Monitoring the tidal response of a sea levee with ambient seismic noise

Thomas Planès ^{*1}, Justin B. Rittgers², Michael A. Mooney¹, Wim Kanning¹ and Deyan Draganov³

¹Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, USA

²Department of Geophysics, Colorado School of Mines, Golden, USA

³Department of Geoscience and engineering, Delft University of Technology, The Netherlands

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Abstract

Internal erosion, a major cause of failure of earthen dams and levees, is often difficult to detect at early stages using traditional visual inspection. The passive seismic-interferometry technique could enable the early detection of internal changes taking place within these structures. We test this technique on a portion of the sea levee of Colijnsplaat, Netherlands, which presents signs of concentrated seepage in the form of sandboils. Applying seismic interferometry to ambient noise collected over a 12-hour period, we retrieve surface waves propagating along the levee. We identify the contribution of two dominant ambient seismic noise sources: the traffic on the Zeeland bridge and a nearby wind turbine. Here, the sea-wave action does not constitute a suitable noise source for seismic interferometry. Using the retrieved surface waves, we compute time-lapse variations of the surface-wave group velocities during the 12-hour tidal cycle for different frequency bands, i.e., for different depth ranges. The estimated group-velocity variations correlate with variations in on-site pore-water pressure measurements that respond to tidal loading. We present lateral profiles of these group-velocity variations along a 180-meter section of the levee, at four different depth ranges (0 m-40 m). On these profiles, we observe some spatially localized relative group-velocity variations of up to 5% that might be related to concentrated seepage.

Keywords: levee monitoring, internal erosion, seismic interferometry

^{*}tho.planes@gmail.com

1 Introduction

Earthen dams and levees (EDLs) - the most common type of embankments in use today - are prone to failure in the form of internal erosion of soils within or below the embankment structure. Internal erosion is induced by concentrated seepage that transports soil particles through the embankment or under its foundation. This process commonly initiates in areas of weakness subjected to a strong hydraulic gradient and is often unnoticeable from visual inspection until it manifests itself at the exterior surface (Fell et al., 2003). Of particular concern, the backward erosion piping mechanism starts at the downstream end of the levee, expelling water and soil particles upwards in the form of sandboils. Under certain conditions, a channel can then retrogradely form beneath the structure until it connects with the upstream reservoir (Van Beek et al., 2010). Once the pipe is fully formed, its diameter is bound to grow, likely leading to a collapse of the structure.

The presence of sandboils alone is not a reliable indicator of imminent piping (Kanning et al., 2008). Sometimes sandboils appear on performing structures that do not present any immediate danger, while other times sandboils appear just a few hours before complete failure (Foster et al., 2000). Therefore, there is a strong need to develop monitoring techniques able to assess the soil condition within or below the structure, to complete or replace the usual visual inspection of the surface. Such techniques could help identify early warning indicators of internal erosion, and help prevent potential catastrophic damages.

One promising monitoring approach is passive seismic interferometry, a technique that enables one to retrieve seismic impulse responses through, most commonly, cross-correlation of ambient seismic noise recorded at any two sensors. This technique, which removes the need for an active source, has experienced a significant growth over the last decade in the fields of geophysics and seismology. It has been used to monitor or image a wide range of natural structures such as reservoirs (Obermann et al., 2015; Boullenger et al., 2015), volcanoes (Sens-Schönfelder and Wegler, 2006; Obermann et al., 2013), fault zones (Wegler and Sens-Schönfelder, 2007; Brenguier et al., 2008), and the earth's deep structures (Ruigrok et al., 2011; Boué et al., 2013; Lin et al., 2013). The technique has also found a few applications in civil and geotechnical engineering, such as buildings (Snieder and Şafak, 2006; Nakata et al., 2013; Ebrahimian et al., 2014) and landslides monitoring (Renalier et al., 2010; Mainsant et al., 2012).

Seismic interferometry has recently been used for levee monitoring. Le Feuvre et al. (2015) demonstrated the retrieval of surface waves along a sea levee using the seismic noise induced by water waves slapping on the structure. The broad frequency content of the noise (5 Hz-80 Hz) allowed the estimation of a shear-wave velocity profile with depth. Presenting only 4 minutes of ambient-noise recordings, their work did not include, though, any time-lapse monitoring aspect.

Planès et al. (2016) presented the retrieval of surface waves from ambient noise on two experimental structures. The first structure was a canal-embankment model undergoing piping in a laboratory test facility. The measured group-velocity variations were found to concord spatially and temporally with the progress of piping erosion. The second structure was a levee embankment loaded gradually until partial failure in a field testing site (IJkdijk).

The estimated group-velocity variations presented correlations with the upstream water level and with local pore-water pressure responses.

In this study, time-lapse monitoring with seismic interferometry is applied to a sea-side levee protecting the town of Colijnsplaat, Netherlands. This levee is subjected to tide-induced load variations (± 1.5 m) and shows signs of concentrated seepage in the form of sandboils in an inland (downstream) ditch. The presence of these sandboils suggests that concentrated seepage paths might exist within the structure. These paths, typically formed by internal erosion, should manifest as local alterations of porosity and effective stress in the structure. These would in turn act as local seismic wave velocity contrasts and could therefore be detected through passive seismic interferometry. In addition, the tidal fluctuations provide a dynamic forcing of the structure that could help identify eroded areas. Because of the modified hydraulic conductivity along seepage paths, these weakened areas could respond differently to the tidal forcing than the rest of the structure. The differences in tidal response could be assessed with time-lapse monitoring of the seismic velocities during the tidal cycle. The monitoring of the Colijnsplaat sea levee thus forms a unique opportunity to test if seismic interferometry performed throughout a tidal cycle would provide greater insight into the embankment's condition.

The survey site and experimental setup are described in section 2. The dominant ambient noise sources are identified and analyzed in section 3. Using the seismic-interferometry method, seismic responses are retrieved from ambient noise in section 4. Finally, the time-lapse monitoring of the structure during a 12-hour tide cycle is addressed in section 5.

2 Survey site and experimental setup

The surveyed sea-levee section is located about 1 km south-east of the town of Colijnsplaat, Netherlands, where the south-western end of the Zeeland bridge is connected to the region of Noord-Beveland (Fig. 1). The structure of the levee is schematized in Figure 2. The current levee is built around an old clay sea levee, thus the core of the levee consists of this old levee and a fill of sand. The levee is lined with a 0.6 m clay cover to prevent erosion. On the sea side, a stone revetment prevents wave erosion. The levee is built on a clay blanket that overlays a sand aquifer. The blanket is approximately 0.6 m thick, but much thinner at the location of the inland ditch. The sand aquifer is approximately 6 m thick and 65 m wide.

A 150 m section of the sea levee located on the north-west side of the Zeeland bridge junction presents several visible sandboils in the downstream drainage ditch (Fig. 3). The sandboils were found to be active during high tide - i.e., visible water flow and sand production, and inactive during low tide - i.e., no water and no sand. During the survey period, the tidal range measured at nearby locations was about 3 m. The identified sandboils are a direct visual indication of concentrated water seepage, a potential factor for internal erosion development. The survey site comprises several potential sources of ambient seismic noise such as the low breaking waves - up to about 20 cm high, the traffic on the Zeeland bridge or secondary roads, and a wind turbine (Fig. 1).

A profile of 88 accelerometers was deployed on the crest of the levee, with a 3.5 m spacing,

112 covering a section of about 300 m (Fig. 3a). These sensors feature a flat response in the DC-
 113 500 Hz frequency range. Each was coupled to the soft ground through a 10 cm-long plastic
 114 spike. The vertical component of the ambient seismic noise was recorded continuously for
 115 12 h from the evening of October 10th to the morning of October 11th 2014 (8pm-8am).
 116 The ambient noise was sampled at 1 kHz, and stored into 16 s-long files.

117 Before the start of the continuous monitoring, a few hammer shots were recorded to get
 118 baseline group-velocities of the surface waves propagating along the levee crest. The picking
 119 of the arrival times in different frequency bands yielded the following group velocities: 125
 120 m/s around 20 Hz, 130 m/s around 15 Hz, 133 m/s around 10 Hz and 147 m/s around
 121 5 Hz. These values will be compared to the group-velocities obtained from the responses
 122 reconstructed through passive seismic interferometry.

Figure 1: (a) Satellite plan view of the survey location comprising the following elements: the accelerometer profile on the crest of the levee; the sandboil area in the drainage ditch; the Zeeland bridge and a wind turbine. The location and viewing angle of pictures (b) and (c) are indicated by the white arrows in (a).

Figure 2: Schematic cross section of the Colijnsplaat sea levee. The reference of the elevation values is the average sea level.

Figure 3: Close-up plan view of the seismic array (a) and pictures (b-d) of three of the major sandboils observed in the drainage ditch. The accelerometer array (black triangles), deployed on the crest of the levee, passes under the Zeeland bridge which supports a main traffic road.

3 Noise analysis and noise-source identification

Identifying and characterizing the ambient-noise sources is an important step for seismic interferometry. The frequency content of the seismic noise constrains the depth range that can be probed by the surface waves - the easiest mode retrieved from ambient noise. The location of the noise sources relative to the array determines whether the travel times - and thus velocities - between sensors can be estimated without bias.

The recorded ambient noise shows distinct features depending on the absence or presence of bridge traffic. We sorted the 16 s noise panels in two categories - “no traffic” or “traffic” - accordingly. The “no traffic” noise panels show quasi-continuous noise events with comparable amplitude moving out from high end to low end of the array - i.e., towards decreasing sensor numbers. In contrast, the “traffic” noise panels exhibit short-duration, high-amplitude noise events that display a moveout pattern initiating from the bridge junction location. An example of a “no traffic” (resp. “traffic”) noise panel band-pass filtered around 10 Hz (50% fractional bandwidth) is presented in Figure 4a (resp. 4b).

The amplitude frequency spectrum of all the “traffic” and “no traffic” noise panels, stacked in each category, is displayed in Figure 4c. The spectrum of the “traffic” noise panels shows a smoothly distributed energy, mainly contained in the 5-20 Hz frequency range. The spectrum of the “no traffic” noise panels shows comparatively lower energy, and features several spikes including the ones at 4.5, 6, 7.5, 14.5 and 17.5 Hz. In Figure 4d, the root mean square (RMS) of the noise amplitude is shown versus the sensor number for all “traffic” and “no traffic” panels, stacked in each category. During “no traffic” periods, the noise amplitude decreases with the sensor number. During “traffic” periods, the noise amplitude is maximum at the bridge location and decreases away from it, i.e., towards both ends of the array. The traffic noise is transmitted from the bridge to the levee through four support pillars located next to the profile, around sensors 66 to 70 (Fig. 1c and 3a). During “no traffic” periods, the dominant noise source is interpreted to be generated by the wind turbine (Fig. 1a). The distribution of the noise amplitude along the profile as well as the direction of propagation of the noise are concordant with the location of the wind turbine. The spikes in the noise spectrum are understood as normal modes of the wind turbine.

Wind-turbine noise is always present during the recorded period of 12 hours. However, each time a vehicle passes over the bridge pillars, the recorded signals become dominated by the traffic noise. Throughout the total number of 2746 16 s-long files recorded during the night, 905 of these files contain traffic events. The proportion of “traffic” and “no traffic” files throughout the night is shown in Figure 5. The proportion of traffic files is as low as 5-10% around 3am and as high as 40-60% around 9pm and 7am.

We were not able to identify noise events from sea-wave action in the records. Weather conditions were very calm during the night and only low amplitude (~ 20 cm) sea wave were observed. Thus we suppose that the noise from sea-wave action is dominated by the traffic and wind-turbine induced noise. The potential of the identified noise sources for imaging and time-lapse monitoring of the structure will be discussed at the end of the next section, after the study of the seismograms retrieved with seismic interferometry.

Figure 4: Individual noise panels filtered around 10Hz during a “no traffic” period (a) and during a “traffic” period (b). The black rectangles indicate the records of the sensors located below the bridge. (c) Amplitude spectrum of the noise stacked over all “no traffic” periods (solid line) and over all “traffic” periods (dashed line), averaged over all the sensors. (d) RMS of the noise at each sensor stacked for all “no traffic” periods and filtered around 6Hz (solid line). RMS of the noise at each sensor stacked for all “traffic” periods and filtered around 10Hz (dashed line).

Figure 5: Proportion of recorded 16 s-long files containing traffic events in 15 min-long windows of time throughout the 12 hour recorded period (8pm-8am).

4 Impulse response retrieval

The passive seismic-interferometry method allows one to retrieve seismic impulse responses - also called Green’s functions - through cross-correlation of ambient noise recorded at two receivers. Several conditions are required to retrieve realistic impulse responses such as uniform distribution of noise sources, white noise, etc. (Wapenaar et al., 2010a,b; Snieder and Larose, 2013, and references therein). Even if these conditions are never reached in practice, the retrieved responses often contain useful information about the studied medium.

An important feature that can be retrieved from noise is the travel time of a propagating surface wave between two sensors. The travel time yields the average group-velocity of the wavelet along the travel path. This group-velocity is itself related to the elastic moduli and density of the material, providing a useful proxy for time-lapse monitoring of internal changes in a structure.

To retrieve impulse responses from noise, the cross-coherence function CCF is used (Nakata et al., 2011). Consider $n_i(t)$ - the ambient noise recorded at sensor i , and $n_j(t)$ - the ambient noise recorded at sensor j , over the same period of time. In the frequency domain, the cross-coherence function $\text{CCF}_{ij}(\omega)$ is obtained as

$$\text{CCF}_{ij}(\omega) = \frac{n_i^*(\omega)n_j(\omega)}{|n_i(\omega)||n_j(\omega)|}, \quad (1)$$

where ω denotes the angular frequency and the asterisk complex conjugation. The cross-coherence operation corresponds to a cross-correlation with an additional normalization of the noise spectrum at each sensor. This normalization - also called whitening - enables the retrieval of narrower wavelets for more precise travel-time measurements (Bensen et al., 2007). Here, the ambient noise is first bandpass-filtered into different narrow bands around 5 Hz, 10 Hz, 15 Hz, and 20 Hz (50% fractional bandwidth). The CCFs are then computed for each frequency band, each possible pair of sensors, and each 16 s-long noise file recorded during the 12 h period. In agreement with section 3, the CCFs are also sorted in the categories “traffic” and “no traffic.” For visualization purposes in this section only, the CCFs are then averaged over the 12 h monitored period in each category. Sensor A2, located at the north-western end of the array, is selected as the virtual source for all the correlation panels shown in Figure 6. These correlation panels correspond to virtual seismograms retrieved from the cross-coherence of noise recorded at each sensor with noise recorded at sensor A2. The correlation panels are represented for each frequency band in the “traffic” and “no traffic” periods.

The different events observed in the correlation panels are interpreted to be surface waves, as indicated by their linear move-out and characteristic dispersion. The surface waves are the easiest mode to retrieve from ambient noise (Wapenaar et al., 2010a). The retrieval of body waves requires noise sources to be at specific locations (Forghani and Snieder, 2010), and sometimes the use of dedicated filters (Draganov et al., 2009; Nakata et al., 2015). For the observed surface-wave group-velocities to be meaningful, the noise sources have to be either uniformly distributed around the two sensors, or located off-end and in-line with the

sensor pair. This is discussed in the context of embankment monitoring in Planès et al. (2016). The apparent group-velocities of the retrieved surface waves are controlled by the angle between the direction of noise propagation and the array line. To recover information about the structure located beneath the sensors, the direction of noise propagation should ideally be aligned with the array - in which case the apparent group-velocity is equal to the true group-velocity.

The “no traffic” correlation panels present a quasi-linear branch at negative times, labeled (1), visible at 5 Hz and 10 Hz (Fig. 6a and 6c), but hidden in noise at 15 Hz and 20 Hz (Fig. 6e and 6g). By picking arrival times at sensors 1-65, the apparent group-velocity of this branch is estimated at 160 m/s at 5 Hz. It is slightly higher than the corresponding active baseline group-velocity (147 m/s). A slight curvature is observed in this branch, making the apparent group-velocity faster on the side of sensor 88 than on the side of sensor 1. The direction of propagation and the observed curvature concurs with the location of the wind turbine (Fig. 1). The seismic noise emitted by the wind turbine is recorded at the end of the array (A88) before reaching the virtual source (A2). This explains the move-out of the branch at negative times. The offset of the wind turbine relative to the sensor line also accounts for the apparent group-velocity to be slightly higher than the true one. Wind turbines have been found to act as ambient seismic-noise sources in the past (Saccorotti et al., 2011; Gassenmeier et al., 2015). At 20 Hz (Fig. 6g), a vertical branch emerges from noise at the time origin. This branch of apparent infinite group-velocity, labeled (3) in the figure, is assumed to be generated by the wave action, breaking parallel to the levee and thus being recorded simultaneously at each sensor.

The “traffic” correlation panels feature two quasi-linear branches at negative times, labeled (2), clearly visible at 10 Hz, 15 Hz and 20 Hz (Fig. 6d, 6f and 6h). The apparent group-velocity of these waves, between sensors 1-65, is estimated at 129 m/s at 20 Hz, 134 m/s at 15 Hz and 139 m/s at 10 Hz. These are also slightly higher than the corresponding active baseline velocities (125 m/s at 20 Hz, 130 m/s at 15 Hz, 133 m/s at 10 Hz). These branches are attributed to the traffic on the bridge. The two different move-out directions are due to the location of the source - the bridge pillars - around sensor A68. These branches are hardly visible at 5 Hz, showing that at lower frequencies the dominant noise is generated by the wind turbine.

Here, the bridge pillars are nearly aligned with the array and the apparent group-velocity of the surface waves retrieved from traffic noise is close to the true group-velocity estimated from hammer shots. The traffic noise is thus well suited for the monitoring of the levee structure. The wind turbine, located south of accelerometer A88, is about a 100m offset from alignment with the array. The angle between the noise propagation direction and the array is thus larger at the south-eastern end of the array than at the north-western end. To reduce possible bias in the analysis, the group-velocity-variation monitoring is focused on the levee section located north-west of the bridge (sensor A1-A65). Along this section, the estimated group-velocity of the wind-turbine induced surface waves at 5 Hz (160 m/s) is found to be approaching the active baseline group-velocity (147 m/s). This levee section is also the one of greater interest because of the featured sandboils. In the following section, the wind turbine noise is thus used for monitoring around 5 Hz, and the traffic noise for

monitoring around 10 Hz and above.

The depth sensitivity of the surface waves is controlled by their wavelength λ , obtained by dividing the phase-velocity by the frequency. To measure the phase-velocity of the retrieved surface waves, we first compute a broadband correlation panel (2 Hz-100 Hz) using sensor A2 as the virtual source (Fig. 7a). We then use this correlation panel to construct a dispersion diagram following Park et al. (1998), represented in Figure 7b. The dispersion diagram shows that the dominant mode of the retrieved Rayleigh wave is the fundamental one, clearly visible from 2-10 Hz, and identifiable up to around 15 Hz. The phase-velocities are manually picked and estimated to be 150 m/s at 15 Hz, 172 m/s at 10Hz and 215 m/s at 5Hz. The picking becomes less unambiguous above 10 Hz as other arrivals are possibly retrieved. The Rayleigh wave phase-velocity is sensitive to S-wave velocity perturbations at depth. The sensitivity of the fundamental mode of Rayleigh waves to such perturbations is concentrated within a depth of one wavelength, while the peak sensitivity is located around $\lambda/3$ (Yang et al., 2007; Lin et al., 2012). The probed depth ranges and peak sensitivities are thus 0-10 m/3.5 m at 15Hz, 0-17 m/6 m at 10Hz and 0-43 m/15 m at 5Hz.

The seismic noise generated from wave action is not usable in this survey. The low-amplitude sea waves form a coherent wavefront propagating in a direction perpendicular to the array line. On the contrary, the sea-levee survey of Le Feuvre et al. (2015) featured highly energetic local sea-waves impacts on the levee that constituted the dominant noise source. The weather condition and agitation of the sea appears to be determinant for the usability of the sea waves as a noise source.

Figure 6: Correlation panels stacked over all “no traffic” periods around 5Hz (a), 10Hz (c), 15Hz (e), 20Hz (g). Correlation panels stacked over all “traffic” periods around 5Hz (b), 10Hz (d), 15Hz (f), 20Hz (h). The origin of the three identified branches - numbered from 1 to 3 - is discussed in the main text.

Figure 7: (a) Broadband correlation panel stacked over all “traffic” periods (2 Hz-100 Hz). (b) Corresponding phase-velocity dispersion diagram. The picked phase-velocity curve between 5 Hz to 15 Hz is shown by the black dashed line.

5 Time-lapse monitoring

The Zeeland bridge supports a highway that presents intermittent traffic 24 hours a day (Fig. 5). Stacking as little as 15 minutes worth of “traffic” or “no traffic” CCFs yields stable seismic responses along the 12 h recording period. A reference impulse response $g_{\text{ref}}(t)$ is defined as the stack of the CCFs retrieved during the first 15 minutes of the recorded period. At any elapsed time $T=0-12$ h, a current impulse response $g_{\text{curr}}(t)$ is defined as a stack of 15 minutes of CCFs around time T .

The travel-time change δt between the reference and a current impulse response is then obtained using the following correlation function:

$$C(\tau) = \frac{\int_{\Delta t} g_{\text{ref}}(t) g_{\text{curr}}(t + \tau) dt}{\sqrt{\int_{\Delta t} g_{\text{ref}}(t)^2 dt \int_{\Delta t} g_{\text{curr}}(t + \tau)^2 dt}} \quad (2)$$

where Δt is a time window centered on and encompassing the surface wavelet of the reference impulse response. The travel-time change δt between the reference and a current impulse response is the value of τ that maximizes the correlation function $C(\tau)$. The relative surface-wave group-velocity change is then obtained as $\frac{dv}{v} = -\frac{\delta t}{t_c}$, where t_c is the center time of the time window Δt . Note that when multiply-scattered events are present, a method that consists in stretching the time axis of the current response can be applied for measuring relative group-velocity changes in the coda (Sens-Schönfelder and Wegler, 2006). In our case, only direct waves are observable so the measurement consists instead in shifting the time axis of the current response.

The relative group-velocity variations at 5 Hz - i.e., for a depth range of about 0 to 43 m, measured for sensor pair A2-A40 during the 12 hour tide cycle are displayed in Figure 8. The tide level measured at a nearby location is also shown, as well as an in-situ measure of pore-water pressure approximately 2 m below the levee. The strong anticorrelation between

the pore-water pressure and the relative group-velocity change is interpreted according to the following mechanism: as the tide level increases, the pore-water pressure builds up in the lower sand aquifer and thus the effective stress and shear-wave velocity decrease (and vice versa). The lag time between tide level and pore-water pressure variation could reflect the diffusion time of the water below the levee and be related to the levee's hydraulic conductivity. The lag time between low tide and low pore-water pressure is about 100 minutes. In contrast, the lag time between high tide and high pore-water pressure is about 40 minutes only. This asymmetrical diffusion behavior is related to the different time scales and processes for water draining out of pores as opposed to water filling pores. When the water level is lowered, water remains trapped between grains due to capillary action. The draining of this water is therefore disconnected from and slower than the tide level lowering. In contrast, when the tide level increases, the water fills the voids synchronously.

Figure 8: The relative group-velocity changes measured during the tide cycle are represented by the black crosses. These are measured using 15-minute stacks of “no traffic” CCFs between sensor A2 and A40 at 5 Hz. The local tide level (in cm) relative to the annual average is represented by the solid gray line. The pore-water pressure measured approximately 2 m below the levee (Fig. 2) is represented in water elevation (cm) and shifted of -195 cm for superimposition with the relative group-velocity change.

The relative group-velocity-change measurements can be used as a proxy to monitor the pore-water pressure variations within or below the structure. To this end, we assess the response of the levee to the tidal forcing along the array using different sensor pairs. To study the levee section of interest, i.e., the section presenting sandboils, the subarray of sensors A1-A66 is considered. These sensors are all located north west of the bridge and are quasi-aligned with the noise sources. Figure 9 represents relative group-velocity variations along this section, during the 12 h tide cycle for three different frequency bands. The three central frequencies and corresponding depth ranges and peak sensitivities are 15 Hz/0-10 m/3.5 m, 10 Hz/0-17 m/6 m, and 5 Hz/0-43 m/15 m. A sensor spacing of 35 m - i.e., 10 accelerometers - is chosen as a trade off between lateral resolution and stability of the group-velocity-variation measurements. To improve the stability of the seismic responses, the stacking period of time of the CCFs has been increased to 60 minutes.

312 The relative group-velocity variations show a spatial variability along the profile. A
313 strong response to the tidal forcing is observed around sensors 15-23 and 30-40, with group-
314 velocity increases of about 3-5%. A weaker response is observed elsewhere, with group-
315 velocity increases less than or equal to 1%. These patterns are localized in the shallower
316 layers and are spread out at larger depths. This might be a result from the lateral-averaging
317 effect of the waves with larger wavelengths. Visually, the position of the sandboils seem to
318 correspond well with the zones of stronger group-velocity variations. It is, however, difficult
319 to assess whether the presence of concentrated seepage is causing the spatial variability of
320 the tidal response. The observed patterns could also be due to an inconsistent composition
321 of the levee along the profile. Nevertheless, it should be possible to detect the initiation or
322 evolution of an internal erosion process by monitoring the tidal response of sea levees over
323 a long period of time. Relative group-velocity variations of the order of 0.1% have been
324 measured, corresponding to pore-water pressure changes of the order of a few centimeters.
325 We foresee that the progress of internal erosion channels would lead to such detectable levels
326 of pore-water pressure and effective stress changes.

327 The resolution of images of such eroded channels is related to the wavelength of the
328 surface waves. The internal erosion channels from upstream to downstream do not likely
329 follow straight lines, but rather show complicated meandering. Their individual diameters
330 are likely on a scale of 0.1 or smaller than the wavelengths we used. The presented monitoring
331 technique could not spatially map the complex distribution of these internal erosion channels.
332 It could rather identify zones of influence surrounding these features, and provide warning
333 indicators that specific levee sections present signs of internal changes.

334 An alternative monitoring option would be to embed automated seismic sources over
335 levee sections to be monitored. In that way, the frequency content or probed depth range
336 could be controlled and active-source seismic interferometry measurements could be per-
337 formed at desired time intervals.

Figure 9: Maps of relative group-velocity changes during the 12-hour tide cycle, along a 180 m-long section of the levee. Different frequencies, i.e., depths ranges, are investigated: 15 Hz/0-10 m, peak 3.5 m (b), 10 Hz/0-17 m, peak 6 m (c), 5 Hz/0-43 m, peak 15 m (d). A plan view of the monitored section aligned with the group-velocity variation maps is shown in (a). The plan view includes the positions of the accelerometers (black triangles) and major sandboils (gray circles).

6 Conclusion

This work concerns the evaluation of the passive seismic-interferometry technique for monitoring internal erosion in earthen dams and levees. We monitored a 300 m section of the Dutch sea levee near the town of Colijnsplaat with 88 accelerometers during a 12 h tide cycle. This levee section comprises several sandboils in the downstream drainage ditch, a sign of concentrated water seepage and possible internal erosion.

Two main sources of ambient seismic noise were identified in the passive recordings: the traffic noise on the Zeeland bridge, which was transmitted to the levee through the bridge pillars; and the noise from the vibrations of a nearby wind turbine. These two noise sources were used to retrieve surface waves propagating along the levee crest in the 5-20 Hz frequency range. In contrast with a previous study, the sea waves were in our case a minor source of noise that did not present useful properties for monitoring the levee. This is likely explained by the much smaller and thus less energetic sea waves observed during our experiment. The agitation of the sea, and possibly the orientation of the levee, seem to determine whether sea waves can be used for seismic monitoring purposes.

We used the traffic- and wind-turbine-induced seismic noise for time-lapse monitoring purposes. First, the travel-time changes of a single seismic response were estimated. This provided a continuous curve of relative group-velocity variation during the 12 hour tidal cycle. These estimated group-velocity variations showed a strong anticorrelation with the in situ pore-water pressure response. The understood mechanism is that an increase (resp. decrease) of pore-water pressure leads to a decrease (resp. increase) of effective stress, and a decrease (resp. increase) of shear-wave velocity. Similarly to the in-situ pore-water pressure measurements, the group-velocity variations showed variable lag times relative to the forcing tide level, characterizing the diffusion of water through the structure. Thus, the passive (and non-invasive) method we propose could be used as a proxy for continuous monitoring of pore-water pressure levels and hydraulic conductivity within or below the structure.

We then estimated relative group-velocity variations for different pairs of sensors along the array and for different frequency bands, i.e depths. This allowed assessing the spatial variability of the levee response to the tidal forcing. Two areas of stronger group-velocity increases - up to 5% - were identified, while the group-velocity increase during low tide remained less than or equal to 1% elsewhere. Even though these areas of strong changes seem to correspond with sandboils locations, it remains difficult to determine whether or not they are causally related to the presence of concentrated seepage or erosion. Other parameters, such as inconsistency of the levee structure along the profile, could possibly give rise to such patterns as well. A possible way to discriminate between baseline variability and initiation or progression of internal erosion would be to monitor the structure over a much longer period of time. Any local evolution of the tidal response pattern would then indicate an ongoing change of the internal structure of the levee.

The wind-turbine- and traffic-related seismic noise are specific to this experiment; high-frequency (5 Hz-40 Hz) ambient seismic noise cannot in general be expected around embankments. The question of the usability of the sea-wave action as a source of ambient

noise is of particular importance for the monitoring of sea levees. More case studies with different weather and sea-agitation levels would help assess the conditions required to use such a readily available source of ambient noise.

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