The 50-Year Anniversary of the Kingsley Dam Wave Erosion Incident

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Abstract-- On May 1st and May 2nd, 1972, a 30-hour windstorm battered and eroded the upstream face of the Kingsley Dam in western Nebraska. The erosion removed a significant amount of the upstream shell and led to the collapse of more than 400 feet (120 m) of the parapet wall running along the crest of the dam. The downstream town of Keystone was evacuated, and crews were summoned to lower the reservoir and begin emergency repairs. The failure of Kingsley Dam would have been the largest dam failure in U.S history, releasing 1.8 million acre-feet (2.2 km^3) of water. The winds eventually subsided, and thankfully, the dam did not fail. Repairs were made and investigations were conducted. The incident was soon overshadowed by the failure of Canyon Lake Dam in South Dakota one month later. Fifty years after the incident, it is important to revisit the lessons that were learned, the warning signs that were missed, and the successful remedial measures and monitoring programs that were implemented after the incident.

I. Introduction

There are few case studies available on dam incidents and failures involving wind-induced wave erosion. Protecting the upstream slope from damaging waves has long been common practice in the design of earthen dams; however, the importance of a properly designed slope protection system can be easily overlooked. When compared to the complex designs of large concrete spillways or elaborate seepage protection systems; the design of slope protection systems can seem relatively easy and straightforward. It can be tempting to reach for a standard design that has worked in the past without spending much time to think about subtle changes in the embankment soils or wind direction that could affect performance. The 1972 Kingsley Dam Wave Erosion Incident demonstrates the importance of not overlooking the proper design, inspection, and assessment of wave protection systems.

II. Kingsley Dam

Kingsley Dam is a large embankment dam located on North Platte River north of Ogallala, Nebraska. The dam is owned and operated by the Central Nebraska Public Power and Irrigation District (Central) for the purpose of storing and releasing water from the approximately 1.7 million acre-feet (2.1 km^3) Lake McConaughy (actually a storage reservoir) for irrigation and hydropower production, and is licensed by the Federal Energy Regulatory Commission (FERC) pursuant to the Federal Power Act as part of the Kingsley Dam Project. [11]

Kingsley Dam is a zoned hydraulic fill embankment with sand/gravel outer shells and a silt/clay core, and was the second largest hydraulic fill dam in the world at the time of construction from 1936 to 1941. The embankment is 163 ft (50 m) tall, 3.1 miles (5 km) in length, and has a fill volume of approximately 26 million yd^3 (20 million m^3). The upstream face generally has a slope of 3 horizontal to 1 vertical (3H:1V), transitioning to 2H:1V near the top, and is covered with riprap for erosion protection. There is also a 3-foot (0.9 m) high concrete parapet wall running along the upstream edge of the crest of the dam. [4] [11] [13]

Figure 1. Kingsley Dam [The Central Nebraska Public Power and Irrigation District (undated photo)].

III. 1972 Windstorm, Damage, and Emergency Response

On the evening of April 30, 1972, Lake McConaughy was slowly rising as it stored water in advance of the upcoming irrigation season. The reservoir was at elevation 3266.4 ft (995.6 m) msl, 23.6 feet (7.2 m) below the top of dam (excluding the parapet wall), and 2.6 feet (0.8 m) shy of full capacity at elevation 3269.0 ft (996.4 m) msl. Total water volume in Lake McConaughy stood at approximately 1.8 million acre-feet (2.2 km^3).

Starting just after midnight, winds picked up across the lake, and by about five o'clock in the morning of May 1, there were sustained winds of 30 mph (50 km/hr) blowing from the west down the 22-mile (35 km) fetch of the reservoir. The winds remained at 30 mph (50 km/hr) through the rest of the morning, and then around noon the sustained winds increased to 40 mph (60 km/hr), with gusts to 65 mph (100 km/hr), creating waves up to 8 feet (2.4 m) high [2] [4]. While Lake McConaughy and Kingsley Dam had experienced winds of similar or higher magnitude in the past, this storm was unique due to the simultaneous combination of the wind direction, the sustained duration, and the relatively high reservoir level.

At around five o'clock in the afternoon, it was noticed that rock riprap slope protection was beginning to slough [3]. Wind speeds started to diminish slowly going into the evening, but were still about 30 to 40 mph (50 to 60 km/hr), and the large waves and riprap sloughing continued. Several large holes began to develop where the slope protection had failed, and erosion now began to progress into the upstream, sandy shell of the dam. At three locations, the erosion and subsequent sloughing progressed back so far as to undercut the parapet wall running along the upstream edge of the crest of the dam [4].

The high winds and crashing waves sent visibly impressive sprays of water over the crest of the dam [8]. Witnessing the breaks in the parapet wall, onlookers were astonished and began spreading news about what was happening at the dam. Upon hearing the news, and fearing the possibility of a dam failure, most of the residents of the small village of Keystone, located in the river valley 5 miles (8 km) downstream from the dam, left their homes and headed for higher ground [4].

Meanwhile, as soon as the riprap damage started to occur, Central began to assemble equipment and personnel to conduct emergency repairs in an effort to prevent a possible breach. In addition to using their own resources, Central asked for assistance from various state and local agencies, as well as from private contractors with heavy equipment nearby. Soon, there was a continuous caravan of 28 dump trucks transporting materials from emergency stockpiles that Central had located near the dam [8]. Concrete "hexapods" were assembled to form barriers across the larger breaks in the upstream slope protection, and rock and gravel were dumped behind these barriers to further shore up the dam. Outflow from the dam was increased from 500 cfs (14 m^3/s) to 1,500 cfs (42 m^3/s) to begin lowering the reservoir. Although much greater rates of release were possible, outflows were kept at rates intended to avoid causing flooding downstream [3] [4].

The winds finally dropped below 25 mph and the waves began to subside at around two o'clock in the morning on May 2, 1972 [3] [4].

On the morning of May 2, state regulators from the Nebraska Department of Water Resources (NDWR) chartered a plane from the state capital in Lincoln to get to the dam as quickly as possible and assess the situation. Upon arriving at the dam, they observed the dam owner was using "all of their available men and equipment plus personnel and equipment of the State Highway Department and the Nebraska Game Commission to accomplish the immediate repairs necessary." Satisfied the imminent threat to the dam had subsided and emergency repairs were well underway, they returned to Lincoln [3]. The next day NDWR issued a press release to assure the public the dam was not in any immediate danger of failing and work was already underway to restore the dam [6].

The wind-driven waves resulted in damage at multiple locations along almost the entire length of dam. The most severe damage extended along a 3/4-mile stretch of the dam where there were twenty eroded pockets ranging in width from 20 feet (6 m) to 700 feet (200 m). In three locations, the sloughing reached into the crest of the dam [4] [8]. Over 400 feet (120 m) of the concrete parapet wall fell into the eroded pockets and up to 6 feet (1.8 m) of the 28-foot-wide (8.5 m) asphalt highway surfacing was either lost or undermined [1] [2]. The total volume of material eroded during the 1972 storm is unknown, but 50,500 yd^3 (38,600 m^3) of rock riprap, spalls, gravel and sand along with 10,000 concrete hexapods were placed in the eroded holes created by the storm [4].

Figure 2. Wind-Driven Waves at Kingsley Dam, May 1, 1972 [7].

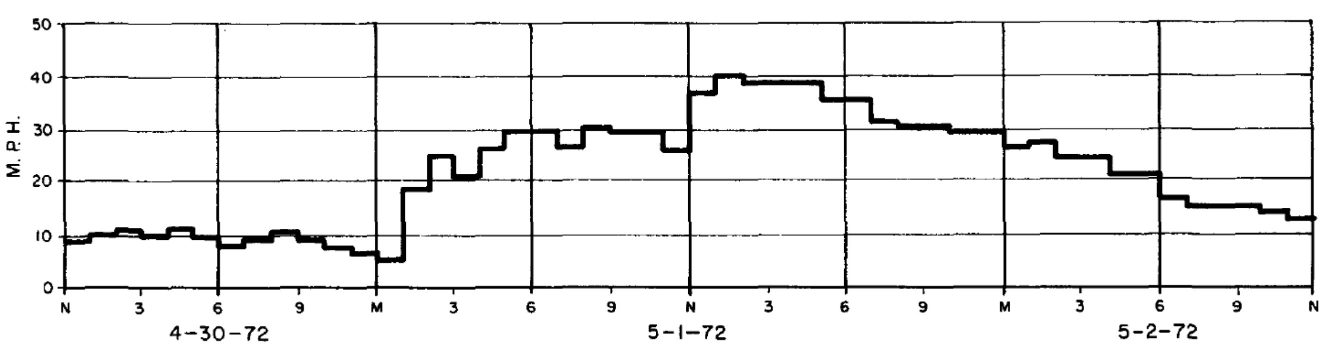

Figure 3. Hourly Wind Velocities at Kingsley Dam during the 1972 Windstorm [4].

Figure 4. A Hexapod like the Kind Used for Emergency Repairs at Kingsley Dam During the 1972 Windstorm [photograph by author Michael Drain].

Figure 5. 1972 Windstorm Damage to Kingsley Dam [5]. Note the collapse of the concrete parapet wall.

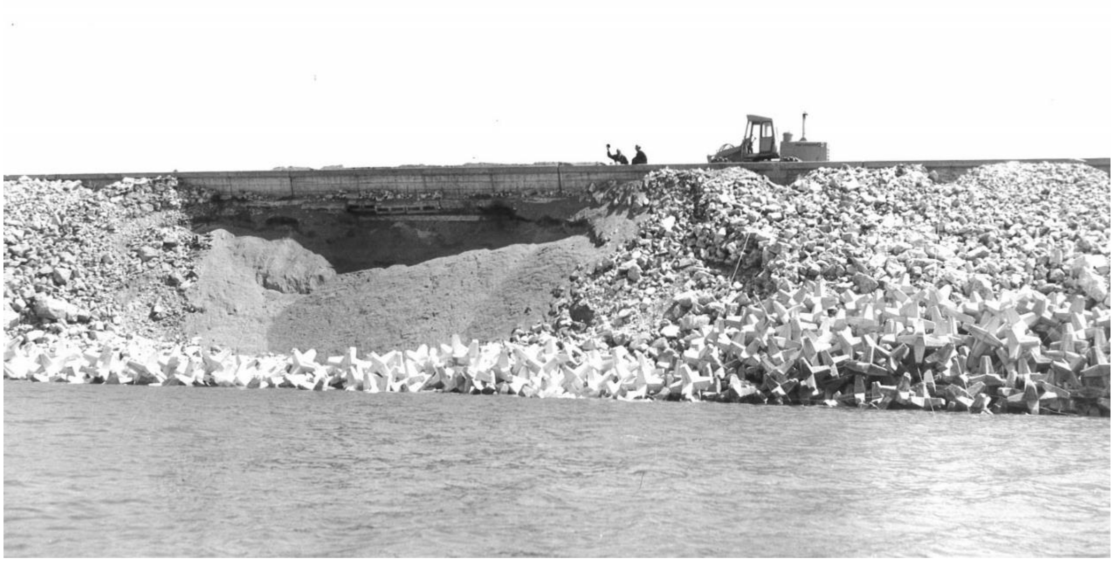

Figure 6. 1972 Windstorm Damage to Kingsley Dam [10]. Note the emergency placement of hexapods at the waterline.

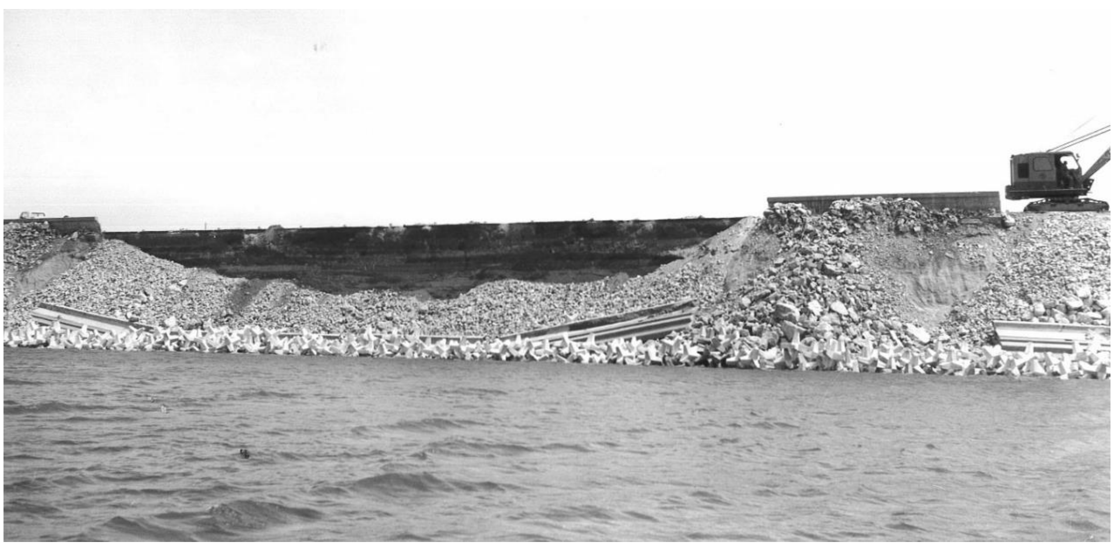

Figure 7. 1972 Windstorm Damage to Kingsley Dam [10]. Note collapsed parapet wall and emergency placement of hexapods at waterline.

IV. INVESTIGATION

Within days of the incident, Central assembled a board of consultants to assess the situation, conduct an investigation, and issue recommendations for repairing the dam. The board of consultants consisted of William A. Clevenger, Orley O. Phillips, and Fred C. Walker [4]. Mr. Clevenger was an eminent geotechnical engineer that worked for several years as the Head of the Soil Properties Section for the US Bureau of Reclamation before becoming the principal in charge of Woodward-Clyde Consultants' Denver Office [14]. Orley O. Phillips was a distinguished engineer and consultant from Denver, Colorado. Fred C. Walker had recently retired as Chief of the Earth Dams Section of the US Bureau of Reclamation [4]. Mr. Clevenger and Mr. Phillips first arrived at the dam on

May 9, 1972. Mr. Phillips and Mr. Walker returned a few days later on May 15. All three consultants visited the dam several more times over the course of a year to assess the dam and the ongoing repairs [4].

During their investigation, the board of consultants found Kingsley Dam had suffered wave damage on numerous occasions between its completion in 1941 and 1972 event. On at least four occasions, windstorms had caused major damage to the dam. After each of these events, significant repairs and/or modifications were made to the slope protection. There were also many other storms between 1941 and 1972 that resulted in minor damage and subsequent repairs. [4]

- Initially, the upstream slope of the dam was protected with precast concrete blocks laid on the dam and tied together with steel rods. After a major windstorm in 1943 resulted in holes 20 feet (6 m) deep in the upstream slope; the concrete blocks were mostly removed, and massive amounts rock riprap were placed across the face of dam overtop a new layer of 15-inch (0.4 m) thick gravel bedding. [4]

- In 1949, a windstorm with sustained winds reaching 38 mph (60 km/hr), broke through the updated wave protection, completely removing the new rock riprap and the underlying gravel bedding in many locations. Slightly larger riprap was brought in to repair the damage, but the repairs did not last long [4].

- Back-to-back storms in the spring of 1950 produced another large notch in the dam. As a result, even larger rock was brought in to cover the upstream face of the dam. [4]

- Smaller events continued to damage the dam through the 1950s, so in 1959, a new slope protection method was introduced. The new protection consisted of 800-pound (360 kg), precast concrete "hexapods" (also referred, mistakenly, as "tetrahedrons", or simply "jacks") tied together with steel cables. Between 1959 and 1963, 41,000 hexapods were placed on the dam. Nevertheless, a strong, 62-hour-long windstorm in April of 1964 caused severe damage along the entire length of the embankment. It is believed that subsequent repairs between 1964 and 1972 were made with more hexapods. [4]

After reviewing all the records and several visits to the dam, the board of consultants issued their report in May of 1973. Ultimately, the board concluded, "the May 1, 1972 damage to the slope protection of Kingsley Dam was initiated with the removal of the cohesionless fine sand of the embankment shell and/or filter blanket from beneath the rock riprap, by wave action. Depressions developed in the protective surface and ultimately all slope protection was removed by the waves..." [4]. The board found that the filter blanket was too thin and inadequate in protecting the underlying fine sand in the dam embankment from erosion. The board also concluded that the previous slope failures over the previous 30 years could also be primarily attributed to the movement of the gravel bedding and embankment sand materials through the voids in the overlying concrete blocks, rock riprap, and hexapods. [4]

The board did note that "…there was never a danger of failure of the dam because of wave damage during the May 1, 1972 storm. If there had been, the reservoir level could have been quickly lowered a sufficient amount to ensure safety, by releasing a large amount of water." They did, however, acknowledge that such an action likely would have resulted in severe flooding in the downstream floodplain. [4]

The state regulator agreed with the board's conclusion. NDWR assistant director Marion Ball explained in 1972 that the core of the dam consisted of clay, which was much less susceptible to erosion than the sandy upstream shell of the dam. He noted that it would have taken a lot of time for the core of the dam to erode and, "Before that could have happened, spillways would have been opened to reduce the lake level rapidly…That action would have caused a major flood, probably the worst flood on the Platte that we've ever had. But it wouldn't have been a disastrous flood. There would not have been a wall of water rolling down the valley [like there would have been if the dam had failed]." [9].

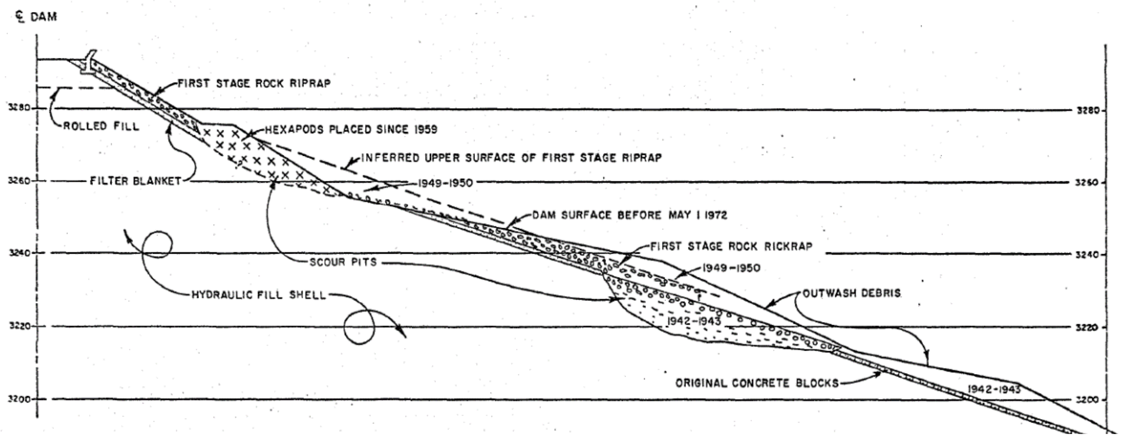

Figure 8. Estimated Condition of Kingsley Dam Slope Protection Prior to 1972 Windstorm [4].

V. REPAIRS

Lake McConaughy was lowered, and emergency repairs were made to provide interim protection until permanent repairs could be made. The board of consultants developed a design for permanent repairs intended to minimize shell and filter particle erosion from beneath the riprap face. First, any eroded shell materials were filled with sand and soil, and a filter layer of fine graded stone was then placed over the embankment shell. Graded rock from 7/16 to 3-inch (1 to 8 cm) in size was used to fill voids around in-place hexapods. The face was then covered in rock fragments up to 12 inches (30 cm) in size to provide additional filtering and frictional resistance to movement, and over that was placed three feet of heavy rock riprap [4].

These repairs were made to both failed and un-failed areas along the length of the dam. In placing these materials, the slope of much of the upper elevations of the upstream face was reduced from 2H:1V to 3H:1V, continuing the new slope down to the point where it intersected with a lower bench that was formed by deposition of the material that had been washed out from above. The board of consultants concluded that the corrective work would result in the erosion protection being stronger than was before the windstorm, and would reduce future wave-induced damage and maintenance costs [4].

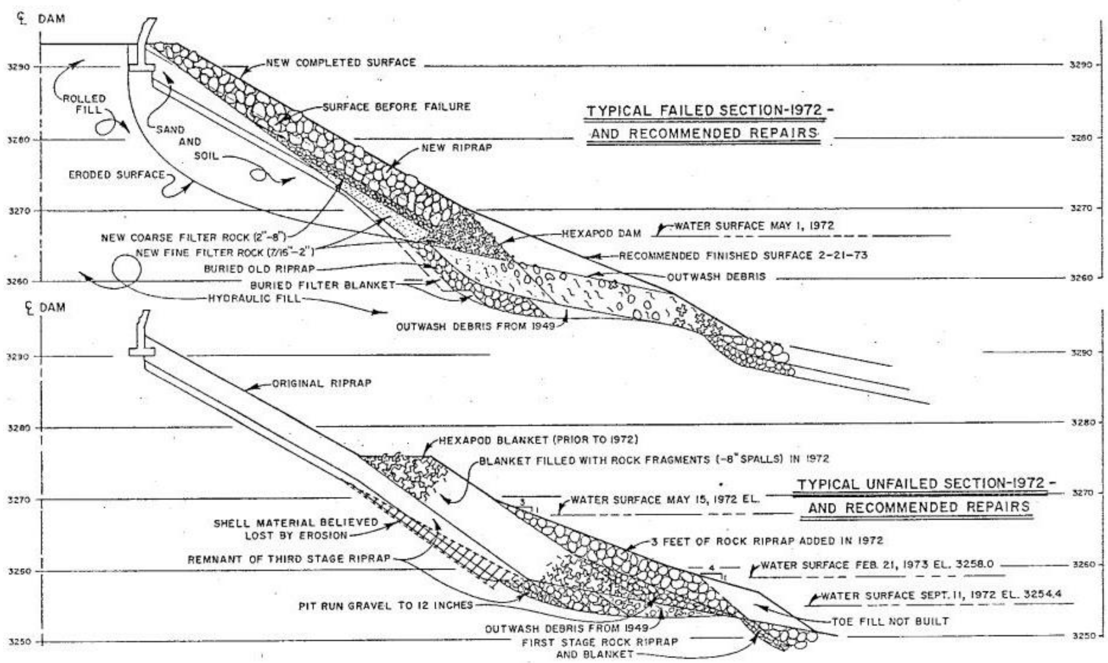

Figure 9. Design for Kingsley Dam Slope Protection Repairs Following the 1972 Windstorm [4].

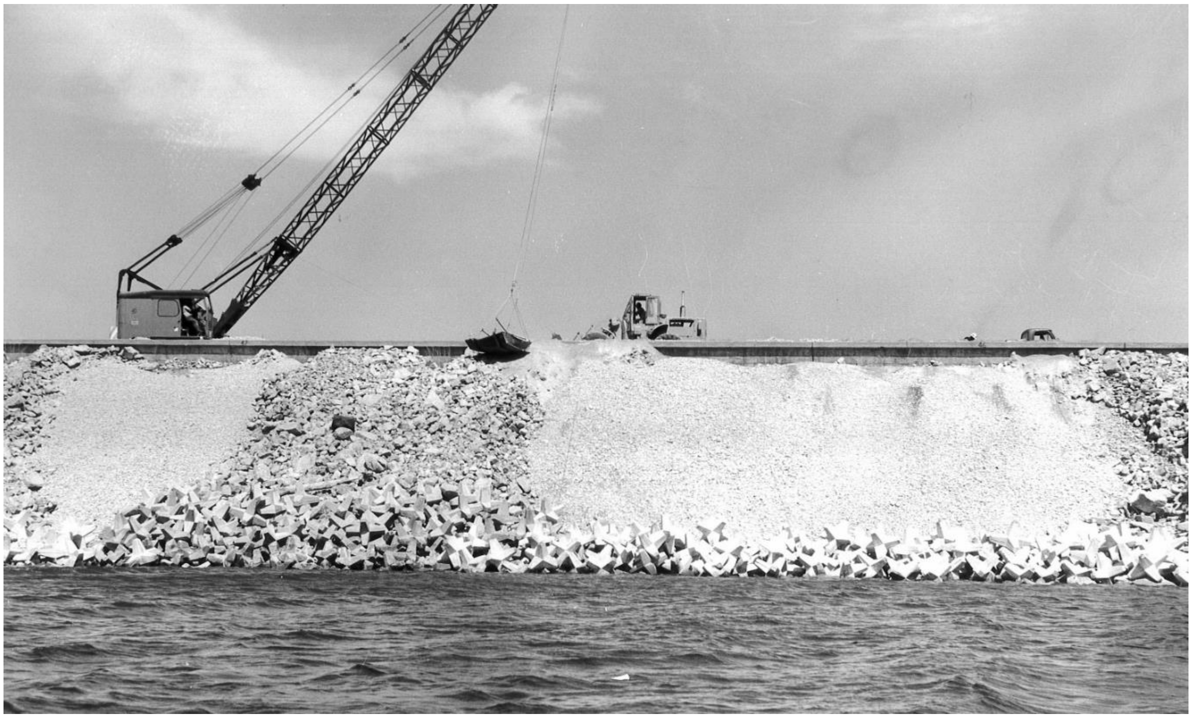

Figure 10. Making Permanent Repairs to Kingsley Dam Following the 1972 Windstorm [10].

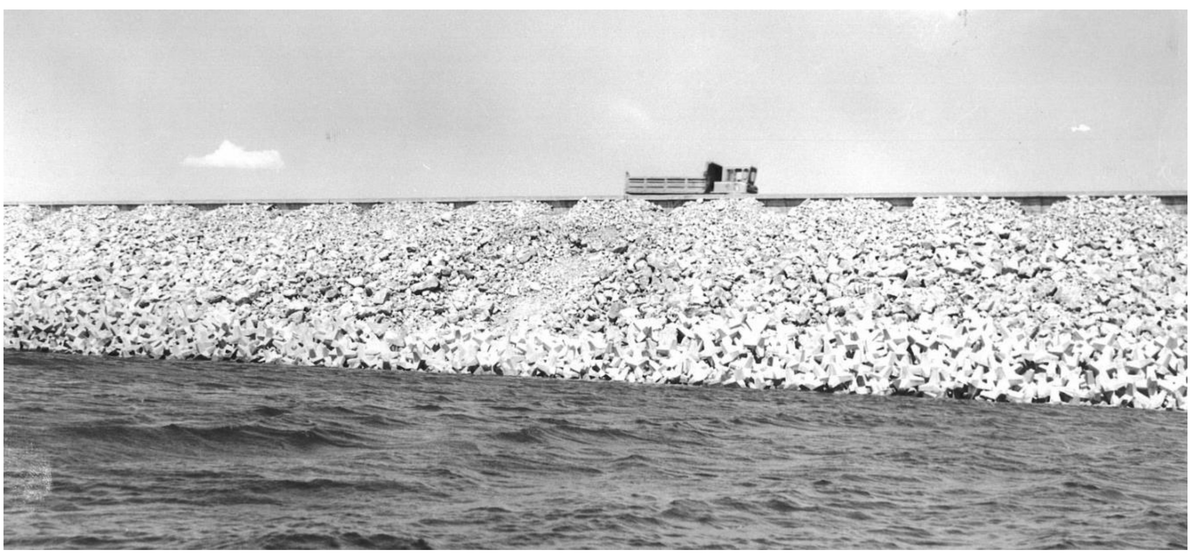

Figure 11. Newly Installed Kingsley Dam Erosion Protection Following 1972 Windstorm Repairs [10].

VI. CHANGES TO OPERATIONS AND MONITORING

In addition to physical repairs, the following changes were implemented to reservoir operations, monitoring, and preparedness following the 1972 windstorm.

- Previously, the normal maximum operating level for Lake McConaughy was 3269.0 ft (996.4 m) msl, 21 feet (6.4 m) below the crest of the dam, and 2.6 feet (0.8 m) above the reservoir level at the time of the windstorm. Following the recommendations of the board of consultants, Lake McConaughy's normal maximum water level was reduced to elevation 3260.0 feet (993.6 m) msl during spring and fall periods that have the greatest potential for sustained westerly winds, and 3265.0 (995.2 m) feet msl during summer and winter periods when the potential for high sustained winds is lower. [4] [13]

- Whereas previously Central had a stockpile of hexapods on site for emergency repairs, following the windstorm the stockpile criterion was modified and increased such that Central now maintains an emergency stockpile of at least 10,000 hexapods as well as 10,000 tons (9,000 metric tons) of heavy rock. [4] [13]
- Central maintains a continuously operating and recording wind gage at Kingsley Dam and checks the condition of the dam from the crest following every large wind event. Central also inspects the face of the dam from the lake side every spring to look for any damage or other change that might have occurred but gone unnoticed from the crest. Central additionally takes photographs of the riprap along the entire length of the dam every five years to maintain a historic record of the condition and facilitate looking for long-term changes. Finally, Central has a series of painted marks on the riprap at a constant elevation along the length of the dam to facilitate these efforts of identifying movement. [13]

Figure 12. Paint Marks on Kingsley Dam Riprap for Monitoring Movement [12].

VII. Lessons Learned

It is important to revisit the lessons that were learned, or reinforced, from the 1972 Kingsley Dam incident:

1. Wave-induced erosion is a viable failure mode for earthen dams. The importance of a well-designed wave protection system should not be overlooked, especially on large reservoirs. The Kingsley Dam incident shows that under certain conditions wave erosion can quickly progress through the upstream slope of a dam in the matter of hours and threaten the integrity of a dam.

2. Appropriate wave erosion protection should include a properly designed filter. Wave protection design is commonly thought of as an exercise to determine the rock or other slope protection needed to resist displacement by wave energy given dam slope and wave estimates. In this case however, the board of consultants concluded the damage was not simply caused by the displacement of the riprap surface

protection by the wave action but rather, by the removal of the fine sand filter layer and fine embankment shell materials through the rock riprap slope protection. The proper design and construction of the filter layer or layers under the surface protection can be just as important as the proper sizing and gradation of the surface layer.

3. Repeated damage and repairs can be a warning sign of a larger problem. The wave protection at Kingsley Dam was in a constant repeated cycle of damage and repair before the 1972 incident. Between 1941 and 1972, there were four documented windstorms that produced major damage, and several other windstorms that produced minor damage. The constant, repeated damage and shifting of the wave protection features should have been a warning sign that there were underlying problems with the wave protection system. Major repairs were implemented, but were either ill-conceived or poorly executed, without greater attention given to whether a change or fix to the overall approach was warranted. Upstream erosion protection for a high-hazard embankment is an important protection feature and should be reliable and robust. While occasional movement, maintenance, and replenishment of protective material might be anticipated, frequent significant damage requiring major repairs should not be tolerated.

4. Dam safety incidents are often the result of a combination of factors. The damage to Kingsley Dam in 1972 was not simply the result of it being a particularly strong windstorm; there had been storms with higher wind speeds. Not only was the wind velocity high, but it was sustained, and came directly down the full fetch of the reservoir. Additionally, the reservoir was nearly full, with water levels near the top of the dam, where the upstream face transitioned from the normal 3H:1V to a steeper 2H:1V slope. Finally, the originally upstream protection was insufficient to prevent removal of fine material from underneath the riprap, which was likely further exacerbated by inadequate repairs following other events.

5. All dams need an operable means of drawing down the reservoir. During the 1972 incident, Central increased outflows from the reservoir to slow the progression of damage and to facilitate emergency repairs. Additionally, Central also has significant additional release capacity that would have allowed for a much more rapid lowering of the reservoir should it have been deemed necessary to avoid a full breach of the dam; though this rapid release would have caused downstream flooding, this would have been insignificant in comparison to the flooding that would have been caused by a dam failure. Following the windstorm, further lowering of the reservoir was implemented to facilitate the permanent repairs.

6. Emergency stockpiles and equipment should be readily available in case of an emergency. Central's on-site stockpile of hexapods, and the availability of sufficient numbers of nearby equipment with the capacity to load, transport, and place it in the developing holes, was critical in slowing the rate of erosion.

7. Operational changes can be a viable risk reduction alternative. Not all dam safety issues require, or exclusively require, a physical modification to the dam. As mentioned earlier, not only was the slope protection for Kingsley Dam improved following the 1972 incident, but permissible operating levels for Lake McConaughy were seasonally adjusted, providing for lower lake levels during those times of year when strong westerly winds are more likely to occur. This further reduces the possibility of a similar event occurring in the future.

VIII. Conclusion

It is widely recognized that engineering failures and incidents provide valuable lessons and advance the state of the practice. The 1972 Kingsley Dam Incident is no different. It provides a valuable example of the damage that can be caused by wind driven waves and how quickly the erosion can progress and threaten the integrity of an earthen dam. Since 1972, the slope protection at Kingsley Dam has performed well with only minor maintenance and the occasional need for small amounts of supplemental riprap. There has been no evidence of loss of embankment material under or through the riprap slope protection.

IX. ACKNOWLEDGMENT

The authors would like to acknowledge Messrs. Clevenger, Phillips, and Walker, the board of consultants that investigated the 1972 windstorm incident. Their report forms a substantial part of the information for this paper, and remains a valuable record of the event, the damage, the underlying causes, and the corrections to this day.

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