The Effect of Climate Change on Earth Dam Failures

Group 7

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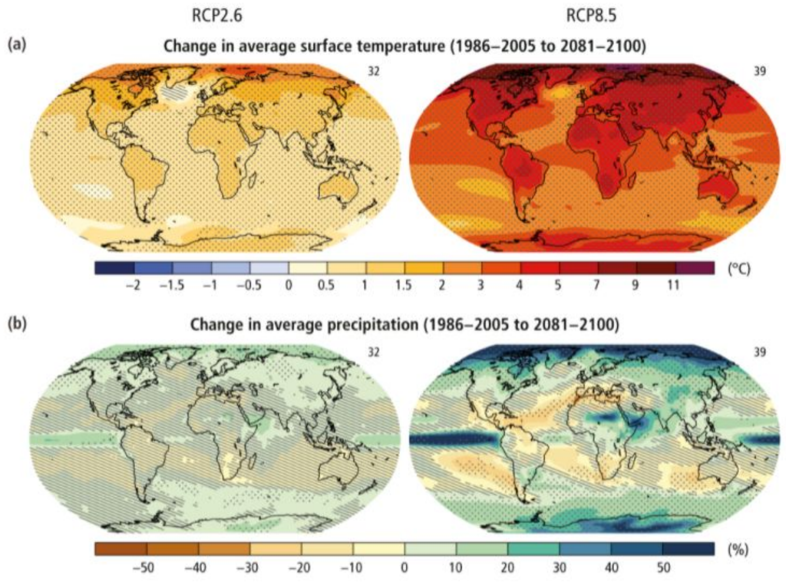
225

The number of dam failures in 2020.

These failures are mainly caused by overtopping, internal erosion of body or foundation

Climate Change and Current Infrastructure



(Pachauri et. al, 2015)

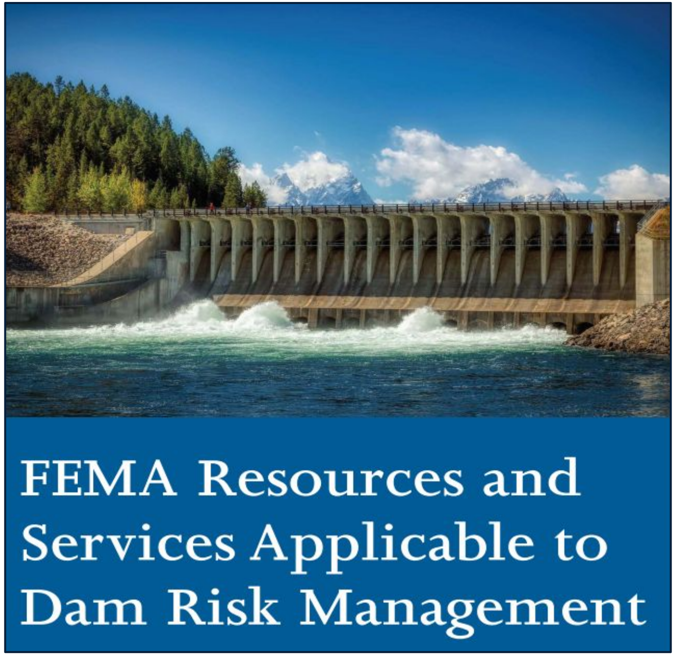
- Many older dams are not built to modern standards and are degrading
- Climate change predictions show increased precipitation over the next century
- Risk of dam failure is increasing due to these extreme storm events

Geotechnical Relevance

What is the relevance of geotechnical engineering to this application area?

Regulations and Considerations

- Geotechnical Discoveries
- Climate Science
- Predictive Modeling
- Factor of Safety
- Infrastructure Regulations



(Dam Safety - FEMA.gov)

Geotechnical Properties

Key Concepts

Effective Stresses

$$\sigma' = \sigma - u$$

Water Table

Pore Water Pressure

Capillary Action

Settlement

Resistant Forces

$$\tau_{max} = c' + \sigma_n' tan\phi'$$

Compaction

Plasticity

Angle of Repose

Grain Size

Seepage

$$q = kA\frac{\Delta h}{L}$$

Porosity

Permeability

Groundwater Movement

Learned Aspects

Environmental Pressures

Earthquakes

Wind

Thermal Resizing

Water Properties

Turbulence

Turbidity

Sediment

Proportions

Differential Stressors

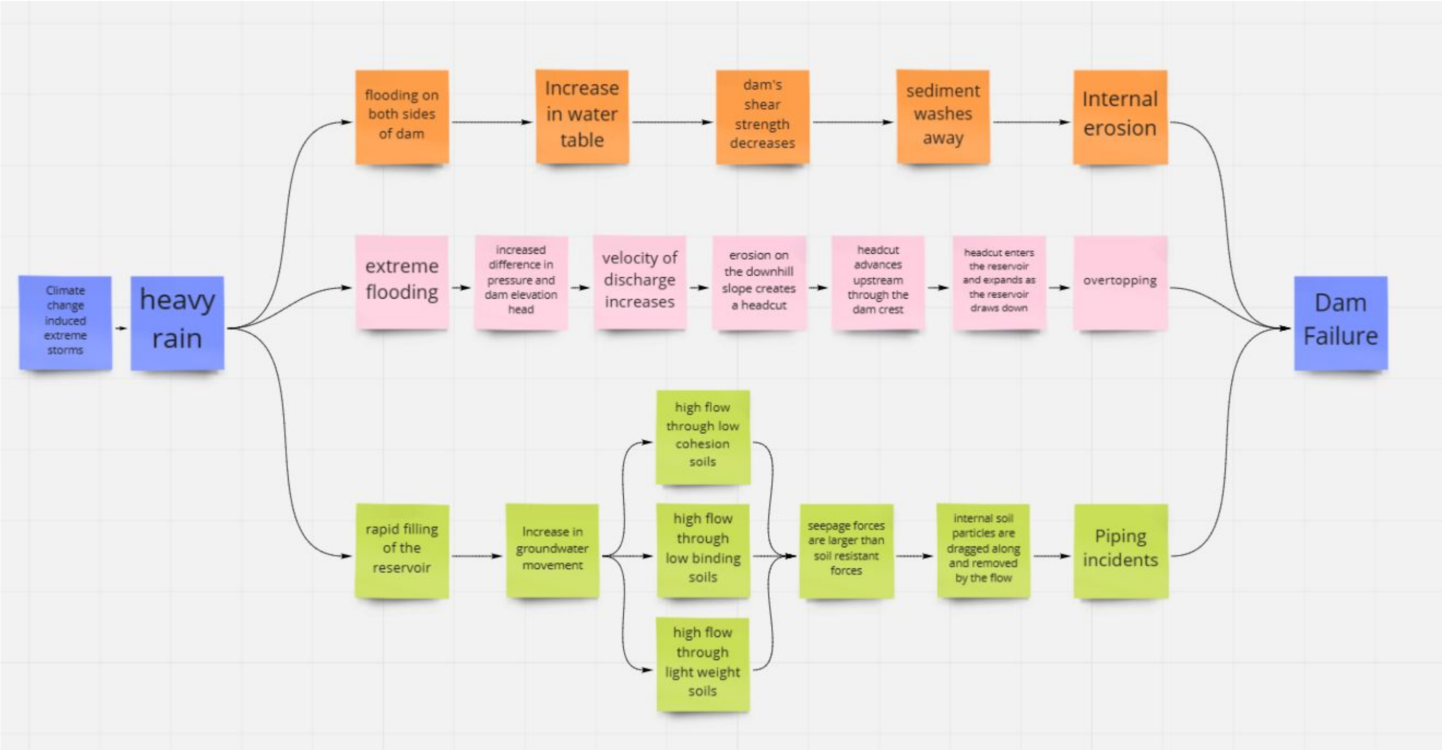
Material Properties

Settlement

Cracking

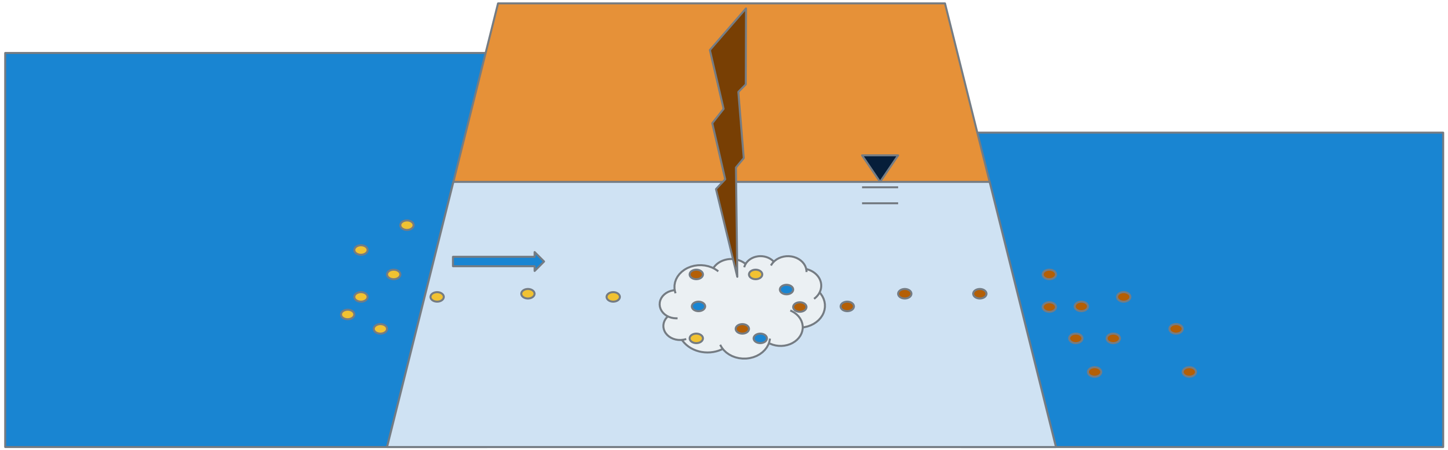
Concept Map

Develop a concept map of linking soil or rock properties to predict performance.


Climate change induced extreme storms
heavy rain
flooding on both sides of dam
Increase in water table
dam's shear strength decreases
sediment washes away
Internal erosion
extreme flooding
increased difference in pressure and dam elevation head
velocity of discharge increases
erosion on the downhill slope creates a headcut
headcut advances upstream through the dam crest
headcut enters the reservoir and expands as the reservoir draws down
overtopping
rapid filling of the reservoir
Increase in groundwater movement
high flow through low cohesion soils
high flow through low binding soils
high flow through light weight soils
seepage forces are larger than soil resistant forces
internal soil particles are dragged along and removed by the flow
Piping incidents
Dam Failure

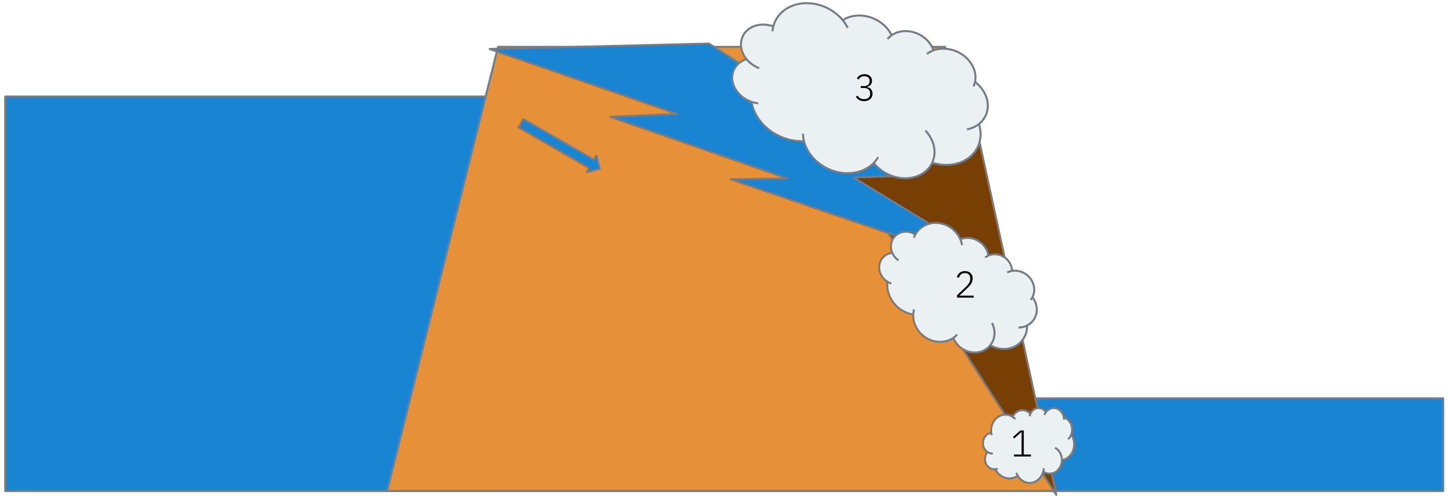
Concept Map

Internal Erosion



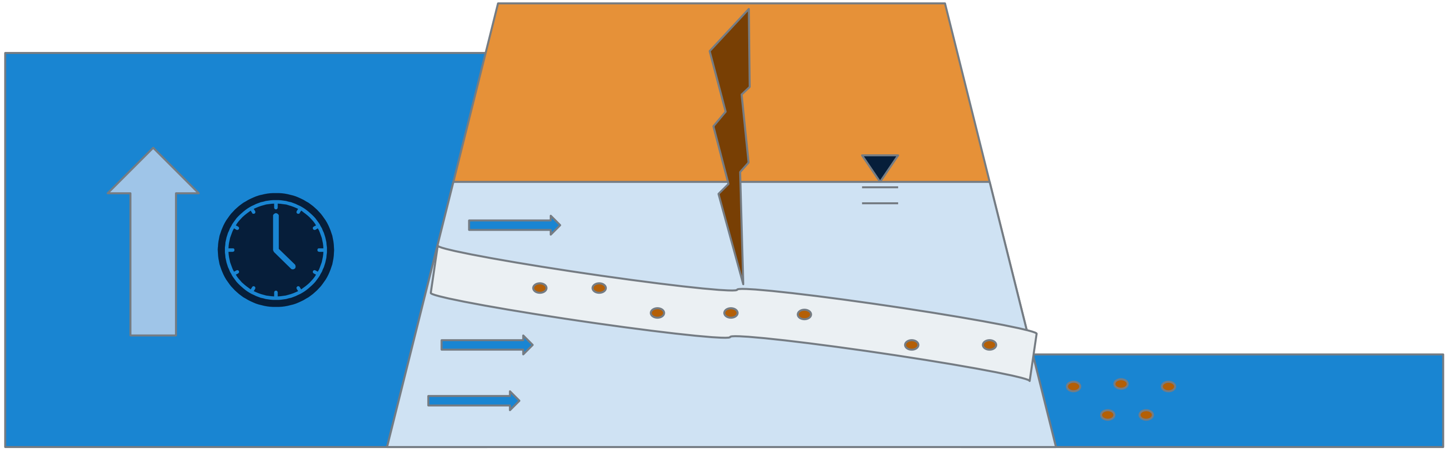
Flooding Upstream and Downstream → Water Table Increases → Shear Strength Decreases → Sediment Washes into the flow → Internal Erosion Failure

Overtopping



Flooding in the Reservoir → Pressure, Elevation, and Velocity Heads Change → Downstream Erosion Creates a Head-Cut → Head-Cut Advances through Dam Crest → Overtopping Failure

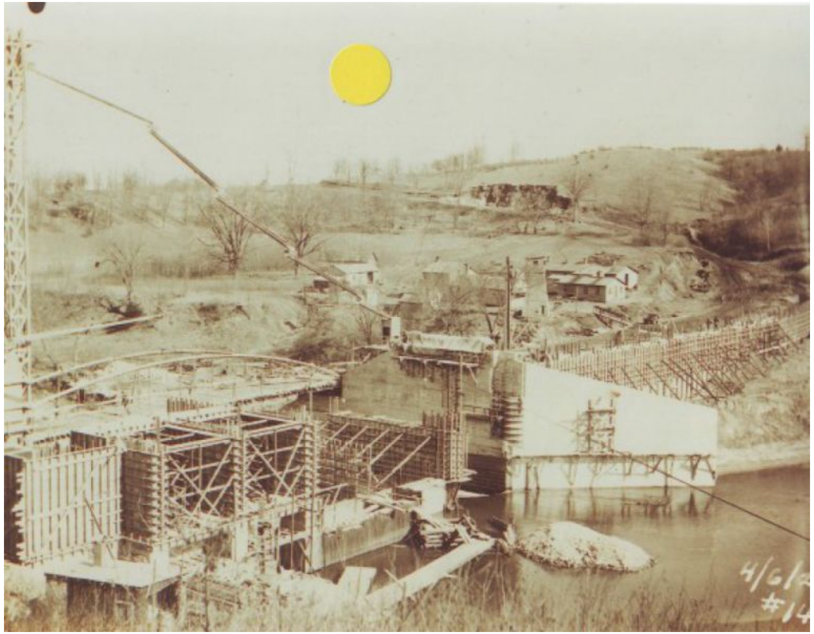
Piping



Rapid Fill and Drawdown of Reservoir → Increase in Groundwater Flow → Seepage Forces exceed Soil Resistant Forces → Internal Soil Particles Erode Creating “Pipes” → Piping Failure

Case Study

Case Study: Delhi Dam in Iowa



- Built between 1922 to 1929 for hydroelectricity on the Maquoketa River, IA
- Primarily used for recreation after 1974
- Failed July 24, 2010, caused $150 million in damages, no fatalities

Timeline of Delhi Dam Failure

July 22nd-24th, 2010

- Heavy rain for two days

July 24th, 2010

- 3:30AM: Whirlpool formed
- 6AM: Seepage detected
- 9AM: Seepage flow became muddy and dirty
- 12PM: Heavy overtopping
- 1PM: Dam fully breached

Causes of Delhi Dam Failure

Primary Cause of Failure: Internal Erosion **Secondary Cause of Failure:** Overtopping

Low Plasticity Index of Soil

The Plasticity Index of the embankment soil was low (PI=9) → low resistance to internal erosion

Differential Settlement

Concrete cutoff wall and embankment material settled at different rates → shear stresses → cracking → seepage paths → internal erosion

Malfunctioning Spillway Gate

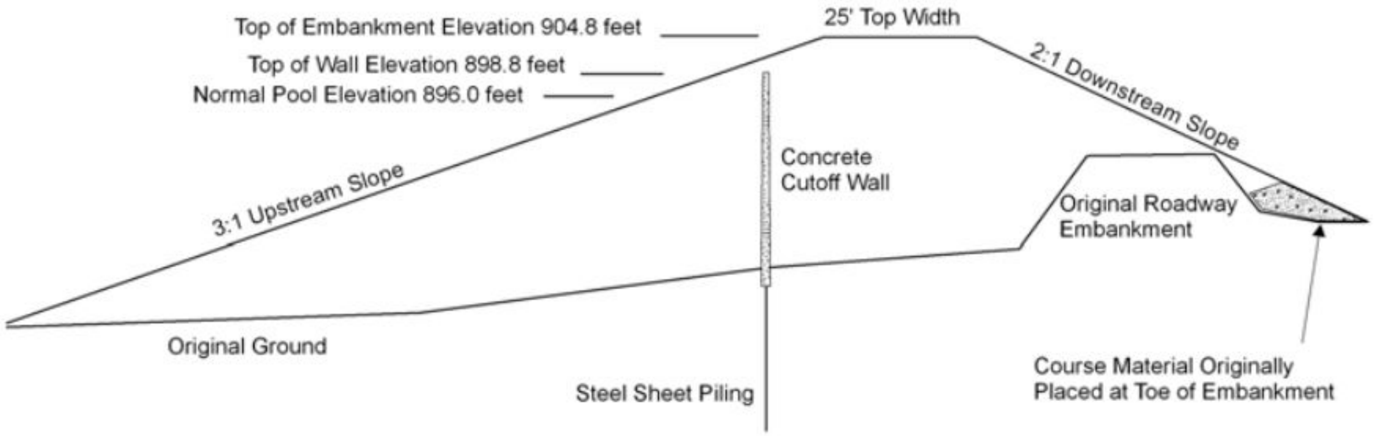
Gate 3 partially closed → spillway not at full capacity → overtopping → rapid erosion of embankment

Failure Cause: Low Plasticity Index

- Plasticity index of the Delhi Dam was 9 (low plasticity)

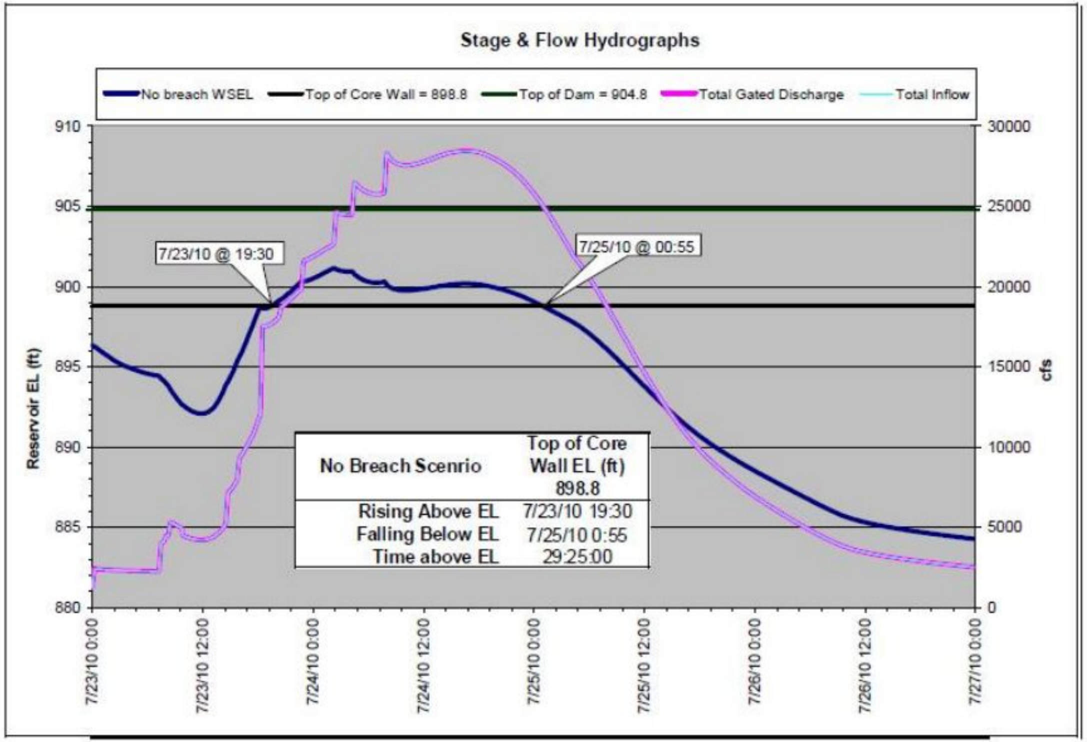
- Teton Dam was also of low plasticity (PI = 4)
- Precursor to total failure of Teton Dam included:
  - Formation of vortexes/whirlpools
  - Muddy seepage detected downstream
  - Only several hours from seepage detection to full breach

Failure Cause: Differential Settlement



- Sheet piling made concrete cutoff wall vertically rigid
- Rest of embankment settled more than concrete wall

Failure Cause: Malfunctioning Gate 3



- Dam would not have overtopped with all three gates fully open
- Even with all three gates fully open, concrete wall is overtopped for 1 day → significant damage from internal erosion

Quantitative Example

Quantitative Example

- Internal erosion was primary cause of failure of the Delhi Dam
- Seepage strips away sediments from the embankment
  - More seepage = more erosion

- Purpose of quantitative example: Delhi Dam had PI = 9 for embankment soil
  - What happens if we use a higher PI instead?

Quantitative Example

Empirical Relationship Between PI and k from *International Journal of Recent Development in Engineering and Technology, Volume 7, Issue 8, April 2018*

$$k = 2 \times 10^{-5} e^{-0.16\,PI} \qquad \text{(Chatra et al., 2018)}$$

where k = coefficient of permeability in cm/s

e = Euler's number $\approx$ 2.7183

PI = plasticity index

Study used total of 36 soil data of three types of fine-grained soils (12 of each type):

CH (Clays with High Compressibility),
CI (Clays with Medium Compressibility), and
CL (Clays with Low Compressibility)

Bureau of Indian Standard Classification system were used.

Quantitative Example

$$PI_{actual} = \boxed{9} \qquad k_{actual} = 2 \times 10^{-5} e^{-0.16\, PI_{actual}} = 2 \times 10^{-5} e^{-0.16\,(9)} = \boxed{4.74 \times 10^{-6} cm/s}$$

$$PI_{hypothetical} = \boxed{15} \qquad k_{hypothetical} = 2 \times 10^{-5} e^{-0.16\, PI_{hypothetical}} = 2 \times 10^{-5} e^{-0.16\,(15)} = \boxed{1.81 \times 10^{-6} cm/s}$$

$$A = Lh = (495\ ft)(43\ ft) = 21285\ ft^2 \times \frac{929.03\ cm^2}{1\ ft^2} = \boxed{1.977 \times 10^{7}\ cm^2}$$

$$h_T = \frac{3790\ acre-ft}{440\ acre} = 8.614\ ft = \boxed{262.55\ cm}$$

$$Q = kA\frac{h_T}{w}$$

$$Q_{actual} = (4.74 \times 10^{-6}\ cm/s)(1.977 \times 10^{7}\ cm^2)\frac{8.614\ ft}{25\ ft} = \boxed{32.3\ cm^3/s}$$

$$Q_{hypothetical} = (1.81 \times 10^{-6}\ cm/s)(1.977 \times 10^{7}\ cm^2)\frac{8.614\ ft}{25\ ft} = \boxed{12.3\ cm^3/s}$$

3x less seepage flow!

Other Applications

Describe other relevant application areas of geotechnical engineering to this topic.

Other Areas to Explore Beyond CEE 3410

Interaction between built structures and soil

Beyond earthfill dams, how might concrete dams fail with respect to soil/structure interaction?

Impact of Natural Disasters on Dams

Looking more closely at the permeability of soil to determine how a high rainfall and wind combination event may fail a dam.

Sensors and Geotechnical Research

Understanding how to detect changes in earthfill dams may alert about failures before they occur.

Societal Relevance

Why are these applications societally relevant?

Ecological

Harms nearby organisms

Economic

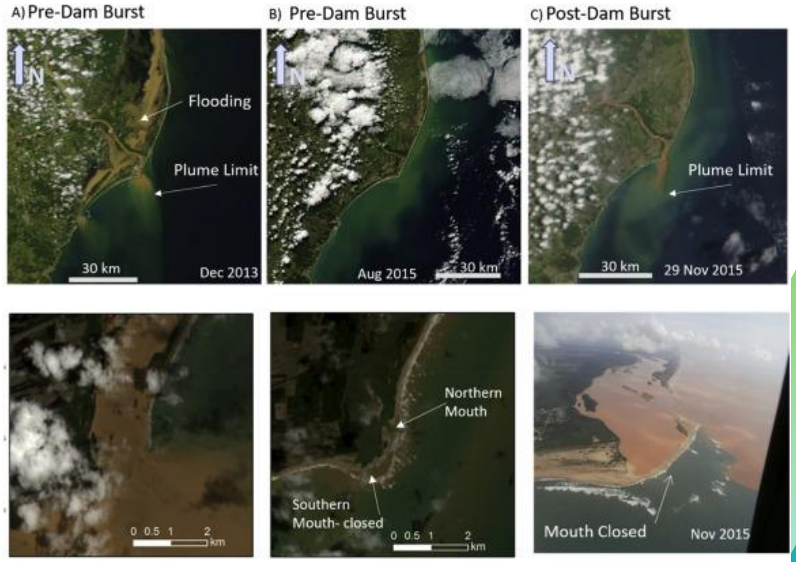
On livelihoods and resources

Human Population

Casualty risks and community displacement

Ecological Impacts

Earth dam failures often release sediments at rapid rates, potentially contaminating waters and cutting off oxygen to organisms in these ecosystems.



Quaresma, et. al

Economic Impacts

Due to the assistance of dams with irrigation, water supply, and flood control, an unanticipated failure requires dispersal of emergency funds to return functionality to a community, avoidable only through major investment in repairs.

Sanford, MI - May 20, 2020

nbcnews.com

Impacts on Human Populations

damfailures.org

Dam failures can lead to catastrophic losses for communities. The Canyon Lake case saw 238 fatalities, along with huge impacts on livability of nearby areas.

- Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J., & Knutsson, S. (2020). Dam Safety Problems Related to Seepage. *Journal of Earth Sciences and Geotechnical Engineering*, *10*(6), 191–239. https://doi.org/10.47260/jesge/
- Bureau of Reclamation. (1976). *Teton Dam Flood - Newdale*. Flickr. photograph, Newdale. Retrieved November 28, 2021, from https://www.flickr.com/photos/waterarchives/5811753523.
- Carter, J. M., Williamson, J. E., & Teller, R. W., U.S. Geological Survey (2002). Retrieved November 28, 2021, from https://pubs.usgs.gov/fs/fs-037-02/pdf/fs-037.pdf.
- Crumb, M. (2010, December 3). *Report: Flood of problems led to Iowa's Lake Delhi Dam breach*. Insurance Journal. Retrieved December 3, 2021, from https://www.insurancejournal.com/news/midwest/2010/12/03/115391.htm.
- Eash, D. A., U.S. Geological Survey (2012). Retrieved November 27, 2021, from https://pubs.usgs.gov/of/2011/1301/pdf/of2011-1301.pdf.
- Einhorn, Erin. "Thousands Fled for Their Lives When Two Michigan Dams Collapsed. More Disasters Are Coming, Experts Say." *NBCNews.com*, NBCUniversal News Group, 14 June 2020, https://www.nbcnews.com/news/us-news/thousands-fled-their-lives-when-two-michigan-dams-collapsed-more-n1230841.
- Fountain, H. (2020, May 21). 'Expect More': Climate Change Raises Risk of Dam Failures. *The New York Times*. Retrieved November 28, 2021, from https://www.nytimes.com/2020/05/21/climate/dam-failure-michigan-climate-change.html.
- McDaniel, L.H., Garton, J.S., Fiedler, W., King, W., & Schwanz, N.T. (2011). Lake Delhi Dam Breach – Two Perspectives. ASDSO Annual Conference. Washington D.C.: Association of State Dam Safety Officials.
- National Academy of Sciences. 2020. Climate Change: Evidence and Causes: Update 2020. Washington, DC: The National Academies Press.https://doi.org/10.17226/25733.
- Sasiharan, N., & Muhunthan, B. (2006, August 16). *Failure report - the case of teton dam*. www.waterpowermagazine.com. Retrieved December 3, 2021, from https://www.waterpowermagazine.com/features/featurefailure-report-the-case-of-teton-dam/.
- The Gazette. (2017, January 3). Lake Delhi Dam reconstruction wins engineering award. *The Gazette*. Retrieved November 30, 2021, from https://www.thegazette.com/news/lake-delhi-dam-reconstruction-wins-engineering-award/.
- Van Aller, H. W., damfailures.org (n.d.). Retrieved December 3, 2021, from https://damfailures.org/wp-content/uploads/2018/06/VanAller_PipingSeepageConduitsAndDamFailures_asdsoSE04.pdf.
- Wright, K. R., & Tschantz, B. A. (2011). The Dam Safety Imperative. *Water Resources IMPACT*, *13*(2), 6–8. Retrieved from https://www.jstor.org/stable/wateresoimpa.13.2.0006.
- Pachauri, R. K., Mayer, L., & Intergovernmental Panel on Climate Change (Eds.). (2015). *Climate change 2014: Synthesis report*. Intergovernmental Panel on Climate Change.
- Lin, X., Huang, G., Piwowar, J. M., Zhou, X., & Zhai, Y. (2021). Risk of hydrological failure under the compound effects of instant flow and precipitation peaks under climate change: A case study of Mountain Island Dam, North Carolina. *Journal of Cleaner Production*, *284*, 125305. https://doi.org/10.1016/j.jclepro.2020.125305
- Temple, D. M., & Hanson, G. J. (2005). Earth Dam Overtopping and Breach Outflow. *Impacts of Global Climate Change*, 1–8. https://doi.org/10.1061/40792(173)407
- Sharma, R., & Kumar, A. (2013). Case Histories of Earthen Dam Failures. *International Conference on Case Histories in Geotechnical Engineering*. https://scholarsmine.mst.edu/icchge/7icchge/session03/8
- Flores-Berrones, R., & López-Acosta, N. P. (2019). Geotechnical Engineering Applied on Earth and Rock-Fill Dams. In *Hydraulic Structures—Theory and Applications*. IntechOpen. https://doi.org/10.5772/intechopen.84899
- Quaresma, V. S., Bastos, A. C., Leite, M. D., Costa, A., Cagnin, R. C., Grilo, C. F., Zogheib, L. F., & Santos Oliveira, K. S. (2020). The effects of a tailing dam failure on the sedimentation of the eastern Brazilian inner shelf. *Continental Shelf Research*, *205*, 104172. https://doi.org/10.1016/j.csr.2020.104172
- Webster, Michael, EAS 4620 - Marine Ecosystem Sustainability, Lecture 4, September 7, 2021, Ithaca, NY
- Goldfarb, Jillian, BEE 2510 - Environmental Engineering Processes, Lecture 12, October 10, 2020, Ithaca, NY

References

Questions?

The Effects of Climate Change on Dam Failures

CEE 3410 Project

Image Source: Bureau of Reclamation, 1976. ID-L-0011, WaterArchives.org.

December 6th, 2021

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Introduction

The Earth is changing. According to *Climate Change: Evidence & Causes*, jointly published by the Royal Society and the US National Academy of Sciences in 2020, the average sea level rise globally has been 3.6 mm (or 0.14 inches) per year. This is due to numerous events like the volumetric expansion of the oceans and the melting of natural ice formations. All these events stem from rising atmospheric temperatures (National Academy of Sciences, 2020).

With Earth's climate warming on a global scale, more extreme weather events are occurring. A warmer climate means more evaporation and increases in air moisture retention. This humidity makes it more likely that weather events will be more cataclysmic; stronger hurricanes and storms will become more common (National Academy of Sciences, 2020).

These changes in weather patterns have significant implications for the built environment, especially structures that interact with water, like dams. At the end of the 20th century, the number of (large) dams in the world reached approximately 45,000. The percentage of dam failures in 2020 is now 0.5%. Out of these dam failures, 31% have been primarily caused by overtopping, 15% by internal erosion of the dam body, and 12% by internal erosion of the dam foundation (Adamo et al., 2020). While 0.5% may sound like an insignificant percentage, half a percent of 45,000 dams already means the failure of 225 dams.

With the average age of dams several decades old, it is unlikely that the original designs of these dams took into account climate change. Such was the case of the Edenville Dam and its failure in May 2020. The dam was designed a century ago and it failed even though the two-day rainfall was not the most extreme possible rainfall event. Several days of rain had already saturated the ground prior to the two days of rainfall, preventing the ground from absorbing the additional rainwater and swelling the Tittabawassee River (Fountain, 2020).

The failure of the Edenville Dam due to changing weather activities as a consequence of climate change is not an isolated event either. The Canyon Lake Dam failed in June 1972 due to heavy rainfall averaging 10 inches in about six hours. The resulting flood from the failure caused widespread devastation, including 3,057 injuries and 238 fatalities (Carter, 2002).

This report seeks to establish the importance of climate change in the context of dams from a geotechnical engineering standpoint. Dam failures can cause ecological, economical, human, and structural damages that are catastrophic in nature. To further reduce the number of dam failures, it is important to understand the impacts that climate change has on dams.

I: Societal Relevance of the Topic

The failure of an Earth Dam can negatively influence surrounding ecosystems and people through risk of water contamination by lowering oxygen levels and the risk of casualties during dam failure respectively. The failure of the Fuñado tailings dam in Southeastern Brazil in 2015 provides a more detailed look into the potential ecological impacts of an earth dam failure. The dam failure allowed for the release of tailings with significantly smaller particle sizes than those in the nearby Doce River system, which led to lower oxygen levels in the water and thus lowered the populations of organisms living in the system. Figure 1A shows the typical sediment release from the dam compared with the larger plume releasing into the ocean after the dam burst (Quaresma et. al, 2020).

To generalize the negative ecological impacts outside of the Fuñado Dam context, dams significantly lower sediment flow to oceans and can cause coastal erosion problems upon construction. The rapid shift in sediment flow upon failure amplifies these effects by altering the sediment proportions in rivers and coastal regions. (Goldfarb, BEE 2510)

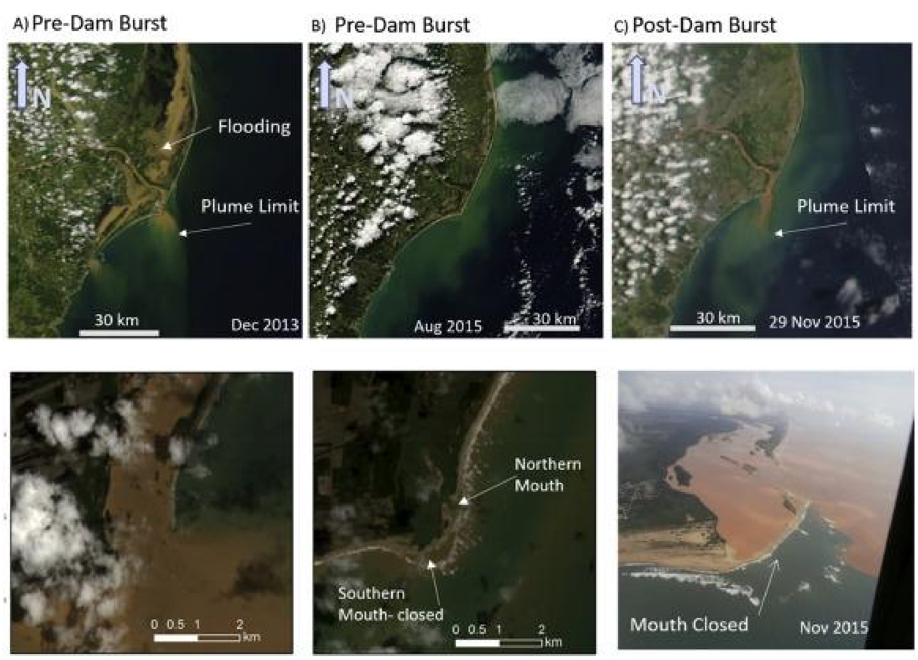

Figure 1A: Doce River System into the Atlantic Ocean Before and After Fuñado Dam Burst.

Beyond ecological influences, dam failures also have societal relevance in their impacts on human activity in a region. The aforementioned Canyon Lake dam failure saw human casualties, as well as displacement of communities in the surrounding areas. Destruction of property in downtown areas of Rapid City resulted in an economic cost of $150 million, with primary losses being homes and cars (Carter, 2002). Damage in the area can be seen in Figure 1B. Further, dams have significance in both urban and rural infrastructure through their assistance with irrigation, flood control, and water supply (NBC News, 2020). Floods like the one that caused the Canyon Dam failure are increasing in frequency due to climate change, and with infrastructure that lacks the ability to withstand high-weather conditions, dam failures will continue to affect communities and ecosystems in severe ways.

Figure 1B: Property Destruction from Canyon Lake Dam Failure (Carter, 2002)

II: Relevance to Geotechnical Engineering

Many dams around the world are over 50 years old and were built under the structural regulations of the time period. As society progresses in the area of geotechnical engineering, many of these regulations are changing based on new information in the field. Although new infrastructure is being built with these regulations in mind, older infrastructure, specifically dams, are not being maintained and updated at the same pace. At the same time, new information in the field of climate change is pushing these regulations to new heights in hopes to keep up with the changing pressures of the natural world. The effects of climate change are inherently placing new stresses on the earth, and soil properties are changing as a result. In order to maintain the required factor of safety designated in current infrastructure regulations, it is important to understand the geotechnical basis of these changes and how dams will respond.

Most of the dam failures correlated with environmental stressors due to climate change occur because of erosion of core materials in one form or another. We covered many ways this erosion could be initiated in CEE 3410 such as changes in effective stresses, seepage, and an imbalance in active and resistant forces. However, there are many other factors that could also play a role in the erosion of dams including properties of water, natural stressors, and differential stresses occurring in a dynamic environment. As shown in Figure 2, all of these factors are interconnected and relate to other geotechnical engineering subtopics.

Figure 2: Web of geotechnical engineering topics relevant to the failure of dams.

There are three main modes of erosional dam failures that are directly linked to specific soil properties discussed in CEE 3410. The first of these modes is internal erosion of core materials which closely relates to the shear strength of soils and changes in the effective stresses on the system (Lin et. al, 2021). The increase in intensity and frequency of storms due to climate change affects the effective stresses present within the dam system. With increased rainfall, the water table under the dam structure will likely increase. This change in the water table is directly linked to changes in the pore water pressure and capillary action. Changes to the pore water pressure and capillary action can then affect the shear strength of the dam structure. If the shear strength of the dam is weakened, the dam is more likely to be affected by erosion or settlement which could ultimately lead to failure.

Another mode of failure is the phenomenon of piping through a dam which is directly related to seepage changes from storm pressures (Sharma and Kumar, 2013). Since climate change is causing such extreme fluctuations of water in dam systems, the groundwater movement beneath the built structure is constantly changing. When thinking about the potential of seepage under a dam due to changes in the groundwater flow, it is important to consider the physical properties of the soil used to construct the site. Soil permeability and porosity are large factors to be considered when understanding the seepage through the dam under differing conditions (Temple and Hanson, 2005). Compaction of the soil during initial construction also plays a major role in regulating the seepage through the structure. Risk of failure due to a piping incident is much higher when all of these properties are not properly taken into consideration during dam construction.

The final main mode of dam failure which can be attributed to changes in the soil properties due to climate change is overtopping (Sharma and Kumar, 2013). Dams are constructed to maintain a certain level of resistance against the pressures applied by the surroundings. Soil properties such as plasticity and grain size naturally contribute to these resistant forces (Flores-Berrones and Lopez-Acosta, 2019). Dams can then be built with determined levels of compaction and angles of repose to ensure they are structurally sound. However, extreme storm events can greatly affect the hydraulic head of the dam, placing additional forces on the system. If these forces were not predicted at the time of dam construction, the risk of overtopping becomes more likely due to the active forces being applied to the dam exceeding the resistive forces of the structure.

While these topics seem to play the largest roles in dam failures, we came across many other geotechnical topics that also contribute to construction decisions and dam failures. Although we primarily focused on the effects of climate change pressures on dam safety, we found that other natural pressures could also play a role in the failure of a dam. In addition to increased rainfall, high winds, earthquakes, and thermal expansion/contraction of internal materials can place unexpected pressures on dam structures and cause cracking of the structure (Flores-Berrones and Lopez-Acosta, 2019). We also found that the properties of the water flowing through the dam might affect its risk of failure. Turbulence, turbidity, and the sediment proportion in the water may all cause additional pressures to the structural materials of the dam (Lin et. al, 2021). Finally, while CEE 3410 gave us a great understanding of the effects of static pressures on geotechnical properties, we found that when understanding the risk of failure of dams, especially due to climate change, it is important to consider the dynamic stresses as well. Many of the case studies we looked at detailed examples where dams failed during rapidly changing conditions. Some of these conditions may affect certain material properties within the dam while others remain unaffected. For example, if settlement occurs in the outer soil filled part of a dam while the concrete core does not move, cracks may form within the dam amplifying other surrounding pressures and ultimately causing the dam to collapse (McDaniel et al., 2011). Overall understanding the relationships between geotechnical properties and how they are affected by external pressures and the properties of the surrounding environment is essential in meeting today's infrastructure regulations and building and maintaining safe dams.

III: Case Study of Interest

The primary case study of this report will be the Delhi Dam, which used to be located on the Maquoketa River in Iowa. Delhi Dam failed on July 24, 2010 after the region experienced significant, heavy rainfall for two days (McDaniel et al., 2011). The local area suffered an estimated $150 million in damages from the dam failure but luckily, no lives were lost in the ensuing floods (Wright et al., 2011). Delhi Dam was reconstructed six years later in 2016, winning the American Council of Engineering Companies of Iowa's Grand Conceptor award (The Gazette, 2017). Henceforth for this report, the usage of the name "Delhi Dam" will refer to the original dam that failed in 2010 and not the newly reconstructed dam.

The Interstate Power Company constructed the Delhi Dam between the years of 1922 and 1929 in order to generate hydroelectric power (Eash, 2012). The hydroelectric generators ceased operations in 1968 (McDaniel et al., 2011) and in 1974, the Lake Delhi Recreation Association purchased the dam and since then, Delhi Dam has been used primarily for recreational purposes as a lakeside resort with getaway activities (Eash, 2012).

At 704 feet long, Delhi Dam was a concrete dam and earthen embankment structure holding back a reservoir of 3790 acre-ft at normal reservoir water levels. A normal reservoir water level for Delhi Dam would be around 896 feet in elevation. The top of the concrete cutoff wall had an elevation of 898.8 feet and the top of the embankment had an elevation of 904.8 feet.

Delhi Dam had four sections: a 60-foot long earthfill section reinforced with concrete, a 61-foot long powerhouse section, a 86-foot long gated concrete spillway section, and a 495-foot long embankment section with a concrete cutoff wall. The spillway section had three vertical lift gates, each 25-foot by 17-foot, to control the reservoir water levels. The embankment section used a slope of 3:1 upstream and 2:1 downstream (McDaniel et al., 2010). Figure 3 illustrates the four sections that Delhi Dam was composed of using a satellite image and annotations. Figure 4 examines a cross section of the 495-foot long embankment section of Delhi Dam, detailing slopes and elevations.

Figure 3: Sections of Delhi Dam using a satellite view (McDaniel et al., 2010).

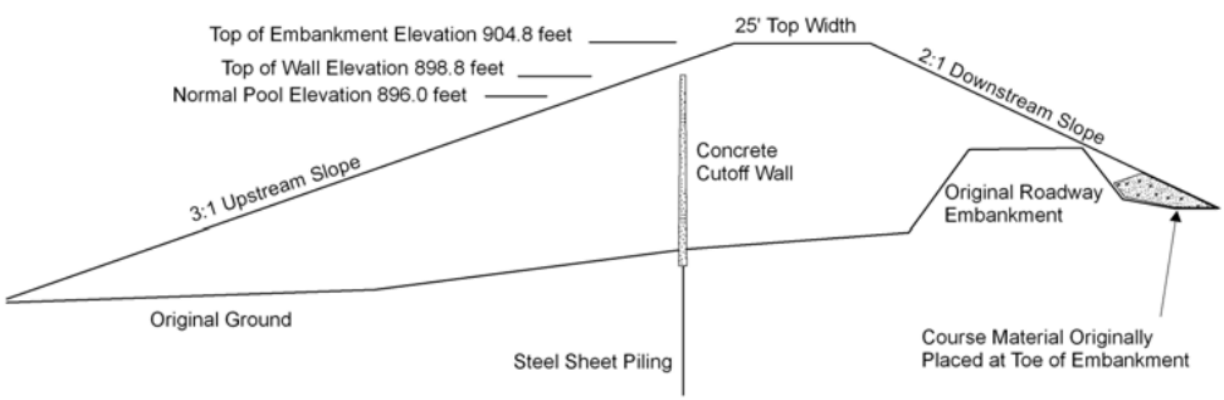

Figure 4: Cross Section of Embankment Portion of Delhi Dam (McDaniel et al., 2010).

Before the dam failure, Delhi Dam had a history of uncooperative spillway gates and they were difficult to open in the past. In fact, in 2009, it was discovered that there was a hole in the left pier for one of the spillway gates, and they were not fixed as of January 2010. Vegetative debris oftentimes became trapped in the gateway, obstructing the passage of water through the spillway. Unfortunately, Gate 3 would not fully open during the July 2010 flooding and the Gate 3 spillway was not serving at its fullest capacity. This was because Gate 3 had concrete damage that was scheduled to be repaired, but the repairs were not completed prior to the failure of the Delhi Dam in July 2010 (McDaniel et al., 2010).

The disaster began on July 22, 2010 when Lake Delhi experienced heavy rain for two days straight. As aforementioned, the spillway capacity was reduced by the inability to fully open Gate 3. It is important to note that no unordinary phenomena occurred prior to the reservoir water level exceeding the top of the concrete cutoff wall. Sagging of the dam and the formation of a whirlpool 4-feet in diameter was noticed by the dam operator at 3:30 AM on July 24, 2010, after the reservoir water level had increased beyond the top of the concrete cutoff wall (McDaniel et al., 2010).

Later that morning, at 6:00 AM, the dam's crest began to settle further into the ground where the whirlpool was earlier observed. Furthermore, it was confirmed that there was seepage on the downstream side of the dam, near the toe of the embankment. Three hours later at 9:00 AM, the seepage flow became brown and dirty. The embankment was fully breached at approximately 1:00 PM, with a breach width of about over 200 feet at its maximum (McDaniel et al., 2010).

Figure 5:

Delhi Dam being breached (McDaniel et al., 2010).

Soon after the failure of Delhi Dam, an Independent Panel of Engineers (IPE) was formed to ascertain the cause of the dam failure. The IPE perused documents from Delhi Dam's early design and construction to the remnants of the dam after failure. According to the IPE's investigative report, the primary cause of failure of Delhi Dam was through internal erosion; the secondary cause of failure was through overtopping flow. The panel came to the conclusion that the following factors were significant in the failure of Delhi Dam: the embankment material, the concrete cutoff wall, and the inability to fully open Gate 3 (McDaniel et al., 2010).

The original design and construction documents were not clear in conveying the intended geotechnical information on the soils which Delhi Dam stood on; what was known was that the dam embankment consisted of a homogeneous material with the reinforced concrete cutoff wall in the center of the dam. Due to the lack of information obtained from reviewing past documentation, the IPE sought out a representative sample of soil from the remnants of the embankment post-failure. The results from testing the soil sample determined that the soil was a sandy-clay soil with a plasticity index of about 9 (McDaniel et al., 2010).

Soils with low plasticity indexes are extremely prone to internal erosion failures, specifically "piping" failure. These soils include both well compacted and poorly compacted sands without uniform cohesion (Flores-Berrones et al., 2019). The testing revealed that Delhi Dam was resting on a sandy-clay with a low plasticity index of 9 (McDaniel et al., 2010), which does not resist internal erosion well.

Delhi Dam is not the only dam to fail with a low plasticity index contributing to the failure either; the Teton Dam failure was a notable dam failure in the dam industry. The plasticity index of the Teton Dam was extremely low (about 4) and a precursor to total failure was the observation of a leak emerging from a tunnel inside the embankment. The water leaking through the embankment was observed as "muddy" (Sasiharan, 2006). Dirtied water stemming from a dam is an indicator of internal erosion as the embankment material is being carried away from the dam structure itself. This initial leak that began shortly after 7:00 AM on June 4, 1976 led to a full breach of Teton Dam at 11:59 AM, a mere hours after the initial leak (Sasiharan, 2006).

This is not dissimilar to Delhi Dam, where there was also "muddy" water observed exiting the toe of the dam. In the case of Delhi Dam, there was also only several hours between the initial observation of the muddy seepage and full breach of the dam (McDaniel et al., 2010).

The IPE also deduced that the Delhi Dam may have had issues with settlements as well. Their report points to the concrete cutoff wall in the embankment section of the dam as the main culprit. While concrete cutoff walls are common in dams to help prevent seepage through the embankment, the material properties of the concrete are much different than the material properties of the embankment soil directly adjacent to the concrete cutoff wall. This encourages the dam structure to settle at different rates due to different compressibilities; this is called differential settlement. Over time, this differential settlement may cause cracking within the dam that may lead to dam failure (Van Aller, n.d.); this is because differential settlements introduces unintended shear stresses between the different materials or sections of a dam. These cracks serve as paths for seepage to traverse through, leading to hasty internal erosion of the dam body (McDaniel et al., 2010).

In the case of Delhi Dam, cracking initiated by differential settlement was caused not only by the differences in material properties between the embankment soil and the concrete cutoff wall, but also by the sheet piling in the design of the dam. As shown in Figure 4, the concrete cutoff wall was situated on top of a sheet pile wall. This configuration made the concrete cutoff wall vertically rigid relative to the adjacent material as the sheet piling strongly prevented settlements. As a result, the embankment material settled more than the concrete cutoff wall and cracks formed from differential settlement. Seepage found its way through the cracks and led to the internal erosion of the Delhi Dam (McDaniel et al., 2010).

Finally, the IPE investigated the impacts of the spillway not operating at its full design capacity due to a partially closed Gate 3. The IPE performed a hydrology and hydraulic analysis using the Hydrologic Engineering Center's River Analysis System (HEC-RAS). With this software, the IPE was able to model numerous alternative scenarios during the July 2010 floods, including the scenario in which Gate 3 was fully open. The results of the analysis using the HEC-RAS model are shown below in Figure 6, where the date and time is represented on the horizontal axis and the reservoir water level elevation is represented on the vertical axis to the left. One black line shows the top of the concrete cutoff wall at 898.8 feet in elevation, and one black line shows the top of the dam at 904.8 feet in elevation. The pink curve reflects the actual reservoir water level elevation with Gate 3 partially closed, and the navy blue line represents the hypothetical reservoir water level elevation under the scenario that Gate 3 was fully open (McDaniel et al., 2010).

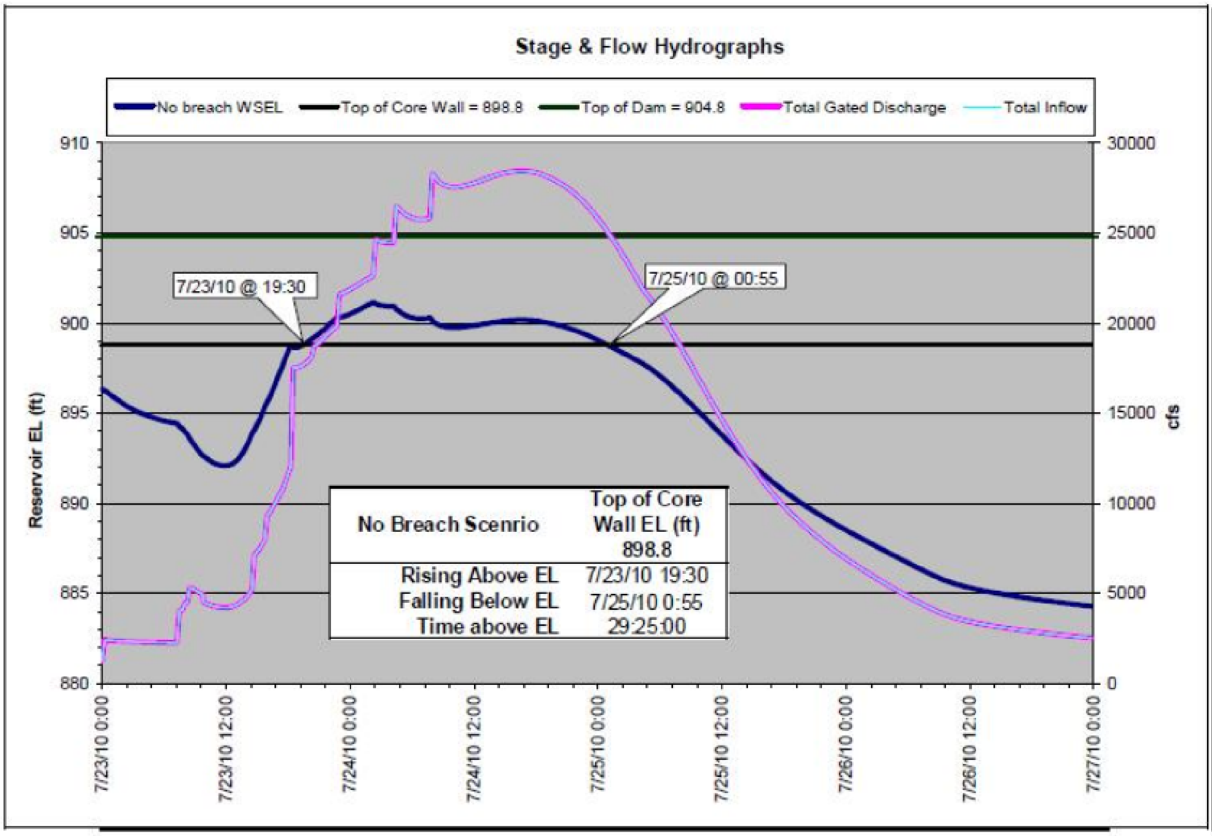

Figure 6: The results of the hydrology and hydraulic analysis performed by the IPE to determine the impact of a partially closed Gate 3 on the reservoir elevation (McDaniel et al., 2010).

According to the results from the analysis depicted in Figure 6, the dam would not have overtopped if the spillway was at its full capacity (i.e. if all three gates were fully operational). William Fiedler, an engineer from the Bureau of Reclamation who was part of the IPE, stated that "[w]ith all three gates open, the dam would not have been overtopped" (Crumb, 2010). However, William Fiedler also noted that the concrete cutoff wall would have been overtopped for a "significant period of time" (Crumb, 2010). The analysis results show that even with all three gates operating at full capacity, the reservoir water level elevation would still have risen above the top of the concrete cutoff wall by a significant amount for approximately one full day; this amount was around 2.4 feet at its peak. The IPE judged that with the reservoir water level higher than the concrete cutoff wall, the seepage resulting from that would be non-negligible and would significantly damage the dam, if not resulting in a full breach. Therefore, damage would have occurred even with all three spillway gates fully open (McDaniel et al., 2010).

IV: <u>Quantitative Example</u>

The Delhi Dam failed primarily due to the internal erosion that resulted from the reservoir water level overtopping the top of the concrete cutoff wall. While the cracking from differential settlements certainly provided a path of least resistance for seepage, the IPE noted the embankment soil's low plasticity index of 9. Soils with low plasticity tend to be most susceptible to "piping" erosion while soils with high plasticity tend to be the most resistant to "piping" erosion (Flores-Berrones, 2019). This report shall utilize a quantitative example to illustrate the impact of using a low plasticity soil on erosion-inducing seepage.

The variables involved with this quantitative example will be:

- Plasticity Index (PI)
- Length, Width, and Height of Dam Embankment (L, w, and h)
- Coefficient of Permeability (k)
- Total Head (h_T)
- Cross-Sectional Area Perpendicular to Flow (A)
- Flow (Q)

The empirical relationship used to determine the coefficient of permeability from plasticity index for fine-grained soils will be from the International Journal of Recent Development in Engineering and Technology, Volume 7, Issue 8, April 2018: Prediction of Permeability Characteristics of Fine Grained Soils and its Validation:

$$k = 2 \times 10^{-5} e^{-0.16\,PI} \qquad \text{(Chatra et al., 2018)}$$

where $k =$ coefficient of permeability in cm/s

$e =$ Euler's number ≈ 2.7183

$PI =$ plasticity index

It is already known that the plasticity index of the embankment soil used in the Delhi Dam was 9. According to the U.S. Department of the Interior's Bureau of Reclamation Design Standards No. 13: Embankment Dams, "impervious earth material that is placed adjacent to a conduit would [have] a plasticity index between 15 and 30" (Engemoen et al., 2012). This quantitative example shall use the lower plasticity index of 15 to demonstrate the difference of even using a liberal plasticity index as the embankment soil for the Delhi Dam.

First, the plasticity indices will be reiterated:

$$PI_{actual} = 9$$

$$PI_{hypothetical} = 15$$

Second, the aforementioned relationship to determine the coefficients of permeability shall be utilized for the two cases:

$$k_{actual} = 2 \times 10^{-5} e^{-0.16\, PI_{actual}} = 2 \times 10^{-5} e^{-0.16\,(9)} = 4.74 \times 10^{-6} cm/s$$

$$k_{hypothetical} = 2 \times 10^{-5} e^{-0.16\, PI_{hypothetical}} = 2 \times 10^{-5} e^{-0.16\,(15)} = 1.81 \times 10^{-6} cm/s$$

Third, it is known that the embankment portion of the Delhi Dam was 495 feet long, 25 feet wide at the portion of the embankment with no slope, and an estimated height of 43 feet tall (McDaniel et al., 2010); the cross-sectional area perpendicular to flow can be calculated:

$$A = Lh = (495\, ft)(43\, ft) = 21285\, ft^2 \times \frac{929.03\, cm^2}{1\, ft^2} = 1.977 \times 10^7\, cm^2$$

Fourth, we know that "the reservoir behind Delhi Dam has an area of approximately 440 acres and a storage volume of 3790 acre-ft at normal reservoir" (McDaniel et al., 2010); the depth of the water (i.e. total head) in the reservoir can be estimated as:

$$h_T = \frac{3790\, acre-ft}{440\, acre} = 8.614\, ft = 262.55\, cm$$

Fifth and finally, with all this information, the flow of the two cases can be calculated:

$$Q = kA\frac{h_T}{w}$$

$$Q_{actual} = (4.74 \times 10^{-6}\, cm/s)(1.977 \times 10^7\, cm^2)\frac{8.614\, ft}{25\, ft} = 32.3\, cm^3/s$$

$$Q_{hypothetical} = (1.81 \times 10^{-6}\, cm/s)(1.977 \times 10^7\, cm^2)\frac{8.614\, ft}{25\, ft} = 12.3\, cm^3/s$$

We can see that if the minimum of $PI = 15$ was adhered to, the seepage flow would have been reduced by nearly three times than $PI = 9$. This reduction of seepage would have reduced the rate of internal erosion by washing away fewer embankment soil sediments.

V: <u>Concept Map and Description of Linkages</u>

While there are many modes of dam failure including settlement, internal cracking due to frost expansion, and wind destruction, there are three main types of failure directly related to the increased intensity and frequency of rain storms due to climate change; internal erosion, overtopping, and piping incidents. Internal erosion occurs when the overall strength of the dam decreases and core structural materials start to wash away with the flow of water. Overtopping occurs when flow is increased to a point where a headcut forms on the structure and quickly increases in size to cause complete failure. Piping occurs when groundwater movement carries structurally supporting soil particles away from the dam until there is an open channel large enough to cause failure. As shown in Figure 7, the exceptional rainfall associated with climate change causes dramatic changes in soil properties leading to a cascade of events ultimately ending in dam failure.

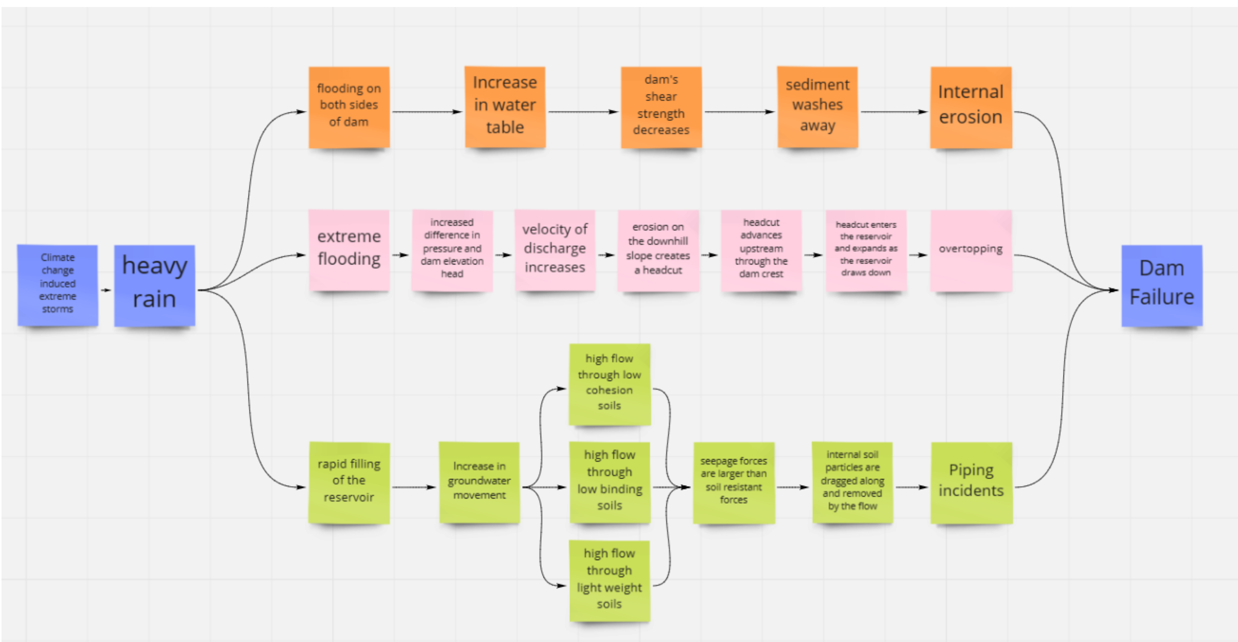

Figure 7: Concept map relating soil property changes due to climate change and the ultimate failure of dams.

Based on the AR5 SYR Climate Change report released by the Intergovernmental Panel on Climate Change (IPCC), there have been many observed changes to the precipitation patterns across the globe correlated to the changing climate and there are even more drastic predicted changes in the future. These changes in precipitation will not be uniform, however it is "very likely" that extreme rainfall events will increase in frequency and intensity over mid-latitude land masses and wet tropical regions as the global surface temperature increases (Pachuari et. al, 2015). According to Figure 8, under the business as usual scenario, mid-latitude areas like North America are expected to experience anywhere from 10%-30% increase in average rainfall by 2100. Similar to many of the infrastructure challenges we are facing currently as global surface temperatures increase, most dams were not built to withstand such dramatic and changing natural pressures, such as increased precipitation, due to climate change. The US Federal Emergency Management Agency (FEMA) has determined that many of the dams built in the last century do not have sufficient flood hazard sensing and protocols, and therefore put the safety of the public downstream of the dam at increased risk (Lin et. al, 2021).

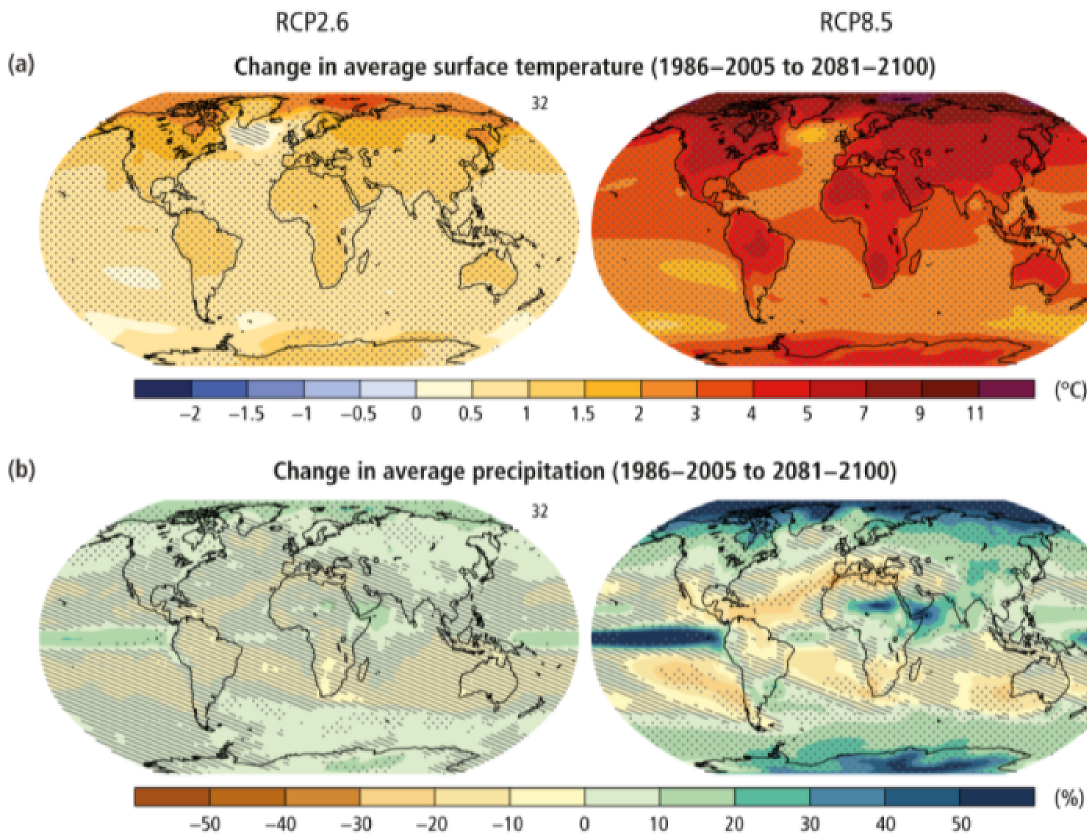

Figure 8: Relationship between projected average surface temperature increase and change in overall precipitation in two climate change scenarios (Pachuari et. al, 2015).

There are many different pathways in which increased frequency and intensity of rainfall events could detrimentally affect the structure, function, and safety of dams. The first of these pathways is initiated when a dam starts to flood on both the upstream and downstream sides of the embankment. This then causes the water table to rise and increase the phreatic surface area over the dam (Lin et. al, 2021). As the groundwater table rises, the effective shear strength of the dam's materials decreases due to fluctuations in the pore water pressure and capillary action in the system. Meanwhile, sediments are being washed from the river bed and the surface of the dam into the flow (Lin et. al, 2021). This combination of pressures from the increase in hydraulic head and sediment deposition from further upstream increases the stress on the gradually weakening dam throughout the duration of the storm event. The dam then becomes vulnerable to the erosion of core internal materials by the turbulent river water in combination with the increased rainwater, ultimately causing it to fail at any time.

Another major pathway of dam destruction due to intense storms starts when there is extreme flooding within the reservoir. This large difference in water levels upstream of the dam and downstream of the dam dramatically increases the differences in hydraulic and pressure heads on either side of the dam crest. Due to conservation of energy, the velocity of discharge must then increase. This increased velocity causes erosion on the downhill slope of the dam resulting in an initial head-cut (Temple and Hanson, 2005). This head-cut is generally initiated at the downstream toe of the dam when the shear stresses applied to the dam exceed the critical resistance keeping the sediment in place (Sharma and Kumar, 2013). The head-cut then advances upstream through the dam crest gradually increasing the downstream slope causing the velocity of discharge to continually increase (Temple and Hanson, 2005). Finally, when the head-cut grows to a size and position where it breaches into the reservoir, the dam fails due to overtopping as the reservoir is quickly drawn down and all potential energy being stored upstream is transferred into the flow.

The final pathway of dam failure correlated with climate change has much more to do with the intensity of storms rather than the quantity of precipitation involved in a particular storm or season. This pathway is initiated when rainfall is so intense that it causes rapid filling and then rapid drawdown of the reservoir (Flores-Berrones and Lopez-Acosta, 2019). This rapid filling causes an increase in groundwater movement throughout the dam. When this water flows through low binding, low cohesion, or lightweight soils such as fine, poorly compacted sands the seepage forces can overtake the small resistant forces keeping the soil particles in place (Flores-Berrones and Lopez-Acosta, 2019). The groundwater flow then begins to erode internal sediments as it flows throughout the structure of the dam. After a large amount of internal material has been washed away through the seepage flow, an empty path or “pipe” is formed through the dam (Sharma and Kumar, 2013). As this pipe grows in size, cracks form throughout the dam, its structural integrity decreases, and the dam ultimately fails.

While changing environmental conditions related to climate change, specifically the increased intensity and frequency of storms, are putting the safety and structural integrity of dams at risk, dam failures may also be contributing to the global temperature rise. There are many ecological impacts involved with dam failure including the transfer of sediments from core dam materials into natural environments downstream of the dam location. The earth’s oceans are currently one of the largest sinks of global CO_2 and thermal energy, but the transfer of dam sediments has the potential to interfere with the natural marine ecosystem therefore affecting its ability to absorb this atmospheric heat and carbon. Specifically, when particulate matter flows into the coastal ocean after a dam failure, the natural stratification of the ocean may be affected. It has been observed that the vertical mixing of the ocean along the continental shelf increases after the arrival of sediments washed downstream after a dam failure (Quaresma et. al, 2020). Many photosynthetic ocean organisms rely on properly timed coastal upwelling events for optimal growth, function, and carbon capture, so when the ocean’s stratification is affected by vertical mixing, these upwellings may occur less frequently or not at all (Webster, 2021). Additionally, the finer particulate matter eroded from the dam site will often float on the surface of the ocean and will be advected into the atmosphere (Quaresma et. al, 2020). The transfer of additional particulate matter in the atmosphere increases atmospheric pollution and can negatively affect the reflection of heat from the sun back into space, further warming our planet.

VI: <u>Relevant Applications</u>

From the topic of built dams and the assurance of a retaining structure, related applications exist in designing systems for hydropower as the extension of a retaining wall with the inclusion of turbines for energy production. Flow would be calculated in a manner similar to that of an earthfill dam, and the use of nearly identical materials to case studies of dam failure would allow engineers to complete necessary improvements to the existing structure. If existing dams were updated by insertion of a hydropower system within the same process of repair, the overlap in objective would make the improvement doubly advantageous through both longevity and energy production (Green, 2010).

Just as well, the previously discussed relation of dams to soils and settlement has important applications in soil research at a large scale. Dams in various regions compared against each other, grouped by structure weight and size, can lend to an accumulation of real-time data to enrich understanding of soil behavior beyond the known. Research into sensors, such as that being done by Professor McClaskey at Cornell University, can be combined with the field of geotechnical engineering to anticipate dam failures and better understand the weak points in interactions between concrete, steel, and soil. This can then be translated to soil behavior with other large structures such as airports, malls, and the bottom surface of ponds and lakes to determine how the soil profile changes over time. By synthesizing all of these topics, engineers open up the potential for restrengthening structures if significant erosion occurs.

Figure 9: Hydroelectric Dams (Green, 2010)

VII: <u>Summary of Learning Outcomes</u>

While the course CEE 3410: Introduction to Geotechnical Engineering at Cornell University provided a broad introduction to numerous topics in geotechnical engineering, engaging in this project allowed us to gain greater insight into the applicability of the concepts that CEE 3410 covered. It allowed us to connect the dots between everything we learned in CEE 3410 in a realistic way.

One major takeaway from completing this project is the realization that the causation of dam failure can be confounding when trying to isolate the root cause of failure. Using the Delhi Dam in our case study as an example, the panel of engineers determined three factors that contributed to the failure, but could not definitively determine which factor was the one, sole cause of the failure. Rather, it is oftentimes a combination of factors or events that ultimately result in a dam failure. Geotechnical engineering is an inexact science; the idea that multiple (potentially unanticipated) factors coming together to produce the current circumstances is applicable all through geotechnical engineering.

This project allowed us to explore some of these factors that we did not explore in CEE 3410, such as erosion and differential settlements. In learning more about these geotechnical engineering concepts, we discovered how fundamental to geotechnical engineering the ideas that were covered in CEE 3410 are. Erosion is dependent on seepage, horizontal flow, and plasticity. Differential settlement is caused by settlements occurring at different rates, generating shear stresses, and ultimately creating cracks that serve as erosion-encouraging seepage paths. It would have been significantly more difficult to understand these more difficult concepts without the basic concepts learned in CEE 3410. Solely within the scope of dam failures, we were able to explore the relationship between climate change and dam failures. Natural disasters, water, and other soil and environmental properties all impact dams and their vicinity in some capacity.

Undertaking a project on dam failures, we were exposed to the devastating consequences should one of these structures fail. Upon the completion of this project, we walk away with a greater sense of responsibility, as our work as civil or geotechnical engineers impacts the surrounding communities of both people and wildlife, in both success and failure. It is clear that scientists and engineers of today know much more than the engineers who built much of the currently existing infrastructure and we still continue to learn as more information becomes available. As civil engineers are responsible for the design of infrastructure and development of major projects, keeping in mind the potential harm to ecological, economic, and community systems that a failure may cause is especially important. From an ethical standpoint, civil engineers especially must ensure the security of their designs in a changing world and climate, as failures can cause major impacts. It will be our job in the near future to take all of this critical information into account when maintaining old structures or building brand new infrastructure to benefit our own communities.

References

Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J., & Knutsson, S. (2020). Dam Safety ProblemsRelated to Seepage. *Journal of Earth Sciences and Geotechnical Engineering*, *10*(6), 191–239. https://doi.org/10.47260/jesge/

Bureau of Reclamation. (1976). *Teton Dam Flood - Newdale*. Flickr. photograph, Newdale. Retrieved November 28, 2021, from https://www.flickr.com/photos/waterarchives/5811753523.

Carter, J. M., Williamson, J. E., & Teller, R. W., U.S. Geological Survey (2002). Retrieved November 28, 2021, from https://pubs.usgs.gov/fs/fs-037-02/pdf/fs-037.pdf.

Chitra, R., Gupta, M., Prakash, H., & Noor, S. (2018). Prediction of Permeability Characteristics of Fine Grained Soils and its Validation. *International Journal of Recent Development in Engineering and Technology*, *7*(4). Retrieved December 2, 2021, from https://www.ijrdet.com/files/Volume7Issue4/IJRDET_0418_02.pdf.

Crumb, M. (2010, December 3). *Report: Flood of problems led to Iowa's Lake Delhi Dam breach*. Insurance Journal. Retrieved December 3, 2021, from https://www.insurancejournal.com/news/midwest/2010/12/03/115391.htm.

Eash, D. A., U.S. Geological Survey (2012). Retrieved November 27, 2021, from https://pubs.usgs.gov/of/2011/1301/pdf/of2011-1301.pdf.

Engemoen, W. Q., Kiene, A. H., Dewey, R. L., McDaniel, T., Knight, K., & Pimley, L., Design Standards No. 13: Embankment Dams Reclamation: Managing Water in the West (2012). U.S. Department of the Interior, Bureau of Reclamation. Retrieved December 2, 2021, from https://www.usbr.gov/tsc/techreferences/designstandards-datacollection guides/ finalds-pdfs/DS13-2.pdf.

Flores-Berrones, R., & López-Acosta, N. P. (2019). Geotechnical Engineering Applied on Earth and Rock-Fill Dams. In *Hydraulic Structures—Theory and Applications*. IntechOpen. https://doi.org/10.5772/intechopen.84899

Fountain, H. (2020, May 21). ‘Expect More’: Climate Change Raises Risk of Dam Failures. *The New York Times*. Retrieved November 28, 2021, from https://www.nytimes.com/2020/05/ 21/ climate/dam-failure-michigan-climate-change.html.

Goldfarb, Jillian, BEE 2510 - Environmental Engineering Processes, Lecture 12, October 10, 2020, Ithaca, NY.

Green, George. “Hydroelectric Dams – The Good and Bad.” *Business Ethics*, 15 Aug. 2010, https://business-ethics.com/2010/08/15/1822-hydroelectric-dams-the-good-and-bad/.

Lin, X., Huang, G., Piwowar, J. M., Zhou, X., & Zhai, Y. (2021). Risk of hydrological failure under the compound effects of instant flow and precipitation peaks under climate change:

A case study of Mountain Island Dam, North Carolina. *Journal of Cleaner Production*, *284*, 125305. https://doi.org/10.1016/j.jclepro.2020.125305

McDaniel, L.H., Garton, J.S., Fiedler, W., King, W., & Schwanz, N.T. (2011). Lake Delhi Dam Breach – Two Perspectives. ASDSO Annual Conference. Washington D.C.: Association of State Dam Safety Officials.

National Academy of Sciences. 2020. Climate Change: Evidence and Causes: Update 2020. Washington, DC: The National Academies Press.https://doi.org/10.17226/25733.

Pachauri, R. K., Mayer, L., & Intergovernmental Panel on Climate Change (Eds.). (2015). *Climate change 2014: Synthesis report*. Intergovernmental Panel on Climate Change.

Quaresma, V. S., Bastos, A. C., Leite, M. D., Costa, A., Cagnin, R. C., Grilo, C. F., Zogheib, L. F., & Santos Oliveira, K. S. (2020). The effects of a tailing dam failure on the sedimentation of the eastern Brazilian inner shelf. *Continental Shelf Research*, *205*, 104172. https://doi.org/10.1016/j.csr.2020.104172

Sasiharan, N., & Muhunthan, B. (2006, August 16). *Failure report - the case of teton dam*. www.waterpowermagazine.com. Retrieved December 3, 2021, from https://www.water powermagazine.com/features/featurefailure-report-the-case-of-teton-dam/.

Sharma, R., & Kumar, A. (2013). Case Histories of Earthen Dam Failures. *International Conference on Case Histories in Geotechnical Engineering*. https://scholarsmine.mst.edu/icchge/7icchge/session03/8

Temple, D. M., & Hanson, G. J. (2005). Earth Dam Overtopping and Breach Outflow. *Impacts of Global Climate Change*, 1–8. https://doi.org/10.1061/40792(173)407

The Gazette. (2017, January 3). Lake Delhi Dam reconstruction wins engineering award. *The Gazette*. Retrieved November 30, 2021, from https://www.thegazette.com/news/lake-delhi-dam-reconstruction-wins-engineering-award/.

Thousands fled for their lives when two Michigan dams collapsed. More disasters are coming, experts say. (2020, June 14). Retrieved from https://www.nbcnews.com/news/us-news/thousands-fled-their-lives-when-two-michigan-dams-collapsed-more-n1230841

Van Aller, H. W., damfailures.org (n.d.). Retrieved December 3, 2021, from https://damfailures.org/wp-content/uploads/2018/06/VanAller_PipingSeepageConduitsAndDamFailures_asdsoSE04.pdf.

Webster, Michael, EAS 4620 - Marine Ecosystem Sustainability, Lecture 4, September 7, 2021, Ithaca, NY.

Wright, K. R., & Tschantz, B. A. (2011). The Dam Safety Imperative. *Water Resources IMPACT*, *13*(2), 6–8. Retrieved from https://www.jstor.org/stable/wateresoimpa.13.2.0006.