LEVEE BODY VULNERABILITY TO SEEPAGE AND IMPACT OF ANIMAL BURROWS

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KEY POINTS

- *A new method to estimate the vulnerability to seepage of damaged earthen levees is presented.*
- *The method uses an expeditious procedure for seepage vulnerability of undamaged levees estimate.*
- *The expeditious procedure is coupled with a finite element analysis software.*
- *The animal burrows cause a reduction of the duration of the critical flood.*
- *The results indicate that the proposed method could be useful for levee-system analysis.*

1 INTRODUCTION

Since the past, earthen levees have been built in the neighbourhood of major rivers to protect urbanised areas exposed to inundations. However, flooding is frequently the result of levee failures.

Seepage-induced piping in the levee body is one of the most common causes of levee failures worldwide and one of the most dangerous, due to the rapid evolution of the processes leading to the collapse. The existence of discontinuities within the embankment can facilitate the onset of the piping-erosion mechanism. Therefore, the presence of animal burrows can increase the seepage exposure of the structures. Nevertheless, mainly due to the difficulties in detecting animal-induced damages to earthen levees, the detrimental effects of burrows are generally neglected in flood-risk assessment, thus inducing possible underestimations.

This study presents a new methodology addressed to the assessment of the seepage-vulnerability of earthen levees supposed to be affected by the presence of burrows. The levee system of the Tanaro River (north-western Italy) is selected as a case study

2 METHOD

The methodology is based on the observation that discontinuities in earthen levees may induce a reduction in the saturation time of the embankment (*Orlandini et al.*, 2015) and a total head increase in the neighbourhood of the cavities (*Cobos Roa*, 2015).

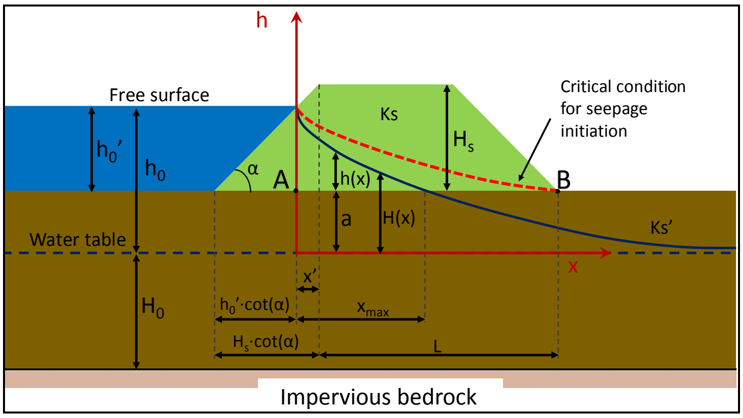

Figure 1. Schematization of the earthen levee and representation of the variables adopted for the definition of the seepage probability of the embankment, *P*. For symbols, see text.

As a consequence, the discontinuities in the levee body make the critical flood duration, i.e. the one able to create the critical conditions for seepage initiation (represented by the red dashed line in Figure 1), shorter than the critical duration characterizing an undamaged levee.

Therefore, if a flood of known magnitude (i.e. defined by a known water level h_0' in Figure 1) is supposed to affect a levee and the hydraulic head distribution corresponding to the critical flood duration, D_{seep}=T hours, is identified for the undamaged structure (levee with no burrows), it is possible to identify the equivalent flood duration, $D_{eq}=T_{eq}$ hours ($T_{eq}<T$), that produces, in the damaged levee (levee with burrows), the same head distribution that characterises the undamaged structure after the T hours-lasting flood.

Based on the definition of D_{eq}, the proposed methodology evaluates the increase in seepage probability induced by the presence of burrows, ΔP_{seep}, and the seepage probability of the damaged levee, P_{DL}. To this end, the virtual reduction in the critical flood duration (from D_{seep} to D_{eq}) produced by the cavities is assessed by analysing the modifications in the total head profiles induced by the discontinuities, by adopting a 2-D geo-hydraulic numerical model: SEEP/W, by Geostudio ® 2008. In addition, the practical methodology developed by *Camici et al.* (2015) and *Barbetta et al.* (2017) is used to calculate the seepage probabilities of the undamaged levee, P, for different flood durations, D:

$$P = f\left(\delta, \frac{h_0'}{H_s}, \alpha\right) \tag{1}$$

where: $\delta=(H_0 D)/(L^2\xi)$; H_0=thickness of the aquifer; D=flood duration; L=horizontal distance between the inner crown of the levee and the external levee toe; ξ=soil porosity; h_0'=water level in the river; H_s=height of the levee crown above the ground level; α=riverside levee slope (see Fig. 1).

The procedure is organised in the following steps:

1. the seepage probability of the undamaged levee exposed to the T hours-lasting flood (D_{seep}), P_{seep}, is computed through the procedure by *Camici et al.* (2015) and *Barbetta et al.* (2017);
2. the undamaged embankment is modelled in SEEP/W and the total head distribution is evaluated for different time steps in the interval 0÷D_{seep} (light blue lines in Figure 2);

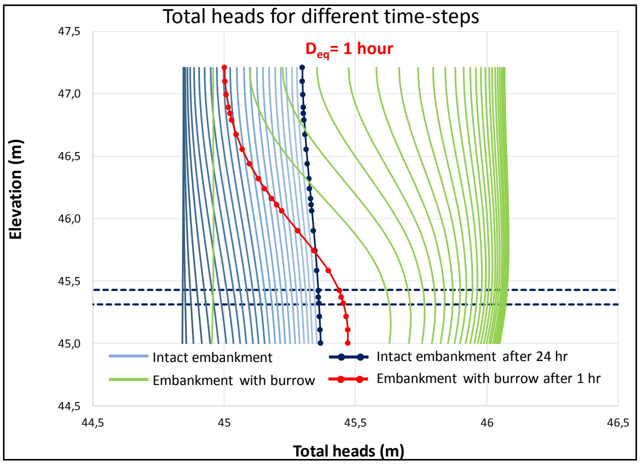

Figure 2. Total head profiles along the vertical section crossing the centreline of the levee, for hourly time steps in the interval 0÷T=24 h: 1) light blue lines=undamaged levee; 2) green lines=levee with burrow; 3) dark blue dotted line=undamaged levee, $D=D_{seep}$=24 h; 4) red dotted line=levee with burrow, $D=D_{eq}$=1 h.

3. the presence of burrows is simulated in SEEP/W by inserting into the embankment cylindrical, horizontal layers of soil, with high hydraulic conductivity ($K_{s,b}$=1 m/s). In each simulation, different locations and lengths of the burrow are considered. The total head distribution within the damaged levee is computed for different time steps, in the interval 0÷D_{seep} (green lines in Figure 2);
4. the total head distributions obtained in the hypotheses of undamaged structure and embankment

affected by the burrow are compared to each other for different time steps in the interval 0÷T hours, to identify the equivalent duration, D_{eq} (red line in Figure 2, where T=24 hours);

5. the seepage probability of the damaged levee, P_{eq}, is computed by considering the undamaged embankment exposed to the flood with equivalent duration, D_{eq};
6. the increase in the seepage probability of the levee, ΔP_{seep}, is computed as:

$$\Delta P_{seep} = P_{seep} - P_{eq}\,; \tag{2}$$

7. the seepage probability of the damaged levee, P_{DL}, is finally computed as:

$$P_{DL} = P_{seep}\left(1 + \Delta P_{seep}\right). \tag{3}$$

3 RESULTS AND CONCLUSIONS

The procedure was applied to 15 levees selected along the Tanaro River (north-western Italy). The geometry of the embankments was deduced by the 2009 Digital Terrain Model of the study area, whereas the hydrological information (h_0’ and D_{seep}) was extracted by the Hydrogeological Management Plan of the Po River catchment Authority (Italian acronym PAI).

The seepage vulnerability was first assessed for undamaged levees, by considering the water levels corresponding to the 200-years return period flood and three possible critical flood durations: D_{seep}=12, 24 and 48 hours. According to *Barbetta et al.* (2017), three vulnerability classes have been identified, depending on the seepage probability: $P<0.3$, low vulnerability class; $0.3\le P<0.6$, medium vulnerability class; $P\ge 0.6$, high vulnerability class. As it was expected, the vulnerability increases with the flood duration: for D_{seep}=12 hours, 67% of the levees is characterised by low vulnerability and 33% by medium vulnerability. If D_{seep} goes up to 24 hours, the percentages of levees with low and medium vulnerability are reverted. Finally, if D_{seep} increases up to 48 hours, 13% of the levees becomes highly vulnerable, 80% are characterized by medium vulnerability and 7% by low vulnerability.

When the presence of burrows is considered, the simulations with SEEP/W highlight a widening of the saturation zone within the embankments: the position of the seepage line advances progressively within the levee body as the length of the cavities increases. The displacement of the saturation lines corresponds to increasing hydraulic heads and decreasing equivalent durations.

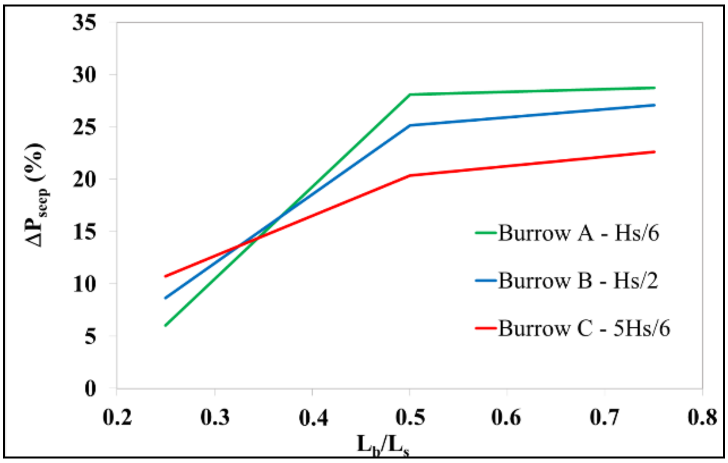

Figure 3. Average increments in seepage probability induced by the presence of burrows in the Tanaro levees, depending on burrow location: A: $h=H_s/6$ (green line), B: $h=H_s/2$ (blue line) and C: $h=5H_s/6$ (red line).

Different burrows configurations were analysed, varying the elevation of the cavity in the embankment, h ($h=1/6H_s$, $3/6H_s$ and $5/6H_s$) and its length Lb (L_b=¼ L_s(h), ½ L_s(h) and ¾ L_s(h); L_s(h) is the width of the levee at the elevation of burrow, h). D was set equal to 24 hours. The analysis highlights that D_{eq} reduces constantly as the length of the cavities increases. This implies that the levee becomes more vulnerable to seepage as the cavity becomes longer, since shorter flood durations are sufficient to reach the critical seepage conditions. Conversely, if the length of the burrow is established and different height positions are compared, it is not possible to highlight a general tendency to the augment or reduction of D_{eq}. In any case, due to the presence of the discontinuities, the flood duration necessary to reach the critical conditions for the onset of seepage is severely reduced: in the worst situation, among the analysed cases, D_{eq} is found to be 0.5 hours.

When ΔP_{seep} is analyzed, the conclusions derived from the analysis of the equivalent durations are confirmed (Figure 3): a direct proportionality always exists between the length of the cavity and the increase in seepage probability, regardless of the height position of the burrow. A correlation between the position of the burrow and the increase in seepage probability is more evident when the longer burrows ($L_b \geq 1/2 L_s(h)$) are considered. Nevertheless, such a correlation must be further analysed.

The increase in seepage probability induced by the burrows can entail a change in the vulnerability class associated to the damaged levee. Overall, it is quite difficult to identify a correlation between the height position of the burrow and the vulnerability class change. However, a correlation between the length of the burrows and the seepage vulnerability class seems to be identifiable (Figure 4).

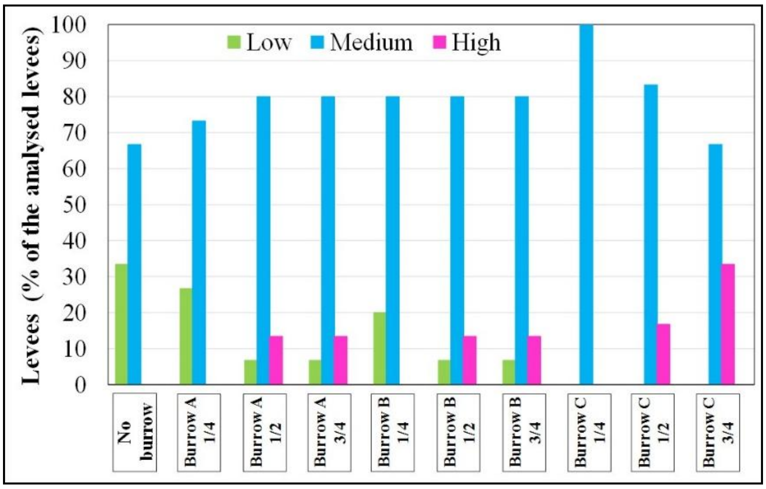

Figure 4. Distribution of the vulnerability classes attributed to the Tanaro levees, for the different burrow configurations.

Even not yet considering the lack of correlation with local ecological features and time-sensitivity of levees consistency, with the primary aim of helping to compare reaches with different features, the proposed procedure represents a novel reliability-based methodology to identify the most vulnerable levees within an entire flood defence system along a river, suitable to address more detailed and focused surveys and analyses. Hopefully, it is a useful tool for managing authorities in charge of flood-risk protection and land planning.

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