Journal of Applied Geophysics 138 (2017) 255–263

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

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

Thomas Planès[a,*], Justin B. Rittgers[b], Michael A. Mooney[a], Wim Kanning[a], Deyan Draganov[c]

[a] Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, USA
[b] Department of Geophysics, Colorado School of Mines, Golden, USA
[c] Department of Geoscience and engineering, Delft University of Technology, The Netherlands

ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form 10 January 2017
Accepted 19 January 2017
Available online 20 January 2017

Keywords:
Levee monitoring
Internal erosion
Seismic interferometry

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 (0m–40m). On these profiles, we observe some spatially localized relative group-velocity variations of up to 5% that might be related to concentrated seepage.

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).

* Corresponding author.
E-mail address: tho.planes@gmail.com (T. Planès).

http://dx.doi.org/10.1016/j.jappgeo.2017.01.025

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

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

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 move-out 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 Fig. 4a (resp. 4b).

The amplitude frequency spectrum of all the "traffic" and "no traffic" noise panels, stacked in each category, is displayed in Fig. 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 Fig. 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 (Figs. 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 12h. 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