GEOTECHNICAL PRACTICE PUBLICATION NO. 2

H_2Geo: Geotechnical Engineering for Water Resources

Edited by

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Geotechnical Engineering for Water Resources

PROCEEDINGS OF THE BIENNIAL DENVER GEOTECHNICAL SYMPOSIUM

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Preface

Geotechnical engineering for water resources in Colorado began about 1,250 years ago at a place called Mesa Verde, when the first reservoir was constructed by the Ancestral Puebloans to collect and store domestic-use water. Today Colorado and its geo-community continue the struggle to properly manage and enhance our scarce water supply; hence, the theme for this seminar - H_2GEO: Geotechnical Engineering for Water Resources. We hope that this collection of seminar papers, presenting Colorado's geotechnical practice and experience related to water resources, will be of value to others in the U.S. and internationally.

Since 1984, the ASCE Colorado Section's Geotechnical Group, in collaboration with the Rocky Mountain Section of the Association of Engineering Geologists and the Colorado Association of Geotechnical Engineers, has organized a biennial series of geotechnical seminars on a wide variety of themes that have been attended by as many as 270 civil/geotechnical engineers, geologists, and other geo-professionals. The geotechnical seminars have been held at area universities or hotels and have offered the opportunity for sharing ideas and experiences among Colorado's diverse geo-disciplines. GeoDenver 2000, a well-attended conference sponsored by ASCE's Geo-Institute, replaced the Biennial Geotechnical Seminar that year.

The H_2GEO Steering Committee convened in July 2003 and held monthly meetings to plan for the October 2004 Biennial Geotechnical Seminar. The Steering Committee members included Dr. Christoph Goss (Conference Chairman), Mark Brooks, David Butler, Darin Duran, Jim Gill, Warren Harrison, Julio Juarez, Hany Malek, Bill McCarron, Prof. Hal Olsen, Minal Parekh, Becky Roland, Dr. Saeid Saeb, and Dick Wiltshire.

Richard L. Wiltshire, Christoph M. Goss, and Harold W. Olsen

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The H_2GEO Steering Committee wishes to take this opportunity to thank all of the authors and reviewers of our H_2GEO: Geotechnical Engineering for Water Resources papers, which are herein presented as Geotechnical Practice Publication No. 2. The authors have spent many hours in preparing and revising their papers, which will be presented at the 2004 Biennial Colorado Geotechnical Seminar on October 22, 2004. These papers have been reviewed by a group of volunteers who put in their valuable time and helped make these papers even better – thank you. The Geo-Institute's Committee on Technical Publications completed its review of our H_2GEO papers in a very timely manner and their adherence to our aggressive publication schedule is greatly appreciated. The H_2GEO Steering Committee would also like to thank Prof. Hal Olsen of the Colorado School of Mines for his work to bring forth the ASCE Geo-Institute's new Geotechnical Practice Publication, an excellent new resource for the geotechnical community. We would also like to acknowledge the assistance of Donna Dickert of ASCE's Book Production Department.

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Prehistoric Mesa Verde Reservoirs

By Kenneth R. Wright[1], P.E., F. ASCE

Abstract

The results of engineering research in Mesa Verde National Park tells a rich story of diligent and industrious early Americans in their planning, building, and maintaining community reservoirs over long periods of time. Field evidence shows that these Indians had knowledge of hydrological and hydraulic principles; they harvested water where modern engineers would say there is none and moved the water into reservoirs under difficult conditions. It was concluded that the early people of Mesa Verde had good organization, a social structure, and were adept at technology transfer from generation to generation and from valley bottom to mesa top. The descendants of the Mesa Verde people can be proud of their technological heritage.

Introduction

The ancestral Puebloans of Mesa Verde, people we refer to as the Anasazi, were able to plan, build, and operate public works projects in southwestern Colorado more than 1,000 years ago. The evidence they left behind has provided ample proof of their civil engineering achievements that spanned hundreds of years. This field evidence rests in canyon bottoms and on mesa tops of Mesa Verde National Park, archaeological sites that were reservoirs for storage of domestic-use water. Four of these reservoirs were explored, analyzed, and documented between 1995 and 2004. These four Mesa Verde public works projects are the focus of ongoing civil engineering research on the water management accomplishments of these early Americans and are identified as follows:

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TABLE 1

Mesa Verde Reservoirs

Structure	Identification	Location	Time Span (A.D.)
Morefield	5MV1931	Morefield Canyon	750-1100
Far View (Mummy Lake)	5MV833	Chapin Mesa	950-1180
Sagebrush	5MV1936	Unnamed Mesa	950-1100
Box Elder	5MV4505	Prater Canyon	800-950

Established by Congress in 1906, Mesa Verde National Park is an 81-square-mile (210 km^2) national treasure in southwestern Colorado. In 1978, the United Nations designated the park as a World Heritage Site. In October 1999, the National Geographic Society ranked the park number six on its list of world wonders. The park is like a giant bank vault with upwards of 5,000 archaeological sites awaiting further study and interpretation. Usually only about three dozen sites are open to the public.

In 1995, Morefield Reservoir in Morefield Canyon was our first public works archaeological site selected for intensive study. This site was also our first enigma. What was a 16-foot (5-m) high mound doing on a rather flat, remote canyon bottom? The 220-foot- (67-m) diameter mound had an upstream tail that, from the air, looked like the handle on an inverted frying pan or even the tail of a fat pollywog. When our work started, one respected scientist thought the site was a huge dance platform and that the upstream tail was an approach walkway. Another scientist, from Arizona, said it was the erosional remnant of a prehistoric terrace. Jack Smith, who earlier served as chief archaeologist of the park, concluded from a 1967 study that it had all the signs of a prehistoric reservoir, minus an apparent water supply source. This was the second enigma. According to Smith, "there just was not enough runoff." In light of these doubts, Smith did not publish his 1967 results until 1999. This was after engineering studies had provided the needed evidence that a water supply did, in fact, exist and that the accumulated sediments and maize pollen in the mound could only have been transported by flowing water. By coupling engineering data with archaeological data, the mystery and questions related to the Morefield Mound were systematically laid to rest.

Anasazi Hydraulics

Early Americans created viable and active settlements in the Mesa Verde area over an 800-year period from about A.D. 500-1300. The public works research related to reservoirs has identified the A.D. 750-1180 period with reservoir building and operation. Archaeologists have divided the overall 800-year time span into distinct periods for study purposes, with the Pueblo I and II periods best representing the time of the four Mesa Verde reservoirs.

TABLE 2

Time Periods

Period	Time Span (A.D.)
Basketmaker III	500-750
Pueblo I	750-900
Pueblo II	900-1100
Pueblo III	1100-1300

The Anasazi had no written language, they did not have bronze, iron, or steel and they did not use the wheel, although they did use stone to good advantage. As a result, American history books tend to underrate them in terms of technical capabilities and social organization. However, as will be demonstrated, the Anasazi had rudimentary knowledge of hydrological phenomena, water transport, and storage. To build reservoirs, they also had good organizational capabilities; otherwise, their large public works efforts requiring major and continuous operation and maintenance work would not have been possible.

To create Morefield Reservoir, the Anasazi first excavated a pond on the valley bottom to reach the periodic shallow water table and to capture infrequent storm runoff. The stored runoff carried sediment that needed to be periodically dredged and cast to the side using crude tools. Over time, the pond bottom rose in elevation and the excavated sediment was accumulated at the edges. Because dredging did not remove all the sediment during each cleaning, it was not long until the pond bottom began to rise in elevation and take the form of a mound into which water would no longer flow by gravity. The Anasazi determined that water could be diverted from the canyon bottom into a delivery canal leading to the rising pond. But sediment deposits still had to be regularly cleaned out and cast to the side, forming berms. By A.D. 1100, this process brought the Morefield Reservoir up in elevation some 21 feet (6 m) above the original pond bottom of 350 years earlier. Not only did the public works of the Anasazi have to withstand drainage basin forest fires and floods, they were also subjected to a regular upstream relocation of their point of diversion. This was done to gain elevation advantage for gravity flow to the rising reservoir pool. Parallel in time with the relocation of the point of diversion of the inlet canal, the Anasazi would have to raise the canal elevation along its alignment to keep up with the rising elevation of the water system, creating the tadpole image. Eventually, the canal was on an elevated berm.

Study of two canyon bottom reservoirs, Morefield and Box Elder in Morefield and Prater Canyons, showed enough similarities to prove that technology transfer existed between the canyons as early as about A.D. 800.

Later in the 10th century, other Pueblo II Anasazi, living on mesa tops rather than the canyon bottoms as with the first two reservoirs, constructed two additional reservoirs that modern engineers would have judged to be ill-directed and bound for failure. There were no natural drainage basins for either and the natural soil surface had a high infiltration rate. What the Anasazi had learned, however, was that the soil contained enough silt and clay particles that when the soil was puddled, the silt and clay migrated to the surface, creating a highly impervious soil surface. Nearby areas that were subjected to busy foot traffic, such as well-traveled paths, the environs of pueblos and upslope agricultural fields, would create runoff from even small rainfalls. Realizing a half-acre (0.2-hectare) of such impervious surface could generate a substantial volume of runoff from only a half-inch (13 mm) of intense rainfall, the Anasazi began harvesting water. Interceptor ditches needed to route the limited water runoff to their newly created depressions for storage resulted in Far View Reservoir (a.k.a. Mummy Lake) and Sagebrush Reservoir.

All four of the reservoirs have enough similarities, even though two are in canyon bottoms and two are on mesa tops, to identify the application of successful public works technology transfer from canyon bottom to mesa top, from settlement to settlement, and from generation to generation.

Box Elder Reservoir

About one-half mile (0.8 km) downstream of the Box Elder Reservoir location on the west slope of Prater Canyon was the village site now known as 5MV3146. The village site was 600 feet (193 m) long and about 300 feet (91 m) wide; it extended downhill from the talus slope of the westerly cliff walls. Jack Smith reported on the site in his 1987 Mesa Verde Research Series. The village contained many kivas that provided winter shelter and more than a dozen groupings of buildings on the southeast-facing slope that received the warm rays of the sun. The Anasazi left piles of refuse (midden) downhill of each of their yet-unstudied building sites that will someday provide a rich area for archaeologists searching for more data on these early and innovative Prater Canyon people. Park archaeologists, while surveying forest-fire damage, mapped the layout of the site in June 2001. Other pueblo villages were built in the general area similar to this one, with a total likely population of about 300.

Close to Box Elder Reservoir were three small pueblo areas, perhaps the abodes of the people who were mainly responsible for maintaining the reservoir as well as tending to the agricultural maize fields nearby. The people of Prater Canyon stayed in the area long after Box Elder Reservoir was abandoned, perhaps until about A.D. 1100. It was about this time that life became more difficult, population diminished in the canyons and there was a movement to cliff dwellings that were more defensible than the Prater Canyon valley villages.

Box Elder Reservoir was the fourth and final reservoir investigated during the 1995-2003 paleohydrology research efforts at Mesa Verde. It is unique in that it was a Pueblo I public works structure dating from an estimated A.D. 800-950 period. It was undiscovered until September 2001, following the 2000 Bircher Fire. Park

Ranger James Kleidon recognized it as a reservoir once the heavy growth of sagebrush on its surface had been removed and its form laid bare by the forest fire; its shape resembled that of Morefield Reservoir, with which the ranger was familiar. The drainage basin of Prater Canyon upstream of Box Elder Reservoir contains about four square miles (10 km^2) and ranges in elevation from 7,250-8,400 feet (2210-2560 m) over a distance of five miles (8 km). Except for the canyon floor, the basin is forested with piñion and juniper. The canyon floor is typically about 500 feet (150 m) wide with canyon walls rising about 400-500 feet (120-150 m) above the floor.

The site of Box Elder Reservoir lies 0.7-mile (1.1 km) directly west of Morefield Reservoir, with a mesa nearly 500 feet (150 m) high separating the two. The reservoir has a height of about 20 feet (6 m), a base width of 220 feet (67 m) and an effective length of roughly 300 feet (90 m); the length is somewhat undefined because the upstream end of the reservoir blends with the natural terrace. Based on visual observation of soil surface color and vegetation pattern, however, the length was judged to be 220 feet (67 m). The surface of Box Elder Reservoir sloped at 4 percent in a southeast direction, unlike Morefield Reservoir, which was flat.

The west to east slope of the reservoir's top surface was judged to be the result of a westerly canyon wall gulch that discharged onto the reservoir surface, the waters of which were likely stored. Following abandonment of the inlet canal from the Prater Canyon thalweg, it was concluded that the waters of the gulch continued to be routed to the reservoir for storage, along with its sediment, resulting in deposition from west to east and the 4 percent sloping surface.

Evaluation and survey of the reservoir site included running a typical Anasazi ditch slope of 1 percent northward from the reservoir to intercept the canyon floor channel area. Evidence of stones that may have been associated with the canal was found 500 feet (150 m) upstream. After further examination of the terrace edge, a series of stacked man-placed stones were found 150 feet (46 m) upstream in an erosional cut; with the stones was a Pueblo I potsherd that verified human activity. It was concluded that these stacked stones represented a late reservoir phase inlet canal. Over the life of the reservoir, there would have been a series of inlet canals that were raised and extended upstream as the reservoir rose in elevation due to sediment inflow, similar to Morefield Reservoir. Additional field research was conducted in May 2003 where streambank stone armoring was documented; it would have provided erosion protection to the canal from the occasional fast flowing canyon stream. Here, a Pueblo I potsherd was also discovered.

Canyon Geomorphology

Over a period from 1995-2000, Prater Canyon was analyzed for comparison with Morefield Canyon using aerial photographs, infrared aerial photographs, topographic mapping, and field surveys. The upstream canyon can be observed from the main park access road. Prior to 2000, it was concluded that the canyon bottom was generally devoid of significant channel cutting, that it contained wetland areas and that it might indicate the existence of fairly uniform geomorphologic conditions 1,300 years ago when the Pueblo I Anasazi occupied the canyon. During these earlier evaluations there was no hint that a prehistoric reservoir existed there.

Unfortunately, the first paleohydrological field inspections of Prater Canyon occurred in October 2002, some two years after the 2000 Bircher Forest Fire. What we found was a canyon bottom that was undergoing change after the fire, with frequent runoff and channel degradation, particularly near the reservoir location.

Nevertheless, a field survey of the full length of the upstream canyon valley bottom showed significant reaches with wetland floor, terraces with a wide flat zone between and a well-shaped and stable 2-foot (0.6-m) wide channel about a foot (0.3 m) deep. At other places, including near the Box Elder Reservoir, the channel was down-cutting as much as 8 feet (2.4 m), followed by downstream deposition areas where the eroded material settled out. Clearly, in October 2002 the floor of Prater Canyon was undergoing a change due to the forest fire and its increased runoff conditions. Because Prater Canyon had been free of forest fires for 100 years or more, the 2000 fire represented a major change in the basin watershed conditions. The Pueblo I people of Prater Canyon also experienced at least low-severity forest fires that, when joined with agricultural areas, produced more frequent runoff events to help fill their reservoir.

Reservoir Stratification

Since Box Elder Reservoir was a recent discovery and had never been excavated, research conducted at Box Elder Reservoir included soil augering into the reservoir sediments, with one hole in 2002 penetrating to a depth of 10.8 feet (3.3 m) and still not reaching the natural soil underneath. Augering was commenced in a natural soil location south of the reservoir so that we could identify and log a natural soil profile. Next, an auger hole was drilled into the reservoir downstream berm, where we encountered mostly dark soils that had the characteristics of dredged material. Due to the density and resistance of the soils, this hole extended to a depth of only 28 inches (71 cm). The second reservoir hole was at the south edge of the reservoir and extended to 42 inches 107 cm). Here, layering was pronounced, carbonate veinlate was noted, and charcoal fragments were found up to 4 millimeters (0.16-inch) in size.

A third auger hole penetrated to 130 inches (330 cm) and found silty clay layers alternating with loam (silty sand) layers, typical of water-deposited sediments and similar in nature to those strata found in the Morefield Reservoir excavation. Iron stains, redoximorphic soils, and charcoal fragments were collected, providing further evidence that the mound was a reservoir. Soil samples from the third hole were tested by Hepsworth-Pawlak Geotechnical, Inc. and gradation analyses were provided, as shown in Table 3.

TABLE 3

Box Elder Reservoir Sediment Gradation
Hole No. PC-R-S3

	USDA Class			USDA Description
Depth, inches (cm)	**Sand**	**Silt**	**Clay**	
9 – 12 (23-30)	9 %	42 %	4 – 9%	Silty Clay
29 – 34 (74-86)	11%	35%	54%	Clay
42 – 45 (107-114)	40%	32%	28%	Clay Loam
54 – 57 (137-145)	6%	32%	62%	Clay Loam

The fourth auger hole penetrated to 77 inches (196 cm) and was similar in nature to the third hole in terms of reservoir evidence. The fifth auger hole was placed in the southwest portion of the reservoir surface for a penetration of 56 inches (142 cm), where it showed distinct sediment layering throughout and other evidence consistent with the reservoir deposition of sediment.

Finally, the sixth 2002 auger hole penetrated the westerly portion of the reservoir to a depth of 61 inches (155 cm) with similar layering noted, including charcoal fragments, sandstone pebbles and pieces of burned sandstone. Near the sixth auger hole, a shallow shovel excavation was made to about 18 inches (46 cm) of depth, where small cobbles were noted along with gravel that would be consistent with deposition from the west canyon wall gully. None of the auger holes provided potsherd evidence; all the sherd evidence came from the ground surface. Additional soil borings in May 2003, with the assistance of Richard Wiltshire of the U.S. Bureau of Reclamation, penetrated to 20 feet (6 m) where original undisturbed natural soil was reached.

Evolution of Box Elder Reservoir

The water storage facility in Prater Canyon did not evolve on its own; prehistoric people caused it to happen about A.D. 800, around the time that Morefield Reservoir was rising up and out of the canyon floor after about 50 years of operation.

The people of Prater Canyon, perhaps blood relatives of those in the adjacent Morefield Canyon who might have moved over the mesa top, needed to supplement the groundwater supply derived from shallow excavation in the canyon bottom. First, they went upstream about 0.7-mile (1.1 km) from their main village area and, using digging sticks, antlers, flat stones, and baskets, they excavated a pond-like hole in the gully thalweg to capture groundwater and an occasional runoff event. Runoff brought with it sediment that soon filled the excavation and was then not quite completely dredged out to the original bottom. After sediment deposition from a number of runoff events, the pond was somewhat higher than the adjacent thalweg, and runoff water needed to be diverted into the pond. Soon, a formalized diversion canal was constructed to divert the surface water flow into the rising pond. It was not too many years before a new inlet canal was needed that was higher in elevation and that extended further upstream. This process continued for well over a century and, with each canal rebuilding and upstream extension, the work needed per gallon (4 liters) of water increased. Soon, filling the reservoir likely required more energy than the water was worth. Besides, shallow excavations elsewhere were likely able to provide for basic water needs from the alluvium.

The final years of the reservoir operation likely represented sporadic diversion of the water of the canyon wall gulch, lying to the west, into the by-then raised mound on the west side of the Prater Canyon valley floor. The gulch also carried sediment into the reservoir and began filling the remaining reservoir storage space from west to east. Finally, in about A.D. 950, the Prater Canyon reservoir was abandoned in the shape and condition it is found in today.

Dating of Box Elder Reservoir was performed by analyzing the evidence, observing the physical characteristics of the site and valley, and tapping into the rich storehouse of ceramic information developed by eminent Southwest archaeologists and anthropologists. The time period of the Box Elder Reservoir was determined by David Breternitz mainly by using potsherds. His findings were reviewed by Colorado State Archaeologist Susan M. Collins. Other artifacts were found nearby. The inventory of the surface ceramics from Box Elder Reservoir is shown in Table 4.

TABLE 4

Tabulation of Surface Ceramics, Site 5MV4505, Prater Canyon, Mesa Verde National Park

Type	Jars	Rims	Bowls	Rims	Total	Percentage
Chapin Black-on-White	--	--	1	--	1	1%
Piedra Black-on-White	--	--	1	--	1	1%
Mancos Black-on-White	1	--	--	1	2	2%
Whiteware	8	--	--	--	8	8%
Chapin Gray	--	1	--	1	2	2%
Moccasin Gray	3	1	--	--	4	4%
Early Pueblo Gray	70*	--	--	--	70	72%
"Corrugated"	6	--	--	--	6	6%
Fugitive Red	1	--	--	--	1	1%
Redware	2	--	--	--	2	2%
TOTALS	91	2	2	2	97	99%

* Two are jar handles.

Based on the analysis of the composition and distribution of the site's ceramics sample, the following conclusions were reached:

1. The prehistoric ceramics are primarily from the Pueblo I period, with approximately 8 percent of the sherds probably belonging to the Pueblo II time period. Pueblo I ceramics at Mesa Verde occur between A.D. 775 and A.D. 900; the few Pueblo II sherds probably belong to the A.D. 900-1050 time period, but appear to be too infrequent to be an important element of the prehistoric occupation of the site.

2. Most of the sherds are eroding out of the berm on the south and southeast margins of the reservoir site. These ceramics are eroding from the berm deposits that define the southern boundaries of the site.

3. Most of the Pueblo II potsherds were observed on top of the site and could have been deposited after the reservoir ceased to be a functional water management system. These Pueblo II sherds could very well represent activity by Pueblo II occupants from a major Prater Canyon community a half-mile (0.8-km) down the canyon.

4. As observed at Mummy Lake (now called Far View Reservoir) and at Morefield Reservoir, most of the ceramics are from jar-shaped ceramic vessels, probably associated with water being carried to nearby domestic habitations (Over 90 percent of the analyzed samples are from jar-shaped vessels). The fact that the vast majority of the ceramics are Grayware, as opposed to Whiteware vessels in the two previously noted reservoirs, indicates that the utilization of the site was probably begun during the Pueblo I time period and did not extend into the Pueblo II time period to any significant degree.

5. No ceramics were recorded in any of the auger test holes. This situation is not surprising due to the fact that the great majority of the ceramics observed at the site appear to be eroding out of the boundary-defining berm. If backhoe or extensive hand-dug trenches could be excavated through the "basin" and across the berm feature, it is likely that in situ ceramics would be found to provide a better chronological control, based on prehistoric ceramics. In situ ceramics were found in the extensive trenches excavated at Mummy Lake, at Morefield Reservoir and at Sagebrush Reservoir.

6. It cannot be explained solely from the ceramic data why this site had a shorter use span than either Mummy Lake or the Morefield Reservoir.

What We Learned about Box Elder Reservoir

1. Box Elder Reservoir technology is related to that of Morefield Reservoir.

2. The reservoir dates from A.D. 800-950 based upon a ceramic analysis.

3. Box Elder Reservoir grew up from the valley floor because of the inflow of sediment that was carried along with the water that was diverted.

4. People continued to live in the area after the abandonment of Box Elder Reservoir, as indicated by the potsherds on the surface of the reservoir that were from a later period.

5. Water was delivered to the reservoir via an inlet canal diverted from the thalweg of Prater Canyon.

6. The Box Elder Reservoir site was built on a line that was directly west of Morefield Reservoir in the adjacent valley.

A Remarkable Legacy

The Pueblo I (A.D. 750-900) and the later Pueblo II (A.D. 900-1100) inhabitants of Mesa Verde knew a lot about water harvesting and water storage; we know this because of the irrefutable evidence they left behind in the canyon bottoms and mesa tops. The four reservoirs described provide a remarkable legacy of the industrious and able people of early Mesa Verde who lived in the deep canyon and on the mesa tops, and whom we know as the Anasazi.