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Effect of Surface Sand Topography Changes on Repeatability of Land Seismic Data in Desert Environment

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SUMMARY

Seismic monitoring in desert environments has many challenges and changes in surface sand topography in one of them. We present a numerical study of the impact of surface elevation changes on repeatability of seismic data recorded with buried receivers. We focus on the early arrivals since they are affected only by the near-surface structure. We define changes in the surface topography as a homogeneous Gaussian random field. We show that for a homogeneous near surface layer, NRMS and predictability depend only on changes in the surface topography but not on its slope. For a heterogeneous near surface we observe worse repeatability for the zones with a thin sand layer (< 5 m), whereas areas of thick sand (> 10m) behave similarly to a homogeneous model may cause significant non-repeatability up to 60% of NRMS error and predictability down to 75%. These numbers are similar to the NRMS measured on field data in Saudi Arabia, suggesting that such factors may be significant for land 4D seismic in a desert. In addition, sand topography variations can accumulate thus explaining experimentally observed trends showing that land seismic repeatability degrades over time from days to months to years.

Introduction

Time-lapse seismic is extremely challenging in desert environment. Even when monitoring with buried receivers, 4D data suffers from non-repeatability due to changes in acquisition geometry, variable source coupling and seasonal variations in the near-surface layers. Bakulin *et al.* (2014) further observed that repeatability of 4D land data seems to degrade with time. This prompted us to study additional factors related to changes in surface sand topography due to wind and infrastructure changes. We expect that such changes may accumulate with time and help explain degradation in repeatability observed in the field data. We conduct a numerical study evaluating this effect and compare with the field observations. Bakulin *et al.* (2014) demonstrated a direct correlation between repeatability of deep target reflections on a stack and pre-stack early arrivals recorded by buried receivers. For this reason we restrict the current study to early arrivals only (0-0.2 s) that depend only on the upper part of the model and can quantify 4D seismic noise caused by surface changes. We perform numerical simulations for a set of 40 statistical models with different standard deviation and correlation length of the free-surface perturbations. We perform statistical analysis of the simulated wavefields in terms of seismic repeatability and demonstrate correspondence to real 4D data from Saudi Arabia.

Model construction and numerical simulation

To study the impact of surface variability on the repeatability of the acquired seismic data we describe the changes in surface elevation as a homogeneous Gaussian random field: $Z(x) =< Z(x) > +Z'(\mathrm{x})$, where $< Z(x) >$ is a profile of mean surface elevation and $Z'(\mathrm{x})$ is a local change. The probability distribution of a homogeneous Gaussian random field is fully defined by its mean value and covariance function $C(r)$, which was considered to be analytical: $C(r) = \sigma^2 \exp(\pi r^2/4I^2)$, where σ is a standard deviation (STD) and I is the correlation length (I).
As an example we take the surface topography from a field data case in a desert environment (Bakulin *et al.*, 2014). From this we construct the mean surface profile and estimate the fluctuations (Figure 1). The mean profile was estimated as a spline approximation of the available dataset, while fluctuation parameters were derived by a moving window estimator (Li and Lake 1994) where $\sigma_0 = 1.16$ m and $I_0 = 46.9$ m. We then vary these parameters so that $\sigma = 2^{-2}\sigma_0, \dots, 2^2\sigma_0$ and $I = 2^{-4}I_0, \dots, 2^4 I_0$ to understand their impact on the wavefield changes and seismic repeatability. Figure 1 shows examples of the constructed models for different fluctuation parameters. Here we use simulations for $x \in [900 \text{ m}, 2300 \text{ m}]$, where the mean trend deviates from the linear function by no more than 2 m.

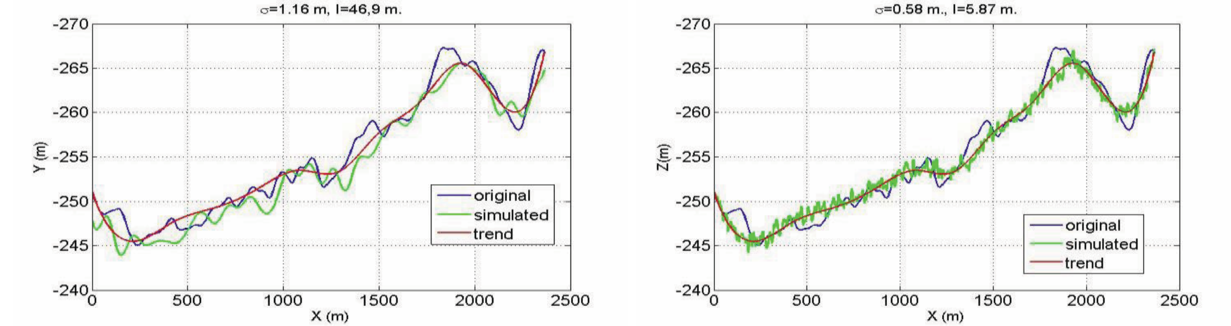


Figure 1 *Examples of surface elevation profiles for different statistical parameters. Blue line represents elevation from the baseline survey, red is the trend, and green is the statistical realization.*

We also consider two types of near surface models. The first model is homogeneous ($V_P = 750$ m/s, $V_S = 312$ m/s, $\rho = 1600$ kg/m^3) with surface topography. In this model only the changes in the surface topography affect the recorded wavefield. The second model is horizontally layered with the same variable surface topography (Figure 2). We assume the vibrator is a vertical force at 0.5 m depth and record vertical velocity using buried receivers at 30 m simulating the actual field experiment geometry (Bakulin et al., 2014). Source and receiver spacing are 7.5 m and 30 m respectively. We modeled using a free surface and a Ricker wavelet with a central frequency of 30 Hz.

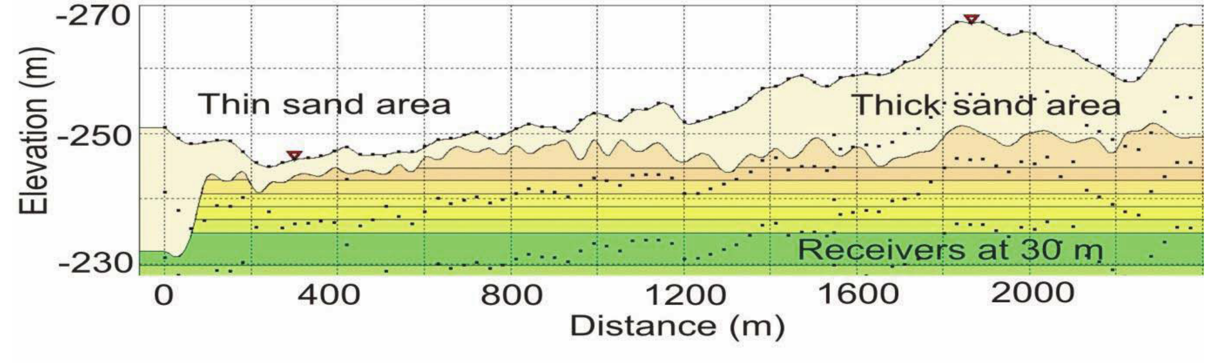


Figure 2 *A sketch of the inhomogeneous model used for the simulation.*

We generated 20 realizations of the surface topography for each set of statistical parameters. Then we simulated the seismic data using an approach based on the combination of the discontinuous Galerkin with finite difference method (Lisitsa et al., 2014).

Statistical analysis and comparison with field data

Following Bakulin *et al.* (2014) we considered only the early arrival seismograms, recorded for lateral offsets of up to 30 m within a time window from 0 to 0.20 seconds. Figures 3 and 4 show examples for different receiver positions and realizations of the surface. For each set of statistical parameters we quantified seismic repeatability using two industry-standard metrics: normalized root-mean square (NRMS), and predictability (PRED) or normalized summed squared crosscorrelation of two traces (Kragh and Christie, 2002).

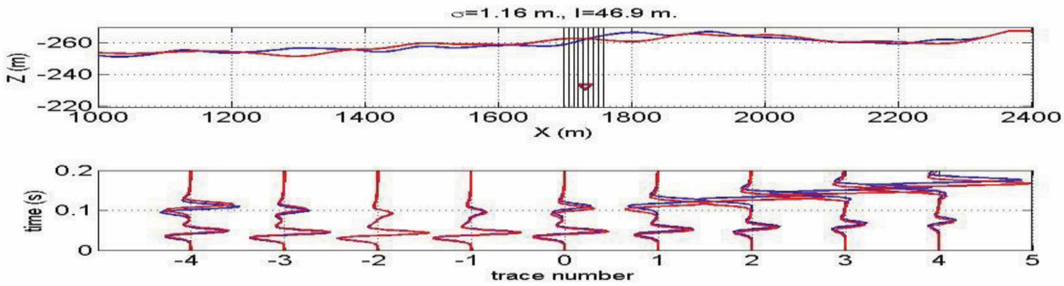


Figure 3 *Examples of the early arrival seismograms computed for two realizations of the surface topography with STD=1.16 m and I=46.9 m. The models, source positions (black lines) and the receiver (red triangle) are presented at the top; the vertical component of the recorded velocity is at the bottom.*

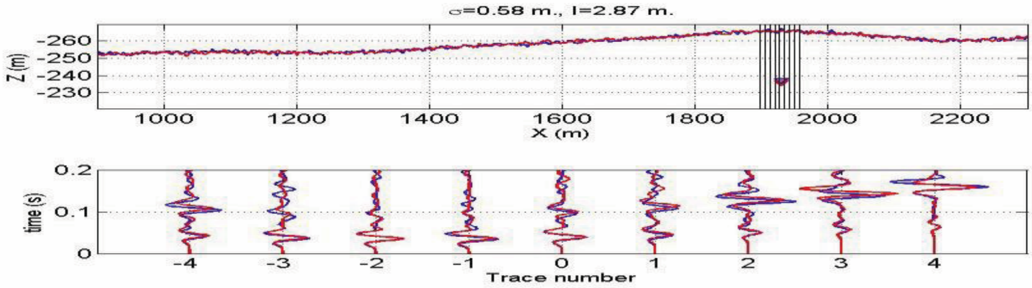
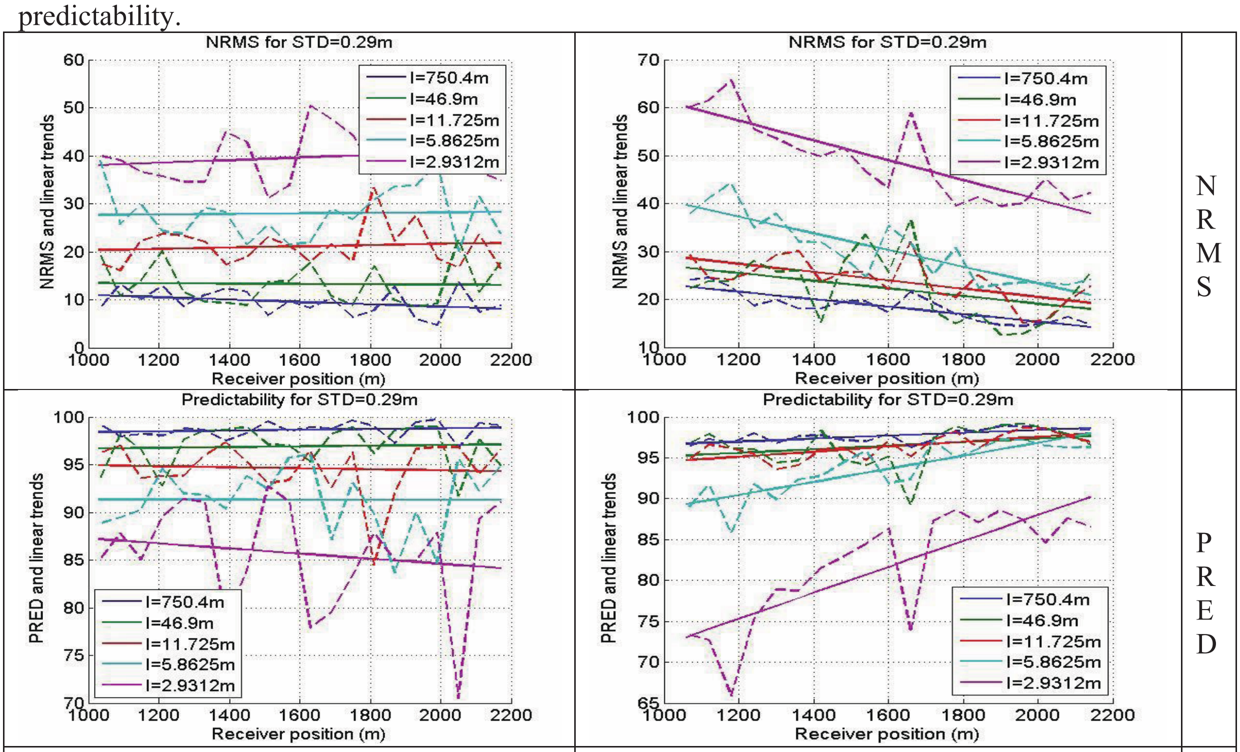


Figure 4 *Examples of the early arrival seismograms computed for two realizations of the surface topography with STD=0.59 m and I=2.87 m. The models, source positions (black lines) and the receiver (red triangle) are presented at the top; the vertical component of the recorded velocity is at the bottom.*

First, we consider NRMS and predictability as functions of the receiver position and constructed regression functions (linear and quadratic). Examples of NRMS, predictability and their linear trends are shown in Figure 5 for both homogeneous and layered models. For the homogeneous models the mean deviation of the linear trend from the horizontal line does not exceed one degree for NRMS and

0.2 degree for predictability. This observation is in good agreement with results of the analysis of correlation coefficients between receiver locations and NRMS and PRED values, suggesting that the NRMS and predictability do not depend on the receiver position. Thus for the homogeneous model the NRMS and predictability can be estimated over all receiver positions as presented in Figure 6. Note that within the range of parameters tested (except for too high correlation length) there is a linear decrease of the log of NRMS with an increase of the log of the correlation length. Moreover the linear regression for these curves has the main coefficient equal to -0.42 on average, which means that the quadratic decrease of correlation length leads to a linear increase in the NRMS. One may also observe a linear relationship between the standard deviation of the topography change and both NRMS and predictability.



Homogeneous model

Full model

Figure 5 *NRMS (top) and predictability (bottom) for the same statistical parameters of the free surface for homogeneous (left) and inhomogeneous (right) models.*

For the layered model, we observe a consistent trend between NRMS decrease and predictability increase from the left side of the model to the right (Figure 5). In other words,., the accumulation of the error is smaller in the thick sand area (Figure 2) (the first weathered layer overlaying more competent bedrock). This is consistent with the field data (Bakulin et al., 2014). Figure 5 shows that for the thin sand area the NRMS values for the layered model are 1.5 times those for the homogeneous model, whereas for the thick sand layer the NRMS values are more similar for both models. A similar trend is true for the predictability, values are lower for the layered model in the thin sand area and the same for the thick sand area.

In the layered model with $\sigma = 0.29$ m and $I = 5.8$ m we observe NRMS around 30 to 40% (Figure 5). Such values are close to the NRMS observed on early arrivals of field data (Bakulin et al., 2014), when surveys were acquired several weeks apart. For the surveys that are several months apart NRMS between early arrivals reaches 60 to 70%. Based on this modeling, this could be a result of sand accumulation, corresponding to an increase of in the modeling (Figure 6). In the field experiment, the differences between early arrivals may be due to different sources of non-repeatability. Our modeling suggests that variations of the surface topography should be considered as an important factor and can significantly degrade repeatability of the data in a desert environment.

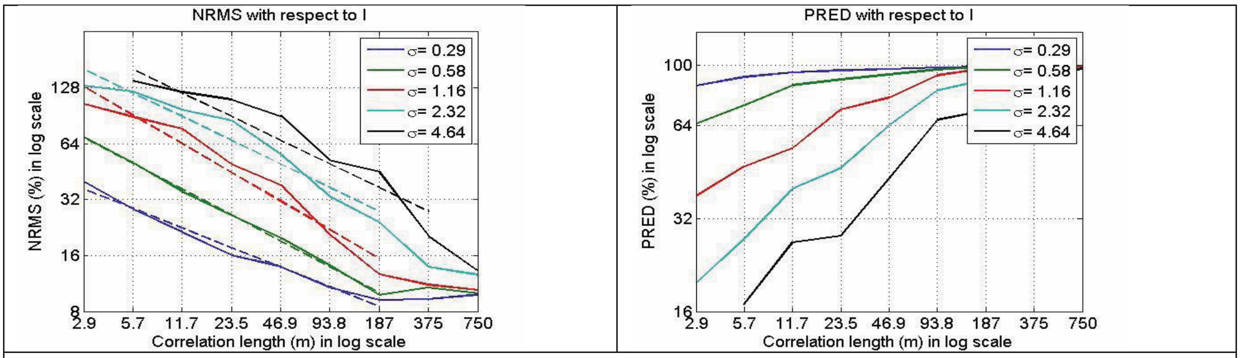


Figure 6 *NRMS (left) and predictability (right) in logarithmic scale with respect to correlation length in logarithmic scale in homogeneous model. Inclinations of the linear trends of NRMS decrease with increasing of the correlation length are independent on the standard deviation.*

Conclusions

We presented a detailed numerical study of the impact of surface sand topography changes on repeatability of land seismic data in a desert environment. In particular, we focused on the early arrivals recorded by buried receivers, because they are affected only by the near surface changes, thus containing the principle information about this part of the model. We defined changes in surface elevation as a homogeneous Gaussian random field with a standard deviation varying from 0.01 to 0.15 of the dominant P-wave wavelength, and correlation length ranging from 0.1 to 30 wavelengths. For a homogeneous subsurface, the NRMS and predictability are independent of the surface slope and receiver position. Elastic modelling predicts almost linear increase in NRMS with increasing standard deviation of the elevation fluctuations. It also shows that a quadratic decrease of the correlation length causes a linear increase in the NRMS. For a layered model with surface topography, NRMS increases (predictability decreases) in the area of thin sand (thickness less than 5 m) suggesting higher impact from near-surface ghosting, whereas in the area of thick sand (more than 10 m) the absolute values of the NRMS and predictability are close to that of the homogeneous model. NRMS values due to relatively small changes in surface topography as expected by windblown sand results in similar values to those measured on field data, suggesting that it may indeed explain at least part of the observed non-repeatability. In addition, topography variations due to sand could accumulate over time, potentially explaining experimentally observed trends showing that land repeatability degrades with time from days to months to years.

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