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Modelling and layout of drainage-levee devices in river sections

Jesús Mateo-Lázaro [a,*], José Ángel Sánchez-Navarro [a], Alejandro García-Gil [a], Vanesa Edo-Romero [a], Jorge Castillo-Mateo [b]

[a] Dept. of Earth Sciences, University of Zaragoza, Pedro Cerbuna, 12, 50009 Zaragoza, Spain
[b] Dept. of Mathematics, University of Zaragoza, Pedro Cerbuna, 12, 50009 Zaragoza, Spain

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A B S T R A C T

A common practice to protect facilities from rising rivers is to build longitudinal dikes or levees to preserve floodplain areas. Since the second half of the twentieth century, flood control with dams has increased significantly. Flood abatement reduces the peak flow but makes the flood last longer and therefore increases and intensifies the filtration time. This paper describes the design and modelling of a levee that decreases the effects of frequent floods on a river plain area where fish farms and electricity production are located. Since the artificial earthen levee is built with highly permeable granular material available in the environment, another problem arises and needs to be solved: the seepage that occurs when flooding from the river persists over time. To address this problem, a drainage-levee system was designed and the theoretical performance is presented in this article. Additionally, the real performance has been demonstrated in recent years since the levee was put into service. This study is one of the first regarding the ensemble of a levee and a longitudinal drainage channel that can greatly reduce seepage towards the river floodplain. There are many works on the stability of fluvial levees in the lower reaches of rivers, but this study presents a case in a section of the river running through the hillslope of the European Alpide belt. The longitudinal slope of the river (almost 0.5%) allows the operation of the drainage with an outlet to the river 1.5 km downstream. The water level of the river during a flood can be 4 m above ground level in the installation areas, meaning that the drainage channel has two purposes; the first is to avoid flooding the soil with surface water accumulation from seepage, and the second is to ensure that the water table remains below the base level of deposits to avoid interactions leading to environmental consequences between the groundwater and the fish tanks.

1. Introduction

The human species has a preference for, is fascinated by and feels seduced to settle near places where the water flows. In fact, many activities and facilities are developed alongside rivers and floodplains. Plants that produce electricity, treat wastewater, and supply water, as well as fish farms and regulating ponds are a few of the many examples of facilities that exist under the risk of flooding and environmental breakdown in these areas.

There are many studies in the relevant literature regarding fluvial defence devices such as levees. A great portion of these studies address the problem of levee stability and, to a lesser extent, the problems caused by seepage during floods. In our manuscript, a device composed of a levee and a drainage channel that manages the water table in areas where facilities, such as fish farms, sewage treatment plants, power plants, etc., are located is presented. The problem of leakage is increasing. This is due to increased human activity near the rivers and to the flood control by dams and reservoirs which decreases the peak flow through the flood abatement process, but increases the duration in which the seepage processes due to flooding occurs.

Levee underseepage analyses are commonly performed to assess the risk of erosion and piping of levee foundation soils. These analyses are also commonly used to estimate the amount of seepage that is expected to pass beneath a levee over time and to assess the risk of excessively high pore pressures at various points in the foundation. The conceptual levee failure mechanisms were already stated in Bogardi and Mathe (1968), where the main phenomena, such as overtopping, slump slide, seepage, under seepage and sand boil were described. Seepage is a primary driver of levee and dam failure, and understanding its potential is of paramount concern to engineers and resource managers. Orlandini et al. (2015) used detailed numerical modelling of rainfall, river flow, and variably saturated flow in the levee to explore the hydraulic and geotechnical mechanisms that were triggered along the Secchia River in Northern Italy on 19 January 2014, where a levee failure occurred resulting in over $500 million in flood damage. Yuill et al. (2013) reported the results of a computational modelling study that simulated the construction of an alluvial floodplain using a suite of simple geomorphic

* Corresponding author.
E-mail addresses: jesmateo@unizar.es (J. Mateo-Lázaro), joseange@unizar.es (J.Á. Sánchez-Navarro), agargil@unizar.es (A. García-Gil), vanesa_edo@hotmail.com (V. Edo-Romero), 720193@unizar.es (J. Castillo-Mateo).

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process-imitating rules. The hydraulic mechanism can induce failure of the engineered fill that overlies natural levee soils (Reading, 1998; Miall, 2000; Lee et al., 2009). While investigating an artificial earthen levee in Mississippi, Lorenzo et al. (2014) found continuous cracks of 10 cm width and 30 cm depth at the northern end, which may be related to high strain induced by the variable near-surface settling of organic-rich sediments. Topographic cross-sections across the levee showed variable differential subsidence of 1–2 m. There is a critical need to improve levee monitoring techniques. A set of in-situ soil data were collected by Sehat et al. (2014) to provide detailed soil properties over a study area and the observed relationship. The subsequent discovery of cracks in one of the zones demonstrated their importance. Flor et al. (2010) evaluated levee failure susceptibility using logistic regression analysis, and tested the relative importance of geologic, geomorphic, and other physical factors that led to levee failures. Satellite and airborne images are important data sources for simulating natural disaster scenarios, which help prevent damage by preventing human settlements in unsuitable areas (García-Meléndez et al., 1998; van der Sande et al., 2003). Yang et al. (2011) studied landslide-induced levee failure by highly concentrated sediment flow using satellite images. Gutiérrez et al. (2015) studied the leakage problems in dams built on evaporates and discovered that the main leakage and the associated enlargement of karst conduits are also caused by settlement measured on the crest of the dam and the occurrence of sinkholes within the reservoir. Additional seepage across the grout curtain in both abutments was also identified. Peco and López-Querol (2012) applied a new methodology to determine the free surface inside earth fill dams under steady flow conditions. A variety of approaches have historically been utilized to perform steady-state underseepage analyses in levees, including flow-nets, closed-form analytical solutions, and numerical techniques, such as finite difference or finite element analyses. Meehan and Benjasupattananan (2012) provide derived analytical equations that can be used to perform a levee underseepage analysis. Kacimov and Obnosov (2015) developed examples of numerical solutions for 1D and 2D steady flow seepage in environments with multiple types of permeable materials. Gillham and Farvolden (1974) performed a sensitivity analysis of input parameters in numerical modelling of steady state regional groundwater flow and developed and described a method for determining the quantitative value of the ratios of conductivity components from field measurements of the hydraulic head.

The design and modelling of a river levee against floods, which aims to protect an area of a floodplain with fish farming facilities and a power plant, on the Pyrenean river is presented. The issue to be solved is to keep dry a 40-acre platform while the water level in the adjacent river is approximately 4 m considering that the terrain is coarse granular and highly permeable. The design involves the implantation of a levee in a longitudinal arrangement, built with loose materials up to the crest elevation above the flood level. An interior drain keeps the groundwater level below the ground surface, with depth enough to prevent damage caused by seepage and sub-pressure in the fish farming tanks when they are empty. The design was analysed with different models and software developed by our research team. The calculation of backwater curves in the river and into the drainage channel considering the hydraulics of surface water and hydraulic models of groundwater such as the flow network calculation and stability models, both mechanical and hydraulic, were performed.

The modelling work has been performed using software developed by the authors of this article in the Department of Earth Sciences from the University of Zaragoza. The SHEE (Simulation of Hydrological Extreme Events) package is an adaptation of traditional hydrological models to DEMs and databases. It has resulted in several publications, including those related to hydrology, Mateo-Lázaro et al. (2013, 2014a, 2014b, 2015, 2016), and uses powerful libraries (e.g., OpenGL, GDI, GDAL, Proj4) for the management and display of DEM and datasets. Additionally, its interface provides rapid and high quality OPENGL graphics, in both RASTER and VECTOR formats.

2. Study area

The study area is located in the floodplain of the right bank of the Cinca River, where installations of fish farms and electricity production facilities are located. The Cinca River is a notable river in the Pyrenees, which has a Mediterranean regime with large fluctuations of flow, ranging from 10 to 3000 m^3/s in extraordinary floods. This river has a braided morphology and presents a very high longitudinal slope, which was measured to be nearly 0.5% over a length of 17 km in the study area. In Fig. 1, the study area at the confluence of the Cinca and Esera rivers is shown. In the natural state, this floodplain is flooded frequently, so a containment levee for floods and an interior drainage channel to lower the water table was built as a solution to the problem. This Fig. was generated with the Sky View Factor (SVF) algorithm, which was programmed for parallel computing units (GPU) and applied to the Digital Elevation Model (DEM) of the Spanish territory, obtained by Lidar and transformed into a regular GRID, 5 m in size. In Fig. 2, the disposition of various structural elements deployed in the environment are shown. Fig. 3 shows the cross-section of the drain-levee device, highlighting the mechanical protection with a riprap on the river side, a Terzaghi-type filter layer, and an impermeable layer that causes the fall of the groundwater level. They will be discussed in detail in the modelling section.

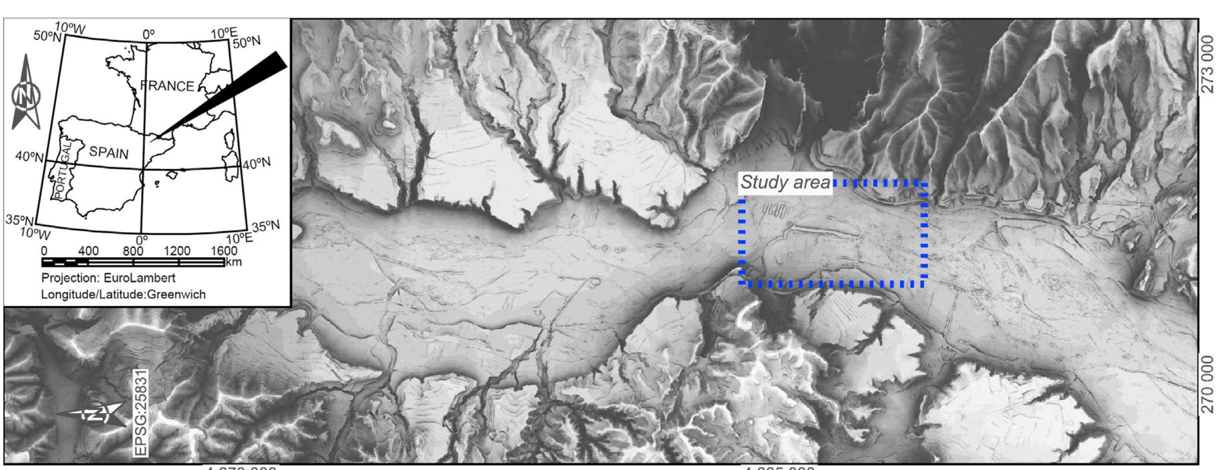

Fig. 1. Digital terrain model showing the study area, with a 5 m grid size, shadowing with the Sky View Factor equation.