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Statistical Analysis of Free-Surface Variability's Impact on Seismic Wavefield

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SUMMARY

One of the main challenges in seismic monitoring is the repeatability of the experiment conditions. Among other reasons changes in surface topography over time may cause strong non-repeatability in acquired seismic data especially in desert environment where the sand dunes can move between surveys. In this paper we present a numerical study of the effects of free-surface variation, defined as homogeneous Gaussian random field, on the seismic data. We show that for homogeneous models repeatability metrics (such as NRMS and predictability) using the early arrivals as measured by buried receivers depend mainly on the perturbation, but not on the smooth trend of the free–surface topography. For models with complex near-surface velocity NRMS for the thin sand area (<5 m) is almost twice as high as in the thick sand area (>10 m). Moreover, we demonstrate that significant non-repeatability (NRMS up to 70%) can be caused by just surface elevation changes.

Introduction

Time-lapse seismic is challenging in desert or permafrost environments, changes in acquisition geometry, free-surface variations, and seasonal near-surface changes may cause significant non-repeatability in 4D seismic data (Bakulin et al., 2014). Here we perform a detailed numerical study of the effect of free-surface variation on the repeatability of seismic data acquired with buried receivers simulating the geometry of a field experiment from Saudi Arabia (Bakulin et al., 2014). We model the free-surface changes as a homogeneous Gaussian random field, considering a wide range of possible variations of standard deviation and correlation length. In addition, we perform simulations for four different near-surface models to observe the combined effect of the free-surface variability and near surface velocity model. We focus on the early arrivals (0-0.2 s) as their repeatability is strongly correlated to the repeatability of deep reflection data (Bakulin et al., 2014). Early arrival waveforms depend almost exclusively on the upper part of the model, thus quantifying 4D noise caused by near surface changes. Statistical analysis of the computed wavefelds, performed in terms of seismic repeatability, shows that simulated data demonstrate trends similar to the ones observed in real 4D data, acquired in Saudi Arabia.

Model construction and wave simulation

To study the impact of surface variations on seismic data we describe the free surface as a superposition of a smooth trend and rapidly varying perturbations defined as a homogeneous Gaussian random field. The probability distribution of this field is fully defined by its mean value and covariance function. In this study we consider a Gaussian correlation function which depends on two parameters: standard deviation (STD) σ and the correlation length (I).

To construct a realistic mean profile and estimate typical perturbations of free-surface topography we take a profile from a field data case in a desert environment (Bakulin et al., 2012). The mean profile was estimated as a spline approximation of the available dataset, while the perturbations were reconstructed using moving window estimator as described in Li and Lake (1994). As a result, estimated parameters of the Gaussian random field were $\sigma_0 = 1.16\,\text{m}$ and $I_0 = 46.9\,\text{m}$. We vary these parameters so that $\sigma = 2^{-2}\sigma_0,...,2^2\sigma_0$, and $I = 2^{-4} I_0,...,2^4 I_0$ to understand their impact on the wavefield changes and seismic repeatability.

Four different elastic near surface models were considered. The first model is homogeneous (V_P = 750 m/s, V_S = 312 m/s, ρ = 1600 kg/m^3) with actual surface topography (Figure 1a). The second one is the model with one interface as provided in Figure 2a, this model will be referred as “irregular”. In Figure 3a a model with a set of horizontal layers is provides, called “layered”. And the fourth one combines complexities of the others (Figure 4a) called “full” model.

We model the vibrator as a vertical force at 0.5 m depth and record the vertical particle velocity using buried receivers at 30 m simulating geometry of the actual field experiment from Saudi Arabia (Bakulin et al., 2014). Source and receiver spacing are 7.5 m and 30 m respectively. We simulated the wavefield using Ricker wavelet with central frequencies of 30 Hz for each near-surface model along with every random model realization of the free-surface. Simulations were performed using a hybrid modeling approach (Lisitsa et al., 2014), so that in the upper part of the model (down to an elevation of -230 m) the centered-flux discontinuous Galerkin method was used, whereas standard staggered-grid finite-difference scheme was applied elsewhere.

Statistical analysis of the wavefields

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. For each model realization 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). First, we analyse NRMS and predictability PRED as a function of receiver position. We construct linear regression functions, as presented in Figures 1-4 (b and c) respectively.

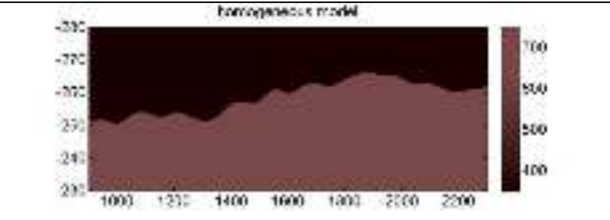


***Figure 1a** An example of a homogeneous model (Vp).*

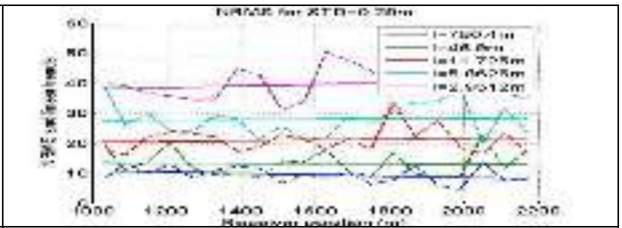


***Figure 1b** NRMS with respect to receiver position for homogeneous models.*

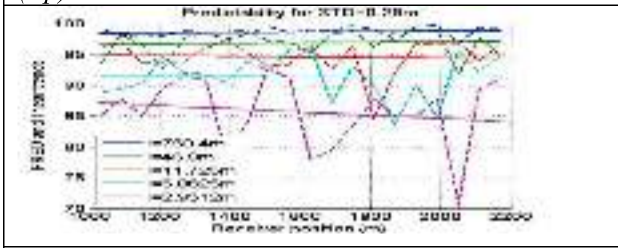


***Figure 1c** PRED with respect to receiver position for homogeneous models.*

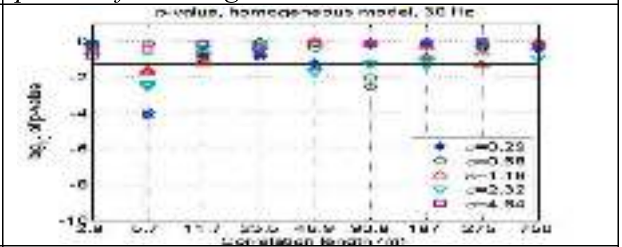


***Figure 1d** Log of p-values corresponding to NRMS and PRED for all free-surface variations.*

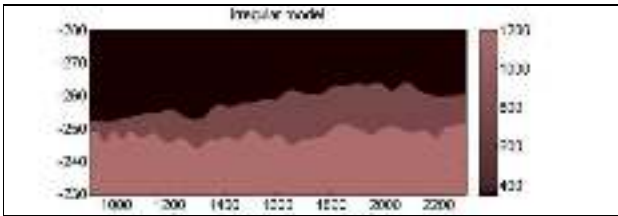


***Figure 2a** An example of "irregular" model (Vp).*

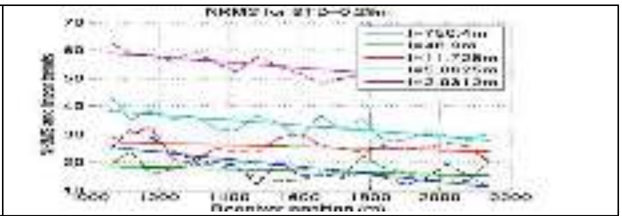


***Figure 2b** NRMS with respect to receiver position for "irregular" models.*

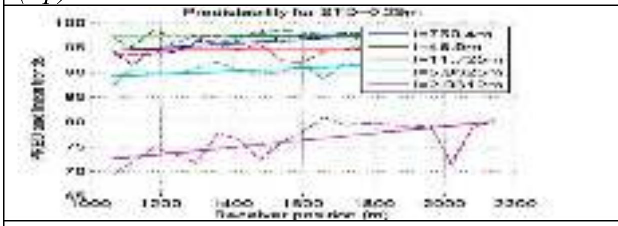


***Figure 2c** PRED with respect to receiver position for "irregular" models.*

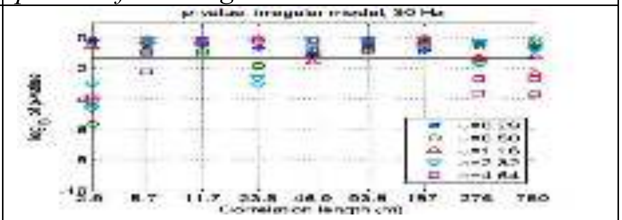


***Figure 2d** Log of p-values corresponding to NRMS and PRED for all free-surface variation.*

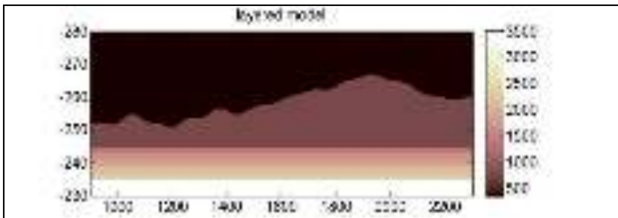


***Figure 3a** An example of a "layered" model (Vp).*

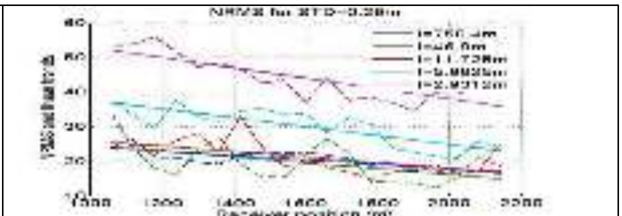


***Figure 3b** NRMS with respect to receiver position for "layered" models.*

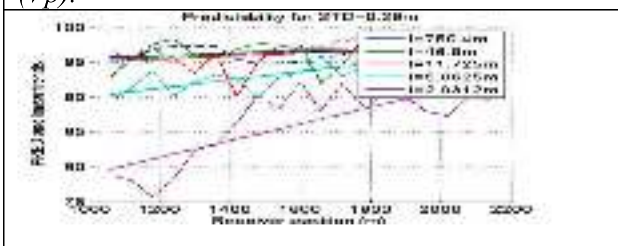


***Figure 3c** PRED with respect to receiver position for "layered" models.*

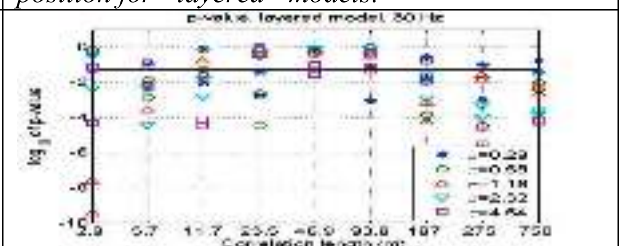


***Figure 3d** Log of p-values corresponding to NRMS and PRED for all free-surface variation.*

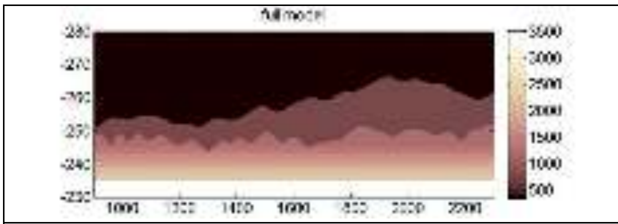


Figure 4a *An example of a "full" model (Vp).*

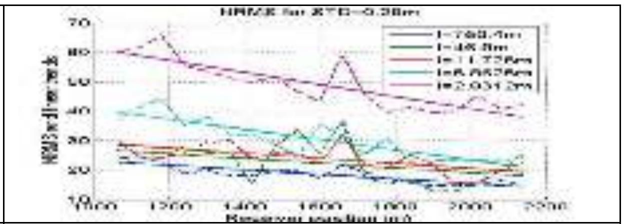


Figure 4b *NRMS with respect to receiver position for the "full" models.*

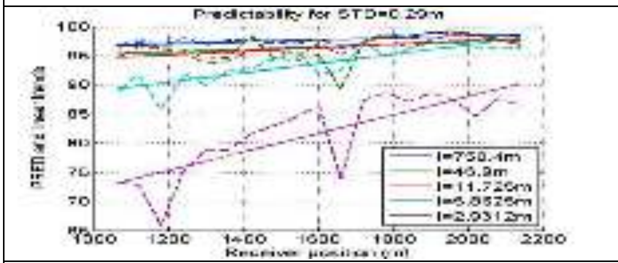
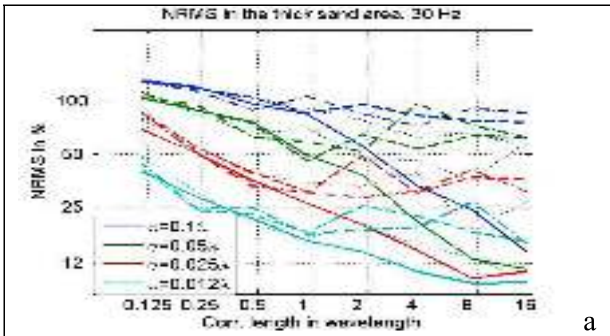


Figure 4c *PRED with respect to receiver position for the "full" models.*

Figure 4d *Log of p-values corresponding to NRMS and PRED for all free-surface variation.*



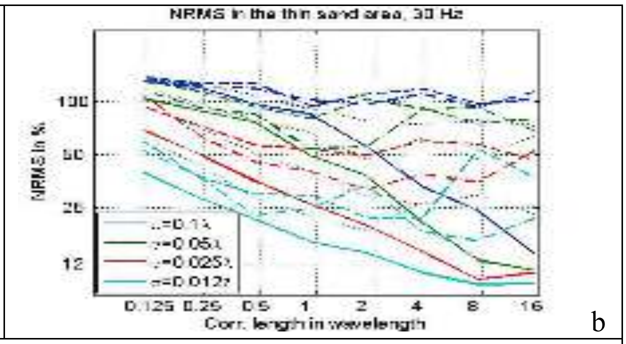


Figure 5 *NRMS with respect to the correlation length for different values of the STD of the free surface variation for thick (a) and thin (b) sand area. Solid lines represent the values for the homogeneous model, dashed lines represent the full model, dash-dotted lines correspond to layered model, and dotted lines correspond to the irregular model.*

We observe no dependence on the receiver position for the homogeneous models, while for complex models the NRMS increases and PRED decreases in the thin sand area (receivers between 1000 and 1600 m. To corroborate these observations, we compute the correlation coefficients (and corresponding p-values) between the NRMS (PRED) values and receiver position (Figures 1-4 d). The p-value is the probability of obtaining the test statistic equal or more extreme than what was actually observed. If the p-value is less than the significance level, the null hypothesis is rejected. It means that if the p-value is greater than 0.05 (black line) the NRMS and PRED are independent of receiver position. Figure 1d indicates that for the homogeneous model the p-values mainly satisfy the criteria, whereas for layered and full model (Figures 3d and 4d) the criterion is not fulfilled. For the irregular model the distribution of the p-values also has no clear trend with values being below and above critical value (Figure 2d). Clearly, for the homogeneous model the variation of the seismic data depends exclusively on the perturbation of the free surface, whereas for the other models, statistical parameters depend on the receiver position as well.

To estimate the values of the statistical measures of the seismic data in dependence on the parameters of the free-surface variations we computed the values of NRMS and PRED for all receivers positions for the homogeneous model, and considered the left two and right two positions for the other models. To make the analysis representative we rescaled the statistical parameters of the free surface variation with respect to P-wave wavelength in the uppermost layer. Figure 5 represents the NRMS for different values of the free surface STD with respect to the correlation length of the free surface variation measured in wavelength. For the thick sand area (Figure 5 a) the NRMS for all considered models is almost the same for the correlation length less than one wavelength. For the correlation length of the free surface variation greater than one wavelength NRMS of the complex models almost stabilizes, whereas that of the homogeneous model NRMS is decreasing with the increase of the correlation length. For the thin sand area, presented in Figure 5b, behaviour of the NRMS is the same as for the thick sand area, however the values of the NRMS are higher. This may mean that for the low correlation lengths of the free surface perturbations their effect on the statistical measures of the early arrivals dominates, however if the variations are smooth enough with respect to the wavelength their effect gets weaker than that of complex near surface.

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 0.006 to 0.2 of the dominant P-wave wavelength, and correlation length ranging from 0.06 to 32 wavelengths.

Modeling results show that seismic data repeatability metrics can strongly depend not only on the free-surface variations but also on the near-surface velocity model. In particular, for a homogeneous near surface, the NRMS and predictability are not correlated with the surface slope and receiver position with almost linear increase of NRMS with increase in the free surface elevation changes. For models with complex near surface structure and 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). Moreover in the thick sand area the NRMS and the PRED are equivalent for all models if the correlation length of the free surface is less than the dominant P-wave wavelength whereas for smoother variations the NRMS for complex models stabilizes. In the thin sand area the behavior of the NRMS and PRED is the same, but the absolute values of the NRMS is higher (PRED is lower) than those for the thick sand area.

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.

Acknowledgements

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