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FEATURE

Wildlife and Safety of Earthen Structures: A Review

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Abstract A wide range of nuisance wildlife dwells in proximity to and within earthen dams and levee systems. Burrowing animals often dig tunnels and holes inside earth structures for habitat or grub and flatten the external slopes for maneuvering and in search for food or preys. Other animals and cattle have less invasive effects on earthen structures. Most of these detrimental activities result in altering external and internal geometry of earthen structures. Damage caused by wildlife in earthen hydraulic structures is typically associated with internal and external erosion and sometimes boils. Animal burrows have an adverse impact on the hydraulic performance and structural integrity of the earthen dams. In addition to their direct damage, wildlife activities could have serious influence on human life, public health and safety, agriculture, food chain, environmental balance, and ecology. Several federal, state, and local agencies in the United States and other agencies and organizations worldwide have reported information on observed wildlife activities in earth dams and levee systems. This information, however, is generally incomprehensive and often sparsely published in local periodicals and maintenance reports. The consequences of animal presence and their activities on earthen structures are recognized by some involved agencies; however, they appear to be generally given disproportionate attention. As such, the majority of the pertinent literature addresses wildlife damage to earthen structures as a nuisance issue that require more efficient management plans and proper maintenance procedures. This review article summarizes published articles as well as internet cited material on nuisance wildlife behavior in earth dams and levee systems. More emphasis is placed on the animals that pose imminent threats to the performance and functionality of earthen structures. Common characteristics of animal burrows and intrusions in earthen dams are discussed and summarized. Documented damages and reported failures of earth structures initiated by animal activities are compiled. Current wildlife management techniques are discussed. Available estimates of cost of damages and failures due to wildlife intrusions are also highlighted.

Keywords Animal burrows · Earthen structures · Hydraulic performance · Structural integrity

Introduction

Numerous federal, state, and local agencies in the United States reported failures in earthen structures due to unobvious reasons. Many of these failures are believed to be due to or initiated by nuisance wildlife intrusions. Apparently, the nature and magnitude of wildlife activities and the damage they make to earthen structures are given disproportionate attention among levee management boards, local agencies, and geotechnical engineers. Visible animal burrows in earthen dams and levees are routinely flagged by levee management boards and maintenance agencies and authorities. From the management standpoint, the damage is perceived as a maintenance issue that requires subsequent repairs. Several maintenance agencies and authorities have developed and implemented wildlife management programs to minimize the population of

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invasive animals and control their adverse consequences including damage to earthen structures. Nonetheless, comprehensive understanding of the root causes and progress of wildlife damage to earthen structures is evidently deficient in the current practice.

A number of burrowing species cause damage, water loss, and potentially flood by excavating earthen dams, irrigation canals, or flood control structures. The Federal Emergency Management Agency [1] reported 23 main species among those posing a threat to earthen dams in 48 states. The severity of damage they cause is dependent on their population, size, and activity. Surprisingly, only 9 states have information and guidance on the effects of animal activities on earthen dams [1]. Among the notable invasive wildlife species are beavers, muskrats, gophers, and ground squirrels in North America and South Asia; and nutria in North and South America [2]. A variety of other burrowing species cause problems on a localized basis. It is often difficult to determine the genesis of breaks in earthen structures attacked by burrowing animal. In fact, invasive damage of these animals could go undetected for a long period of time [3]. Depending on the nature and severity of damage, it may be impossible to assess failure causes with any degree of accuracy if the evidence has been washed away by adjacent waterways. In addition to potential loss of life and property, subsequently required repairs to failed or damaged earthen structures could cost millions of dollars.

The authors have always noted during their consulting and academic experiences the effort and time spent to estimate hydraulic and strength parameters required for seepage and stability analyses of earthen structures. While estimating geotechnical parameters is based on field and laboratory testing, it is a very challenging process which typically involves engineering judgment. For this purpose, the presence of holes and burrows and other forms of wildlife damage to earthen structures appear to be overlooked by geotechnical analysts. Modeling animal cavities within an "idealized" levee or dam cross section is evidently unusual in classical geotechnical analyses. For such cases, the validity of practice-driven assumptions and the applicability of typical analyses methods are undoubtedly questionable. Therefore, it is necessary that engineers and geotechnical analysts recognize the nature, genesis, and extent of wildlife damage to earthen structures.

Case studies and reports addressing failures and damages in earthen structures due to wildlife activities are generally qualitative in nature and approach the problem from a management viewpoint. Additionally, very few studies were made to model and quantify the damage to earth structures form an analytical standpoint. This review article shows that the pertinent literature seems to give disproportionate attention to this subject. In addition, the review indicated that very few well-documented research and case studies were fully dedicated to address the adverse impact of animal activities on earthen structures from a geotechnical standpoint. There are numerous reported total and partial earthen structure failures due to unobvious causes or following observed adverse animal activities. This further proves the evident deficiency in literature pertaining to this topic. Many of the cited references in this article were found on the internet in the form of local management reports, internal communications, newsletters, presentations, and reported news. Significant amount of the literature in the area of wildlife address the ecological and environmental impact of animal activities and habitat. However, studies on the synthesis of failures mechanisms of earth structures due to wildlife activities appear to be absent from the literature.

Scope

In this article, a literature search was made to summarize and categorize wildlife hazards to earth structures. The focus of this article is to highlight the detrimental effects of animal intrusions on the safety and functionality of earthen dams and levees. Selected case studies and documented failures of earthen structures caused or initiated by animal activities were cited. Available estimates of economic impact of these damages are also highlighted. Relevant information reported by Federal, State, and local agencies were collected, reviewed, and classified. In fact, gathering this material is an attempt to encompass pertinent available information and categorize them as appropriate. Details pertaining to behavior, biology, and reproduction of the intruding wildlife as well as their impact on public health and environment are beyond the scope of this article. For these purposes, the reader is referred to specialized ecological, public health, environmental, and other pertinent studies. Failures and damage to earthen structures due to uncontrolled plant growth and man-made encroachments are also beyond the scope of this article. The reader is advised to review relative literature such as "A Technical Manual on the Effects of Tree and Woody Vegetation Root Penetrations on the Safety of Earthen Dams" [4].

Nuisance Wildlife Species and Earthen Structures

Reported wildlife damage to earthen dams and levees is primarily due to burrowing and grazing activities. A flood protection plan prepared by the Department of Water Resources (DWR) lists burrowing animals among 25 factors that have adverse effects on the performance of the Central Valley Levee System in California [5]. Burrows weaken levee sections; contribute to erosion and gully formation, and present hazards for livestock and humans [6]. Levee systems are deteriorating over time due to the combined effect of burrowing activities and flood storms [7]. FEMA [1] reported three major categories of distress due to wildlife activities: structural damage, hydraulic alternation, and surface erosion. Internal erosion is one of the most common causes of failures in earthen structures [8, 47]. The severity of wildlife damage is dependent on the size, location, and interconnectivity of cavities within the dam or levee section. With delayed remedial actions, the nature of the damage becomes more progressive and complex, and potentially of unknown severity and consequences. From a geotechnical viewpoint, long-term effects of wildlife activities in intruded earthen structures are dependent on a variety of factors including soil type, steepness and height of slopes, and crest width. Many burrowing animals dig deep holes and isolated hidden dens in earthen structures. Therefore, it is usually difficult to assess the impact of their damage on the core of earth structures during routine investigations. Hydrology of adjacent waterways and groundwater as well as the adequacy of routine repairs are key factors in evaluating the immediate and long-term wildlife damage to earthen structures.

Animal intrusions on both the upstream (waterside) and the downstream (land side) alter the strength characteristics and hydraulic configurations of earthen dams. Depending on severity, location, and connectivity of the animal intrusion, the structural damage could range from local surface failures to global instability of the earth structure. The hydraulic changes due to animal intrusions include flow net distortion, shortening, or blocking typical flow paths, creating new preferential flow paths, and lowering the phreatic line. Some animals reduce vegetative cover on earthen dams which in turn could decrease soil retention on slopes and crest and exacerbate internal and external erosion [1]. From a geotechnical standpoint, this impact could be more detrimental if burrowing activities are on the waterside of the earth structure, particularly when combined with a flood stage during large storm events. Details relative to burrowing activities, and characteristics and extent of wildlife intrusions will be subsequently discussed.

Wildlife Burrowing Activities

Several animal species attack man-made earthen structures on regular basis for a variety of reasons. Some species excavate burrows, tunnels, and den entrances for shelter or food storage, while other predatory animals will enlarge these structures via digging in search of prey. Similarly, herbivorous species will forage on vegetation growing on embankment dams. These occurrences create isolated, inter-connected internal cavities, or surface depressions in earthen structures all of which are detrimental to the safety and performance of the invaded structures. As will be discussed, some of wildlife damages can be easily identified, such as surface erosion; other effects such as internal erosion may not become visible until safety of the earthen structures is jeopardized.

Twenty-three nuisance wildlife species are listed in the technical manual for dam owners prepared by FEMA [1]. Many of these species share common characteristics, but the pattern and size of burrows and severity of damage they cause to earthen structures could substantially vary. Table 1 summarizes the geographic extent of the detrimental wildlife in the United States. While the severity of their damage is not known with certainty, it is evident that the strong presence of certain species could be an imminent threat to earthen structures in the United States. Active rodents such as muskrats and beavers are reported in more than two thirds of the surveyed states. Selected photos of wildlife damage in earthen dams and levees are shown in Fig. 1. Table 2 summarizes typical burrow characteristics

Table 1 Severity of problem: extent of wildlife detrimental impact on earth structures in the United States by specie [1, 24]

#	Species	Magnitude of reported damage, %[a]	Number of states[b]
1	Muskrats	71	34
2	Beaver	67	32
3	Mountain beaver	N/A	N/A
4	Groundhog or woodchucks	N/A	24
5	Pocket gopher	23	N/A
6	North American Badger	17	8
7	Nutria	4	2
8	Prairie dog	8	4
9	Ground squirrel	15	6
10	Armadillos	4	5
11	Livestock	25	12
12	Crayfish	4	2
13	Coyote	4	N/A
14	Rat, mice, moles, and voles	10	5
15	River otter	4	N/A
16	Gopher tortoise	4	N/A
17	Red and gray fox	4	N/A
18	Canada goose	N/A	N/A
19	American alligator	2	N/A
20	Ants	4	N/A
21	Reptiles	N/A	3
22	Human vandals	N/A	3

[a] Percent of the surveyed state considering specie a significant dam safety issue

[b] Reported problems by state representatives and federal agencies

N/A not available

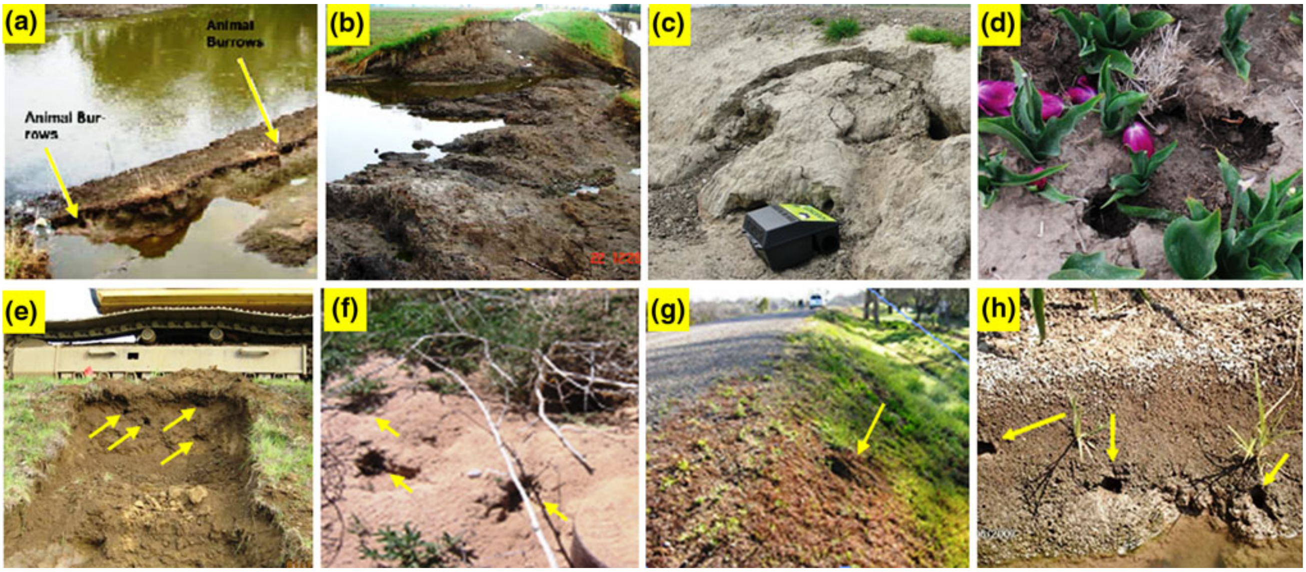

Fig. 1 Wildlife damage to earthen structure: (**a**, **b**) Pin Oak levee failure due to muskrat burrows in Winfield, Missouri [104]; (**c**, **d**) earth dikes near tulip fields damaged by rats in the Netherlands [35]; (**e**, **f**) deep cavities and surface burrows of rodents [20]; (**g**) animal burrows in highway embankments [20]; (**h**) crayfish damage in the banks of the Nile River in Egypt [133]

of damage to earth dams by specie. These characteristics could provide general guidance to wildlife management programs as well as design practices.

Wildlife damage to earthen structure is a complex process particularly in close proximity to waterways. Burrowing activities of wildlife in earth structures are sophisticated biophysical processes that are generally difficult to observe during routine levee management. Wildlife damage to earthen structures could be progressive in nature with inherently uncoupled consequences. Studying hydrological records of waterways adjacent to earthen structures is necessary to assess the progress of damaged sections. Considering the time span of damage occurrences, these records are not always readily available and often technically inadequate. Severity of damage depends on geometry, material, and condition of the earthen structure as well as type, population, and typical activities of the dominating wildlife species. For example, variability in geometry and material of zoned earthen structures could have a strong influence on the pattern and severity of wildlife damage. Damage is also influenced by other environmental and ecological conditions. Hence, synthesis of damage mechanisms due to wildlife activities over a long period of time is more challenging than it appears. Appropriate maintenance and routine repairs minimize the possibility of sudden failures. However, absent or incomplete maintenance records add to the complexity of the problem. Damages and alternations to earth dams due to wildlife activities can be grouped into three main categories: loss of structural integrity, hydraulic alternations, and surface erosion. Unless indicated otherwise, the subsequently presented material is based on the Technical Manual for Dam Owners [1].

Loss of Structural Integrity

Several animal species excavate dens, burrows, and tunnels within earthen dams, causing large cavities that weaken their structural integrity. Typical animal burrows can range from the size of a bowling ball to a beach ball and larger. Burrowing animals may encounter loose or less compacted native zones in earthen dams during excavation, leading to a localized collapse. Heavy rain and snow melt could also loosen soils surrounding a burrow. In addition, animal dens could erode and collapse under the load of heavy equipment and vehicles that use the crest of earthen structures as a throughway.

The collapsed zones could progressively lead to sinkholes or depressions appearing on the surface of earthen structures. Because burrows can occur several feet below surface, the deformation or sinkhole visible at the surface could be several times the size of the original burrow. As illustrated in Fig. 2, the collapsed soils can represent a significant portion of the dam embankment. Localized and even global slope instability can result from a collapsed animal burrow. Depending on the location, size, and number of animal burrows, the safety and functionality of earthen structures could be jeopardized. If portions of the crest are affected, a loss of freeboard can result, thus endangering the dam during storm events. Downstream

Table 2 Typical damage to earth dam by species [1, 24, 117]

Species	Typical damage	Typical burrow shape and activity indicators	Typical active side
Muskrats	Large burrows that can cause internal erosion and structural integrity losses. Digging upward unto the embankments causes significant internal burrows	Burrows as deep as 10 ft below water surface	Waterside
Beaver	Excavating bank burrows cause internal erosion and structural integrity losses		Waterside
Mountain Beaver	Shallow location of the extensive burrows could cause ground cave in. This leads to hydraulic alternation and structural losses	Tunnels, dens, and mounds—1–9 ft deep, 2 ft high chambers	Waterside
Groundhog or woodchucks	Burrows can weaken embankments and create pathways for seepage	Mound, 2 or more entrance burrow system	Landside
Pocket gopher	Generally a threat to small dams and underground utilities. Cause internal erosion and structural integrities. Attracts badgers (predator) which is very detrimental to earthen dams	Fan or horseshoe mounds, plugged burrow entrances	Landside
North American badger	Dig for prey and construct dens for shelter. Cause severe damage to hydraulic structures. Cause internal and external erosion. Compromising structural integrity by creating large voids	Large burrows 5–30 ft long and 2–3 ft chamber. Single elliptical entrance with mound. 12 in in diameter	Waterside
Nutria	Construct extensive burrows as shelters in the upstream slope. Weaken earthen dams to the point of collapse	4–6 ft long tunnels, and 1–3 ft across compartments	Waterside
Prairie dog	Cause internal erosion and structural integrity losses	20–50 burrow entrances, mounds of 12 ft high	Landside
Ground squirrel	Cause internal erosion and structural integrity losses. Attracts badgers (predator) which is very detrimental to earthen dams	Large colonies with clustered above ground mounds. Burrows: 2–10 in diameter, and 10 ft long	Both
Armadillo	Cause internal erosion and structural integrity losses	Burrows 7–8 in diameter, up to 15 ft length	Both
Livestock	Damage to earthen dams by removing stabilizing vegetation, trampling and rooting. External erosion due to lost vegetative cover and creation of erosion pathways	Varies	Both
Crayfish	Burrows in earthen dam embankments; extensive burrowing may cause internal erosion and structural integrity losses	Along shore line: 1/4–2 in in diameter with cone shaped mound	Both
Coyote	Generally not a major threat. Den construction/enlargement and digging out prey living in dams can cause structural integrity losses	Several opening dens from few to 50 ft.	Landside
Rat, moles, and voles	Construct tunnels from their upland dens to hunting grounds in dams. They dig extensive burrows system that pose a real threat in the form of internal erosion and structural integrity losses in dams	2–24 in tall volcano-shaped mounds, 1–2 in wide runway system	Landside
River otter	Dig big dens for shelter (with underwater and above water entrance). Large dens in bank embankment and underwater entrances provide pathways for internal erosion	Large bank dens with underwater entrance	Waterside
Gopher tortoise	Burrows and spacious chamber can cause structural integrity losses	Burrows 40 ft long and 10 ft deep. Large mounds	Landside
Red and gray fox	Generally not a major threat. Digging out burrowing animals can cause structural integrity losses	Several 10 in wide entrance halls	Landside
Canada goose	Nesting on or near earthen dam could cause external erosion	…	Waterside
American alligator	Sometimes dig burrows or dens causing internal erosion and structural integrity losses in earthen dams	…	Waterside
Ants	Colonies consisting of series of tunnels that exacerbate existing cracks that could cause structural integrity losses	Underground colonies	

slope failures, regardless of their extent, reduce the effective width of the embankment and loosen surface soils. This results in further weakening of earth structure. Depending on the condition of earth structure, prolonged high water in adjacent waterways, and stormy weather conditions could speed up the damage progress and could eventually lead to massive slope instabilities. Failure is likely to be imminent when the slopes of an earth embankment are attacked from waterside and land side causing significant narrowing of the section (Fig. 3).

Hydraulic Alternations

The most significant and often least obvious impact of wildlife intrusions on embankment dams is hydraulic alteration. Hydraulic alteration can manifest itself in different ways including flownet distortion, internal erosion and piping, and physical barriers to the natural flow of waterways.

Each dam has unique hydraulic characteristics and flownet configurations. A distorted flownet may not be a visible problem but it can have a dramatic impact. As illustrated in Fig. 4a, upstream burrows allow the normal water elevation to extend into the dam embankment, forcing the phreatic surface further into the embankment. Likewise, downstream intrusions can allow the phreatic surface to daylight higher on the downstream slope. The combined effect could lead to major alterations to the hydraulic configurations of earth structures. The adverse consequences of changes to the phreatic surface include shortening of seepage paths, increase in seepage volumes, internal erosion of embankment materials, and subsequent

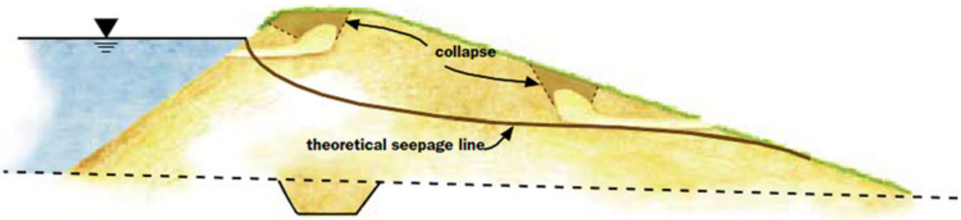

Fig. 2 Sinkholes and loss of structural integrity due to animal burrows [1]

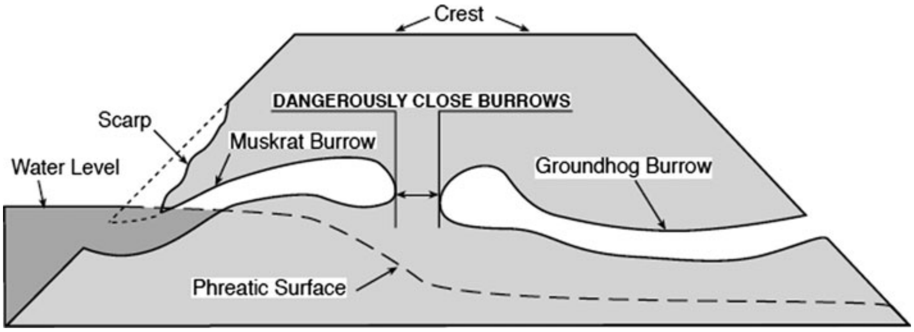

Fig. 3 Dangerously close animal burrows (From Ohio Department of Natural Resources Division of Water Fact Sheet 94-27)

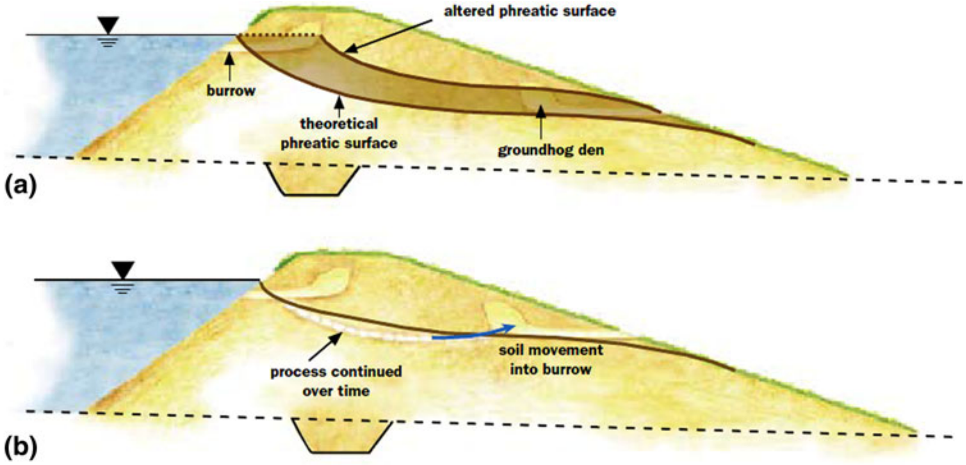

Fig. 4 Hydraulic alternations due to animal burrows: (**a**) shortening seepage path; (**b**) piping [1]

reductions in the factor of safety against slope failure. These changes obviously impair the hydraulic performance and functionality of earthen structures.

Internal erosion occurs when water flows through a cavity, crack, and other continuous void within an earth dam. These openings may be a result of one or more of these concurrences: inadequate compaction during construction, differential settlement, desiccation, earthquakes, burrowing animals, and decay of woody vegetation roots. Fell et al. [8] described the process of internal erosion and piping in four phases: initiation of erosion, continuation of erosion, progression to form a continuous internal channel, and formation of a breach. Although both terms are used interchangeably, McCook [9] makes a distinction between internal erosion and piping. Internal erosion involves flow of water through a continuous defect or crack within a compacted fill, foundation, or at the contact between a fill and foundation. The mechanism of piping involves flow through the pore space of an intact soil mass which has no internal cracks or discontinuities. Earth dam failures usually happen as a result of internal erosion rather than piping incidents [9]. In fact, reported failures in earth structures due to real piping are rare. Because many of the internal erosion failures result in a tunnel or pipe-shaped erosion feature through the earth structures, they are often referred to as piping failures by engineers, but by this definition these cases are not true piping events. FEMA [1], however, defines piping as an uncontrolled movement of soil particles caused by flowing water. As shown on Fig. 4b, piping will often start in a burrow on the downstream slope. Flowing water moves soil particles from the earth dam to the burrow, leaving a void that is quickly filled with soil particles from deeper within the section. Water pressure and flow generally increase further into the earth dam; therefore, the rate of movement of soil particles will also increase. A pipe-like seepage path is progressively formed extending from the downstream slope to the upstream slope. A dam breach is almost certain to develop in these instances.

External problems can also arise from wildlife activity around an earth dam. Beaver and similar species build hydraulic barriers that block the natural flow of waterways by compacting tree trunks, limbs, branches, and other materials into a mound. Beavers typically obstruct waterways to create deep waters which help them hide from predators. As a result, the hydraulic function of the dam is altered in several ways. First, beaver mounds may block principal and emergency spillways and riser outlets, resulting in increased normal pool levels and reduced spillway discharge capacity. Second, sudden high discharges from the dam could occur if the beaver dam fails. Third, beaver dams located upstream of the dam can clog water control structures as debris from the beaver dam floats downstream. Finally, elevated tail water caused by beaver activity can accelerate erosion of the downstream toe of the dam.

Surface Erosion

The foraging behavior of some animals on open area vegetation associated with earth dams can reduce or eliminate vegetative cover on their sections. Livestock grazing combined with other mechanical activities, such as animal trafficking and grubbing, lead to loss of surface stabilization, reduction in soil retention, and formation of irregular surface and gullies. These geometrical changes can further create potential erosion paths on the dam's crest and slopes, particularly on waterside. With continuous neglect and exposure to water level fluctuations, these eroded surfaces would require more than simple maintenance. In fact, long-term external erosion can lead to excessive loss of cross section and a reduction in freeboard. These impacts can further increase the dam's vulnerability to extensive damage and even sudden failure during large storm events.

Common Characteristics of Wildlife Intrusions

In this section, it is intended to shed light on some geological, geometrical, structural, and other preferences of the burrowing animals dwell within or near earthen structures. The reported studies are focused on specific species; however, they are indicative of the general wildlife behavior and preferences pertaining to damage in earthen structures. These observations could be used to rationalize the pattern and severity of some reported failures in earthen structures. Thorough understanding of the patterns of wildlife damage and favorable burrowing conditions can also be used to improve management strategies. Studies that focus on the biophysics of the behavior of burrowing animals are beyond the scope of this article.

Soil Type

Soil type has a significant impact on behavior and habitat of burrowing animals. Soil provides these animals with effective physical protection and supports the plants and animals, primarily insects that many burrowing animals consume. Soil type also affects the population and distribution of burrowing animals. For example, the digging activities and population of cotton rat in Florida are much higher than those in Kansas. Laboratory studies indicated that this difference is due to soil characteristics; sandy soils in Florida promote digging while the hard soils in Kansas are rather prohibitive. An example of the simplest type of excavation that serves for protection is exhibited by the Namib golden mole and the marsupial mole. These two species tunnel through dunes whose loose, sandy soil will not support a permanent burrow. Thus, as the animals push through the sand ("sand swimming"), their excavations collapse behind them. In these soils, the golden mole comes above ground for just a few holes each night to look for prey [10].

Soil properties have an impact on the geometry and size of burrow dimensions. Laundre' and Reynolds [11] compared maximum depth, total volume, total length, volume to length ratio, and complexity of burrows of five small burrowing species against texture and bulk density of soil. Burrows of Wyoming ground squirrels were deeper, longer, and more complex as percentage of silt and clay increased and percentage of sand and bulk density decreased. Average maximum depth of montane vole burrows increased as soils became sandier. Length and volume of deer mice burrows increased with increases in bulk density and percentage of clay. Volume, length, and complexity of kangaroo rat burrows were greater in soils with higher amounts of clay and silt. Townsend's ground squirrel burrows did not appear to be affected by the soil properties measured. A difference in maximum depth of burrows changes the location of the reservoir of nutrients for recycling, increases the depth of soil aeration, and, especially in arid and semiarid areas, alters shallow subsurface water recharge patterns. Despite the geometrical differences, the five species were found in sandy loam, loamy sand, or loam, where the prime component was sand up to 53% and clay was only about 15% [11]. This study indicated a positive correlation between the size of burrows and the bulk density and percent of silt. Conversely, the burrow sizes had an inverse correlation with percent of sand. These geological preferences appear to be in line with the fundamentals of soil mechanics.

Crayfish normally exists in geological formations having some fine-grained soils. Clay and silt should typically be 10–20% of the total amount of sand and gravel [12]. Clay content is necessary for maintaining soil moist conditions and cohesion. Coarse-grained soils are structurally unstable for constructing crayfish burrows, but with sufficient clay content they allow for more efficient burrowing and minimize digging energy.

A survey made on armadillos in 1974 indicated that they prefer sandy and loamy soils. Their populations were reported highest adjacent to creek or river beds [13]. The survey showed that unfavorable areas include marshy soils and those with shrub and grassland.

A case study conducted at the USDA-ARS Hydraulic Engineering Research Unit in Stillwater, Oklahoma highlights the impact of soil type on failure of homogeneous earthen dams. A series of large-scale physical tests were performed on 1.3 m high embankments to study erosion processes due to internal erosion [14]. Three different materials were used in the tests ranging from non-plastic silty sand to lean clay. In order to simulate natural intrusions or man-made encroachments, a continuous 40 mm diameter steel pipe was placed through the embankment. The test sections were subjected to a constant upstream pool elevation. The pipe was then removed leaving a tube-like cavity in the embankment before commencing with testing. The rate of internal erosion and breaching width observed in these tests varied by several orders of magnitude. The silty sand embankment was technically fully eroded in 60 min, whereas the lean clay embankment experienced a relatively slow and fairly limited downstream damage over a period of 72 h [14]. While soil preferences of burrowing animals could vary, the results of this study highlight the consequences of animal intrusions in earthen dams and their correlation with soil-type preferences.

Based on these case studies and examples, it is evident that burrowing animals have strong geological preferences dictated by their habitat, size, soil type, and condition. The results and conclusions of the foregoing studies can be utilized to synthesize reported damages in earthen dams attacked by wildlife.

Moisture and Water Table

Burrowing environments can be characterized as dark and moist of moderate temperature. Moisture content of the soil is very important to burrowing animals because they facilitate more cost-effective excavation, especially for soils which become extremely hard when dry. When soil becomes saturated due to rising water elevations of waterways, burrowing animals can be trapped in their tunnels and drown. High moisture content is necessary for animals in their burrow systems, particularly in arid environments where evaporative water may be significant above ground. High moisture content promotes excavation, reduces water loss, and maintains moderate temperatures for burrowing animals. Additionally, seeds stored in the high humidity would absorb moisture, thereby actually providing preformed water to these animals. Open burrows generally maintain high moisture content. Plugged burrows quickly reach 100% relative humidity, even when soil moisture is extremely low. When water tables rise these animals may abandon their burrows, as happens for some rodents in alpine meadows when the spring melt occurs [134]. Hydrology of groundwater and adjacent waterways has a direct impact on the design of burrow system including size and elevation of dens and escape paths.

Movement and Energy

Burrowing animals generally minimize movement energy by following flatter slopes [15]. While they try to maintain a balance between gravity cost and excavation cost, pocket gophers dig their tunnels in directions that are independent of hillslope [15]. California ground squirrels prefer to burrow in a horizontal direction regardless the steepness of hillsides slopes, which presumably requires less energy than digging straight down [6]. Correlations between the body weight of animals and both trail angle and natural ground slope were developed by Reichman and Aitchison [16]. Vleck [17] proposed energy cost models for fossorial rodents which can be used to estimate cost of burrowing and explain burrowing preferences. These energy-driven movements appear to have an extremely significant impact on the behavior of animals and their burrowing activities.

Geometrical Characteristics

Many dam owners do not realize the presence of wildlife activities until a significant damage or a sudden failure is reported. This can be partly attributed to the fact that animal burrows and cavities run deeper than visible surface holes. In addition, the size of internal cavities generally exceeds the size of these surface holes by several folds. Confirming size and connectivity of internal burrows during routine inspection is almost impossible. In addition, vegetation on levee slopes can even make it very challenging to detect surface burrows [18–20].

Larger burrowing animals excavate larger holes in earth structures [21]. Geometrical optimization is necessary to limit burrowing effort. While burrows provide animals with shelter and protection, they could limit their movement. They could also allow snakes to enter the burrow system and consume them or their young. Plugging the burrow may inhibit snakes from entering. However, other species would dig through the plugs and may actually be drawn under fresh soil collapses as an indication of recent excavations by potential prey. On several occasions badgers block the subsidiary exits of ground squirrel burrow before digging into the main entrance and extracting the adults and their young. Colonial burrows have many entrances and a more complex layout than individual burrows [6]. It is interesting to note that the structures of the male squirrel burrows are short, simple, and shallow as compared to the complicated and mazy female burrows. Muskrats are aggressively burrowing species to the extent that one animal can replace about one cubic meter of soil in 1 year [22]. The main geometrical characteristics of selected wildlife species are summarized in Table 2.

These complex predation and ecological characteristics have a significant impact on the geometry of burrow systems. Further details on wildlife preferences and characteristics of rodent burrows are discussed by Reichman and Smith [10].

Extents of the Problem

Wildlife activities and their detrimental impact on earthen structures are observed worldwide. As previously indicated, wildlife nuisance activities is a complex issue that encompasses safety, environment, ecology, economy, and other aspects. This section includes examples of reported wildlife impact on earthen structures worldwide with more emphasis on the United States. The nature and severity of common wildlife damage to earthen structures will be the focus of these discussions. The selected examples, however, should not imply comprehensiveness of the presented material.

The United States

There are numerous wildlife species across the United States that continuously attack the infrastructures of the nation. The following discussions on the adverse activities of these species indicate the severity of losses as well as deep concerns and high risk they pose to earthen structures.

Ground squirrels are adaptable and prolific species living in a variety of habitats including agricultural areas, rangeland, urban areas, and industrial sites. Their ability to thrive under diverse environmental conditions is one of several characteristics that make them a pest. The burrows average about 4.3 in in diameter and 5–34 ft in length. The burrows on flat land are generally 30–48 in below the surface, but could be as deep as 28 ft on occasions. A record burrow system had a total length for all tunnels of 741 ft with 33 openings. In spite of their relatively small size, ground squirrels may burrow completely through a levee section. As such, squirrel burrows can act like a pipeline carrying floodwaters into or completely through a levee section, resulting in massive structural damage and potential breaks. Erosion, seepage, sloughing, and subsidence are more frequent occurrences in squirrel's burrow system. Additionally, loose soil from burrow excavations is highly erodible, causing additional degradation of the levee section. Once squirrels dig to some depth or distance into the levee that damage to the structural integrity remains even after the squirrels are removed and their burrow entrances cave in and are no longer apparent. The deep cavities remain or eventually are filled with loose, sloughed soil. Since the collapsed soil is not compacted, it can be easily penetrated by water or re-dug by other burrowing animals. Levee sections with ground squirrel populations, or known to have been previously subjected to squirrel burrows, must be more closely monitored during flood patrolling. These sections often require more intensive flood fighting to minimize further structural damage and circumvent instabilities that could eventually lead to dramatic failures.

Not only do beavers obstruct waterways by building their dams but they also dig a system of tunnels in earthen structures. These tunnels and holes could significantly affect the integrity of earthen structures. Continuous water flow through beaver tunnels could cause downstream erosion [23]. Beaver tunnels are typically 1–4 ft below normal water levels. Beaver dens could be 5–10 ft in diameter and several feet in height. Their damage to earthen structures was cited by 32 of the 48 states [1, 24]. In Southern Hinds County, Mississippi State, a levee section behind a local's residence almost failed within a few hours from the first spotted land side leakage. Upon inspection by the division of dam safety in the State of Mississippi, beaver dens and tunnels were exposed and the levee segment appeared to be badly damaged [23]. A similar levee failure was reported in DesSoto County, Mississippi State, after a heavy rainfall. In this case a land side hole was targeted toward a house approximately 200 ft away from the levee [23].

In addition to the damage they cause to crops, muskrats are most noted for their damage to water-retaining structures due to burrowing. They burrow into earthen dams, dikes, levees, and railway embankments, thereby weakening these structures. Their activities also damage the banks of canals, streams, rivers, farm ponds and irrigation, and drainage ditches. Small farm ponds can suffer the heaviest muskrat damage to the extent that may even drain a pond. Muskrats dig underwater entrance tunnels typically 5–6 in in diameter and 10–50 ft long. These tunnels lead to one or more nest chambers above the water level which could be supplemented with small ventilation vertical tunnels and hidden dens. In New York State, muskrat is one of the most widely distributed furbearers [25]. It is found even in marshes close to urban centers. Historically, during the era of transportation by canal in the mid 1800s, canal companies paid bounties on this burrowing rodent. Muskrat burrows in dikes form large potholes in Michigan, where they are reported as a threat to the safety of vehicles traveling on these dikes [26].

Marmots, which are abundant in the Western United States, live among rocks and boulders which are used for dens and lookout posts [27]. In the spring of 1992, it was determined that marmots had penetrated a levee-protected recreational area in Lewiston, Idaho. The integrity of a three mile stretch of the levee system along the Snake River was compromised. Research conducted by the United States Corps of Engineers (USACE) [28] on the levee core concluded that marmot burrows could lead to levee breaks, especially during high water stages. These breaks along the levee alignment could cause significant property damage in the nearby downtown business section of Lewiston and even loss of human life [27]. Wildlife biologists of the USACE contacted Animal Damage Control personnel to take necessary animal control measures to save the recreational area and adjacent properties.

Burrowing is the most commonly reported damage caused by nutria. They weaken flood control levees that protect low lands. In some cases, they can dig tunnels in these levees to the extent that water will flow unobstructed from one side to the other, which requires complete levee reconstruction [29]. They also undermine and break through banks in flooded fields used to produce rice and crawfish [30]. The damage caused by nutria to Louisiana levees before Katrina Hurricane was significant. Their damage in Louisiana became so severe that in 2005 a bounty program was in effect to aid in controlling the animal. Nutria has become pests in many states, eroding river banks and destroying irrigation systems. In addition to Louisiana, they are notorious in Maryland, Texas, and other states.

Armadillos have been successful in extending their range throughout the southeastern states [13]. They occupy such a diverse range of habitats that their effects on the surroundings depend largely on their location. Armadillos benefit from their burrowing and eating patterns by creating dens for furbearers and destroying large quantities of injurious insects and their larva. Those activities in urban and suburban areas are recognized as a source of considerable nuisance and moderate damage. The most noticeable sign left by armadillos are the shallow feeding burrows shaped like inverted cones approximately 2 in deep and 2 in in diameter at the surface. While most food excavations are shallow, the animal can dig shoulder deep in an ant hill or termite colony. Erosion along the banks of waterways could intensify the burrowing damage of armadillos. In one case a 3 ft deep and 20 ft long gully was formed. Armadillos have caused collapse of levees, dikes, and dams in Louisiana [13].

South Florida hosts hundreds of thousands of Central American green iguanas [31, 118]. The highest reported green iguana density is 626.6 animals per square kilometer in Florida. Assuming that each animal digs a burrow, this density is equivalent to a minimum of 6.2 burrows per hectare. They invade riparian slopes of highway embankments, canal banks, and flood protection levees and dig extensive burrows and holes, which cause an imminent threat to these structures particularly during flood events. Iguana burrows could reasonably penetrate 30% of a levee section. Small amounts of erosion in invaded levees could cause instability in less than 5 years. The burgeoning population of iguana in South Florida spurred Palm Beach County commissioners to petition the Florida Fish and Wildlife Conservation Commission to add them to the state list of regulated "Reptiles of Concern" [32]. Their large size burrows combined with the damage they do to ornamental plants makes them an unwanted pest to homeowners. In addition, there is evidence that these animals have begun to inhabit basic traffic and air corridors causing airplane collision hazards on airport runways at the Homestead Air Reserve Base in Florida. They are also present in other airports around Miami, Tampa, and Puerto Rico [31]. Reported burrows from three surveyed sites in two counties in South Florida indicate iguana densities of 1,740, 1,883, and 2,825 burrows per hectare. Their typical burrows have been measured to be approximately 2 m (6.7 ft) deep and as much as 20 cm (7.8 in) in diameter. The increasing propagation of green iguanas poses a real threat to Florida's infrastructure and ecosystems by potentially reducing the effectiveness of flood management systems [31].

Canada

Pocket gophers are endemic to North America from central Canada to Panama. They are perceived as efficient "digging machines." Studies on excavation rates and burrow volumes of various species of pocket gophers were cited by Witmer and Engeman [33]. A single gopher hole has a minimum volume of approximately 0.68 m^3. In general, a single animal can excavate 18 m^3/ha per year. The presence of these burrows could lead to excessive seepage, piping, and eventually washouts, especially with water surges [34]. Muskrat activities are also known for creating safety issues for vehicles traveling on the dikes in Canada. This has been experienced in Ontario where large potholes are formed [26].

The Netherlands

Muskrats cause several forms of damage to Holland's infrastructure and economy including damage to earthen structures, irrigation system, crops, fisheries, and nature [22, 26]. Muskrat activities have been reported as a threat to the security of the dike and drainage systems in The Netherlands [22, 26]. The holes made by muskrats in ditches interfere with drainage systems. Reported damage to earth dams due to intensive burrowing was severe to an extent that some of these structures have lost their retaining function. In this respect, larger well-engineered dams and dikes are less vulnerable to subsequent failure due to Muskrat burrows. However, often century-old smaller polder dikes, where smaller damage may have already lead to landslides or bursts, are much more vulnerable. These older polder areas are found most in the densest populated areas of the Netherlands including residential areas, airports, and other important centers that could be inundated by such failures [22].

The burrowing activities of brown rats could also seriously jeopardize Holland's dikes and dune systems, as well as its lucrative tulip industry [35]. Therefore, good water management in the Netherlands does not only involve regulating water levels but also dictate keeping brown rats and similar rodents such as coypu, and muskrats from destroying canal banks, endangering dikes, and devouring tulip bulbs. Protecting Holland's dike system from collapsing due to animal burrows guarantees 100,000 people in this area safe living [35].

The Mediterranean and North Africa

Porcupine is a terrestrial mammal covered in long spines or quills which live in family groups in their complex burrow systems. It is found in the Mediterranean including mainland Italy and the island of Sicily, Morocco, Algeria, Tunisia, Libya, and along the Egyptian coast [36]. Porcupine is known to collect thousands of bones that they find at night and store them in their underground burrow system. The intensity of the invasive activities of porcupine was responsible for a major levee failure in the urban area of Sinalunga, Italy in 2006 [36].

Wildlife damage to properties and infrastructures was neglected for a rather long period in Egypt. Before the construction of the High Dam, the annual increase of flood water level regularly forced rats to desert their burrows and invade surrounding areas and Nile banks. With almost stable river stage maintained by the High Dam, the seasonal invasions by rodents have significantly dropped [37]. In Giza and Qalyoubiya Governorates, red swap crayfish has caused unacceptable damage to irrigation and drainage systems, primarily through burrowing in poorly constructed levees and canal banks [38]. Similar damage is reported in Portugal, the United States, and Kenya [38].

China

In the early 1980s, there was a widespread outbreak of rodents in the agricultural areas of China. A study conducted in the south part of the Inner Mongolia Plateau in China indicated high burrowing activities within earth structures. The spatial distribution of burrow holes of the rat-like hamster is affected by periods of intensive agricultural activities; most of the observed animal burrows are constructed in river banks, and in non-irrigated and non-plowed wastelands [39]. The density of burrows of the hamster in the wasteland was estimated to be about 67.7 holes per hectare, while the density in irrigated farmland was about 35.6 holes per hectare [39].

Australia

The burrowing activities of yabby, a native crayfish, are noted in small and large dams in western and central Australia [12]. They leave significant damage to retaining walls of channels and dams, and banks of rivers and streams. A thorough study was performed by Lawrence [12] to evaluate the degree and pattern of damage caused by yabbies in Western Australia.

Wildlife Management

Management of Wildlife damage has made great strides in the past few decades moving from uncoordinated private efforts to organized integrated pest management approaches employing a variety of pest control tactics. Some of the tools of the past such as trapping or shooting are still critically important in these programs. Most wildlife damage managers prefer nonlethal solutions to wildlife damage problems, especially when these approaches are economical and acceptable to both society and the agricultural industry. However, lethal methods must sometimes be employed when relocation of animals is not feasible, or when other methods prove ineffective [40]. The common management techniques of different wildlife animals are presented below with emphasis on four animals, namely, beavers, pocket gophers, muskrats, and squirrels. These animals were selected because of their strong presence in earth dams and their superb survival capabilities.

Management Techniques

There are generally two main types of wildlife management: (1) non-lethal control methods, (2) lethal control methods. Harvesting or killing unwanted animals are the most common, and often the most effective, methods of reducing animal damage, even though lethal control is becoming increasingly less acceptable to the public [41, 42]. These two main management options are discussed below.

Non-Lethal Control

The following are selected examples of the commonly used non-lethal damage control techniques for different animals.

Beavers: Live trapping has become a fairly popular method to remove problem beavers in urban areas, provided that suitable relocation sites are available [42]. Nevertheless, even with trapping, the rapid reproduction rate of beavers coupled with their ability to travel many miles to discover new territory, allow them to re-colonize habitat where beavers have been removed [43, 44]. Various types of traps are available for capturing beaver including Cage and Clamshell Traps [42, 45, 46]. These traps are specifically designed to capture beavers and have been used in reintroduction programs.

Pipe Pond Leveler: Flooding caused by beaver dams can be controlled and maintained at a tolerable level using pipe pond levelers [47, 48]. It consists of flexible corrugated plastic pipes inserted through the beaver dam to allow water to flow. The upstream end of the pipe is usually protected with large wire mesh to keep beavers from plugging the pipe [49]. While an important tool, these devices have two main limitations. First, they only protect trees from flooding due to water impoundment, not from stripping or cutting by beavers. Second, pipes are effective only in areas that can tolerate some flooding and maintain at least 3 ft of water depth.

Exclusion: Exclusion protects ornamental trees and plants from beaver damage by placing hardware cloth, screens, metal flashing, plastic culvert, or drain tile around the plants. It is easy and inexpensive to protect a few individual plants [46]. Exclusion is rarely practical for protecting acres of timber or treebelts. Riprap can be used on earthen dams or levees. Electrical barriers, which produce an electrical field, have been effective in ditches and other narrow water channels.

Repellents: Beaver repellent can be effective to prevent plants from cutting or discouraging beaver occupancy of selected sites. A solution of 10% creosote and 90% diesel fuel sprayed or painted on tree trunks reduces gnawing damage by beavers [46] as does a mixture of acrylic paint and sand which acts as an unpalatable abrasive. Chemical extracts from native tree species that beaver avoid (Jeffery pine) may also be effective as a beaver repellent [50].

Pocket gophers: Live trapping of gophers is labor intensive and can be very costly particularly as the live animals are not desired by most homeowners. The following are some of the other methods used to control damage induced by pocket gophers.

Habitat Modification: These methods take advantage of knowledge of the habitat requirements of pocket gophers or their feeding behavior to reduce or eliminate damage. This could be achieved using herbicides to remove their food base [51, 52].

Repellents: Whitmer et al. [53] tested selected, potential repellents in pen and field trials to determine their ability to reduce consumption of palatable foods by pocket gophers. Only sulfur-based compounds (predator urines) deterred feeding by captive gophers. Chemically hot, bitter, and noxious compounds and plants did not deter gopher feeding. Rapid reinvasion of available habitat by pocket gophers in a field trial occurred despite the presence of encapsulated sulfur-based chemicals on trial plots. Some predator odors have been tested as gopher repellents and showed some promise. Commercially available sonic devices are claimed to repel pocket gophers. There is, however, no scientific supporting evidence. The plants known as caper spurge, gopher purge, or mole plant (*Euphorbia lathyrus*) and the castor-oil plant (*Ricinus communis*) have been promoted as gopher repellents, but there is also no evidence of their effectiveness. In addition, these chemical compounds are not recommended as they are both poisonous to humans and pets [33].

Muskrats: Extensive research has been done in the past 50 years to investigate different muskrat management approaches. Two books were written solely on muskrat management: O'Neil [54] addressed southern coastal areas and Errington [55] detailed the practical management of muskrats in northern areas. These books cover the different ecological, biological, and geological aspects of muskrat production in different parts of United States. The following is a brief summary of selected non-lethal methods for muskrat control.

Exclusion: Muskrats in some situations can be excluded from digging into farm pond dams through stone riprapping of earth dams [26, 56]. Serious damage often can be minimized, if anticipated, by constructing dams such that the downstream is sloped at 3H:1 V and the upstream slope is 2H:1 V with a crest width of not less than 8 ft (2.4 m), preferably 10–12 ft (3–3.6 m). The normal water level in the pond should be at least 3 ft (91 cm) below the top of the dam and the spillway should be wide enough that heavy rainfalls will not increase the level of the water behind the dam for any length of time. Other methods of exclusion can include the use of fencing in certain situations where muskrats may be leaving a pond or lake to cut valuable garden plants or crops.

Habitat Modification: Muskrats are primarily vegetarian animals, feeding mostly on the roots and stems of aquatic plants. Therefore, the best way to modify their habitat is to eliminate aquatic or other suitable food found in marshes. Several methods of eradicating marsh vegetation were investigated by Wilson [57]. Burning prevent marsh buildup, and in conjunction with flooding of needle rush-sawgrass, resulted in 75–100% eradication of less desirable vegetation. Specific burning dates and techniques vary by marsh type and area [54, 58]. If farm pond dams or levees are being damaged, one of the ways that damage can be reduced is to draw the pond down at least 2 ft (61 cm) below normal levels during the winter. Then fill dens and burrows and riprap the dam with stone. Once the water is drawn down, trap or otherwise remove all muskrats. Water level manipulation is another efficient muskrat management technique. Abnormally low water levels directly influence muskrats by exposing them to increased predation, nutritional stress and winter freeze-outs [59–62].

Squirrels: Ground squirrel can be trapped and translocated successfully. Translocation has been used as a management tool to remove animals and as a conservation technique to re-establish extirpated population [63]. Researchers in this field suggested that the destruction of squirrel burrow systems can reduce the rate of their reinvasion [64]. However, the potential value of burrow destruction as a control method is yet to be proven.

Habitat Modification: The California Department of Water Resources [65] has experimented with habitat modification through the planting of selected plant species as a method for the control for the California ground squirrel. These experimental plantings were based on the premise that traditional maintenance practices create a "disturbed state" similar to grazing that is favorable for the ground squirrel. Therefore, the planting and retention of selected species would result in a decrease in ground squirrel populations [66]. Fitzgerald and Marsh [67] reported that after considerable effort with a variety of plant species, the planting in these particular experiments on the Sacramento River Flood Control project levees failed to significantly reduce the population of ground squirrels. In fact, in some situations appeared to substantially increase their numbers.

Lethal Control Methods

Lethal techniques are also used to control the population and activities of invasive species near earthen structures. For the same species discussed above, the following summarizes some of the common lethal control methods.

Beavers Alligators are among the predators that prey on beavers if the opportunity occurs. The American Alligator (Alligator mississippiensis) has been evaluated as a control method in the Southeast United States. However, this method has proven to be ineffective as beavers rarely travel far from water and are relatively safe from most predators [42]. Poison bait substances, such as strychnine alkaloid baits have been evaluated as a lethal control, but are not approved for this purpose. They also cause political and practical problems [46]. Shooting beaver from boats or from land may or may not be an effective control method [42] and raises significant safety concerns.

Trapping: Body-grip traps are designed to cause quick and humane death of beavers and are usually placed in beaver runways or at lodge entrances. Body-grip traps, when used correctly, present little risk to non-target animals. Leghold traps are versatile tools for the capture of beaver and are usually placed near, or in, active runways of beavers and anchored in water deeper than 4 ft to insure the quick drowning of beavers.

Snares: Snares can be set to catch beavers' bodies [68]. The snares consist of a cable formed into a loop with a locking device and a swivel to reduce cable twisting and breakage. Snares are typically placed in beaver runways or at the lodge entrance.

Pocket gophers: Several rodenticides are currently available for pocket gopher control. The most widely used is strychnine alkaloid on grain baits. In order to poison pocket gophers, the bait is placed in their tunnel systems by hand or by a special machine known as a burrow builder. Underground baiting for pocket gopher control (using strychnine) presents minimal hazards to non-target wildlife [69]. The main drawback to baits is their high susceptibility to decomposition in humid and damp burrows. Artificial burrows are made to attract gophers and intercept their burrows. Gophers may inquisitively enter the artificial burrows, gather bait in their cheek pouches, and return to their original burrow system to consume the bait [70, 71].

Trapping: Trapping is extremely effective for pocket gopher control in small areas and for removal of remaining animals after a poisoning control program [72]. For effective trapping, the first requisite is to find the tunnel. The procedure varies depending on whether traps are set in the main tunnel or in the lateral tunnels. Trapping is most effective in spring and fall when gophers are pushing up new mounds.

Muskrats A broad overview of earlier muskrat management in North America was presented by Deems and Pursley [73]. In the United States and Canada, no state, province, or territory granted total protection to muskrats. Hunting and trapping seasons exist in several states and all Canadian provinces [42]. A commonly used toxicant for muskrat control is zinc phosphide at a 63% concentrate [74]. The baits are generally made by applying vegetable oil to cubes of apples, sweet potatoes, or carrots; and sprinkling on the toxicant. The bait is then placed on floating platforms or in burrow entrances.

Trapping: There have probably been more traps sold for catching muskrats than for catching any other furbearing species [74]. A number of innovative traps have been constructed for both live trapping and killing muskrats, such as barrel, box, and stovepipe traps. Where it can be done safely, shooting may eliminate one or two individuals in a small farm pond. A combination of trapping and proper use of toxicants is the most effective means in most situations.

Squirrels From 1900s until 1950, ground squirrels were routinely controlled with strychnine poisoning programs [75]. However, strychnine is a dangerous, nonselective poison, and there is considerable risk of killing other wildlife species that do not avoid bitter tastes [76]. Compound 1080 (monofluoroacetic acid) was used for ground squirrel control in the 1950s through 1970s, but it was nonspecific and resulted in mortality of non-target mammals, birds, and insects [77]. Currently, agriculturalists eliminate ground squirrels with anti-coagulant bait, fumigation, trapping, and shooting [78]. Each technique has its limitations. Shooting is time consuming and ineffective when animals remain in their underground burrow system. Trapping is labor intensive. Zinc-phosphide-treated baits kill 85–90% of ground squirrels that eat it, but survivors avoid treated baits [79]. Aluminum phosphide is an inexpensive fumigant, which suffocates squirrels. It is toxic to all burrow-dwelling animals and very effective. However, labor costs make it too expensive in many situations.

The above lethal and non-lethal animal control methods are summarized and compared in Table 3.

Detection Methods

There are several methods available to detect and map underground voids. These methods are universally used for various applications including cavity detection in earthen structures. Among these methods are gravity survey, resistivity methods, seismic reflection, and Ground Penetrating Radar (GPR). Gravity survey is a nondestructive geophysical technique that measures differences in the earth's gravitational field at specific locations. It has numerous applications in engineering and environmental studies including locating voids and karst features, buried stream valleys, water table levels, and soil layer thickness. The success of the gravity method depends on identifying variations in the measured gravitational field due to differences in the bulk density of earth materials. Gravity survey is considered as one of the most inexpensive geophysical methods when investigating a wide area with relatively large caverns [80–82].

Resistivity methods have also been applied for this purpose due to the fact that the electrical resistance of the void is higher than the surrounding soils (e.g., [83, 84]). Research on applying the high-resolution seismic reflection

Table 3 Summary of the different methods of animal control

Class	Method	Beaver	Pocket gopher	Muskrat	Squirrel
Non-lethal	Exclusion	X	X	X	X
	Repellent	X	X		X
	Habitat modification	X	X	X	X
	Frightening devices			X	X
	Live trapping and translocation	X			X
Lethal	Traps	X	X	X	X
	Shooting	X		X	X
	Snares	X			
	Baiting		X	X	X
	Toxicant		X	X	X

method to cavity detection was conducted in late 1980s [85]. However, the resolution of these methods was insufficient for detecting small holes in river embankments, which may facilitate piping and breaching during major flood events. Another way for detecting voids is to make use of high-resolution short wavelengths [86]. However, the higher the resolution of the data acquired, the larger the impact of small heterogeneities in the collected data, which could complicate the interpretation of the results.

The applicability of GPR to locate cavities such as pipes or tunnels was recognized in the 1970s [87]. Since air-filled voids provide an excellent dielectric constant contrast, GPR has been successfully used to identify animal burrows in earthen structures [88]. Very reliable information was obtained about lithology and internal structure of river banks, such as the identification of a flood terrace, detection of damage failures due to water percolation, outwashing, and erosion, and the localization of old buried cables and pipes. Kinlaw et al. [89] used GPR to visually view underground burrows of Gopher Tortoise. Field studies that utilize GPR to monitor river embankments have been reported by Di Prinzio et al. [90]. A summary of the different imaging methods is provided in Table 4.

Table 4 Selected methods of subsurface void detection and mapping

Method	Measured parameter	References
Gravity survey	Density	[82, 118–121]
Resistivity methods	Electrical resistivity	[83, 84, 122, 123]
Seismic reflection	Seismic velocity	[85, 124, 125]
Ground penetrating radar	Dielectric constant	[88–90]

Repair Techniques

Earth structures require routine inspection to locate animal burrows and perform necessary maintenance. After the burrowing rodents have been removed, all potential problems must be repaired as soon as possible to safeguard these structures. The backfilling of burrows has been reported as a relatively easy and inexpensive way to insure proper operation of a dam. It is recommended [91] that dens be eliminated immediately as damage from just one long hole can lead to failure of the dam. Texas Commission on Environmental Quality [92, 93] recommended repair procedure that depends on the severity of the wildlife damage. If the burrows are shallow and scattered across the embankment, repair consists of tamping backfill soil into the holes. The soil is placed as deep as possible and compacted with a pole or using a mechanical tamper. For large burrows, on the other hand, TCEQ recommends filling with mud packing. This method involves placing one or two lengths of a vent pipe vertically over the entrance of the den with a tight seal between the pipe and the den. A mud-pack mixture is then poured into the pipe until the burrow and pipe are filled with the earth-water mixture. The pipe is removed and more dry earth is tamped into the den. The mud-pack slurry is made by adding water to a mixture of 90% soil and 10% cement. Entrances are then plugged with well-compacted earth and vegetation is reestablished.

If a rodent hole extends through a dam section, it is recommended to first locate its upstream entrance. The area around the entrance is then excavated and backfilled with impervious material, plugging the passage entrance so that reservoir water is prevented from saturating the dam's interior. Filling the tunnel with cement grout is a possible long-term solution, but pressure cement grouting is an expensive and sometimes dangerous procedure. Pressure exerted during grouting can cause further damage to earth embankments via hydraulic fracturing (opening of cracks by high-pressure grouting). Thus, grouting should be performed only under the direction of an engineer [93].

The National Association of Flood and Stormwater Management Agencies [135] reported that destruction of animal burrow can be a complicated issue if the burrowing animal happens to be an endangered species. The problem of meeting federal clean water act and endangered species act requirements is extremely difficult to resolve and becomes even more complicated when state water quality and fish and wildlife certifications are involved. For some projects, the maintenance manuals have to be modified to insure that the necessary regulatory permits are provided for operations and maintenance in a timely manner, endangered habitat and species are protected, and water quality regulations are met.

The above summary illustrates that although inspection and backfilling of animal burrows has been performed in several cases, levee breaches and dam failures have been reported in the literature caused by hidden burrows that extend to critical locations making the structure vulnerable and increasing the risk of failure. The following section discusses some of these cases.

Reported and Potential Failures

Despite efforts made by levee owners to provide sufficient structural integrity and hydraulic functionality by performing necessary inspection and maintenance, problems may develop and can lead to costly failures. Levee breaches are generally caused by excessive forces from the retained water, weakness in the levee material or the levee foundation, and seismic activities. Overtopping of levees by floodwater and waves is one of the most visible causes. Seepage through or under a levee is less visible, far more difficult to predict, which makes a major concern for levee owners. Under-seepage refers to water flowing under the levee in the underlying foundation materials and is often accompanied by sand boils. These boils can lead to progressive internal erosion and levee failure. Through-seepage refers to water flowing through a dam or levee prism directly resulting in erosion and associated structural damage to the landside slope and possibly full breach of the levee [94]. Levee failures that are not flood or seismic-related are called sunny-day failures. These failures occur on relatively calm-days from internal degradation that has occurred over time [95]. Poor foundations, weak construction materials, and animal activities all aggravate these distresses [96].

As discussed in "Nuisance wildlife species and earthen structures," burrowing animals are naturally attracted to the habitats created by dams and reservoirs and can endanger the structural integrity and proper performance of the earth structure. The burrows and tunnels of these animals generally weaken earthen embankments and serve as pathways for seepage. This kind of damage has resulted in several failures of dams and levees in the past few decades. Selected examples of levee breaches and dam failures due to animal activities are presented in this section. The reported failure modes reflect the extent of the damage that could be caused by wildlife to earth structures. Five well-documented case studies are presented in detail to show the importance of early detection and proper maintenance on the functionality and integrity of these structures. Additional examples are summarized in Table 5.

Iowa Beef Processors (IBP) Waste Pond—Failed 1993 [97]

The IBP Waste Pond was constructed in 1971, and was used for the storage of wastewater from the IBP Beef Processing Plant near Wallula, Washington. When full, the pond had a surface area of 37 ac and a maximum storage capacity of 270 ac ft. The pond was located on a natural drainage course, and was impounded behind a 15 ft high, 1000 ft long earthfill dam. In 1981, the dam was inspected as part of the United States National Dam Safety Program. The resulting report concluded that the facility did not have an overflow spillway, and could thus not handle any floods from the 55 square mile drainage basin above the dam. Further, the embankment stability was considered questionable, and the dam was riddled with animal burrows. In 1985, IBP hired a consultant to perform a geotechnical investigation of the dam. The consultant found that the embankment stability was adequate, provided seepage remains at low levels within the embankment. The consultant also cautioned the owners that animal burrows in the embankment is a problem, and could initiate internal erosion and piping failures if intercepted the seepage line within the dam. The consultant recommended that the burrows be filled and the animals be removed from the site.

The failure of the dam occurred in the early hours of January 25, 1993 when a Union Pacific freight train derailed on a washed out section of track downstream from the dam. The breached section had a width of 60 ft and a depth of 19 ft below the dam crest. The dam most likely

Table 5 Selected levee breaches and dam failure (or near failure) related to animal activities

Case	Location	Date (M/Y)	Failure mode	Reference
Sid White Dam	Near Omak, WA	05/1971	Seepage through animal burrows. Caused second dam to fail and dumped debris into town of Riverside	[126]
Lower Jones Tract	California Delta	09/1980	Seepage and rodent activities	[127]
Water's Edge Dam[a]	North of Cincinnati, Ohio	10/1992	Water flow through animal burrows	[97, 128]
Iowa Beef Processor Waste Pond Dam[a]	Wallula near Richland, Washington	01/1993	Uncontrolled seepage through the animal burrows, exiting on the downstream face and causing erosion	[129]
Persimon Creek Watershed—Site 50	Mississippi	06/1998	The dam failed due to erosion of an emergency spillway. Ongoing beaver activities clogged primary spillway	[130]
Sunrise Duck Club (Suisun Marsh)	Suisum Marsh, California	07/1999	High tide and possible beaver activities	[110]
Pischieri Pond Dam[a]	Cleveland, Ohio	1999	The dam was breached when an inspection found a void in the dam.	[97, 128]
Upper Jones Tract	California Delta	06/2004	High tide, under-seepage and rodent activities	[131]
Foenna Stream[a]	Sinalunga, Italy	01/2006	Porcupine burrow, internal erosion and levee subsidence	[36]
Truckee Canal	Fernley, Nevada	01/2008	Woody vegetation and animal burrows present	[132]
Pin Oak levee[a]	Winfield, Missouri	06/2008	Muskrat burrows	[97, 103]

[a] These cases are described in "Reported and potential failures"

failed directly from uncontrolled seepage through the animal burrows, exiting on the downstream face and causing erosion. Evidence of similar erosion below animal burrows was found at the west end of the dam. Additionally, burrows were noted in the sides of the breach. The embankment was composed of silty soil which made it highly susceptible to internal erosion and piping. It is likely that the erosion backcut rapidly toward the upstream face, eventually breaching the dam.

Foenna Stream Levee—Failed 2006 [36]

The levee is located along the Foenna stream near Sinalunga in Central Italy. In 2005, the presence of animal burrows along the levee was reported by the residents of the area surrounding the stream. Typical maintenance was performed by authorities including removal of visible animal burrows. On January 1, 2006, during an ordinary flood event, levee seepage occurred during the flood. An outflow on the downstream face, about 2 m below crest level, caused the ejection of brown water, which is indicative of internal erosion. On the upstream face of the levee, a hole of about 30 cm in diameter was discovered at about the same height. Although efforts were made by authorities to close the hole, the top of the levee suddenly subsided causing overtopping flow and a trapezoidal-shaped breach developed. The urban area near the Foenna stream was completely flooded.

Following the flood event, sections of the levee were surveyed by researchers using non-destructive testing and geophysical scanning techniques to assess the presence of tunnels and animal burrows in the levee. Results revealed that wild animal activities played a major role in changing the hydraulic safety of the levee. It was found that the levee failure was caused by the presence of porcupine burrows near the middle height of the upstream face leading to internal erosion and uncontrolled seepage through the levee section. It was also concluded that maintenance carried out before the flood event was insufficient. Researchers have indicated that animal removal from the levee site was necessary and that more rigorous backfilling should have been performed to avoid such failure.

Water's Edge Dam—Failed 1992 [97]

Water's Edge Dam is located just north of Cincinnati in southern Ohio. The dam is a 22.7 ft high homogeneous earthen embankment, with a top surface area and total storage volume of 19.3 ac and 90.8 ac ft, respectively. It is considered a Class II dam in Ohio. This is a significant hazard classification where failure of the dam would cause structural damage and flooding to high value business property, but loss of human life is not envisioned. During the Thanksgiving of 1992, a consulting office was notified by the Warren County Emergency Management Agency Director that the pool level in the dam was very high and a vortex had formed along the upstream slope. County officials were concerned about a possible dam failure. Engineers discovered that a vortex had formed where water was pouring into a burrow entrance on the upstream slope surface. The water followed the burrow almost horizontally through the dam and had collected in what looked to be a den just below the crest on the downstream slope. Water then flowed through another burrow and exited along the downstream toe area. It is believed that the turbulence in the den area caused a sinkhole to develop which had uncovered the den and burrows. Engineers filled the uncovered den with straw bales which slowed the flow and erosion. The lake level eventually fell below the burrow entrance on the upstream slope and the dam did not completely fail.

The repair consisted of removing approximately half of the downstream cross section of the dam and rebuilding the embankment. A new spillway system was added which included an open-channel emergency spillway through the left abutment. A portion of the upstream slope was also removed and rebuilt. In essence, the majority of the embankment was rebuilt as a result of the damage induced by animal burrows.

Pischieri Lake Dam—Failed 1999 [97]

Pischieri Lake Dam is located south of Cleveland in the northeastern part of Ohio. The dam is a 36.7 ft high homogeneous earthfill embankment, with a top surface area and total storage volume of 5.5 ac and 60 ac ft, respectively. The dam was constructed in 1957 and was originally a low-hazard Class III dam. Following the events below, the dam was reclassified as a Class I high-hazard dam because reevaluation of dam conditions and characteristics indicate that its failure will likely cause loss of human life.

A routine safety inspection of the dam by engineers revealed two major findings. First, a subdivision consisting of single-family homes was constructed directly downstream of the dam which eventually could increase risk and hazard level. Second, inspection located two 12 in diameter holes on the downstream slope, about half way down the embankment. Water was flowing out of the holes at a rate of less than one gallon per minute. The upstream slope was checked for a vortex or any sign of flow, but none were found initially. While moving debris and leaves along the waterline at the upstream slope, a burrow was uncovered. Water poured into the burrow and out of the holes on the downstream slope rapidly at a rate estimated to be approximately 20 gallons-per-minute. The debris was moved back over the burrow and the flow was subsequently slowed considerably.

Because of the failure concerns, the embankment was excavated near the left abutment through a 4–5 ft portion and the lake level was lowered by approximately 3 ft. With the lake level below the burrow entrance, flow through the burrow was stopped. A siphon lake drain was installed about 3 weeks later and the siphon was used to further lower the lake level by another 4 ft. The section of embankment where the burrow was located was excavated and re-built. The owner decided to repair the entire upstream slope which was riddled with collapsed burrows. The upstream face of the embankment has been covered with a clay liner and riprap stone.

Pin Oak Levee—Failed 2008 [97]

The Pin Oak levee is located near Winfield, a town of about 800 people north of St. Louis in Missouri. On June 27, 2008 the Mississippi River burst through the levee sending a torrent of muddy water into Winfield. Officials believe that the levee break began in an area where muskrats had been digging. It is also believed that the original breach could be attributed to burrows created sometime in the past and even though the holes were plugged, the area remained problematic. Residents and flood fighters were alerted that burrowing muskrats brought down the saturated Pin Oak levee shortly before dawn [98]. Residents and flood fighters gathered to patch the troubled spots in the levee, however, the levee ultimately failed flooding the town of Winfield.

The above examples demonstrate the fact that damage to earth structures due to animal burrows should not be underestimated as it could lead to costly failures. More involved measures should have been taken in the above cases to locate existing animal burrows. Should these preemptive remedial actions were taken; the dramatic failure of these earth structures could have been avoided.

Economic Impact

Earth dam and levee failures are generally rare under normal conditions, but they can cause immense damage and even loss of life when they occur. These failures could develop over a long period of time, such as the accumulated effect of melting snow upriver or debris blockage. However, they could also occur without much warning, such as from flash floods. The size of earth structures and reservoirs makes a difference in the potential damage. Some dams and levees hold back huge reservoirs of water; others are relatively small. The consequences of damage and failure vary accordingly. The impact normally goes beyond the direct cost of failure. Changes to quality of life, cultivation, transportation, and demographics of impacted areas could overweigh the cost of the rebuilding failed earth structures. In this regard, it is important to realize the magnitude of damage that invasive wildlife activities can cause to canals, levees, dikes, and other earth structures. As previously discussed, burrowing animals should not be overlooked as facilitators of failure in earth structures [34, 65]. Failure to control nuisance animal activities could ultimately result in major canal breaks or complete loss of earthen dams, subsequent concomitant law suits and damages could run into the millions and even billions of dollars [34]. However, due to the complexity of the issue, it is generally difficult to identify failures of earth structures that are solely due to animal activities. In addition, the costs of reported damage are often approximate estimates of loss in property, crops and infrastructure. In view of this, the following is a summary of selected examples of earthen structures failures that are believed to be primarily or partially caused by animal activities. Selected risk studies on potential failures due to burrowing activities are discussed later in this section.

Losses Due to Past Failures

California

Division of Flood Management of the California Department of Water Resources (DWR) maintains 300 miles of urban levee and associated rights-of-way, including access roads, maintenance and patrolling roads, and access ramps, in the north Central Valley of California. This flood management system is of incalculable value to the economy of Northern California and the entire nation. Breaches of hydraulic structures in this system can flood urban and agricultural sites, destroy aquaculture, contaminate drinking water, facilitate the spread of invasive plants and animals, mix freshwater and saltwater, and disperse hazardous waste. The widespread of animal burrows in the Delta and the central valley of California is believed to be responsible for a significant portion of these losses.

In 1980, crop losses and physical damage to earthen structures (e.g., levees, dams, roadbeds) due to California ground squirrels alone was estimated at $70 million [99]. Largely due to the effectiveness of the recent wildlife control programs, the 1997 estimates decreased to $20 to 28 million [99]. For comparison, the annual economic impact to California agriculture from all non-predator vertebrate pests (birds, rodents, large mammals) has recently been estimated at about $95.9 million with a reduced employment of about 400 jobs annually [99].

A levee section near Marysville, California, broke during a flood and caused devastating damage to agricultural and urban areas and subsequent litigation for years [31]. Courts ruled in favor of the plaintiffs against the state, resulting in a claim of more than $1 billion, excluding litigation costs. The specific cause of the breach was not determined, but burrowing animals figured prominently in the case.

In February 1986, a serious widespread flooding in Northern California, including the Central Valley, caused dramatic damages estimated to be in excess of $400 million [67]. Severe flooding occurred in the Sacramento-San Joaquin Delta between 1980 and 1986, causing an estimated total damage of $100 million. Eighteen islands were inundated during this period, prompting five Presidential disaster declarations and one State emergency declaration. During this period, FEMA authorized reimbursement of approximately $65 million for emergency repair work [100]. It is believed that the nonstop invasive activities of wildlife in earthen structures and flood control systems in California are responsible for weakening the State's levees and dams, which explains the size and widespread of the damage.

Another incident, which was unrelated to storms, occurred when 11,000 ac of farmland near Stockton, California, were flooded from a breach in the Jones Tract Levee, causing $22 million in infrastructure damage and an additional $25 million of loss in private properties [101]. The cause of the break was attributed to animal burrows, erosion, and high delta tide [102].

Missouri and Midwest States

Initiated by animal burrows, the Pin Oak levee break discussed previously flooded about 150 homes in Winfield, Missouri [98]. Total damage to infrastructure and property was estimated to be around one billion dollars [103]. Officials reported that about 3,000 ac (1,214 ha) of crop land was submerged. The Pin Oak levee failure was the 36th in 2 weeks in the Midwest. Twenty-four people were killed during these storms and torrential rains in the Midwest due to these failures. More than 38,000 people were driven from their homes, mostly in Iowa where 83 of 99 counties were declared disaster areas. Thousands of homes and businesses were flooded in one of the worst Midwest floods in 15 years according to officials and farmers. These floods had a significant effect on the crops market. In July 2009 prices of corn, main feed for livestock and a major constituent in hundreds of food and industrial products, subsequently almost doubled the 40-year average in the US market. The effect extended to global food prices as U.S. prices rise has alarmed everyone from central bankers to food aid groups. In addition to property and infrastructure damages, these heavy rains were responsible for more than $6 billion in crop damage in the Midwest States including Iowa, Illinois, Indiana, Missouri and Nebraska, according to the American Farm Bureau Federation [103]. The estimated total damage exceeds $10 billion [104].

Washington [105]

As previously discussed, the dam of IBP Waste Pond near Wallula in Washington, failed due to neglecting wildlife burrowing activities. The dam failed when a northbound freight train derailed at the location of the weakened dam section. Five locomotives went off the tracks and into the flood waters, injuring the three crewmen. The estimated cost of this failure was $5 million which included the cost of the locomotives, environmental cleanup, and repair of the rail line. In addition, the cost of constructing a new waste facility was several million more dollars.

Nevada

Truckee Canal's earthen levee ruptured on January 5, 2008 after heavy rains in Fernley, 30 miles east of Reno [106]. The storm flooded over 300 homes and forced the rescue of dozens of people in helicopters and boats [107]. No injuries were reported, but approximately 3,500 people were temporarily stranded [106]. Truckee Canal, which can carry up to 1,000 ft^3 of water per second, was carrying only about 600 ft^3 of water at the time of the breach, i.e., the canal was not full. This indicates that there might have been a structural weakness within the breached levee over the years. In view of this, officials indicated that the levee break cannot be solely caused by heavy rains. While not known with certainty, officials strongly believe that the structural damage was initiated by gophers.

Florida

Throughout southern Florida, iguanas burrows have begun appearing in many areas, including canals, levees, and dikes used for flood control, and water management. Service infrastructure directors, civil engineers, construction professionals, and water managers in Florida, have estimated the cost to properly repair a single iguana hole to be approximately $400. With a minimum reported density of about 6.2 burrows per hectare, these repairs are estimated to be around $2,480 per hectare [31]. Considering that it takes an iguana only about 2–3 days to construct a new burrow, the cost of maintaining the integrity of these structures could be substantial [31].

Risk Studies and Emergency Plans for Potential Failures

California

The Sacramento-San Joaquin Delta includes 57 islands, approximately 1,100 miles of levees, and hundreds of thousands of acres of marshes, mudflats, and farmland [3]. This freshwater Delta provides valuable soil for agriculture, habitat for over 500 species of flora and fauna, and is an essential source of drinking water for over 23 million Californians [65]. Delta water is also distributed to wildlife refuges, consumed for power plant cooling and other industrial uses and for commercial services. In addition, there are several hundreds of highways, pipelines, power lines, and railroads cross the Delta. These miles of levees, pipelines, and roadways, lie just east of many seismic active faults. The widespread of animal burrows in California's levee system could reduce its seismic resistance during earthquakes. A 6.5 magnitude quake is projected to cause disruption of water delivery from the Delta that may last for 28 months, with 21 Delta islands flooded [3]. Necessary earthwork repairs and removal of saline water could impair pumping of the Delta water for about 1 year. Economic impact includes loss of revenue from approximately 85,000 ac of agricultural land as crops flooded, and costs associated with repairing as many as 3,000 homes inundated with flood water. After 1 year, such damage is estimated to reach at least $6 billion [65].

A study was performed to assess the impact of a major seismic event on the levees system in the delta area in California [108]. According to this study, preliminary impact of 50 breaches within the Delta levee system would approximately cost $10 billion and more than 10,000 jobs could be lost each year over a period of 3 years. For comparison, the corresponding economic impact of 100 breaches was estimated to jump to approximately $32 billion [108]. The growing risk in this region makes the current reliance on Delta levees imprudent and unsustainable. Over the next 50 years, there is a 66% chance of a catastrophic levee failure in the Delta, leading to multiple island floods and the intrusion of seawater. As such, it is estimated that a large earthquake near the Delta area would cause major interruptions in water supplies for Southern California, the San Joaquin Valley, and the Bay Area, as well as disruptions of power, road, and shipping lines. These interruptions would cost the State's economy approximately $40 billion [109].

A risk analysis study was made to estimate the probability of levee failures in the Delta and Suisun Marsh in California as a result of incidents other than seismic or flood events, referred to as "sunny-day" events [110]. Regardless of water elevation, burrowing animal activities and pre-existing weaknesses in the levees and foundation are the key factors behind sunny-day events. Most practicing engineers, scientists, and maintenance personnel in the Delta and Suisun Marsh believe that rodents are continuously weakening the levees in the Delta by creating a maze of internal and interconnected galleries of tunnels [110]. Based on the records of six levee failures recorded in the Delta and two sunny-day failures in Suisun Marsh at the mean high water level, a failure rate of 0.0969 sunny-day failure per year was estimated [110]. This is approximately 10% probability of failure each year or one failure every 10 years mainly due to burrowing activities of rodents. In view of the economical impact of levee breaches in the Delta area, this is believed to be a very high risk.

Tennessee

The state of Tennessee has many high-hazard farm ponds, watershed, and flood control dams that appear to be deficient or damaged [111]. Some of these earth structures could experience sudden failure that could lead to significant losses to the State's economy. Problems include those initiated by animal burrows, and excessive and improper vegetation growth on earth dams.

Kentucky

Kentucky State inspectors have rated 70 of the 395 high- and moderate-hazard dams as deficient [112]. State officials believe that many deficiencies such as animal burrows could eventually threaten the integrity of these dams. Therefore, Kentucky environmentalists and State officials are pushing for legislation to require emergency action plans in case of dam failures [112].

Oregon

Animal burrows, which are responsible for internal erosion and piping of dams, are believed to be one of the threats to Bonneville Dam. In an attempt to assess the effect of a catastrophic failure of the Bonneville Dam, a GIS-based analysis was performed to study the impact of the dam failure on Interstate 84 and the surrounding highway system, electricity supply, nearby population and cities, freight transport, downstream dams, and bridges. This study was motivated by the cosmopolitan nature of the area around Bonneville Dam and the population's reliance on the dam for water and power supply [113]. The results of the study indicated that a sudden break of the Bonneville dam would cause significant damage to the downstream dams. Cities and populations in close proximity with either the Columbia River or its tributaries would be greatly affected. The dam failure would have a great effect on electricity generated and would cause a dramatic damage to the transportation system along the interstate I-84 as well as river transportation [113].

Connecticut

Due to the observed wildlife damage in earthen structures in the State of Connecticut, the town of East Hartford spent $4 million in 2008 to rehabilitate nearly four miles of town-owned dikes that protect it from the Connecticut River [114]. According to the Association of State Dam Safety Officials, muskrats and beavers are the two most common wildlife species to cause structural damage to levees. In addition, moles are eroding the surface of these levees. Therefore, the USACE is requiring an ongoing program to control wildlife and remediate their damage to earthen structures. Surprisingly, the Wildlife Department instructed dam owners in East Hartford to not trap the burrowing animal. While the State of Connecticut has provided $5 million in 2009 to improve these levees, the future impact of this trapping ban on the cost of levee repairs is unknown [114]. From a technical standpoint, ban of animal trapping casts doubts on the effectiveness of any performed repairs. Therefore, lawmakers of the State of Connecticut should consider the potential consequences of this ban on trapping in view of public safety and human interests [114].

Northern States

Northern states report adverse animal activities in earthen structures. While not known with certainty whether those activities could lead to failures, rodent burrows are significant and reported in Montana and North Dakota [115]. Severe damage in earthen structures in these states is caused by ground squirrels, prairie dogs, badgers, and coyotes [115].

Rodent damage on the Northern High Plains has caused estimated economic losses of millions of dollars every year. Ground squirrel caused $800,000 damage in Montana during 1973, whereas prairie dogs caused a loss of about $2 million in South Dakota during 1980. Initial control of prairie dogs in South Dakota would cost approximately $1.2 million. Additionally, maintenance measures would be needed about every third to fifth year depending on percentage success of the initial control and management practices thereafter [116]. The breakdown of the cost of these damages and required repairs is not available, but it is believed that the damage to earthen structures initiated by animal burrows is a major component.

Summary and Conclusions

Adverse wildlife activities and their damage to earthen structures are observed worldwide. However, their long-term effect on the performance and integrity of earthen structures appears to be overlooked. The yearly cost of failed earthen structures and other infrastructures due to animal burrows in the United States and worldwide exceeds billions of dollars. It is unfortunate that wildlife damage to earthen structures is dealt with as a maintenance issue. The general damage pattern and geometry of animal burrows are cited in numerous references; however, the specifics and details appear to be missing. More importantly, burrowing mechanics and subsequent failures in earthen structures, which are believed to be very complex, are not well understood. In order to assess the vulnerability of earth structures that are believed to be at risk due to wildlife activities, it is necessary to study the progress of past failures and their mechanisms. This may not be achievable in the absence or inadequacy of well-documented information about reported failures, particularly hydrology, progress of damage, types and population of burrowing animals, and routine maintenance performed prior to failure. The authors believe that collaborative efforts between biologist, botanist, ecologist, environmentalist, and geotechnical engineers are inevitable for thorough understanding of wildlife damage to earthen structures. Such collaborative studies and critical visions are believed to be absent at the present time.

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