ON THE LIGHT PENETRATION IN NATURAL SANDS

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ABSTRACT

Sand-textured soils are found in a wide range of landscapes, from coastal areas to dune fields. The quantification of light penetration through these soils is of considerable interest not only for remote sensing applications, but also for agricultural, ecological and geophysical studies. Despite its importance, however, the literature on this topic is still scarce. Moreover, the available light penetration (transmittance) datasets for these soils are affected by experimental and modeling limitations. These include, for instance, the use of samples with morphological and mineralogical characteristics markedly different from those of naturally occurring sand-textured soils. To overcome these limitations and strengthen the current knowledge about light penetration in these soils, commonly referred to as natural sands, we propose the use of a predictive *in silico* experimental framework supported by measured data. Our findings demonstrate that it is necessary to properly account for the varying particle distributions and the iron oxide contents of natural sands in order to obtain penetration depth estimations that can be reliably employed in investigations involving these soils. In addition, our *in silico* experiments allow for a diversified assessment of the light transmission profiles of natural sands at different depths with respect to spectral and angular dependencies.

Index Terms— Sand, transmittance, penetration depth.

1. INTRODUCTION

The high-precision remote sensing of targets covered by natural sands requires reliable information about the depth from which the measured signal originates [1]. This information is directly associated with these soils' light attenuation characteristics, which are also relevant for a number of related fields. For example, the depth to which light can penetrate natural sands is central in agricultural and ecological investigations on the germination of stress-adapted seeds [2, 3, 4] and the photochemical transformation of chemical compounds (*e.g.*, pesticides) [1]. It also represents an important piece of data in geophysical studies relying on the optical dating [5] of sand deposits [6], specially those found in regions more vulnerable to environmental changes like coasts and deltas [7].

Natural sands are primarily composed of grains (particles) of weathered rocks immersed in a pore space. These rocks correspond to the core material of these soils, which is typically a silicate mineral such as quartz [8]. Trace amounts of impurities, such as iron oxides (*e.g.*, hematite, goethite and magnetite), can substantially affect their spectral signatures, particularly in the spectral region of interest for our research (400 to 1000 nm), and are largely responsible for their color [8]. Depending on the weathering process, the core material may occur as pure particles, coated particles or mixed with impurities [9]. The particle coatings correspond to a mineral (*e.g.*, kaolinite) matrix that can embed the impurities [8]. These may also occur as pure particles [9].

Light penetration in natural sands can be measured (in terms of transmittance) directly using a spectrophotometer [3, 4, 10, 11]. Alternatively, it can be estimated indirectly using the germination of light-sensitive seeds or the presence of growing algae as bioindicators [1, 2, 3, 4]. However, despite noteworthy efforts in these areas, there are only a few transmittance datasets available in the literature to date. These cover a limited range of naturally-occurring sand-textured soils and their generalization is often hindered by experimental constraints.

Among these constraints, one can highlight the absence of key morphological features of natural sands (*e.g.*, the complex size distribution patterns of their constituent grains) in soil samples artificially prepared and mixed in the laboratory [10, 12], as well as the selection of samples with specific characteristics (*e.g.*, negligible presence of iron oxides) to facilitate the detection of transmittance signals [11]. Moreover, modeling initiatives [10, 11] used in conjunction with these experimental efforts do not incorporate in their formulations arguably the most fundamental physical characteristic of natural sands, namely their particulate composition.

In order to overcome these constraints and strengthen the current knowledge about light penetration in natural sands, we employed a predictive *in silico* experimental framework that comprehensively takes into account the mineralogical and morphological characteristics of these materials, notably their granular nature. Using actual measured spectral data as reference and sand characterization parameter values consistent with well-established soil information provided in the related literature, we performed controlled experiments to

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evaluate the light penetration depth of representative samples of natural sands. Our findings demonstrate that one can obtain tighter bounds for this physical attribute when one appropriately takes into account the ubiquitous presence of iron oxides in their particulate composition. They also provide a high-fidelity picture about the spectral variations on the transmittance of these soils due to changes in the light incidence geometry and sample thickness.

2. IN SILICO EXPERIMENTAL FRAMEWORK

In our investigation, we considered samples from two natural sand deposits with distinct morphological and mineralogical characteristics, namely a hematite-rich Australian dune field and a magnetite-rich Peruvian beach site, henceforth referred to as AD and PB samples, respectively. The actual reflectance curves measured for these samples were made available in the U.S. Army Topographic Engineering Center (TEC) database [13] under the identifications TEC #10019201 and #10039240 respectively. We employed these curves as references for our *in silico* experiments.

In the characterization of the AD and PB samples, we considered quartz as their core material and kaolinite as their coating matrix. In addition, we employed mean values for their porosity (0.425) [14], grain roundness (0.482) [15] and grain sphericity (0.798) [15]. The remaining parameter values used in their characterization are given in Table 1. We remark that these values were chosen from physically valid ranges [8].

Note that the percentages of the sand-sized and silt-sized particles depicted in Table 1 are employed to compute the dimensions of the samples' grains (whose average values are presented in Table 2) using a particle size distribution provided by Shirazi *et al.* [16]. Also, based on the samples' descriptions [13], we assumed that the presences of moisture and clay-sized particles were negligible.

Samples	s_a	s_i	μ_p	μ_m	μ_c	r_{hg}	ϑ_{hg}	ϑ_m
AD	85	15	0	90	10	0.75	0.01	0.0
PB	92.8	7.2	50	0	50	0.35	0.045	0.17

Table 1. Parameter values used to characterize the natural sand samples, namely AD (Australian dune) and PB (Peruvian beach), considered in this investigation. The texture of the samples is described by the percentages (%) of sand (s_a) and silt (s_i). The particle type distributions considered in the simulations are given in terms of the percentages (%) of pure (μ_p), mixed (μ_m) and coated (μ_c) grains. The parameter r_{hg} corresponds to the ratio between the mass fraction of hematite to ϑ_{hg} (the total mass fraction of hematite and goethite). The parameter ϑ_m represents the mass fraction of magnetite, which is assumed to appear as pure particles [9].

Samples	m_a	m_i
AD	0.236	0.045
PB	0.265	0.044

Table 2. Average dimensions (given in mm) of the major axes m_a and m_i that respectively define the ellipsoids used to represent the sand-sized and the silt-sized particles forming the AD (Australian dune) and PB (Peruvian beach) samples.

During our *in silico* experiments, we have computed directional-hemispherical reflectance and transmittance curves using a first-principles light transport model, SPLITS (*Sp*ectral *Li*ght *T*ransport Model for *S*and) [8]. More specifically, its stochastic ray-optics formulation includes parameters describing the morphology and mineralogy of the particles forming sand-textured soils, as well as the distribution of these particles within the pore space. To enable the reproduction and extension of our experimental results, we have made SPLITS available online [17] along with the supporting spectral datasets (*e.g.*, refractive index and extinction coefficient curves [9]) associated with various minerals considered in this investigation.

Each modeled curve was obtained using a virtual spectrophotometer [18] and casting 10^6 rays (per sampled wavelength) onto the sand samples. For the baseline reflectance experiments, we considered the samples' thickness equal to $1\ m$, a default value that guarantees depth-invariant readings [1] like those obtained in the actual measurements [13]. For the transmittance experiments, we considered distinct values for the samples' thickness to quantitatively evaluate their light penetration depth. This is usually defined as the depth in which the impinging light is reduced by $\geq 99\%$, yielding transmittance readings $\leq 1\%$ [1, 19]. We make use of this definition in the analysis of our *in silico* experimental results.

3. RESULTS AND DISCUSSION

Initially, we computed reflectance curves (named modeled-R) for the AD and PB samples to verify the suitability of the parameter values (Table 1) used in their characterization. As it can be observed in Fig. 1, these curves closely agree with their measured counterparts. Note that the iron oxide amounts depicted in Table 1, albeit realistic, correspond to a small fraction of the samples' total mass. Thus, one might assume that the iron oxides would have a low impact on the attenuation of light interacting with these samples. To examine the plausibility of this assumption, we also computed reflectance curves (named modeled-U) for both samples considering a $10\times$ reduction in the values of the iron oxide parameters (r_{hg}, ϑ_{hg} and ϑ_m) depicted in Table 1. As it can be verified in Fig. 1, although these curves are qualitatively similar to their measured counterparts, they have a distinctively higher magnitude. This illustrates the importance of properly accounting for the rela-

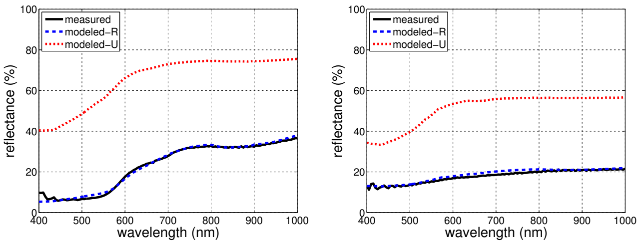

Fig. 1. Comparisons of measured [13] and modeled reflectance curves obtained for the AD (left) and PB (right) samples. The modeled-R curves were computed considering the values for the iron oxide parameters (r_{hg}, ϑ_{hg} and ϑ_m) provided in Table 1, while the modeled-U curves were computed considering a $10\times$ reduction of these values. All curves were obtained considering an angle of incidence of $0°$.

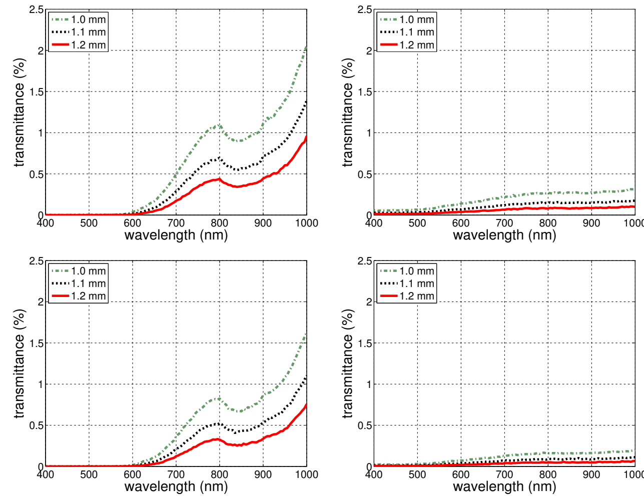

Fig. 2. Comparisons of modeled transmittance curves computed for the AD (left column) and PB (right column) samples considering the values for the iron oxide parameters (r_{hg}, ϑ_{hg} and ϑ_m) provided in Table 1, distinct thicknesses (1.0, 1.1 and 1.2 mm), and two angles of incidence: $0°$ (top row) and $45°$ (bottom row).

tively small, but pivotal, presence of iron oxides [9].

In our subsequent experiments, whose resulting graphs are presented in Fig. 2, we noted a nonlinear decrease in the samples' transmittance as we increased their thickness. Although the transmittance values tend to zero, their decrease becomes less accentuated with larger thickness values. Moreover, the transmittance values were higher at the longer wavelengths. This may be attributed to the relatively low extinction coefficients of the iron oxides, notably hematite and goethite [8], at those wavelengths. These observations are consistent with the qualitative trends depicted in the spectrophotometric experiments performed by Woolley and Stoller [3] and Benvenuti [4] on colored sand samples. Also, in the graphs presented in Fig. 2, it can be verified that an increase in the angle of incidence, from $0°$ to $45°$ (with respect to the zenith), resulted in a slight, but noticeable, transmittance decrease.

Woolley and Stoller [3] reported transmittance values (from 350 to 800 nm) below 2% for a depth of 1.1 mm in their sample composed of particles with a diameter between 0.3 to 0.5 mm. It has been noted that transmittance decreases with a decreasing particle size [1, 4, 10, 12]. Accordingly, for sand samples characterized by smaller particles, one should expect a lower light penetration depth. For the samples considered in our investigation, which are assumed to be mostly composed of particles smaller (Table 2) than those found in the Woolley and Stoller's sample [3], a thickness of 1.2 mm was sufficient to obtain transmittance values below 1% as indicated by the corresponding curves presented in Fig. 2. Incidentally, a light penetration depth of 1 mm was reported in the Benvenuti's experiments (from 400 to 800 nm) [4]. He did not provide, however, the diameter of the particles forming his sand sample, just their type distribution. More specifically, 93% of his sample's granular portion was composed of sand-sized particles. Incidentally, this distribution is similar to the ones considered in our investigation (Table 1).

It has been suggested [1, 3, 4, 12] that, for a given particle size distribution, a lighter-colored (less absorptive) sand sample allows more and deeper light penetration than a darker-colored (more absorptive) one. However, to the best of our knowledge, no controlled experiments specifically performed to quantitatively examine this behaviour in natural sands have been reported in the literature to date. Hence, for comparison purposes, we repeated our transmittance experiments considering a $10\times$ reduction in the values of the iron oxide parameters (r_{hg}, ϑ_{hg} and ϑ_m) provided in Table 1. As expected, the resulting transmittance curves presented in Fig. 3 are significantly higher than those presented in Fig. 2. In the AD sample case, they also show a distinct behaviour in the 800 to 900 nm region. These aspects can undoubtedly be associated with the reduced attenuation of the light traversing samples characterized by uncommon lower amounts of iron oxides, particularly hematite (like in the AD sample case) and magnetite (like in the PB sample case). In addition, the curves presented in Fig. 3 depict transmittance values below 20%, but well above 1%, at a depth of 1 mm. Recent spectrophotometric measurements [11] performed on a coarse (85% of the particles with a diameter between 0.5 and 1 mm) "white" sand sample with insignificant iron oxide amounts resulted in transmittance values below 20% for a depth greater than 3 mm. In our *in silico* experiments, this depth (thickness) resulted in transmittance values below 4% as depicted in Fig. 3.

Clearly, for investigations involving landscapes formed by natural sands, the usefulness of light penetration bounds depends on whether or not their estimations properly accounted for the actual morphological and mineralogical characteristics of these materials. Our findings, obtained using an *in silico* experimental framework centered at the particulate compo-

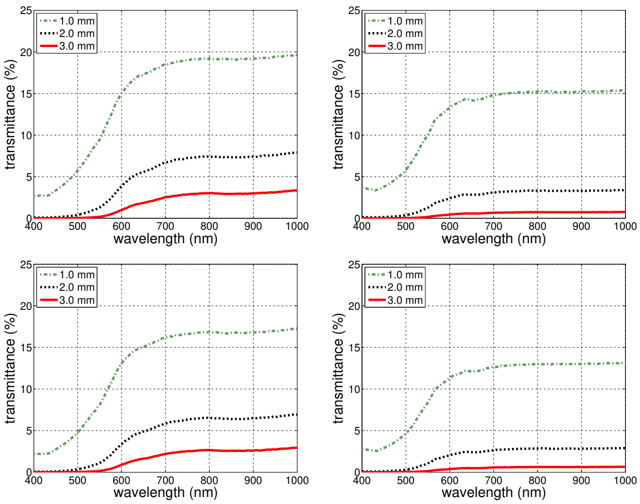

Fig. 3. Comparisons of modeled transmittance curves computed for the AD (left column) and PB (right column) samples considering a $10\times$ reduction in the values of the iron oxide parameters (r_{hg}, ϑ_{hg} and ϑ_m) provided in Table 1, distinct thicknesses (1.0, 1.1 and 1.2 mm), and two angles of incidence: $0°$ (top row) and $45°$ (bottom row).

sition of natural sands, demonstrated not only the key role played by the iron oxides, but also how the light penetration depth in these soils can be largely overestimated if the presence of these minerals is quantitatively and/or qualitatively overlooked.

4. CONCLUDING REMARKS

The number of works aimed at the study of light penetration in natural sands is still relatively small. In many cases, researchers had to resort to the use of artificially-prepared sand samples and simplified experimental conditions due to logistics constraints. Given the fundamental importance of this topic, we believe that the scientific community should provide a continuing support for more measurement efforts in this area. Moreover, it should also foment the pairing of these efforts with the use of simulation frameworks that can predictively reproduce the spectral responses of these soils. These synergistic collaborations would likely lead to considerable advances in this area.

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