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Accelerated lifetime modeling on the basis of wind tunnel analysis and sand storm aging

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Abstract

Wind effects in arid locations cause sand abrasion on optical surfaces and protective systems. Sand abrasion is identified as a large contributor to overall power plant efficiency loss. It is reflected in recent SolarPACES conferences that the awareness for the topic of sand abrasion is rising \[1\][2][3]. Sustainability is mandatory for next generation’s CSP fields and in this sense all effort is put into lowering cost of structure, providing reliability and lowering cost of maintenance. In this study, we will report on accelerated lifetime modeling with a multi-layer model, combining aerodynamic wind tunnel data with aging under sand storm conditions.

Keywords: CSP; accelerated lifetime testing; sand abrasion; atmospheric boundary layer wind tunnel technique; sand storm facility.

1. Introduction

Sand abrasion is described as a fluid mechanical problem determined by its ambient conditions. Ambient conditions are defined by sand-related and wind-related parameters. Sand-related parameters are, to name the paramount, sand size (distribution), soil sealing, and sand flux profile. Wind-related parameters are first of all wind velocity, terrain, frequency of occurrence and micro to mesoscale \[4\] atmospheric boundary layer. Fluid mechanics and geomorphology offer a wide range of empirical and theoretical models to describe aeolian sand flux. Since influencing parameters are numerous and associated with various scientific disciplines (geology, geography, meteorology etc.), published approaches are often at great variance. Our aim was to describe sand flux, its vertical distribution and grain momentum, using parameters easy to access but significant for the plant site. Several existing models were linked, adapted and extended by parameters considered as crucial, such as grain momentum being proportional to damage and soil sealing \(S\) on site reducing the effects of saltation and suspension.
To sum up, the model comprises influence of vegetation and ground conditions around the field, collector type, grain size, soil characteristics and wind conditions. Hence, the main site parameters, wind profile and vertical sand flux distribution, are computed and their impact is projected over a period. Scenarios similar to published experimental set-ups were modeled to evaluate and validate the model.

**Fig. 1.** Block diagram of the MLAST model with subroutines.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| $A_{\text{ref}}$ | area of a reference specimen of 4 by 4 cm². |
| $C(z)$ | concentration [kg / m³] |
| $d$ | particle diameter [m] |
| $k$ | von Karman constant, ~0.41 [-] |
| $m, m(z)$ | amount of sand [kg] |
| $N$ | Rouse number [-] |
| $p$ | momentum [kg m/s] |
| $q$, $q_{\text{ref}}$ | sand flux [kg / m² s] |
| $q_{\text{ref}}$ | reference sand flux [kg / m² s] |
| $u^*$ | friction velocity [m/s] |
| $u$, $u(z)$ | velocity [m/s] |
| $\rho$ | density of air [kg/m³] |
| $S$ | soil sealing, incl. vegetational coverage [-] |
| $v_{\text{thr}}$ | settling velocity of a grain [m/s] |
| $z$ | height above ground [m], index ref reference, index max maximum transport height. |
| $z_0$ | surface roughness [m] |

**2. Set-up of model**

Of the three modes of aeolian sand transport, creep, saltation, and suspension [5], the latter is determining for this model, as it affects heights of CSP collectors. It is caused by vertical turbulences in the atmospheric boundary layer, lifting grains and keeping them suspended, while the horizontal wind velocity drags them onwards [7]. The model consists of the wind velocity profile altered by roughness of terrain and CSP structures [4] which is input to the calculation of suspended sand fluxes [9][10] concluding in the calculation of sand particle momentum accumulated over a period of time, e.g. the life time of a CSP structure.
2.1. Wind profile

The wind profile in the atmospheric boundary layer is given by equation (1), with \( u \) [m/s] denoting the friction velocity and \( z_0 \) [m] the surface roughness [4]. The surrounding landscape and the CSP field itself were both characterized by a specific roughness and friction velocity. At the edge of the CSP field a transition area was defined.

\[
U(z) = \frac{U_*}{\kappa} \ln\left(\frac{z}{z_0}\right)
\]

(1)

The friction velocity is the crucial wind parameter for aeolian sand flux. Besides indicating the slope of the lin-log velocity profile, it is proportional to the vertical turbulence intensity and thus the vertical drag on sand grains [10].

Since friction velocity is proportional to vertical turbulence intensity, criteria for each transport mode were set up relating the settling velocity \( v_{thr} \) of a grain in air to the friction velocity, which is, for instance, \( v_{thr} u_*^3 \leq 0.1 \) for long-term suspension [7]. The settling velocity can be determined from Stokes’ law.

2.2. Measurements of velocity profile and turbulence intensity

The boundary layer conditions of atmospheric flows typical at solar power plant sites were simulated at the wind tunnel at the University of the Armed Forces, Munich, Germany, using a sophisticated simulation technique. Velocity and turbulence distributions were realized.

![Fig. 2. (Left) Boundary layer: (■) simulated conditions relevant for CSP site (wind tunnel measurement) and corresponding turbulence intensity (♦); comparison with theoretical boundary layer profile (▲) [11]. Shaded area of graph marks the relevant simulation height range for models in scale 1:10 to 1:50. (Right) Installation adapting the boundary layer (foreground) and heliostat model (background).](image)

Depending on the potential power plant sites the topographic and environmental conditions can vary significantly and therefore require different theoretical prediction approaches. Two different types of theoretical boundary layer based on the EC 1 [11] and [12] can be applied.

The boundary layer installations to the wind tunnel were such that the desired profile was realized and the results of the unperturbed boundary layer are shown in figure 2. The installations to adapt the profile and turbulence level
of the boundary layer need to match the model scale. The whole installation then reaches a length of 10 to 12 m preceding the collector model. The basic boundary layer realized is characterized by a turbulence level of up to 25% in the relevant model height. This guarantees that the forces and moments acting on the collector model are of the correct order of magnitude.

Having described the characteristics of the basic boundary layer, the following paragraph describes the raising of the layer profile by obstacles. The topography, the relief of an area with natural and manmade obstacles, affects the atmospheric process from the micro to mesoscale [4]. On encountering an obstacle the boundary layer profile becomes distorted (Fig. 2 right). The part still following a lin-log law ends above the obstacle height. The distorted part below signifies higher turbulence and even back flow is possible.

![Fig. 3. (Left) boundary layer lin-log profile. $z_0$ is found at the intersection with the ordinate, $u^*/k$ is the inclination. (Right) obstacles perturb the boundary layer profile.](image)

![Fig. 4. Solar Thermal Power Plant, near Upington, South Africa. Examplary topography shows open sand areas, small and sparse vegetation, collectors and buildings [Courtesy of La Moncloa, E].](image)

The surface roughness $z_0$, introduced in eq. 1, is a method to define land-use categories which quantify this raising effect by the parameter $z_0$ for as different landscapes as grass lands, agricultural land, forests, mountains, towns, and CSP collector fields, to name a few [6].

The typical topographical situation found at CSP sites (example see Fig. 4) involves a low value for $z_0$ surrounding the field, $0.005 \text{m} < z_0 < 0.05 \text{m}$, while in the field the value rises up to $0.2 \text{m} < z_0 < 1.2 \text{m}$. 


2.3. Sand flux and its vertical distribution

The aeolian transport of sand occurs in three different modes: suspension, saltation and creep [5]. In this model only sand carried in suspension and saltation is taken into account since creep does not reach heights critical for CSP collectors. Even though there are numerous published approaches that describe saltation and suspension (see, for example, [5][7][15][16]), none that we know of adequately fits the conditions at a CSP plant, hence they had to be revised as suspension was widely underestimated.

Saltation describes a jumping movement of sand grains caused by the wind's upward drag and impacts of other grains [5]. Being limited to the first meter above ground, it mainly contributes indirectly to the impacting sand fluxes on the collectors. It can be seen as an initial movement prior to suspension. The analytical approach given by [8] suited our requirements best, as it is not based on one specific experimental situation but deduced from analysis of the physical phenomenon.

To lift a particle into suspension in an arbitrary fluid the upward drag force of the fluid must be greater than the downward force of gravity. Referring to Stokes' law this implies that the upward fluid velocity, i.e. vertical turbulence, must be greater than the settling velocity $v'_{thr} \, [\text{ms}^{-1}]$ of the particle in the fluid, denoted vertical threshold velocity $v_{thr}$.

Criteria distinguishing suspension and saltation are usually related to friction velocity [14][7]. They are deduced from wind profiles above landscapes of arid or desert regions with corresponding surface roughnesses of $z_0 = 0.005 \text{ m} - 0.05 \text{ m}$ [4]. Under such conditions even strong winds do not provide vertical turbulence intensities high enough to cause suspension of grains considered in this model. As a consequence, existing models and experiments only show suspension of grains with $d \leq 0.1 \text{ mm}$.

Here, the findings presented on the turbulence level have to be incorporated. For a typical CSP site a turbulence level of 25 % signifies that the vertical velocity component is as high as a fourth of the horizontal velocity component. The smaller the particles the smaller the threshold velocity lifting the particles into suspension and the longer the suspension distance. However, as the focus lies on the damage done to collectors, suspension distances as short as a few meters are taken into account. The sample calculation depicted in fig. 5 demonstrates the results that a spectrum of vertical velocities of up to of 5 m/s can lift a 0.4 mm particle to the top of a heliostat.

The maximum height of suspension $z_{max}$ was drawn from several dust monitoring surveys [17][18][19], but had to be inter- and extrapolated assuming that $z_{max}$ increases with wind velocity.

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Fig. 5. (Left) A bouncing sand particle modelled with a simple differential equation $\ddot{z} = 1/\text{m} \cdot \text{F}_{wp}(z) - g$, demonstrating that a gust of 5 m/s raises a 0.4 mm particle to reach the top of a heliostat. (Right) Sand blowing of a crest triggering suspension, Mojave desert, California (Wikipedia).
Supporting our statement and sample calculation, there is evidence that even bigger grains can be suspended if strong vertical turbulences are present \cite{17}\cite{18}\cite{19}. Assuming surface roughnesses for the CSP field of $z_0 = 0.8 - 1.2$ m, winds blowing at $8 \text{ m/s}$ suspend abovementioned grains with respect to existing criteria given by \cite{7} or \cite{14}, because friction velocities, thus vertical turbulences, are distinctly higher.

To obtain a vertical distribution of sand flux $q(z,d,u) \left[ \text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \right]$ per unit cross sectional area and unit time, a modified version of Rouse’s profile with Rouse number $N$ is applied \cite{13}, in which $N$ is related to the abovementioned criteria. The suspended sediment concentration profile calculates the vertical sand mass flux at a specific height. Originally derived for fluvial sand transport it was verified for aeolian transport if $N$ was chosen appropriately \cite{13}.

The vertical distribution $q$ is used later in the MLAST model to determine grain momentum $m(z) \times u(z)$ and thus sand abrasion damage. As $N$ indicates the decay of $q(z,u,d)$, saltation leads to high $N$, meaning a fast decay and negligible sand fluxes for $z = 1$ m and above. In contrast suspension related $N$ are small leading to significant sand fluxes for up to CSP structure heights.

The reference sand flux $q_{ref}(u,d)$ at height $z_{ref}$ was based on analytical and experimental approaches \cite{8}\cite{21}. The maximum transport height $z_{max}$ was inter- and extrapolated from sand storm surveys \cite{17}\cite{18}\cite{19}, leading to:

$$q(z,u,d) = q_{ref}(u,d) \left( \frac{z_{ref} \left( z_{max} - z \right)}{z(z_{max} - z_{ref})} \right)^N$$ \hspace{1cm} (2)

2.4. Site specific input parameters: applying the model to operational scenarios

The MLAST model is designed to be adapted to a scenario for a specific site. Thus, applying the model starts with a survey of the site concerning the behavior of the boundary layer as it develops over the landscape with its characteristic surface roughness $z_0$ and the lifting of the boundary layer caused by the obstacles the CSP structures represent. The effect is modeled by a change in surface roughness $z_0$.

The next step in applying the MLAST model is to survey the sand composition and soil sealing on the site and the surrounding 50 km.

Two test cases are presented. They differ in sand grain size distribution, surface roughness, and different CSP technology: (Example a) a Fresnel field in the Thar desert, India, (Example b) a heliostat field in Upington, Kalahari desert, South Africa. Table 1 summarizes the input parameters for both sites.

| Table 1. Input parameters for the MLAST model of the test cases characterizing surface roughness, grain size distribution ([22][23]), and soil sealing. |
|---|---|
| Input parameter | Fresnel field, Thar desert, India | Heliostat field, Upington, South Africa |
| $z_0$, surrounding landscape [m] | 0.0275 | 0.045 |
| $z_0$, CSP structures [m] | 0.2 | 1.2 |
| fraction, d 0.2-0.4mm [%] | 40 | 20 |
| fraction, d 0.4-0.63mm [%] | 45 | 15 |
| fraction, d 0.63-1mm [%] | 5 | 5 |
| Soil sealing S [%] | 10 | 12.5 |

The next step in applying the MLAST model is to survey the behavior of wind on the site using wind statistics with average and peak wind speeds including 50 year’s gusts and modeling 20 years of operation. From the wind statistics is derived the definition of wind time for a normal operational year which describes the amount of time wind acts on the CSP structures above the saltation and suspension threshold velocities. The scenario is complemented by modeling of high storm events: the 50 year’s gust and if applicable the occurrence of sand and
dust storms. The results from wind tunnel experiments of the CSP structures to be set-up on the site provide knowledge of the velocity profiles and turbulence intensity levels preceding the CSP field and within.

The results of the MLAST model are projected amounts of sand and resulting damage proportional to the momentum $m \times u$ and dependent on height. The model is set to calculating the mass of sand on a 4 by 4 cm² area (corresponding to a typical specimen size used in DIN 52 348) placed at heights of 1 m, 3 m, 6 m, 10 m, and 12 m respectively.

Fig. 6. (a), (b) Exemplary prediction results for Fresnel field in Thar desert, $A_{ef} = 4 \times 4$ cm²: (a) predicted sand masses, (b) predicted momentum. (●) average winds acting over 20a, (■) 50 year’s gust, 0.5 h at 50 m/s. (c) Sand samples of different sands used in abrasion testing and qualification. (d) Specimen (mirror film) exposed to quartz sand, grain size 0.5-0.7 mm, 300 g, facility: sand storm wind tunnel, 12 m/s, 45° impact angle, size 2.5 x 2.5 cm². Dark area unscathed surface, grey area sand abraded.

2.5. Testing of materials, coatings, and components

Following the evaluation and setup of the model, a parametric study and evaluation of all relevant test parameter is carried out as base for lifetime test planning with respect to average and maximum operation conditions for one operation site.

The lifetime testing of materials, coatings, and components consists of sand abrasion tests using standard (DIN 52 348, ASTM D 968-05, MIL-STD 810F) and adapted methods in combination. The adapted methods refer to tests performed in a sand wind tunnel of Göttingen type where sand storm conditions are simulated with control of sand and wind velocities up to 42 m/s, relative humidity and temperature. With the arbitrary control of velocity, amount of sand, relative humidity, and temperature this method exceeds the three standards mentioned.

Using original site sand material is to be preferred. The site sand material is tested and qualified by measurement of grain size distribution and sand specification. The sand size distribution is evaluated and the relevant grain diameters crucial for aeolian sand damage chosen.

The parametric lifetime tests are then performed with standard and adapted methods with original site sand while the reference tests are performed with the sand material specified in DIN and ASTM.
The results of the lifetime testing are specimen systematically exposed to sand abrasion, which are evaluated concerning e.g., increasing haze, decreasing transmission, and decreasing coating thickness.

3. Conclusion

A multi-layered model was developed combining the fluid mechanics of atmospheric boundary layers and aeolian sand transport to calculate sand fluxes (MLAST model). Experimental wind tunnel data from over 4,000 configurations of solar power plant equipment, experimental data from systematic sand abrasion test series, and numerical modeling was integrated into this model. Measurements of boundary layer turbulence and comparison with theoretical boundary layer profiles were reported. Local site and wind conditions need to be surveyed and suitable datasets acquired to feed the MLAST model and efficiently simulate a specific CSP site and operational scenarios with average and maximum conditions.

In applying the multi-layered model, a prediction can be found for height dependent cumulative damage. The MLAST model site-specifically determines the sand exposure equivalents in amount of sand for long periods of exposure, say 20 years. Thus, lifetime prediction is found in combination with systematic sand abrasion test series using standards (DIN 52 348, ASTM D 968-05, MIL-STD 810F) and adapted methods.

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