected from soil cores at fixed distances from the tree stem in three layers at seaward and landward positions. Moreover, Root tensile tests were conducted to estimate the biomechanical characteristics of roots that provided to the parameters of root reinforcement models. The spatial distribution of root reinforcement and the intrinsic-variability of stabilizing components in relation to horizontal and vertical distances from a tree stem were calculated. Three models of Wu & Waldron (W&W), Fiber Bundle (FBM), and Root Bundle Weibull (RBMw) were applied. The results showed that Root Volume Ratio (RVR) and the number of roots (NoR) decreased with distance from the tree stem. Root tensile forces increased with root diameter. Finally, calculated root reinforcements at 0.75 m distance associated with the highest value while the lowest value was observed at 1.50 m from the tree stem with a minor difference between seaward and landward positions. Soil detachment ratio (SDR) as approximately 10% higher at landwards positions than seaward, due to different geomorphological conditions that affected the soil detachment process. The similartity of the values of root reinforcement among root systems at seaward and landward positions may suggest that stem density would not be an important parameter in managing mangrove forests as a coastal protection measure. Yet, RVR at different distances and NoR by increasing significantly with soil depth and being different at seaward and landward positions, could improve their potential role as a nature-based solution for shoreline protection.

Keywords: *Avicennia marina*, root reinforcement, root system, soil-bioengineering, Soil Detachment Ratio.

1. Introduction

Coastal erosion is a significant hazard to coastal communities, and the mitigation of such hazard is challenging for many reasons (Dean and Galvin, 1976; Van Rijn, 2011). Nearshore vegetation affects the rate of erosion and deposition of sediments on sandy coasts by moderating the magnitude of tides and waves (Mitra, 2020). Vegetation including mangroves and seagrasses, change the hydrodynamics of waves such to dissipate energy and thus, slow down the process of erosion (Feagin et al., 2011; Shepard et al., 2011; Smee, 2019). Reduced wave velocity and turbulence may enhance sedimentation (Anderson and Smith, 2014; Cellone et al., 2016). Roots and rhizomes of nearshore vegetation may reinforce and stabilize coastal sediments. Hence, the propagation of nearshore vegetation may be considered a practical bioengineering method for the protection of coastal zones (Feagin et al., 2019).

Mangroves are unique forest ecosystems that reduce the negative impacts of natural soil erosion while maintaining services such as providing construction timber, firewood, charcoal, livestock forage, honey bee habitat and pharmaceutical herbs i.e. saponin, flavonoid, tannins (Rezaii, 1993; Bell and Lovelock, 2013; Thompson et al., 2017). In fact, mangroves mitigate coastal erosion during severe rainstorms by reducing the erosion caused by surge as well as reducing wind erosion (Das and Crépin 2013). They also protect coastal assets by providing bunds that face wave motion (Othman, 1994), stabilize the coastline by reducing wave erosion and enhancing sedimentation (Mazda et al. 2002). A global analysis showed that mangroves function as strong walls that break high waves and prevent water from intruding adjacent lands with high velocity causing excessive soil erosion (Gedan et al., 2011).

The south coast of Iran is covered with approximately 20,000 hectares of mangrove forests with patchy distribution. Among such ecosystems, the mangroves of Qeshm Island and Bandar-e Khamir are signigicant for their vast area (10,000 hectares), also having the highest diversity and largest mangrove-dependent community in the region (Sagheb-Talebi et al., 2014). Two endemic species of Iranian mangroves include the white mangrove (*Avicennia marina* (Forssk.) Vierh.), and the red mangrove (*Rhizophora mucronata* (Poir.)) (Safiari, 2003). As mentioned above, developing mangroves are considered an effective bioengineering method to protect soil against erosion as an alternative to conventional engineering methods (soil nailing or concrete piling). Yet ironically in the study area, they themselves are threatened by soil erosion from increasing flood events and forest degradation due to climate change and human interventions (Sagheb-Talebi et al., 2014). Little is known about the relationship between survival rates and biomass production of mangrove species and their impact on coastal erosion.

Seafront mangroves species such as *A. marina* have deep, twisted roots that spread like a net and trap soil, keeping it from erosion. Moreover, *A. marina* can tolerate extreme weather conditions and high salinity (Rippey and Rowland, 2004). Root systems control the hydrological and mechanical properties of soil in the rooting depth, favouring stabilization (Gyssels et al., 2005; Hudek et al., 2017; Schwarz et al., 2015; Sidle and Bogaard, 2016). Root reinforcement is influenced by root distribution also, the biomechanical characteristics of soil (e.g., Wu et al., 1979). Such condition is related to botanic, climatic and environmental factors (Hales et al., 2009; Hales & Miniat, 2017) i.e. plant species, stand origin and structure and physical and chemical properties of soil (Bischetti et al., 2005; Deljouei et al., 2020). It has been observed that root reinforcement is systematically dependent on various environmental conditions such as soil moisture (Fan and Su, 2009; Hales et al., 2009), plant functional types (Moresi et al., 2019, Hales, 2018), and plant age (Dazio et al., 2018). In this study, potential environmental controls on mangrove root reinforcement are considered which comprise depth of inundation and wave energy as they actually lack quantitative information.

Due to the factors of complex soil-root interactions, heterogenous root distribution and complicated mechanical properties of both soil and roots, assessing root reinforcement remains a challenge (Cohen et al., 2011). Analytical models for soil reinforcement have been developed over the last four decades to support the assessment of hillslope stability as well as to enable appropriate design of soil bioengineering methods (Bischetti et al., 2021; Phillips et al., 2021). Wu & Waldron (W&W) developed a pioneering mechanical model based on the assumption that roots are elastic fibers extending perpendicular to a shear surface and that all roots break at the same time (Wu, 1976; Waldron, 1977). Simplicity of the model led to its world-wide application (Mehtab et al., 2020). On the contrary, roots with different diameters break depending on their individual tensile strength after which the stress is redistributed over the remaining roots. So, the simplified W&W model associates with significant overestimation of root reinforcement (e.g., Operstein and Frydman, 2000; Pollen and Simon, 2005; Docker and Hubble, 2008). Pollen and Simon (2005) developed the Fiber Bundle Model (FBM) as a solution. The model assumes that all roots are parallel and have similar elastic properties. When each root breaks, the load is repetitively redistributed over the remaining roots until all roots (the entire bundle) are broken. Thereofre, the FBM model was found more conservative in estimating soil reinforcement (Bischetti et al., 2009; Mao et al., 2012). An extended version of FBM developed by Schwarz et al. (2013) was the Root Bundle Model weibull (RBMw). RBMw model is based on strain-step loading of a fiber bundle. It integrates a survival function that includes various mechanical properties of roots by implementing empirical relationships along with biomechanical and geometric characteristics of roots, and root distribution in soil. Compared to the

106 W&W model, RBMw requires more parameters, although it predicts more accurate results (Schwarz et al.,
107 2013).

108 This study investigates root characteristics and their mechanical behavior according to distances from the
109 stem at seaward and landward positions by applying different root-reinforcement models. Current knowledge of
110 the underground parts of the mangrove ecosystems is minute. While only few studies have shown that mangrove
111 species can protect shallower soil against coastal erosion (Thampanya et al., 2006; Van Tang et al., 2020), no
112 study has quantified soil reinforcement provided by mangrove roots. In particular, a systematic understanding of
113 Root Volume Ratio (RVR), Number of Roots (NoR), Root Length Density (RLD), and root resistance of
114 mangroves is obtained as measuring underground processes is very difficult, especially at regular flooding areas.
115 Hence, this study aims to: (i) investigate root characteristics and distribution (RVR, NoR, and RLD), (ii)
116 measure the mechanical properties of roots (i.e., root tensile), (iii) compare estimations of the root reinforcement
117 models of W&W, FBM, and RBMw and finally (iv) underline the accuracy of different methods by comparing
118 their estimations. Finally, the role of mangrove forests in protecting coastal erosion is verified by analyzing the
119 results.

120 **2. Material and methods**

121 *2.1. Study site*

122 Hara Biosphere Reserve situated between the southern coastline of the main body of Iran and the northern
123 coastline of Qeshm Island is chosen as the study site. The study focuses on the mangrove forests of Qeshm
124 Island (as part of Hormozgan province) with an area of ~6750 ha (Fig. 1). With an average annual precipitation
125 lower than 200 mm, the regional climate is dry and classified as subtropical. The evaporation rate is higher than
126 annual precipitation and the annual relative humidity is 64%. Therefore, the mangroves only reach heights of 3-
127 4 m. The soil (pH=7.67) has a very fine texture and consists of loam, sand, and clay. When saturated, it can
128 retain 56.8% of moisture (Mohammadizadeh et al., 2009). Electrical conductivity (EC) of the saturated soil and
129 water salinity is reported 63.5 dS/m and 37.5 to 38.5 ppt, respectively (Khodadadi-Jokari, 2003). Atmospheric
130 temperature varies from 10°C to 45°C, and the water temperature fluctuates as much as 20°C between summer
131 and winter. Tidal waves vary between 4.6 m (during fall and spring seasons) and 0.3 m (during winter and
132 summer seasons), respectively. During the high-tide season, the mangrove trees are submerged up to their
133 crowns.

Fig. 1. Location of mangrove forest in Qeshm Island

2.2. Measurements of root distribution and biomechanical properties

The underground biomass and root distribution were measured using the core sampling method for 10 *A. marina* trees (Montagnoli et al., 2012; Fortier et al., 2013; Berhongaray et al., 2015). Trees with the mean diameter of 0.25 m at breast height (DBH) were sampled by a hand-driven corer of 0.10 m diameter, 0.10 m length and 0.0079 m^3 volume. Samples were collected along transects perpendicular to the coastline at fixed distances of 0.75 m, 1.00 m, and 1.50 m from the tree stem at both seaward and landward positions and at 0.00-0.10 m (top layer), 0.10-0.20 m (midlayer), and 0.20-0.30 m (bottom layer) depths. Root biomass was collected in the field by sieving (0.002 m mesh size). Root diameters were measured in the field using a digital caliper. The final biomass was determined by washing and drying roots in a 70°C oven while weighing them until reaching a constant weight. RVR (in m^3 m^{-3}), is the total volume of roots in a particular soil volume (Ni et al., 2018); NoR (dimensionless) is the, Number of Roots (as a function of diameter); and RLD (Root Length Density, in m^{-2}) is the mean value of root length per sample soil volume which calculated. In addition, tensile tests were carried out on root samples collected around the tree stem.

2.3. Tensile measurements

Undamaged root specimens collected from each core were washed, sprayed with 15% alcohol, kept in plastics, and retained at 5°C until the tensile test was carried out (Chiaradia et al., 2016; Abdi and Deljouei,

2019). Within three days after the root sampling, tensile tests were conducted on fresh roots. Roots with the length of 0.15 m were placed in the clamps of the Universal Testing Machine (SANTAM Co./SMT-5, Tehran, Iran), and mechanical tests were conducted at a steady 10 mm min^{-1} speed until rupture. Only specimens that broke near the middle of the root segment were considered (Ji et al., 2012).

The main results of the tensile tests fit the relationships between the root diameter and biomechanical properties as follows:

$$F_{\max} = F_0 \phi^{\xi}, \quad (1)$$

$$E = E_0 \phi^{\beta}, \quad (2)$$

where F_{max} is root tensile resistance (N), E is root elasticity (MPa), F_0 and E_0 are constant coefficients (N and MPa, respectively), ξ and β are exponents (dimensionless), and ϕ is root diameter in mm.

2.4. Root reinforcement models

In this study, root reinforcement (C_r in N m^{-2}) assessment was conducted using three models: W&W, FBM and RBMw.

The W&W (Wu et al. 1988) model calculates root reinforcement assuming that all roots break at the same time and thus, each root contributes individually to the tensile resistance as follows:

$$C_r = k' \sum_{n=1}^{N} \frac{4F_{\max,n}}{\phi_n^{\,2}\pi}.RAR_n, \quad (3)$$

where k' is a coefficient of 1.2 (Wu, 1976), N is the number of classes of root diameter and RAR_n is the root area ratio (the ratio between soil area covered by roots and the entire soil profile, in m^2 m^{-2}) for the n-th class.

The FBM (Pollen and Simon, 2005) model applies load to the bundle of fibers and distributes it evenly over each root as a function of the number of roots in the bundle. The load is redistributed after each root breaks. This model assumes that the roots are perpendicular to the shear surface and the distribution of stress across the roots is uniform (Schwarz et al., 2010b). The shortcoming of this method is that the heterogeneous distribution of load due to different stiffness root diameter classes are not considered (Schwarz et al., 2010b). The formulation of FBM is as follows:

$$C_r = \max\left(\frac{4F_{\max,j}}{\phi_j^2\pi}.RAR_j.j\right), \quad (4)$$

where j is the weakest root which is still intact upon loading of the root bundle, RAR_j is the RAR of the root j.

The RBMw (Schwarz et al., 2013) model, is a strain-step fiber bundle model that considers the failure probability of roots due to its variable mechanical properties. RBMw simulates force-displacement behavior of a root bundle based on a distribution of root diameter and a series of power-distributed relationships between biomechanical properties (Eqs. 1 and 2) and ϕ, and between root length (L in mm) and ϕ (Eq. 5).

$$L = L_0 \phi^{\alpha} \quad , \tag{5}$$

where L_0 is a constant coefficient (in mm), and α is an exponent value (dimensionless).

C_r is calculated by summing up the force contributions F (in N) for each root multiplied by the Weibull survival function S, as follows:

$$C_r = \sum_{i=1}^{N} F(\phi_i, \Delta x) S(\Delta x^*) \quad , \tag{6}$$

where Δx is the displacement unit in mm and S is a function of the normalized displacement Δx^*. The following equation calculates $S(\Delta x^*)$:

$$S(\Delta x^*) = \exp\left[-\left(\frac{\Delta x^*}{\lambda} \right)^{\omega} \right] \quad , \tag{7}$$

where λ and ω (dimensionless) are scale and shape Weibull parameters, respectively.

The ratio between displacement is estimated by each tensile test and the corresponding displacement values are calculated using fitted values of tensile forces:

$$F(\phi_i, \Delta x) = \frac{\pi E_0}{4 L_0} \phi_i^{2+\beta-\alpha} \qquad F(\phi_i, \Delta x) < F_{max}(\phi_i) \tag{8}$$

In this research, all input parameters (F_0, E_0, L_0, ξ, β, and α) were calculated from tensile tests.

2.5. Soil detachment ratio

Erosion of estuaries that contain mangroves occurs primarily through the action of waves and tides that apply shear stress on surface sediments (Nguyen & Luong, 2019). Rates of soil detachment depend on the magnitude of the shear stress applied, and is resisted by the cohesion of the sediment as well as the subsurface

200 root system. *A. marina* roots develop a fibrous mat in shallow subsurface (Baylis, 1950) that adds support
201 against such flow erosion. Without a mangrove specific erosion rule, soil detachment rates (SDR) were
202 calculated using a standard equation developed for terrestrial root systems that are subject to concentrated flow
203 erosion. SDR was calculated as

204 $$SDR = \exp^{(-b \times RD)} \exp^{(-c \times RD \times \phi)} \quad , \tag{9}$$

205 where b and c are constant parameters with 2.15 and -0.13 values, respectively (Vannoppen et al., 2017). We
206 acknowledge the lack of data on the parameter values for mangrove, hence they are considered same as the
207 average values for roots penetrating a silty loam (Vannoppen et al., 2017). Root Density (RD) is calculated in kg
208 m^{-3} as follows:

209 $$RD = \frac{M_D}{V} \quad , \tag{10}$$

210 where M_D (kg) is the dry living root mass and V (m^{-3}) is the volume of soil sample (i.e., 0.00785 m^3). SDR
211 values range between 0 and 1. Conrverely, higher values indicate the less efficiency of roots in reducing soil
212 erosion.

213 *2.6. Statistical analysis*

214 The normality and homogeneity of data were checked before performing the analysis. Since the data did not
215 fit a normal distribution, a log transformation was applied. Mean values of RVR, NoR, RLD, and C_r for seaward
216 and landward positions were compared by ANOVA among three distances from tree stems. Additionally, an
217 ANOVA test was applied to compare root reinforcement models (i.e., W&W, FBM, and RBMw). It was also
218 possible to assess variations in tensile force since the roots were collected from both sides of the tree samples.
219 Analysis of covariance (ANCOVA) was used to determine whether the position of the samples affected root
220 tensile forces or not. Root diameter was considered as a covariate factor based on the preliminary use of
221 ANCOVA, which yielded the lowest residuals. Confidence intervals were established at 0.05 probability levels.

222 **3. Results**

223 *3.1. Root distribution*

224 *3.1.1. Root Volume Ratio*

225 As indicated in Figure 2, RVR values generally decreased with soil depth at both seaward and landward
226 positions. They decreased systematically moving away from the tree stem (from 0.75 m to 1.50 m distance),

with relatively higher ratios at seaward positions. The ANOVA test showed that mean values of RVR at different distances from tree stems were significantly different ($F=5.49$, $p<0.05$) i.e. significantly lower at 1.50 m distance than the two other. At similar positions in terms of distance and depth, corresponding RVR measurements at seaward and landward postions were not significantly different ($p>0.05$; Fig. 2).

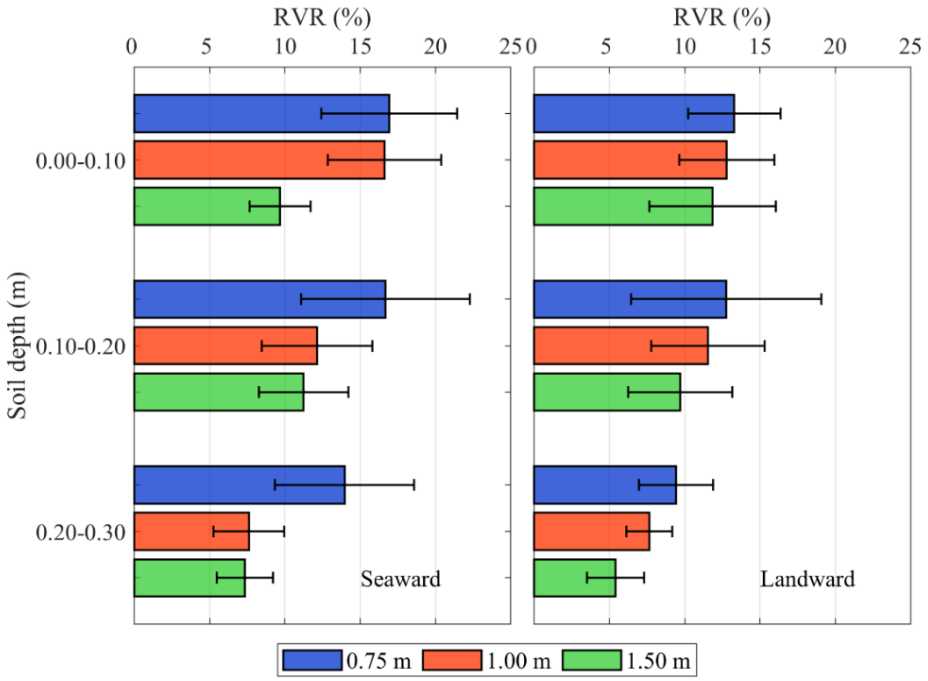

Fig. 2. Variability of RVR values at different positions (distance from tree stem and soil depth) at seaward and landward positions

3.1.2. Number of roots

Highest NoR values were observed near the core of the tree stem yet, they were more dense at seaward than landward positions (Fig. 3). As illustrated, NoR generally reduced with soil depth at both sides (landward and seaward). Regarding seaward positions, average NoR values in the top and bottom layers of soil at 0.75 m from the stem were 16694 and 4982, respectively. Corresponding values reduced to 7277 and 3603 at 1.00 m, also 6142 and 5061 at 1.50 m distance. Landward NoR values were generally lower. The average values obtained for the top and bottom layers were 7933 and 3414 at 0.75 m distance, 7413 and 4928 at 1.00 m distance and finally, 4775 and 3603 at 1.50 m distance, respectively. While 45% percent of roots were found in the top layer, only 25% were observed in the bottom layer. In cores taken from near tree stem positions, the declining rate of NoR with soil depth was sharper in comparison to farther distances (Fig. 3). Although root diameters varied from 0.1 mm to 17.2 mm at seaward positions, the majority of roots (99.4%) were very fine (within the <1 mm diameter

class), regardless of the distance from the stem. Less than 0.4% of the roots were 1-2 mm in diameter and about 0.2% were just greater than 2 mm. At landward positions, roots diameters ranged from 0.01 to 20.93 mm of which 98.2% were less than 1 mm. 1.6% of the roots were 1-2 mm in diameter and 0.2% were just thicker. Comparing the NoR between seaward and landward positions revealed no significant statistical difference between corresponding distances from tree stems and soil depths ($p>0.05$; Fig. 3).

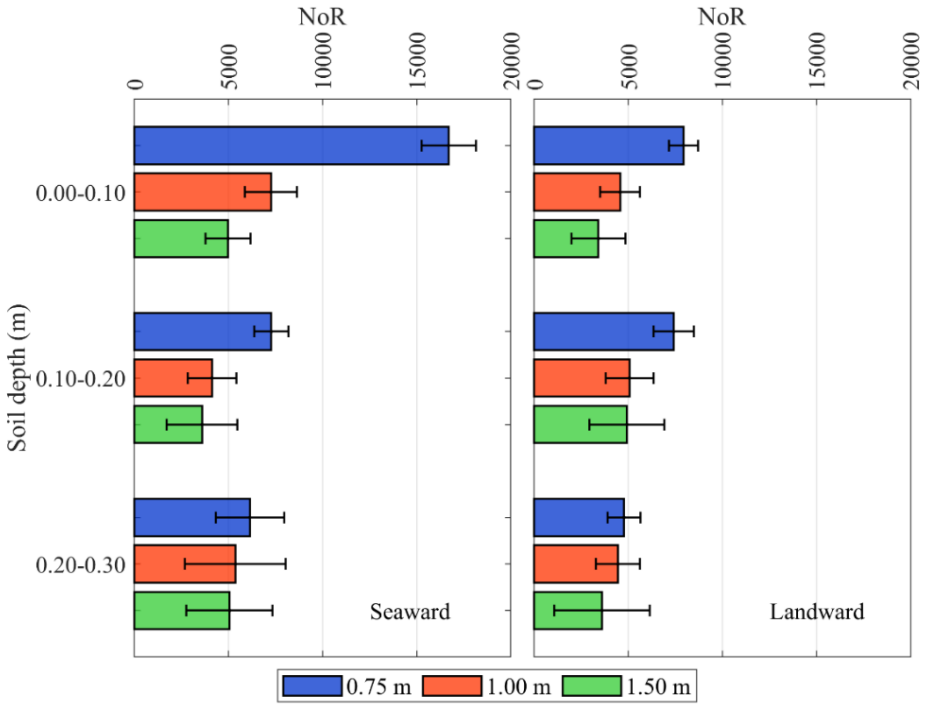

Fig. 3. Number of Roots at the distances of 0.75 m, 1.00 m, and 1.50 m from the tree stem for both seaward and landward positions

3.1.3. Root Length Density

As shown in Fig. 4, the measurements of RLD were consistent at seaward and landward positions. In most cases, the RLD value at seaward position was higher than its corresponding value at landward position. The top layer at 0.75 m and 1.50 m distances and the mid layer at 1.00 m distance were exceptions. However in all cases, the mean value of RLD at corresponding positions were not significantly different ($p>0.05$; Fig. 4). Furthermore, RLD values were not significantly different ($p>0.05$) at any specific depth of a the same distance at both sides. In addition in different soil depths at a certain distance RLD values were quite similar ($p>0.05$; Fig. 4).

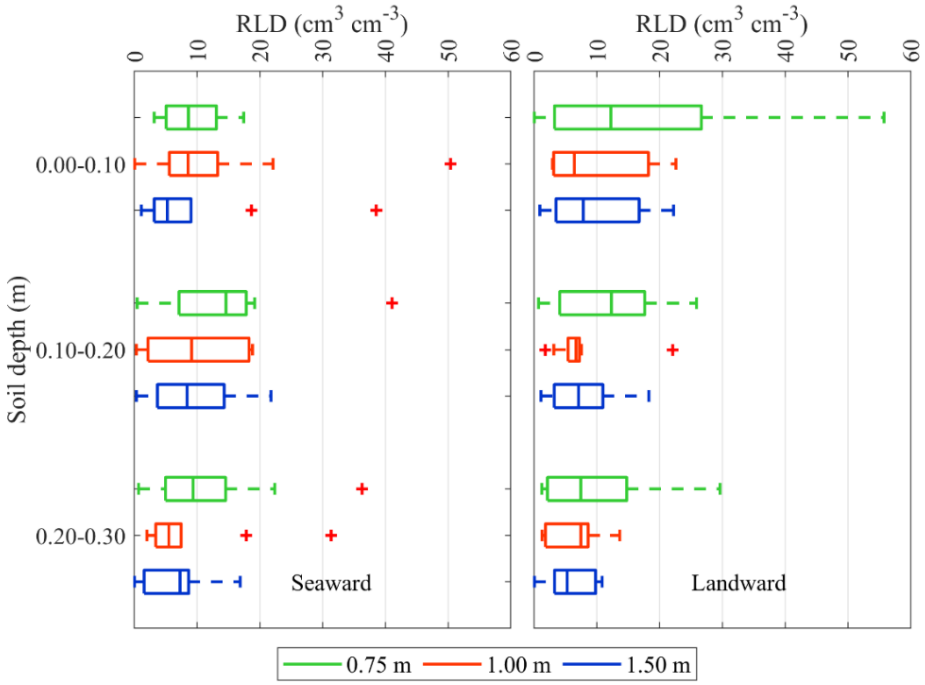

Fig. 4. Values of RLD at different distances from the tree stem and different soil depths at seaward and landward positions

3.2. Root tensile test

Laboratory tests were conducted on 59 sample roots from seaward positions and 39 sample roots from landward positions with diameters ranging from 0.21 mm to 8.85 mm. The relationship between root diameters and tensile forces is shown in Figure 5. As shown, failure forces increased with root diameters at both directions (seaward and landward). Results indicated that maximum tensile forces ranged from 2.2 N to 226.6 N at seaward positions (where root diameters varied between 0.23 and 8.76 mm), and from 0.6 N to 287.9 N at landward positions (where root diameter varied between 0.21 and 8.85 mm). Failure forces were not significantly different (ANCOVA, $F= 0.58$; $p>0.05$) in the two directions whereas root diameter, as a covariate parameter, was significant ($F= 114.2$; $p<0.05$). ANCOVA verified similarities between the curves of force against root diameter at different distances, making it possible to aggregate data and achieve a single force vs. root diameter curve.

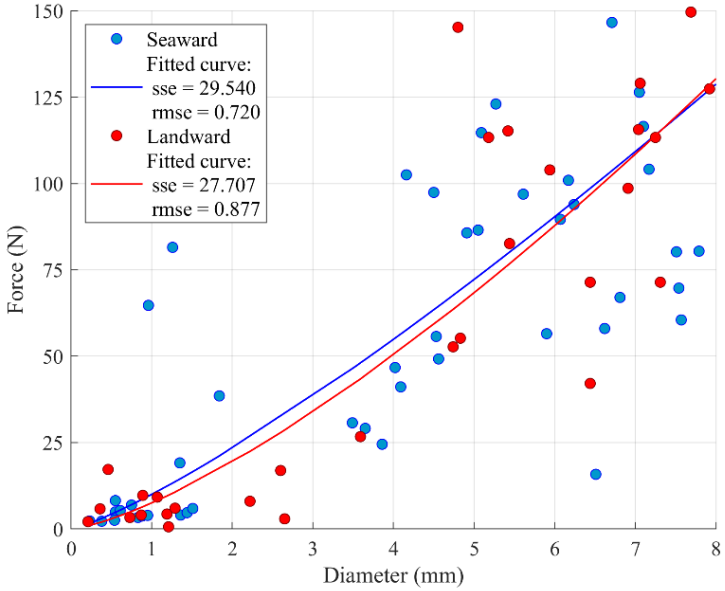

Fig. 5. Root diameter-tensile force relation at seaward and landward positions

3.3. Root reinforcement models

3.3.1. Input parameters

All three models require the relationship between tensile force and root diameters (Eq. 1). The results of root tensile tests indicated strong correlations between the mechanical and geometrical characteristics of roots and root diameters through a power-law regression line. In particular, an appropriate fit was obtained for the ultimate resistant force and Young's modulus (Fig. 6). The results of tensile tests fitted a survival function with robust fitting performance (Fig. 6).

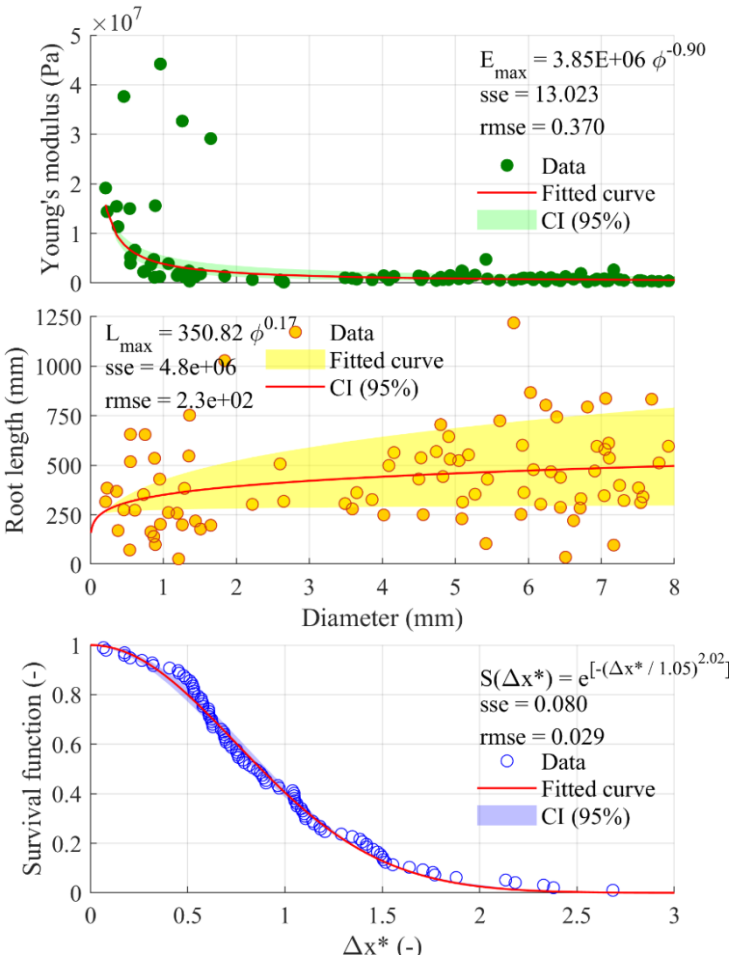

Fig. 6. Calibration of input parameters of the root reinforcement models

3.3.2. Assessing root reinforcement using different root reinforcement models

In all three models, C_r decreased with distance from the tree stem. The average values of C_r at 0.75 m distance seaward were 9710.55 N m^{-2} for W&W, 3468.90 N m^{-2} for FBM, and 1880.62 N m^{-2} for RBMw (Fig. 7). Also at 1.50 m distance seaward, C_r values of 6240.85 N m^{-2}, 3245.70 N m^{-2}, and 1604.88 N m^{-2} were obtained for W&W, FBM, and RBMw models, respectively (Fig. 7). The graph shows that C_r values reached 4271.33 N m^{-2} for W&W, 3251.80 N m^{-2} for FBM, and 1130.36 N m^{-2} for RBMw at 0.75 m distance landward. C_r values of W&W, FBM, and RBMw models at 1.50 m distance landward were 3711.35, 1947.40, and 1763.39 N m^{-2}, respectively. Therefore, the estimated value of C_r by RBMw at the distance of 1.50 m was 9.9% higher at the landward than seaward position (Fig. 7). For all models, the highest Coefficient of Variation (CV) was obtained in the top layer landward (Table 1). Except for the midlayer seaward, the RBMw model estimated the lowest CV among all root reinforcement models (Table 1). The ANOVA test showed that root reinforcement estimated by W&W, FBM, and RBMw models at different distances were not statistically significant at seaward

and landward positions (p>0.05; Fig. 7). Also, statistical analysis showed that root reinforcement in each model and at each direction did not vary significantly among distances (p>0.05; Fig. 7).

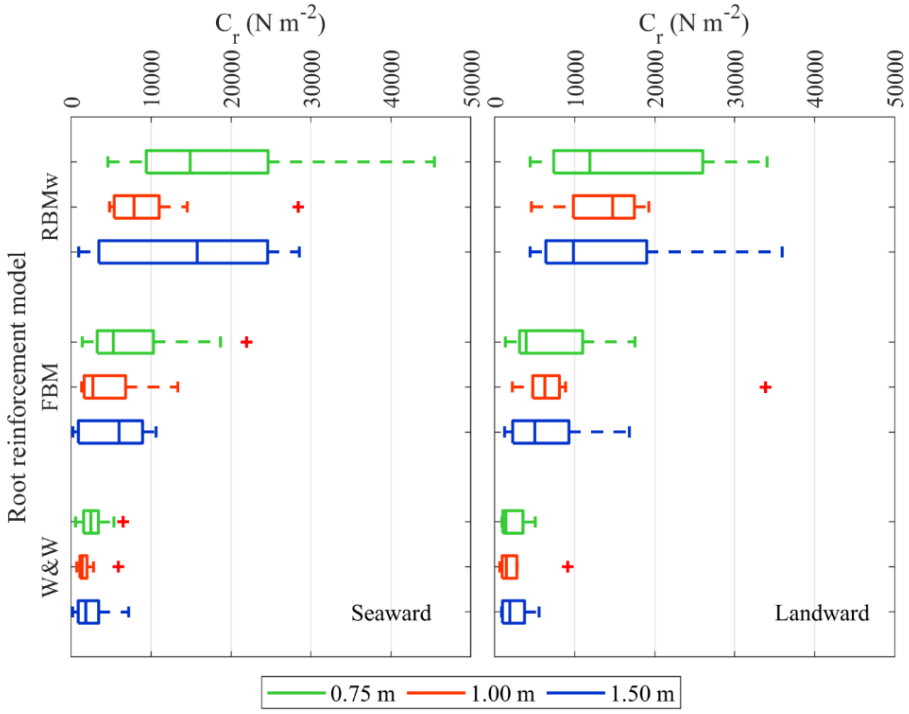

Fig. 7. Root reinforcement (C_r) of Wu & Waldron Model (W&W), Fiber Bundle Model (FBM), and Root Bundle Model-Weibull (RBMw) at different distances of landward and seaward directions. Bars denote standard error (±SE).

Table 1 Coefficient of variation (CV) of root reinforcement values estimated by Wu & Waldron Model, Fiber Bundle Model, and Root Bundle Model-Weibull at different distances of landward and seaward directions

Position	Depth (m)	CV		
		W&W	FBM	RBMw
Seaward	0.00-0.10	0.74	0.94	0.69
	0.10-0.20	1.13	1.35	0.85
	0.20-0.30	0.81	0.83	0.96
Landward	0.00-0.10	0.96	1.02	0.78
	0.10-0.20	1.69	1.68	1.14
	0.20-0.30	0.85	0.87	0.77

Results showed that all models resulted in significant differences among root reinforcement values, ranging from 31 N m^{-2} to 34000 N m^{-2} (Fig. 8). More specifically, C_r ranged from 80 to 52000 N m^{-2} for W&W, 70 to 34000 N m^{-2} for FBM, and from 31 to 9000 N m^{-2} for RBMw (Fig. 8). W&W provided the highest and RBM provided the lowest values (more conservative and thus, appropriate to apply).

The results of ANOVA tests showed that among all models, the C_r estimated by W&W was significantly the highest (F= 11.61, p<0.05; Fig. 8) and that of the RBMw was signifcantly the lowest (Fig. 8).

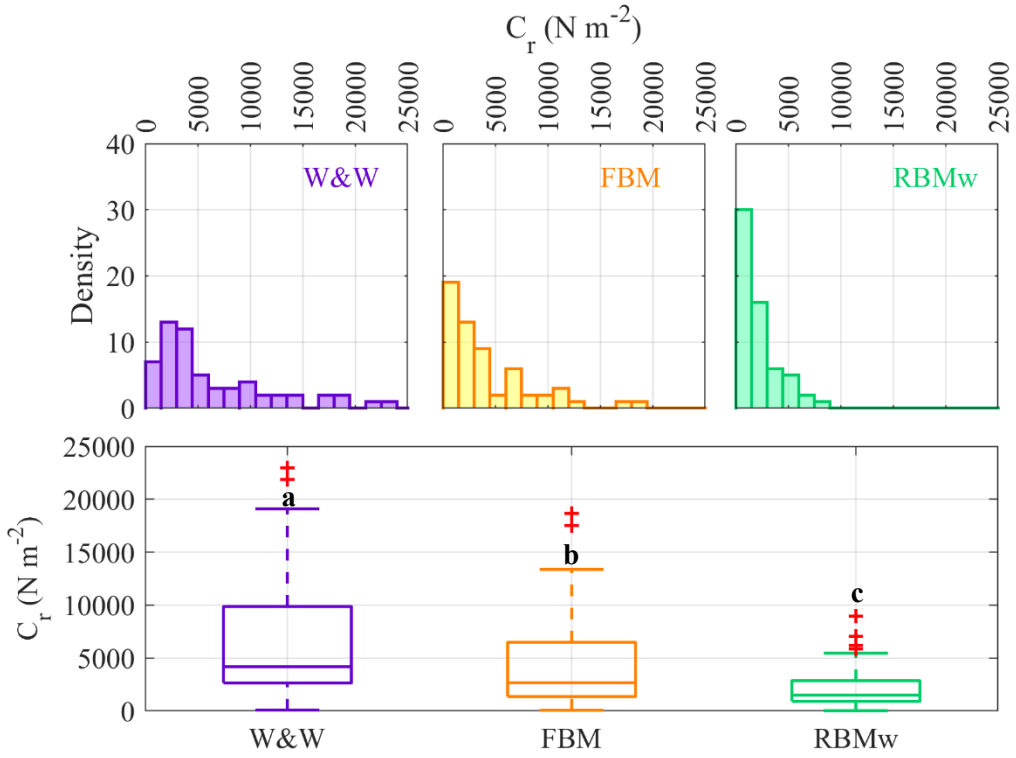

Fig. 8. Comparison of root reinforcement of Wu & Waldron model, fiber bundle model, and root bundle model-Weibull. Boxes with the different lowercase letters are significantly different (p<0.05).

3.4. Soil detachment ratio

According to Table 2 at seaward positions, the mean value of SDR ranged from 0.31 (at 0.75 m distance, top layer and at 1.00 m distance, midlayer) to 0.49 (at 1.50 m distance, midlayer). At landward positions, the values varied between 0.39 and 0.48 at 0.75 m distance, midlayer and 1.50 m distance, bottom layer soil depth, respectively. Overall, mean SDR values were higher at landward positions (0.42 *vs*. 0.38, respectively).

Table 2 Soil detachment ratio (SDR) values at different distances and different soil depths at seaward and landward positions

Position	Distance (m)	Depth (m)	SDR			
			Min	Mean	Max	SE (±)
Seaward	0.75	0.00-0.10	0.001	0.31	0.56	0.06
		0.10-0.20	0.006	0.34	0.77	0.06
		0.20-0.30	0.001	0.32	0.56	0.06
	1.00	0.00-0.10	8.6×10^{-5}	0.36	0.62	0.06
		0.10-0.20	0.117	0.31	0.53	0.04

		0.20-0.30	0.299	0.48	0.68	0.04
		0.00-0.10	0.020	0.39	0.91	0.07
	1.50	0.10-0.20	0.187	0.46	0.89	0.07
		0.20-0.30	0.318	0.49	0.70	0.04
Mean			**8.6×10^{-5}**	**0.38**	**0.91**	**0.02**
		0.00-0.10	0.092	0.40	0.72	0.06
	0.75	0.10-0.20	0.117	0.39	0.63	0.05
		0.20-0.30	0.181	0.41	0.72	0.06
		0.00-0.10	0.086	0.40	0.81	0.07
Landward	1.00	0.10-0.20	0.120	0.40	0.66	0.05
		0.20-0.30	0.205	0.44	0.64	0.04
		0.00-0.10	0.117	0.46	0.78	0.06
	1.50	0.10-0.20	0.046	0.38	0.92	0.08
		0.20-0.30	0.114	0.48	0.88	0.07
Mean			**0.046**	**0.42**	**0.92**	**0.02**

4. Discussion

As resulted in previous studies, root density dramatically decreases with soil depth (Stokes et al., 2009; Moresi et al., 2019; Abdi and Deljouei, 2019). Decreasing root density with soil depth has been correlated with less nutrient availability, less soil aeration, and higher presence of compact layers (Moresi et al., 2019; Abdi and Deljouei, 2019). Similar investigations were carried out on *Alnus subcordata*, *Acer velutinum*, and *Parrotia persica* native and pioneer species of the Hyrcanian ecoregion to identify root density patterns. Results show that patterns were similar to *A. marina* in all layers and not significantly different (Abdi and Deljouei, 2019). Furthermore, in several studies, decreasing root densities in the horizontal direction were investigated in relation to distance from the stem, tree diameter, species, and micro-topography (Genet et al., 2005; Schwarz et al., 2010a; Ji et al., 2012; Dazio et al., 2018; Bordoni et al., 2020; Cislaghi et al., 2021). Spatial variability of root expansion (i.e., vertical and horizontal) depends on many variables including climate, local soil, land use management as well as associated vegetation communities (Sidle and Ochiai, 2006). The total number of roots in this study was completely different than other researches, taking into account the species, distance from the stem, and numbers of very fine roots which could be explained by the greater concentration of soil nutrients near the soil surface (Castañeda-Moya et al., 2011). Specific environmental conditions of Iranian mangrove due to permanent tide stress may justify the unusual mass and deeper root system. In this study, fine roots were the main part of the total rootstock, providing 98.2%-99.4% of standing root biomass. The primary function of fine roots in absorbing water and soil nutrients was clarified (Sanchez 2005), especially during early root development. In contrast, coarse roots represented a higher fraction of total root biomass in Florida and Mexico

(Castañeda-Moya et al., 2011; Adame et al., 2014). The results of this study showed that root densities were not significantly different at seaward and landward positions. Chiatante et al. (2003) stated that asymmetric cross-sections cause variations in mechanical characteristics of roots. Furthermore, Di Iorio et al. (2005) reported that larger root sections could be resulted from higher loading stresses. Consequently, results may support the hypothesis that the roots of the trees that were investigated by mechanical stresses had the same condition seawards and landwards. Morphoplasticity (Marler and Discekici, 1997) or phenotypic plasticity (Ganatsas and Spanos, 2005) describes the ability of plants to adapt with environmental conditions. The similarity between the number of roots in corresponding seaward and landward positions could indicate that the plant reacts to stress by thickening its roots instead of increasing its root number.

RLD is a root characteristic specified as either root length per unit of soil volume or root length per unit of soil surface (Stokes et al., 2009). RLD is often used as an indicator for stabilizing slopes and soil that is explored by a root system in search of nutrients and soil water (Aziz et al., 2017; Bordoloi and Ng, 2020) since it better reflects the quantity and structural aspects of roots (Yang et al., 2018; Hamidifar et al., 2018; Lobmann et al., 2020). Its value decreases with soil depth due to the higher nutrient level in top layer of soil (Pandey et al., 2000; Hoad et al., 2001; Bayala et al., 2002, 2004). The erodibility of topsoil is known to be dramatically less as the density of root length is higher (e.g., Mamo and Bubenzer, 2001a, b; De Baets et al., 2006; Knapen et al., 2007; Osman and Barakbah, 2011). RLD reduction with distances from tree trunks was evident in all depths. The rate suggests potential competition directly under the tree crowns for water and nutrients (Odhiambo et al., 2001; Bayala et al., 2004). The most contributive factor of soil aggregate is RLD such that lower RLD in further distances is expected to reduce soil stabilization more (Demenois et al., 2017). From a soil bioengineering perspective, RLD is defined as a mechanical soil reinforcement method (Osman and Barakbah, 2011). High RLD values imply a higher cross-section area of roots on a potential shear surface per unit of soil surface in terms and thus, higher mechanical reinforcement (Ghestem et al., 2014; Boldrin et al., 2017).

The relation between root diameter and tensile force was found significant which complied with the results of other studies in which the tensile force strongly depended on root size (Genet et al., 2010; Boldrin et al., 2017; Abdi and Deljouei, 2019; Deljouei et al., 2020). Therefore, hence it is necessary to take the root diameter into account as a covariate for root tensile force analysis (Vergani et al., 2012; Moresi et al., 2019; Abdi et al., 2019). The relationship between root diameter and tensile force was investigated as a positive power-law function in previous studies (Bischetti et al., 2005; Genet et al., 2010; Vergani et al., 2012). Different cellulose to lignin ratios justified this relationship, with smaller roots having higher cellulose:lignin (Genet et al., 2005).

Such result were also due to the chemical composition of root tissues; root tensile forces had a significantly negative correlation with cellulose and holocellulose amounts and a significantly positive correlation with lignin and its ratio to cellulose (Ye et al., 2017).

According to the results, the estimates of root reinforcement by the W&W model significantly varied with those of FBM and RBMw models. In literature, the value of k' coefficient used in the W&W model depended strongly on the root bending angle as wells as the effective internal friction angle of soil (Wu, 1995; Danjon et al., 2008). Hence, it was suggested to use the correction factor k'' instead. Most researchers quantified its value from 0.4 (Preti, 2006) to much lower values in order to correct the overestimation of the W&W (Operstein and Frydman, 2000; Docker and Hubble, 2008; Cislaghi, 2018; Deljouei, 2019). Bischetti et al. (2009) compared W&W and FBM models, and showed that k'' coefficient was correlated with the number of roots. For a density smaller than 400 m^{-2} roots, a greater than 0.5 value may be assumed for k'' (Bischetti et al., 2009). Cislaghi (2018) suggested that various combinations of k'' should be used with 0.3 being most appropriate. This study suggests that considering k'' of 0.3 for the W&W model provides the closest estimation to RBMw-values. Deljouei (2019) identified k'' be 0.3 for small *Carpinus betulus* trees (0.75-0.325 m DBH), 0.4 for medium trees (0.326-0.575 m DBH), and 0.1 for large trees (0.576-0.825 m DBH) for most accurate estimations in the W&W model. Moreover, the k'' coefficient was estimated 0.3 for small and medium trees of *Fagus orientalis*, and 0.2 for large trees. Among root reinforcement models, W&W is the simplest as it requires a limited number of input parameters (i.e., RAR and tensile force-root diameter curves). However, it is necessary to estimate the C_r value more accurately and avoid overestimation, therefore FBM will improve the estimations of root reinforcement ratios of other models and overcome the hypothesis of simultaneous root-breaking. Several authors suggested that FBM provides encouraging estimates using available parameters, whereas RBMw requires many input parameters for an accurate and reliable estimation of the mechanical characteristics of a root system (Schwarz et al., 2013). In comparison to FBM, RBMw enables a less simplified breaking process for the bundle of roots by considering a progressive failure of roots due to their heterogeneous distribution. The main variable influencing root reinforcement estimations by W&W, FBM, and RBMw models is root diameter distribution (Vergani, 2013). Different studies, field observations and laboratory tests show that the mechanical properties of roots highly vary even within the same diameter class. Such quality is due to the anatomy and geometry of roots, resulting in different failure forces and displacements which is considered in the RBMw model by fitting in the survival function parameter ω.

SDR values showed that soil erosion reduction due to the presence of roots in landward position were circa 10% higher than seaward position. The finding is useful in conserving or restoring mangrove forests at seaward positions and provide nature-based shoreline protection as shoreline protection in mangrove ecosystems are mostly needed is this direction. Although the soil stabilizing and erosion reduction effect of tree roots for soil in various forest ecosystems are well-known (e.g., Abdi and Deljouei, 2019; Abdi et al., 2019), the functional role of mangrove forests in reducing erosion at seaward and landward directions (i.e., landward and seaward positions) has not been described yet. In line with the results of this research, Gou et al. (2020) showed that difference in SDR values may be related to differenent geomorphological conditions that affected the soil detachment process (De Baets et al., 2007; Li et al., 2015). The study also revealed indirectly that different conditions whould be seriously considered in erosion control revegetation efforts.

Compared with the simplest model (W&W), the RBMw enables a comprehensive evaluation of root reinforcement with only few additional parameters and performs reasonably accurate predictions. Results of this study provide helpful information and tools for quantifying root reinforcement as a crucial factor for understanding numerous hydrologic and earth surface processes. Our results highlighted that the RBMw model estimations for root reinforcement were more conservative in which the lowest quantities among the three adopted models were obtained. In order to apply the results of this study to other mangrove areas, the RBMw estimation is recommended among other soil erosion prediction models. Finally, the significant role of *A. marina* in reducing soil erosion and conserving nutrient levels in the mangrove forest were evident in this research.

5. Conclusions

This research estimated the effect of the most significant mangrove species (i.e., *Avicennia marina*) at present time in Iran on soil stability. RVR, RLD, RD, and SDR were calculated at various soil depths with respect to the biomechanical characteristics of roots. Study results showed that root reinforcement greatly enhanced soil stability, highlighting the effectiveness of white mangrove trees in preventing and mitigating soil erosion. Recently, using natural material to increase shear resistance and stiffness of soil has become very common at different places. Geotechnical engineers recognize the role of roots in strengthening soil and the contribution of root resistance in improving soil stability very well. Results indicated that RVR, RLD, root distribution, and biomechanical root characteristics were not significantly different at seaward and landward positions from the tree stem. In contrast, values of all parameters decreased with soil depth and distance from the tree stem. Additionally, it was concluded that quantifying root reinforcement with W&W, FBM, and RBMw

models reflected significantly different results through which the W&W overestimated root reinforcement compared to the FBM and RBMw models. The results are particularly important to consider in managing soil erosion in Iran and other similar regions and demonstrate that developing *A. marina* communities can be an effective bioengineering technique for soil stabilization in coastal regions.

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