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Sand boil observations and geotechnical characterization of river embankments for the development of a backward erosion piping database

Observations de terrain et caractérisation géotechnique pour la mise en place d'une base de données des phénomènes d'érosion régressive

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ABSTRACT: Sand boil formation at the toe of river embankments is the typical manifestation of initiation and progression of an internal erosion process known as backward erosion piping, which is recognized to be a major concern in many river systems worldwide. In Italy, more than 130 sand boils have been detected along the Po River, many of them experiencing recurrent reactivations during high-water events. As a consequence of such widespread occurrence and the risk for the safety of the surrounding territory and human activities, the development of a sand boil database has been increasingly seen as an essential tool for identifying triggering conditions and giving priorities for the implementation of mitigation measures. In recent years, as part of the activities of the European Project LIFE SandBoil, a GIS-based web application was developed in order to catalogue the sand boils observed along the Po River. The database allows keeping records of a comprehensive set of information, e.g. geometry of the river embankments, subsoil stratigraphy, data on the sand boils, and characteristics of high-water events. Taking a piping-prone cross-section along the Po River as reference, the paper aims at describing the main features of this versatile and flexible tool, which is meant to help in understanding the conditions causing initiation and the sand boil dynamics, as well as to support flood risk management against backward erosion piping.

RÉSUMÉ: Les phénomènes de boulance à l'aval des digues fluviales sont le signe d'initiation et progression d'un processus d'érosion interne qui se développe au sein des fondations, dans les couches de sables. Ce mécanisme, qui est connu sous le nom d'érosion régressive, est de loin le mécanisme le plus dangereux pour la stabilité des systèmes d'endiguement de plusieurs grands fleuves européens. En Italie, plus de 130 cas de boulance ont été recensés le long du fleuve Pô, lors des crues enregistrées pendant les trente dernières années. En raison des fréquentes manifestations d'érosion discernables en surface et des dégâts très importants, tant matériels qu'humains, qui pourraient être générés par la rupture des digues, le développement d'une base de données est de plus en plus considéré comme un outil fondamental pour identifier les conditions d'initiation du processus et donner des priorités pour la mise en œuvre de mesures de mitigation. Cet article vise à décrire les principales caractéristiques d'une application Web basée sur un SIG, qui a été récemment développée dans le cadre des activités du projet européen LIFE SandBoil afin de cataloguer toutes les amorces d'érosion régressive identifiées le long du Pô. La base de données permet de stocker une grande quantité d'informations, telles que la géométrie de la digue, la stratigraphie du sous-sol, la charge hydraulique, ainsi que les principaux indices alertant sur le mécanisme d'érosion.

Keywords: Backward erosion piping; sand boils; river embankments; Po River; piping database.

1 INTRODUCTION

Backward erosion piping is a major concern for the stability of many river embankment systems worldwide (Van Beek, 2015), during high-water events. The initiation and progression of this phenomenon is typically revealed by the presence of one or multiple sand boils, landward of the river embankment. Indeed, when the hydraulic head difference across the water retaining structure increases so much as to result in excessive underseepage and high local gradients in the underlying aquifer, uplift of the blanket layer may occur and erosion initiates at the exit point. A bubbling spring of fluidized sand is thus observed on the ground surface, most often accompanied by ejection of eroded soil particles to form a sand volcano around the exit zone: sand basically looks like a boiling fluid, hence the name "sand boil". Once started, the erosion within the aquifer develops progressively in the upstream direction, i.e. towards the river, resulting in shallow pipes beneath the river embankment that cause in turn settlements, with a significant risk for the structure stability. The different phases of the backward erosion piping process, from boiling phase to failure of the water-retaining structure, have been investigated and described by various authors and a detailed description can be found in Van Beek (2015).

In Italy, sand boils are very commonly detected near the toe of the Po River embankments. Indeed, over the last 30 years, more than 130 sand boils have been catalogued: most of them have been mapped in the main course of the river and suffer from recurrent reactivations during high-water events, but those located in the delta area reactivate also at relatively moderate water levels. It is also worth mentioning that sand boils observed along the Po River may be of remarkable size, with some sand volcanoes having an external diameter greater than 3 m. In such cases, abundant and continuous erosion is very likely to occur beneath the river embankment, thus posing a major threat to the structure integrity.

In the last few years, the Interregional Agency for the Po River (AIPo), the Italian authority in charge of flood protection and flood damage reduction in the Po River basin, has been very active in collecting as much data as possible in river segments exhibiting ground manifestation of backward erosion piping. Indeed, the synergic use of a wide variety of data, including geometric features, stratigraphic arrangement, geotechnical and hydraulic characteristics of the foundation subsoil, together with groundwater flow models and records of hydraulic loads in past activations, may undoubtedly help in identifying triggering conditions of piping phenomena, assigning hazard classes to the different river embankment sections, enabling the identification of priorities for mitigation interventions. As a result, a piping database may serve as a useful tool to effectively support flood risk management.

Following early attempts of systematic collection carried out by both the Po River Basin District Authority (AdBPo) and AIPo (Aielli et al., 2019), a GIS-based web application has been recently developed as part of the activities devised in the European project LIFE SandBoil (2020).

This paper describes the main features of this flexible and versatile tool, making reference to a representative cross-section of the Po River, which experienced repeated reactivations of a so-called "historical sand boil".

Figure 1. (a) Satellite view of the Po River basin and location of the selected cross-section; (b) Reactivation of a sand boil in Guarda Ferrarese, during the 2018 high-water event.

2 THE SELECTED RIVER SECTION

In order to provide a meaningful example of the typical stratigraphic features encountered in Po River embankments prone to piping, the cross-section located near Guarda Ferrarese (Figure 1(a)), in the lower catchment of the watercourse, is described herein. This river stretch has indeed a well-known history of internal erosion and sand boil activity, hence over the last years it has been selected to conduct field studies and numerical models for underseepage research (e.g. García Martínez et al., 2020a, 2020b; Marchi et al., 2021; Bertolini et al., 2022). According to the available records, the first evidence of piping was reported in 1994, when it caused severe damage to the road embankment running parallel to the river; more recent sand boil reactivations observed in this segment date back to 2014, 2018 and 2020.

During the 2014 high-water event, in particular, evidence of major underseepage, in the form of a high energy sand boil, was observed, with the throat of the sand boil moving outside the sandbag ring and thus requiring re-ringing alongside, as also shown in Figure 1(b).

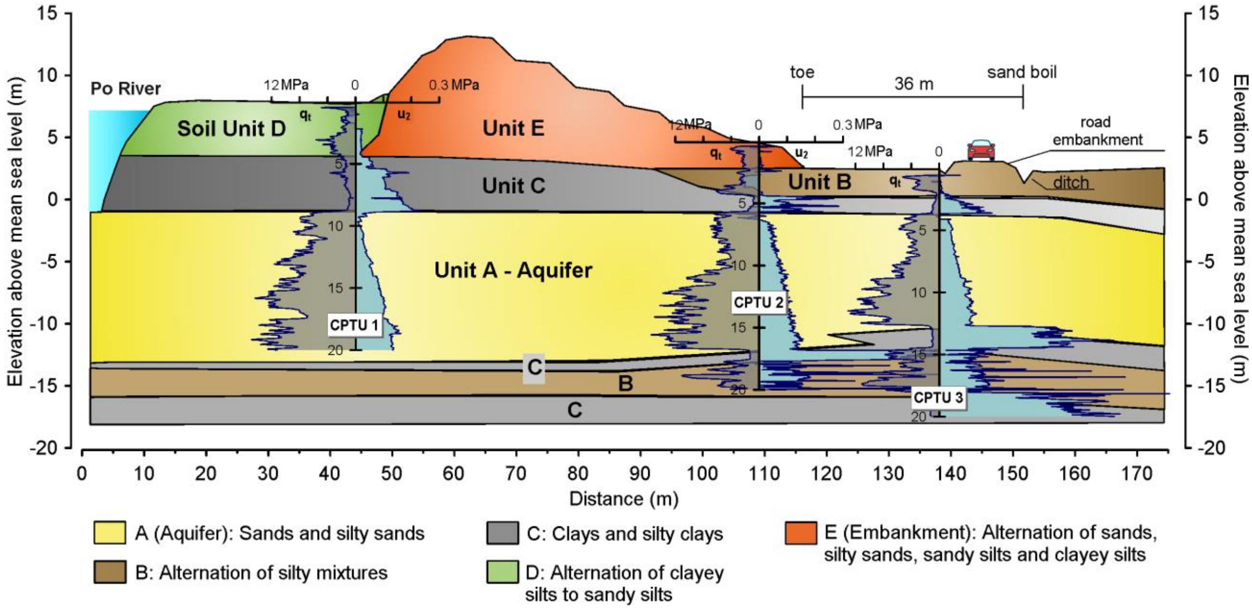

Figure 2. Stratigraphic model of the investigated cross-section in Guarda Ferrarese, with CPTU log profiles (vertical scale magnified). Modified from García Martínez et al., 2020a.

Table 1. Field measurements (net head on the river embankment, ΔH, and length of the vertical pipe, L) and local hydraulic gradients in the fluidized vertical pipe (i_{pipe}) during the monitoring period.

Date (d/m/year)	ΔH (m)	L (m)	i_{pipe} (-)
7/11/2018	4.65	1.46	0.53
9/11/2018	5.12	1.51	0.51
11/11/2018	5,82	1.54	0.50
20/11/2018	2.01	0.73	0.46

In 2018, despite a moderate flood intensity, a sizeable sand boil, having a 1m external diameter volcano, was recorded in a collector ditch as in previous activations. While the flood event was still underway, a comprehensive set of field measurements could be collected, encompassing sand boil geometry, grain size characteristics of the ejected sand, concentration of the sand–water mixture in the sand boil throat, together with a number of relevant hydraulic parameters, such as head loss in the vertical pipe, flow velocity, water discharge, all then interpreted in relation to the water level reached in the river (Marchi et al., 2021). Such field observations turn out to be key pieces of information when predictive models of piping initiation or progression (e.g. Robbins et al., 2020) are used. A selection of the collected hydraulic and geometrical data, namely the head loss *ΔH* between the river and the landside ditch, the length *L* of the vertical pipe, and the average gradient in the vertical pipe, i_{pipe}, is shown in Table 1. The vertical pipe was found to have a funnel shape, with a diameter of about 20 cm at the bottom to approximately 35 cm near the exit.

Figure 2 shows the stratigraphic model of the river embankment and the underlying subsoil, as obtained from interpretation of continuous coring boreholes and piezocone tests (CPTU) carried out along a cross-section drawn through the sand boil area. It is worth noting that the stratigraphic arrangement includes a 9–12 m thick sandy aquifer (Unit A), fed upstream by the river and overlain by a clayey soil unit (labelled as *C*) and a predominantly silty layer (Unit B), both forming a fine-grained soil cap typically referred to as *blanket* layer. The thickness of the blanket appears to reduce in proximity of the sand boil location, creating favorable conditions for backward erosion piping initiation. The susceptibility to backward erosion piping was also increased by the excavation of a ditch parallel to the road embankment, as shown in Figure 2.

The grain size analysis of the eroded soil, carried out on samples either collected in the volcano crater or obtained from the fluidized sand in the vertical pipe, provided evidence of a fine, uniform sand, with d_{10} and d_{50} in the ranges of 0.100–0.138 and 0.178–0.228 mm, respectively (Marchi et al., 2021).

Recent geotechnical campaigns carried out in this area have been especially meant to provide a better insight into the hydraulic parameters of the soil units forming the river embankment system, the attention being especially focused on the blanket layer and the aquifer involved in piping effects. Different experimental strategies and methods have been adopted (Lefranc tests, dissipation tests, CPTU-based empirical correlations) in order to obtain an accurate description of the subsoil permeability (*k*) and its spatial variability through the cross-section. Table 2 summarizes a few representative data for *k*. Details on this subject can be found in Bertolini et al. (2022).

Groundwater level monitoring through a few piezometers located landside (close to the toe, in proximity to the sand boil and approximately 400 m from the river embankment) revealed that the sub-artesian confined aquifer, corresponding to Unit A, is well synchronized with the river, whereas the phreatic surface in Unit B is governed by rainfall and evapotranspiration.

Table 2. Mean values of soil permeability k, as deduced from Lefranc tests and CPTU interpretation.

Soil units	Lefranc test ***k*** **(m/s)**	CPTU dissipation ***k*** **(m/s)**	CPTU correlation ***k*** **(m/s)**
A	8.9E-07	1.9E-06	9.1E-06
B	1.6E-06		1.0E-06
C		4.7E-09	4.6E-09
D			1.6E-07
E			1.2E-05

3 THE SAND BOIL DATABASE

The database described in this paper has been developed within the ongoing European project LIFE SandBoil, whose main objective is the development of an innovative and sustainable technology for the mitigation of backward erosion piping in river embankments. The project is coordinated by the University of Bologna and involves the Interregional Agency for the Po River, Officine Maccaferri Italia, and the North Transdanubian Water Directorate as project beneficiaries.

The database is a web application, built in a geographic information system (GIS). The design of the database was coordinated by AIPo, who is also responsible for data collection and uploading. The application has been designed in such a way that it can easily accommodate data from various river basins, in addition to the Po, and thus become an international database of backward erosion piping phenomena observed worldwide.

3.1 The Database Structure

The database (Hortus, 2021) is basically organized into two main sections, corresponding to the river and the sand boil, respectively. The first section allows specifying the different rivers for which sand boils are defined and the relevant hydrometric stations where river water levels are measured. These measurements are then used as input data by the flood simulation algorithm to obtain the river levels in cross-sections where piping evidences are detected during flood events.

The sand boil section allows uploading a wide variety of information about each river segment affected by piping, with respect to the following items:

- the river embankment, in terms of geometric profile, embankment components, subsoil stratigraphic arrangement;
- the flood event causing the activation/reactivation of a sand boil, described in terms of duration, maximum discharge, data from nearby piezometers;
- the sand boil itself, in terms of geolocation, geometrical features of the sand boil, type of activity, characteristics of the ejected sand, and details on adopted emergency actions.

Figure 3 shows a GIS digital map of the Po River basin, with green dots representing the sand boil locations currently entered into the database.

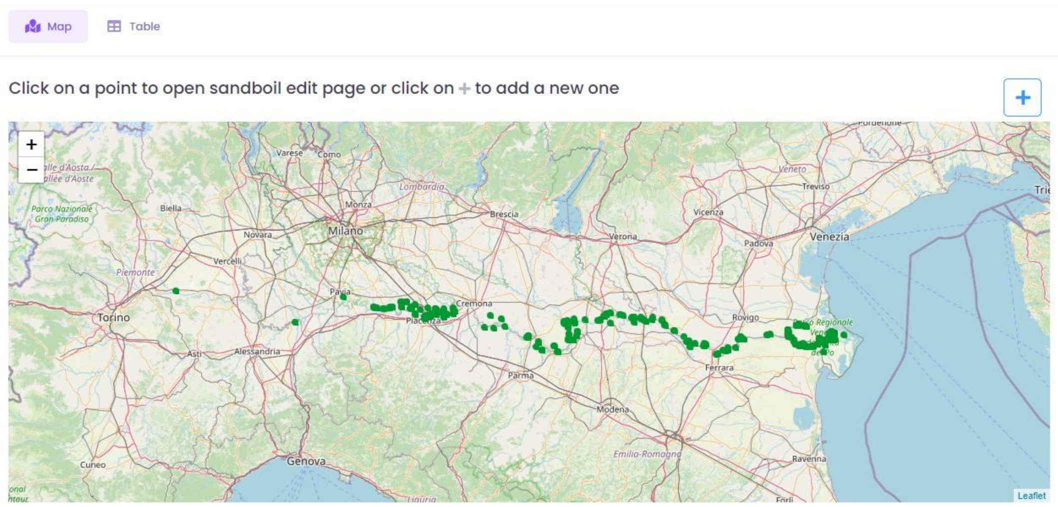

Figure 3. Map showing the location (green symbols) of the sand boils detected along the Po River (downloaded from the database).

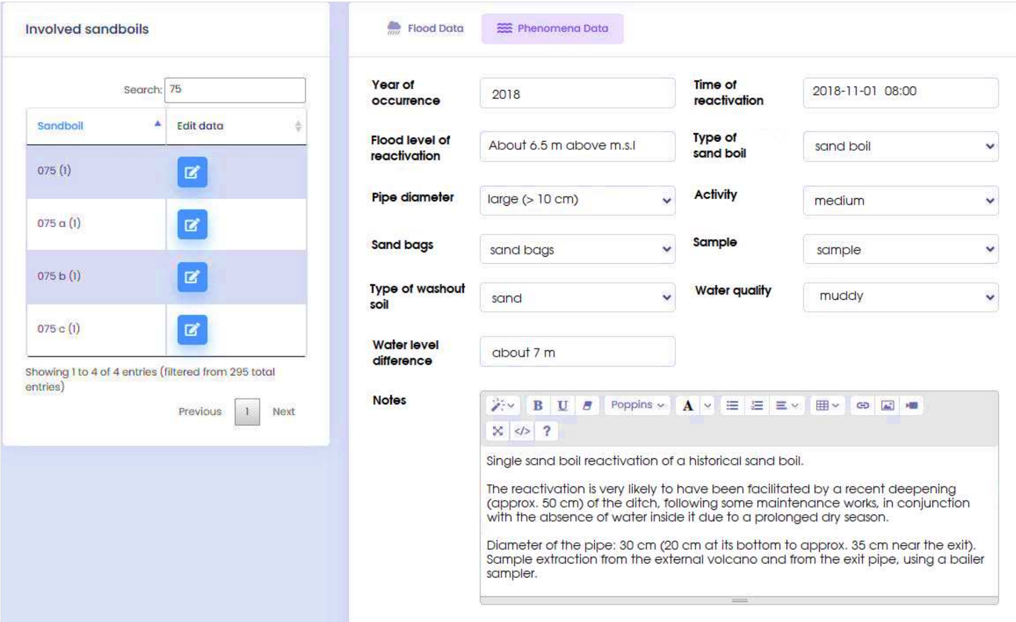

Figure 4. Example of data entry window in the web application, with reference to the sand boil No. 75 located in Guarda Ferrarese, reactivation of November 2018.

An example of the adopted interface for entering data and information is provided in Figure 4, with reference to the window containg data fields on sand boil geometry and piping activity during a high-water event. The entered data refers to the 2018 reactivation of the sand boil in Guarda Ferrarese.

3.2 Database Query

The data stored in the database can be easily exported or interpreted through graphs that allow analysing the effect of different flood events on a selected section along the Po River or comparing the response of different piping-prone river embankments during a specific high-water event. The sand boil management tool allows indeed creating two different types of graphs, referred to as "river graphs" and "historical graphs". The first type consists in a profile of the maximum high-water level reached along the watercourse during a flood event, with the indication of the river embankment sections that experienced some piping activity.

An example of historical graph is given in Figure 5, which provides an overview of the activations/non-reactivations observed at Guarda Ferrarese, for the flood events occurred from 2000 to 2020. The red bars are used to indicate activations or reactivations of the sand boil, the green ones are adopted when no evidence of piping was detected. In Figure 5, the horizontal red line reveals that the minimum water level causing past reactivations is equal to H_{min} = 7.63 m above m.s.l., whereas the maximum hydrometric level (H_{max} = 9.42 m above m.s.l.) for which no activation was observed is shown by the green line.

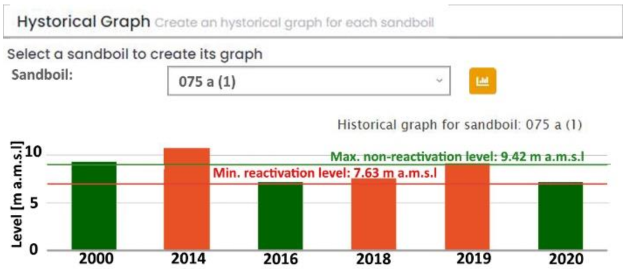

Figure 5. Example of data extraction in the form of "historical graph", with reference to the sand boil No. 75 detected in Guarda Ferrarese.

4 CONCLUSIONS

The paper has described the main features of a database that has been recently developed in order to catalogue the sand boils detected along the main Italian watercourse, i.e. the Po River. The database fields have been presented with respect to a well-documented river embankment section, located in the lower stretch of the Po River, which has experienced recurrent reactivations of a so-called historical sand boil. This flexible and versatile tool appears to be capable of providing an effective assessment of backward erosion piping hazard along the Po River and thus supporting flood risk management against this phenomenon.

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