# SYNTHESIS OF WILDLIFE-TRIGGERED FAILURES IN EARTH LEVEES

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<th>Journal:</th>
<th>Canadian Geotechnical Journal</th>
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<tr>
<td>Manuscript ID</td>
<td>cgj-2016-0484.R1</td>
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<tr>
<td>Manuscript Type:</td>
<td>Article</td>
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<tr>
<td>Date Submitted by the Author:</td>
<td>20-Mar-2017</td>
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<tr>
<td>Complete List of Authors:</td>
<td>Saghaee, Gholamreza; McGill University, Civil engineering and applied Mechanics Mousa, Ahmad; Monash University, School of Engineering Meguid, Mohamed; McGill University</td>
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SYNTHESIS OF WILDLIFE-TRIGGERED FAILURES IN EARTH LEVEES

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Revised submission March 19, 2017

https://mc06.manuscriptcentral.com/cgj-pubs
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Abstract

Earth levees are subject to a wide range of wildlife intrusion patterns that cause mass removal and subsequent serious deformations. Such invasive activities leave the body of an earth embankment with burrow systems of complexity beyond modeling. This study investigates the impact of different idealized configurations of animal burrows on the geotechnical performance of levees. For this purpose, centrifuge testing was conducted on homogenous scaled-down 1H: 1V levee models built from silty sand material. Modeling involves introduction of horizontal cylinder-shaped waterside and landside burrows at different elevations within the levee section. The reference (intact) and deteriorated levee models were subject to a centrifugal acceleration of 35g, which was kept constant as the water level behind the levee model was gradually increased. The deformation profile of the model was tracked and the crest displacements are concurrently measured. Miniature pore pressure transducers (PPT) embedded within the levee body provided respective pore pressure measurements. A three-dimensional finite element model was developed to investigate the hydraulic performance and verify the failure patterns of the deteriorated levees. Compared with intact levee, the presence of animal intrusions was found to increase the exit hydraulic gradient for both waterside and landside intrusions. Shallow animal burrows appear to cause larger exit gradients than higher ones. Similarly, waterside burrows exhibited a notably higher pore pressure and larger hydraulic gradient. The waterside damage yielded a quicker and more violent failure than that associated with the landside case. The failure mechanisms for both the waterside and landside burrows are quite dissimilar despite their abrupt nature.

Keywords: stability of earth structures; geotechnical performance of levees; wildlife intrusion patterns; centrifuge modeling; seepage analysis
INTRODUCTION

The damage to earthen structures caused by invasive wildlife activities is observed worldwide. Such natural exploits are often associated with economic losses in infrastructures and adjacent properties. Animal burrows have been known to negatively influence the hydraulic performance of earth dams and in severe cases could potentially lead to a complete loss of their structural integrity. Failures and losses related to animal activities in earth structures are discussed in further detail by Bayoumi and Meguid (2011). These damages caused by nuisance activities could remain concealed for a long time until the safety of an earth structure is massively jeopardized (Blach et al. 2010).

Breaches of earth dams are typically driven by a variety of actions including excessive forces from the retained water (floods), low strength materials, or seismic activities. The consequences of wildlife activities in levees can be categorized into structural damage, surface erosion, and hydraulic alterations (FEMA, 2005). These adverse outcomes are often related. Changes to hydraulic performance is one of the most common causes of failure in earthen structures, which typically lead to internal erosion and piping (Fell, 2003). While internal erosion naturally occurs in solid earth structures, the hostility of the consequences is exacerbated in the presence of cracks or cavities within the soil mass.

Controlling seepage through earth dams and levees is an important design requirement to prevent excessive uplift pressures, piping and erosion of material through losses into cracks, joints, and cavities (Sherard et al. 1963; Arulanandan and Perry 1983; FEMA 2011; Sherard and Dunnigan 1985). Extensive research has been done on intact earth structures to study the mechanisms of piping (van Beek et al. 2010; Sellmeijer et al. 2011; van Beek et al. 2011; Zhou et al. 2012), erosion (Bonelli and Brivois 2008; Boukhemacha et al. 2011; Xu et al. 2012), and overtopping (Schmocker and Hager 2012; Sharp and McAnally 2012). A significant amount of the literature in the area of wildlife investigates the ecological impact of animal activities and habitat (Bayoumi and Meguid 2011). However, studies related to the
synthesis of failure mechanisms of earth structures due to invasive wildlife activities are very scarce in the literature. Visual inspection of wildlife damage in earth structures might leave an average observer with the false impression that they are meant to be erratic and random. The convoluted nature of these burrow systems in earth dikes and dams hides ingenious engineering that could go beyond comprehension. This probably stands behind the limited effort in studying the underlying mechanics of deterioration and their impact on performance. Wildlife develops numerous strategies and techniques in attacking earth structures. Species dwelling in these structures typically have a strong preference either by intruding from the waterside or landside, occasionally both sides (Bayoumi and Meguid 2011). Equally important, predation and other ecological characteristics of wildlife have a significant impact on the location and geometry of burrow systems.

SCOPE

This research investigates the impact of location and elevation of animal burrows on the behavior of earth levees. Understanding of the failure mechanism of damaged earth structures - even at an abstract level - is thus pivotal for sound post-failure analysis and potentially adequate design. In doing so, equidistant horizontal cylindrical array of burrows is introduced at different elevations within a centrifuge levee model. This arbitrary damage configuration is supported by the dominance of near horizontal animal burrows in earth structures (Chlaib et al. 2014). Both waterside and landside attacks are closely examined by monitoring the surface movement, global deformation, and changes in pore pressure distribution due to the introduction of these cylindrical-shaped burrows.

Description of the physical model, summary of the methodology used to introduce animal burrows within the model, and details of the performed centrifuge testing are presented herewith. The test results of an instrumented intact levee model, including surface displacements and pore pressures, are summarized and compared with those measured for deteriorated levee cases. The effects of the configuration of animal burrows on the hydraulic performance and stability of levees are accordingly
discussed. Three-dimensional finite element analyses are utilized to support the hypothesized reasons for the alternations to phreatic surface and the failure mechanisms of the deteriorated levees.

**EXPERIMENTAL PROGRAM**

Hori et al. (2007) successfully used the Kasama soil (silty sand) for centrifuge modeling of earth dams (Table 1). Its weak cohesive nature has bestowed favorable conditions for wildlife invasive activities. The low-to-medium plasticity offers wildlife a reasonable balance between stability of cavities and relative ease in digging. A side slope of 1H: 1V seems to warrant initial stability of the levee model and simultaneously - from experimental feasibility standpoint - provides an ample chance of failure in the case of deteriorated levee (Saghaee et al. 2016). While relatively steep slope is uncommon for engineered earth dams, this configuration allows for viably investigating both serviceability (prior to failure) and ultimate limit states. A line of horizontal equispaced cylindrical burrows was introduced at different elevations within the levee section. Each test case has one set of burrows at the same elevation on either the waterside (WB) or landside (LB) of the model (Fig. 1a). Centrifuge modeling enables close examination of the animal burrows’ effect on the stability and hydraulic performance of the levee section in a controlled environment. For benchmarking, an intact levee section was tested in a similar fashion. The details of the experimental program reported by Saghaee et al. (2016) are summarized below.

**Setup and burrow configuration**

A 1:35 scaled-down section was built to model a 5-m high levee with a 4-m crest width and 1H: 1V side slopes. The Kasama soil was compacted in the centrifuge box to a moisture content of approximately 30% in nine 25-mm thick lifts to the desired height. In order to eliminate the risk of disturbance, the levee section was shaped carefully and incrementally by removing the soil (excavation) to shape the predefined levee model (Fig. 1a). Thin-wired 100-psi pore pressure transducers (PPT - Model GE Druck PDCR 81-347) were placed during the construction stage at preselected locations along the centerline of the model.
to monitor pore pressure changes during the test (Fig. 1a). The use of sufficiently long PPT wires minimized the impact of interference on the measured deformations. The wires were monitored for unusual tension or movement during the experiments.

Animal burrows were modeled as cylindrical cavities using six stainless steel rods of 8.5 mm diameter, spaced at 50 mm apart (Fig. 1b). At 35g-acceleration level, a customized pullout system gradually extracted the pre-installed rods during the centrifuge flight. This method has successfully introduced burrows at mid-height and three quarter of the levee height, $H_B/H_L$ of 0.5 and 0.75, respectively. The model embankment (143 mm height and 400 mm width) experienced gradual spinning towards the targeted centrifugal acceleration (35g). The centrifuge box containing the model was equipped with a transparent face to allow for visual monitoring of the deformations during testing (Fig. 2). The levee construction procedure and further modeling details are provided by Saghaee et al. (2012a and 2012b).

The foregoing configuration arbitrarily mimics site conditions whereby clustered animals (high population) exercise invasive activities. The burrow length and diameter are inspired by the typical activities of large digging carnivores. For example, the American badger is known to dig slightly elliptical openings averaging 20 to 30 cm in diameter and extend horizontally up to 9 meters into the ground (Bayoumi and Meguid 2011). Accurate modeling of real burrow network can be tedious and time-consuming, therefore, a row of cavities is deemed to warrant qualitative representativeness of sufficient damage that would eventually lead to failure. It is, therefore, important to realize that the study seeks understanding of seepage patterns and failure mechanism of deteriorated earth structures rather at the conceptual level.

**Material characterization**

The Kasama Soil was fully characterized for model construction and numerical simulation. This includes index tests, particle size distribution, standard proctor, shear strength and hydraulic conductivity...
tests. Figure 3a depicts the gradation curve for the Kasama Soil. The material is classified as silty sand (SM) in accordance with the USCS. Constant head permeability tests suggested a coefficient of hydraulic conductivity of approximately $3.8 \times 10^{-5}$ m/s. The levee model was constructed inside the centrifuge box using the compaction and excavation technique. This method involves two steps: (1) placement and compaction of the soil in equal thickness lifts (layers) up to the desired height and (2) removal of the soil (excavation) in order to shape the levee cross section. This levee construction procedure was strictly followed for both the intact and deteriorated levee models. Sagheea et al. (2015) discussed in further detail the compaction test in relation to the construction of the model. Drained strength and stiffness of the soil used to build the levee model were evaluated for consolidated-drained triaxial tests at three confining pressures: 50, 150, and 200 kPa (Fig. 3b). Soil specimens were prepared in a mold and tamped in four layers following a procedure similar to that used to build the levee. Hydraulic conductivity was also measured and was found to be about $3.8 \times 10^{-5}$ m/s. The average moisture content of the prepared specimens was found to be approximately 30%, which is comparable to that of the levee model before raising the water level. The soil properties and parameters are summarized in Table 1.

**Testing procedure**

The centrifuge testing started by spinning up the model to an initial acceleration of 10g. A payload (including the setup and the model) of about 800 kg reached the targeted centrifuge acceleration (35g) at an angular speed of 78 rpm. The overall performance of the model appeared to be adequate with the monitoring instruments functional at this acceleration level. The maximum error associated with stress non-linearity (approximately 0.7%) falls within acceptable limits (Taylor 1995). Gradual pullout of rods commenced at a rate of 0.33 mm/sec immediately upon reaching the maximum acceleration. The negligible settlement observed at the crest during the pullout is indicative of repeatability of cavity introduction and initial conditions. Following rod removal from the levee body, the water level on the waterside was gradually raised at elapsed time of 4,000 second using a dedicated water pump. The
process of increasing the water level lasted for about 200 seconds allowing for steady-state conditions (constant PPT readings) to be reached for each 20 mm increment. The water was then maintained at a target level ($H_w$) using onboard head leveler and subsequently monitored using a PPT installed within the main drain.

**Monitoring scheme**

Digital photography captured numerous images of soil deformations. Three high-resolution digital cameras (10.0 MP, 6x optical zoom) were affixed outside the centrifuge box to monitor the planar soil deformation through the transparent wall. Two cameras closely monitored waterside and landside slopes and the central camera covered the whole levee model including the foundation. The progression of geometrical changes of the cross section was snapshotted at 5-second intervals. A HD camcorder continuously monitors the profile of the model. Additionally, two laser LVDTs were used for measuring the crest settlement along the centerline of the model. High resolution still imaging during the centrifuge flights allowed for post processing of deformations using Particle Image Velocimetry (PIV) analysis (White et al. 2003). A thin soil layer near the transparent wall was mixed with 5% styrofoam beads 1 mm in diameter to texturize the soil and allow for the deformation to be accurately measured.

**OBSERVATIONS**

The study investigated the impact of the burrow’s configuration (attack side and elevation) on the performance of the modeled levee. The following observations are used to envisage the nature of failure in deteriorated levees. The deformation, hydraulic performance and failure progress of the deteriorated models are separately discussed.

**Deformation field**

The measured crest settlement for both deteriorated models (WB and LB) are depicted against that of the intact model in Figure 4. All cases generally experience a gradual increase in crest settlement up to
approximately 2 mm prior to elevating the water level (at \( t = 4,000 \) s). An abrupt increase in the crest settlement is noted shortly after the water level was raised. The deteriorated models exhibit a distinctive failure response commencing at elapsed time of about 6,000 s (Fig. 4). The WB and LB models experienced excessive and abrupt settlement followed by rapid failure at elapsed times of approximately 6,500 s and 7,700 s, respectively. Comparatively, the crest settlement measured for the intact levee, however, plateaued at about 9 mm and showed no signs of distress up to the end of the experiment.

Contours of the vertical and horizontal deformations for all cases are post-processed using PIV analysis during raising the water level (from \( t = 4,000 \) s to \( t \approx 6,300 \) s). The cumulative vertical and horizontal displacements from PIV analysis are illustrated in Figure 5, respectively. Positive vertical and horizontal displacements indicate downward and lateral movements toward landside, respectively. As expected, the maximum vertical and horizontal deformations of intact levee cross section are smaller than those of the deteriorated models (Figures 5b and 5c). Whilst similarity is apparent, the contours of the vertical displacements (subsidence) for the WB model suggest higher settlement than the LB model. This is in line with the trends of crest settlement observed within the same time interval (Fig. 4). The LB model exhibited larger vertical deformations at the closed end of the burrows and around the waterside toe (Fig. 5b). Horizontal deformations of the intact model are rather insignificant with an average hovering around zero displacement. The top of the foundation of the deteriorated models demonstrated moderate to high vertical settlements on the order of 4 to 8 mm increasing toward the waterside toe. This deformation pattern stands behind the noted tilt of the model toward the waterside.

The horizontal deformation contours for WB and LB models are similar – with larger horizontal deformations around the waterside slope. Based on the observed contours, the average horizontal displacements for the deteriorated models are around 40% of their vertical displacements. Considering the modeling scale at 35g, vertical and horizontal displacements of a full size levee section could be approximately 25 cm and 10 cm, respectively.
Hydraulic response

Pore pressure readings obtained during the experiment allowed for gauging the hydraulic response of the model. As depicted in Figure 1a, the PPTs measured pore pressures at three locations within the landside toe: P1, P2 and P3. It is worth noting that the previously described levee deformations might result in slight changes in the elevations of the installed PPTs. The total head \( h_t \) was accordingly calculated based on the corrected elevation of the PPT after settlement \( z_{cor} \) as follows:

\[
z_{cor} = z_o - \Delta z
\]  \hspace{1cm} (1)

\[
h_t = z_{cor} + h_p
\]  \hspace{1cm} (2)

where:

- \( z_o \): the initial height of the PPT above the datum (levee base);
- \( \Delta z \): the corresponding settlement (linearly interpolated); and
- \( h_p \): the pressure head

Figure 6 illustrates the impact of attack side on the hydraulic gradient \( i \) for the intact, LB and WB models. The figure shows the gradients for the deteriorated models with burrows at their mid-height. The hydraulic gradient near the exit toe was calculated as the quotient of the total head difference and the distance between the respective PPTs. Compared with the intact case, the hydraulic gradient is found to be higher for the deteriorated models with an increasing trend towards the landside toe drain. The hydraulic gradient of WB case was greater than that of the LB case. It should be noted that although these gradients could be different from local gradients, they are yet indicative of the burrow configuration effect on hydraulic response.

Figure 7 depicts the traced (approximate) phreatic surfaces for the three cases overlain on high-resolution still images. The slightly darker shades indicate the wet soil (below the phreatic surface), whilst the light shade represent the partially-saturated and drier regions (above the phreatic surface). The intact
model exhibits the classical steady-state flow of water with the phreatic surface between the maximum retained water level (waterside) and ending at the toe drain (Fig. 7a). This is not the case for the deteriorated levees as the presence of the cavities alters the classical seepage path (Fig. 7b and 7c). For the LB model, the water seeped through the waterside slope and favorably collected in the burrows. The phreatic surface was parallel to the burrows within the levee prior to running parallel to the landside slope towards the landside toe (Fig. 7b). In the case of WB, the burrows allowed direct access for water with minimal head loss along their length. The preferential near horizontal flow path created early in the seepage process resulted in raising the phreatic surface, which eventually exited near the toe of the model (Fig. 7c). Compared with the LB case, the higher profile of the phreatic surface for the WB model explains the higher measured exit gradients (Fig. 6).

Subject to the dominating wildlife species at the levee location, attacks from the waterside could target lower elevations. Thus, a line of burrows at the bottom quarter \( (D_b/H_L = 0.75) \) of the model’s height was introduced. Figure 8 depicts the effect of the burrow elevation on the hydraulic performance of the deteriorated levee. The normalized hydraulic gradient was used for this purpose. The measured gradient \( (i) \) is divided by \( H_W/H_L \) in order to relate head loss to water levels on the waterside. The low-elevation burrows \( (D_b/H_L = 0.75) \) yielded a hydraulic gradient of about twice that of the mid height burrows \( (D_b/H_L = 0.5) \) (Fig. 8). Similar to the raw hydraulic gradient, the normalized gradient provides a somewhat qualitative measure of the hydraulic performance for deteriorated levees.

**Failure progress**

Still imaging of the models taken during the centrifuge flights was used to conceptualize the progress of failure. The investigated LB and WB cases show distinctive failure mechanisms despite their abrupt nature. The following summarizes the key observations for both models.

The key characteristics and signs of failure of the levee model with landside burrows (LB) are captured in selected images from time stamp \( (TS = t/t_f) \) of 0.431 to 1.0 (Fig 9). The first visible landside
crack appeared at a TS of 0.833 and laterally propagates as isolated distresses near the apex of burrows as shown in Figure 9b. Interconnectivity of cracks on the landslide was spotted at a TS of 0.847 (Fig. 9c). Sliding and separation of the bottom half of the landslide slope seem to commence at a TS of 0.880 (Fig. 9d). Further deepening of the cracks eventually has led to complete loss of structural integrity at a TS of 1.0 (Fig. 9f).

Until a TS of 0.9963 the waterside burrows (WB) model showed no signs of through-seepage (Fig. 10a). The rapid distress signs are subsequently captured in selected images from a TS of 0.9989 to 1.0 (Fig. 10 b thru f). The first appearance of seepage and washing of landslide toe commence at TS of 0.9989 (Fig. 10b). Subsequent deep horizontal cracks in landslide slope (Fig. 10c and d) propagate swiftly in a toppling mode (Fig. 10e) until complete failure. At this stage, half of the landslide section is almost washed instantly as illustrated in Fig. 10f.

**NUMERICAL ANALYSES**

**Model description**

Three-dimensional finite element analysis was performed using Plaxis 3D software (Plaxis, 2015) to further support the visual observations of the physical model. This was of a particular importance given the distribution and shape of the burrows within the body of the model as well as the possible scale effects in the centrifuge model. A full-scale numerical model that captures the geometric features of the levee and the created burrows was developed. The conducted seepage analysis assumes a homogenous isotropic material under steady-state conditions. The stress and stability analyses were performed using the Mohr-Coulomb failure criterion. Utilizing geometrical symmetry, only one-half of the embankment was modeled to reduce the mesh size and the computation time needed for the analysis. The FE model dimensions, mesh and hydraulic boundary conditions are shown in Figure 11. To reduce the
computational complexity of the 3D model, animal burrows were modeled as a highly permeable soil ($k = 10^3$ m/s) with negligible stiffness as compared to the surrounding soil. This was achieved by changing the properties of the levee material contained within the burrow geometries such that the new material would have insignificant resistance to deformation and water flow. This modeling approach eliminated numerical singularities that might have arisen if voids were to be explicitly modeled. It also enabled identical meshing for intact and deteriorated models. Quadratic tetrahedral 10-node elements allowed for the curvilinear modeling of the cylindrical cavities using a refined mesh around the burrows. The average element size of the mesh is 0.45 m with elements on the order of 0.15 m in the refined area in the vicinity of the burrows. The total number of elements and nodes is 30,452, and 45,903, respectively. Table 1 summarizes the properties and parameters used in the analyses.

**Seepage analysis**

Figure 12 depicts the contours of pore pressure at 2D cross sections taken at the centerline of the intact and deteriorated models. The calculated pore pressure at four different locations within the body of the levee are given in Table 2. Comparatively, the phreatic line of LB model is somewhat similar to the intact model - with the dead end of the burrows dragging it further downward (Fig. 12b). The traced phreatic line for LB model, as observed in the experiment (Fig. 7b), is found to be in good agreement with that obtained using the numerical analysis. While pore pressures of LB are slightly lower than the intact model, the hydraulic gradients of the former are still higher. The pore pressure contours for the WB and LB models are quite dissimilar. For the WB model, the prevalence of higher pore pressure is noted in the burrow region as well as the foundation level. The near horizontal extension of the contours is likely to be triggered by the burrow presence - very much similar to the traced phreatic line in Figure 7c.

Figure 13 depicts the pore pressure distributions across the levee for three different elevations in the intact and deteriorated models. The results show that the increase in pore pressures is consistently and considerably higher for the WB compared with the LB and intact models. The increase was more
pronounced near the landside slope. Compared with the intact model, the slightly lower phreatic line for
the LB resulted in a small decrease in the pore pressures (Table 2). This general hydraulic performance
for the deteriorated models is in fair agreement with the experimental observations expressed in terms of
the arbitrary-defined hydraulic and normalized hydraulic gradients depicted in Figures 6 and 8,
respectively.

**Stress analysis**

The loss of structural strength within the body of the levee due to the presences of cavities is
evident in the deteriorated models. To have an insight into the failure pattern and mechanism, the shear
strain contours for WB model are shown in Figure 14a. The shear strain for the WB model bands along
what seems to follow the failure surface. Additionally, strain concentrations extend along the burrow. The
visually traced failure from the experiments (Fig. 14b) as well as the model geometry at failure (Fig. 14c)
are qualitatively consistent with the numerical results. The progression of failure from the toe level
towards the crest, as observed in the experiments, is intercepted by the weak plane at the burrow
elevation. Such observation can be linked to the horizontal cracks that appear at the landside slope (Fig.
10c) followed by excessive sliding (Fig. 10d). The loss of strength is further exacerbated by the respective
increase in pore pressures in the toe area –where failure surface is initiated– (Fig. 12c). Further movement
of the toe towards the landside deepen the horizontal cracks and eventually cause the observed toppling
failure-like pattern (Fig 10e and f).

**Stability analysis**

To investigate the effect of strength reduction on the stability of levee slopes, the strength reduction
method is used in this study, where the soil strength is artificially weakened until the soil fails (Plaxis,
2015). This is established by decreasing the cohesion and tangent of the friction angle in the same
proportion:
\[ \frac{c'}{c'_r} = \tan \varphi' / \tan \varphi'_r = strength \; reduction \; ratio \] (3)

where \( c' \) and \( \varphi' \) are the input strength parameters for the Mohr–Coulomb failure criterion and \( c'_r \) and \( \varphi'_r \) are reduced strength parameters that are just large enough to maintain equilibrium. In FEM, no assumption needs to be made about the shape or location of the failure surface. Failure occurs through the zones within the soil mass in which the shear strength is unable to resist the applied shear stresses. Based on this approach and considering the toe of the landside slope (LS) as a reference point, the stability of both the intact and deteriorated levees is investigated. Figure 15 demonstrates that the safety factors for the intact and LB levees are about 1.3 whereas the deteriorated WB levee was on the verge of failure with a factor of safety approaching 1.0.

The effect of the levee side-slopes is numerically examined in Figure 16. The slope angles were adjusted in three stages from 1H: 1V to 3H: 1V and the safety factor against slope instability was calculated for both the intact and the deteriorated levees. For the three investigated geometries, mid-height burrows were introduced at the waterside and the burrow length was gradually increased up to 75% of the levee width at that location. Results show that the introduction of burrows resulted in a general reduction in the factor of safety. As the burrow length increased from 0 to 75% of the levee width, the factor of safety for the three investigated slopes, namely, 1H: 1V, 2H: 1V and 3H: 1V decreased from 1.3, 1.85 and 2.3 to 1.0, 1.33 and 1.76, respectively. These results suggest that the adverse effect of the induced cavities is not limited to a specific geometry and the reduction in the safety factor depends on the extent of the cavity into the levee.
SYNTHESIS OF FAILURE

Supported by the foregoing experimental observations and numerical results, the inferred scenarios, thus, represent the authors’ best judgement on the progression of failure in the deteriorated levee models.

Levee with landside burrows

Figure 17 summarizes a conceptual synthesis of the failure of LB model with the perceived chronological order indicated in boxes. The burrows evidently provide preferential path for the water flow toward the landside. Driven by the presence of cavities, the seeping water approaches the burrows from the closed end and the top possibly carrying some fines. The conducted analysis has shown that seepage into the burrows creates a concentrated flow around the burrows (see Fig. 17b). This flow makes the walls of the partially filled burrows vulnerable to erosion. The seeping water with the carried/washed fines exit on the landside end of the burrows causing distress and disintegration of the surrounding area. This coupled with the free water seepage at the burrow level leads to structural deterioration locally propagating around individual burrows. Crest settlement started to develop progressively with the development of the visible landside cracks between the burrows (Fig. 9b through e). Eventually, the structural integrity of the burrows is completely jeopardized (Fig. 4 and Fig. 9f).

Levee with waterside burrows

A schematic of the proposed failure progression in WB levee section is shown in Figure 18. The burrows’ proximity to water exacerbates flow and particle migration within the model and eventually weakens its structure. Unequivocally, this direct water access to the cavity system jeopardizes the
hydraulic performance of the levee by raising the phreatic line. As compared with the LB case, the uninterrupted water entry obviously reduced head losses and yielded considerably higher pore pressures (Fig. 13). The “buildup” of pore pressure—manifested in the higher phreatic line—is more intense because the water entering effortlessly at the waterside does not exit the burrow as easily. The “entrapment” of large pore pressures near the center of the model probably promotes transverse (lateral) seepage between the burrows. The lateral flow is associated with fines migration causing disintegration and weakening in the zone between the burrows, which is signified in the development of parallel cracks between the burrows. This flow pattern leads to erosion of the walls of the water-filled burrows. Subsidence develops across the levee section with interaction between adjacent burrows. As failure is approached, the high pore pressure leads to excessive seepage at the toe (Fig. 10b) and the initiation of slip plane due to the loss of effective stress (shear strength). The intersection of the slip surface with the horizontal cracks around the burrow area forms a toe wedge (A) and a middle wedge (B). With further through seepage, the toe wedge slides and topples leading to crumbling of the middle wedge (Figs. 10c and d). Under the high “blocked” pore pressure, the complete wash out of the levee section is inevitable. This mechanism justifies the rather steep trend of crest subsidence (Fig. 4).

SUMMARY AND CLOSING THOUGHTS

This study has investigated the effect of idealized configurations of wildlife attack on the hydraulic performance and structural integrity of earth levees. Animal invasive damage was modeled as idealized cylindrical cavities within the levee models. For this purpose, a series of centrifuge experiments on scaled-down levee sections having waterside and landside burrows at different levels were conducted. An identical intact section has undergone the same experiment for referencing. Compared with the intact levee, the deteriorated models exhibited peculiar seepage pattern. The experimental results indicated that the presence of the introduced cavities has dreadful impacts on the hydraulic performance and stability of
levee. Utilizing the centrifuge observations, the study postulates distinguishing failure mechanisms associated with the attack side. Numerical simulations of the seepage and stress analysis have further supported the proposed hydraulic response and failure mechanism. The effect of slope angles is numerically examined for three different side slopes, namely, 1H: 1V, 2H: 1V and 3H: 1V with mid-height burrows. Results showed that the introduction of waterside burrows resulted in an average reduction in the factor of safety by about 25%.

The aforementioned findings collectively explain the unexpected and abrupt failures that could develop in levees deteriorated due to wildlife activities. The deduced failure scenarios advocate that subsidence in deteriorated levees is triggered by the combined effect of cavity destruction and loss of strength. Unmistakably, the use of crest settlement (subsidence) as a failure indicator in deteriorated levees is indicative but incomprehensive. Their apparent intactness prior to failure could be quite misleading. This has significant bearing on levee system management, as the damage (size of cavities) of concealed burrow systems within a levee section could be much larger than what the visible openings demonstrate (Bayoumi and Meguid 2011). Of note, the results reported in this study are rather limited by the investigated parameters including the levee and burrow geometries. Obviously, the size and density of the burrows could also be very critical. Thus, generalization of the outcomes requires further investigation on other materials, geometrical features of earth structures and deterioration levels and patterns.

ACKNOWLEDGMENTS

This research is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) under grant number 311971-11. The assistance of the support staff at C-CORE centrifuge center in St. John’s, Newfoundland, Canada is highly appreciated.
REFERENCES


List of Tables and Figures

Table 1. Characteristics of the Kasama soil

Table 2. Pore pressure comparison at selected points

Fig. 1. Model configurations: (a) geometry and location of pore pressure transducers (P1 through P3); (b) plan view of the model with waterside burrows (Saghaee et al. 2016)

Fig. 2. Test setup installed on the plain strain centrifuge box

Fig. 3. Kasama soil characterization: (a) particle size distribution; (b) triaxial consolidated-drained stress-strain curves for confining pressure of 45, 98, and 150 kPa

Fig. 4. Measured changes in crest settlement with the increase in water level for Intact, levee with landside burrow (LB) and levee with waterside burrow (WB)

Fig. 5. Contour plot of cumulative vertical and horizontal deformations due to rising water level from \( t \approx 4,000 \) s to \( t \approx 6,300 \) s for: (a) Intact, (b) landside attack (WB), (c) waterside attack (LB)

Fig. 6. Hydraulic gradients near the exit for the deteriorated models with burrows at the mid height versus intact model

Fig. 7. Inferred phreatic surface for the levee models: (a) intact; (b) LB (prior to failure); (c) WB (prior to failure)

Fig. 8. Effect of burrow depth on the hydraulic gradient near the exit for waterside burrows (WB) at \( H_w = 94 \) mm

Fig. 9. Failure of levee with landside burrows (LB) \([t_f = \text{time to failure}]\)

Fig. 10. Failure of levee with waterside burrows (WB) \([t_f = \text{time to failure}]\)

Fig. 11. Vertical cross section through middle burrow of FEM model: geometry (in m) and boundary conditions

Fig. 12. Steady-state pore pressure distribution: (a) Intact (b) LB (c) WB.Fig. 13. Pore water pressure distribution at horizontal sections across the levee

Fig. 14. Stress analysis of WB model: (a) shear strain \((x10^{-3})\) (b) side view of the observed failure in WB model (c) top view of failed section

Fig. 15. Factor of safety of landside slope for LB and WB levees at time stamp \( T = 6,300 \) s
Fig. 16. Effect of side slopes on the safety factor for levees with mid-height burrows

Fig. 17. Proposed failure scenario for the LB levee (sequence of distress events is indicated)

Fig. 18. Proposed failure scenario for the WB levee (sequence of distress events is indicated)
Table 1. Characteristics of the Kasama Soil

<table>
<thead>
<tr>
<th>Property</th>
<th>Values</th>
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<tr>
<td>$G_s$</td>
<td>2.67</td>
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<tr>
<td>Moisture content (%)</td>
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<tr>
<td>LL</td>
<td>14.1</td>
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<td>PL</td>
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<tr>
<td>$\gamma_d$ (max) (kN/m$^3$)</td>
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<tr>
<td>OMC (%)</td>
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<tr>
<td>$\gamma_{sat}$ (kN/m$^3$)</td>
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<td>$\gamma_{unsat}$ (kN/m$^3$)</td>
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<tr>
<td>E (MPa)</td>
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</tr>
<tr>
<td>$\nu$</td>
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<tr>
<td>$\phi'$ (°)</td>
<td>32°</td>
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<tr>
<td>$\psi$ (°)</td>
<td>0°</td>
</tr>
<tr>
<td>$c'$ (kPa)</td>
<td>5.9</td>
</tr>
<tr>
<td>$k$ (m/s)</td>
<td>$3.8 \times 10^{-5}$</td>
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Table 2. Pore pressure comparison at selected points

<table>
<thead>
<tr>
<th>Point</th>
<th>Pore water pressure (kPa)</th>
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<tbody>
<tr>
<td></td>
<td>Intact</td>
</tr>
<tr>
<td>K (WL)</td>
<td>63.75</td>
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<tr>
<td>O</td>
<td>0</td>
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<td>P</td>
<td>5.54</td>
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<tr>
<td>Q</td>
<td>7.57</td>
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</table>
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