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Considering the Multiple Arch Dam: Theory, Practice and the Ethics of Safety in a Case of Innovative Hydraulic Engineering

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ABSTRACT

Various factors influence the technological decisionmaking process and lead engineers to devise solutions to technical problems that cannot be construed as "single-best" answers that respond to the desires of all interested parties with equal alacrity. In this article, the technology of dam building in the early 20th century is examined with specific attention given to the work of John S. Eastwood and his development of the reinforced concrete multiple arch dam. This type of dam offered a way of reducing the cost of dam construction by as much as 50 percent over more traditional technologies and was promoted by Eastwood as part of his search for a better, more efficient means of storing water in the arid western United States. Beyond introducing the reader to a distinctive type of water storage technology, the article elucidates some of the vagaries that intercede into the space separating the world of engineering from the world of science. In this context, the role of practice (or experience) is contrasted with more mathematically oriented approaches to design that are often characterized as "scientific." In conclusion, the article stresses that the scientific and rational nature of modern technology is not always as absolute as generally believed. Safety remains a relative value that only has meaning in terms of how people choose to evaluate a wide range of factors and influences. A key lesson illustrated by Eastwood's experiences in promoting the multiple arch dam is that society, and the legal system, cannot afford to relinquish its responsibility over the technological decisionmaking process to "experts" without appreciating the traditions and technical prejudices that may color their view of what is safe and/or acceptable.

When considering water resources development and the decisionmaking process that controls how hydraulic technologies are implemented, historians and public policy professionals often view engineering

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projects as representing a "single-best" solution to a problem. After all, modern engineers are supposedly trained to provide efficient, scientific answers which, although some parties may find them to be politically or socially undesirable, comprise rational reactions to a situation.

A difficulty with this conception of engineering is the presumption that all engineers ultimately will discern a similar "objective" design so long as they devote enough time and effort to solving a problem. Of course, this is not always the case. However, society as a whole is reluctant to abandon the notion that engineering is an exact science capable of developing ideal responses to technological quandaries.

Although we should not be enamored by a blind faith in technical proficiency, we often take comfort in thinking that adherence to a "scientific method" will foster value-free solutions that, at the very least, are optimal within an engineering context. As part of such thinking, a faith has developed that mathematically-based, theoretical approaches to technical problem solving are more rigorous, and hence more valid, than methodologies stressing the importance of qualitative considerations based upon practical experience. In a legal environment where the influence of expert opinion on judicial proceedings is often quite great, this tendency can have far reaching ramifications affecting the very heart of how our society governs itself.

This paper examines a type of hydraulic technology developed and promoted in the early twentieth century as part of a search for a better, more efficient means of storing water. The first reinforced concrete multiple arch dam was built in 1908–09 by John S. Eastwood in response to the problem of erecting large storage dams while using a very small amount of material.[1] Eastwood's work in developing the multiple arch dam reflected both an interest in designing inexpensive, economical structures and a desire to devise a technically superior method of water storage. In promotional literature, he unabashedly extolled the virtues of his designs by counselling potential clients with advice such as, "Why Build Any Other Type of Dam When You Can Get the Best For Less Money."[2] He further asserted that his self-proclaimed "Ultimate Dam" could be "fitted to any site long, short, high, low, straight, curved, angular, wide or narrow, with greater economy of cost for safety than any other type, because it is designed on TRUE SCIENTIFIC PRINCIPLES."[3]

1. *See* D. Jackson, A History of Water in the American West: John S. Eastwood and the 'Ultimate Dam' (1908–1924) (1986) (unpublished Ph.D dissertation, University of Pennsylvania; for general biographical information on the life of John S. Eastwood). This dissertation contains much of the material presented within this article and is the most comprehensive document available concerning Eastwood's career as a dam engineer. *See also* Whitney, *John S. Eastwood: Unsung Genius of the Drawing Board*, 19 Montana: The Magazine of Western History 38 (1969) (for a good condensed treatment of Eastwood's life).

2. Eastwood, *Eastwood Bulletin*, 5 W. Engineering (1915) (a four-page promotional leaflet was distributed with this technical journal).

3. *Id.* (emphasis in original).

Between 1908 and 1924, when Eastwood died, 17 dams were built using Eastwood's multiple arch designs. A few other engineers became multiple arch dam advocates in the late teens, 1920s and early 1930s, but by World War II the technology had passed out of the design lexicon of American engineering.[4] It became nothing more than an arcane structural type that received, at best, cursory notice in hydraulic engineering textbooks. No multiple arch dams have been built in the United States since World War II but the technology continues to play a role in the world's water resources development. Many of Eastwood's dams, as well as multiple arch dams designed by other engineers, remain in service as they enter their seventh decade or more of operation.

Beyond introducing the reader to a distinctive type of water storage technology, this article elucidates some of the vagaries that separate engineering from the world of science. After providing essential background on the basic principles of dam design, attention focuses on how theoretical methods of design based upon mathematical formulas were used (and later judiciously ignored) by Eastwood in his search for a "scientific" design. In this context, the role of practice, or experience, in the evolution of his design method will be explained and contrasted to more mathematically oriented methods of structural design employed by other early twentieth century dam engineers. In addition, the importance of visual appearance as a criterion by which the engineering community assessed the validity of dam designs will also be discussed.

The distinction between a mathematically rigorous, yet not necessarily imaginative, method of[5] engineering design and a more visually intuitive, yet still carefully reasoned, approach to design has most recently been brought to public attention by Professor David Billington of Princeton University. A structural engineer by training and a leader in the development of thin shell design theory, Billington has devoted much of his career to the study of technological history. In his 1983 book *The Tower and the Bridge: The New Art of Structural Engineering*, Billington examines a range of developments in bridge, roof and building design that have occurred since the early 19th century. His overall analysis includes discussion of how the proliferation of wrought iron, steel and reinforced

4. Aside from Eastwood, the most prominent engineers associated with the promotion of the multiple arch dam were Lars Jorgensen, Fred Noetzli, and B.F. Jakobsen. Interestingly, all three were Europeans who immigrated to California in the early 20th century after receiving advanced technical training at European universities. *See* Jorgensen, *Multiple Arch Dams on Rush Creek, California*, 81 Transactions Am. Soc'y of Civil Engineers 850 (1917); Noetzli, *Improved Type of Multiple Arch Dam*, 87 Transactions Am. Soc'y of Civil Engineers 342 (1924); Jakobsen, *Stresses in Multiple Arch Dams*, 87 Transactions Am. Soc'y of Civil Engineers 276 (1924). The disappearance of the multiple arch dam from American engineering practice is reflected by the lack of articles on the subject since the early 1930s in the Transactions of the American Society of Civil Engineers.

5. D. Billington, The Tower and the Bridge: The New Art of Structural Engineering (1983).

concrete during the industrial revolution opened up possibilities for engineers to develop new structural forms which differed dramatically from those suited for traditional stone masonry work. In addition, Billington develops a concept of "structural art" based upon the ideals of material conservancy, economic efficiency and visual elegance. Without restating at length the principles underlying Billington's idea of "structural art," his views on the evolution of engineering design in the late nineteenth and early twentieth century are worth noting:

> [Following World War I,] everything from factory management to the unconscious sex drive was thought to be amenable to scientific analysis. The truths of life were bound up in formulas which great minds, in academic settings, were carefully setting about to refine and solve . . . In structural engineering this faith in formula led to an emphasis on mathematical analysis which . . . seemed to require that designers justify their works by sophisticated calculation . . . [but] the leading structural artists resisted that trend and sought rather to base design on simplified calculations and on observations of physical behavior.[6]

In his book, Billington does not focus on dam design or any specific issues surrounding the development of the multiple arch dam. Nonetheless, in discussing the evolution of thin shell concrete design, he makes observations directly relevant to an analysis of American dam building:

> [A]s the 1920s wore on, science-based formulas gained prestige. The major results of these formulas were to create a scientific discipline of analysis isolated from design, to set up standard methods of analysis which would come to have quasi-legal status in codes of practice . . . this was not a question of intuition versus rigor, or of approximate and uncertain estimates versus precise and scientific predictions. The primary uncertainties in reinforced concrete behavior have never been removed by mathematical analysis however rigorously consistent.[7]

In other words, the structural engineering establishment of the early twentieth century vigorously embraced the idea that the use of mathematically sophisticated analysis necessarily would foster more accurate methods of design even if mathematical models did not always correlate with physical reality. Billington clearly rejects the position that more complicated mathematical techniques necessarily leads to a more accurate calculation of stresses within a structure. In fact, his notion of "structural art"

6. *Id.* at 213–14.
7. *Id.* at 214–15.

promotes a view of engineering in which practical experience supplements and guides the use of mathematical theory as a means of developing more efficient and socially useful designs. However, the more pervasive trend in 20th century engineering has been antithetical to the principles of "structural art" and has embraced mathematical theory as a primary determinant of structural design rather than as a significant, yet somewhat subordinate, tool in the overall design process.[8] As described below, Eastwood's experiences in promoting multiple arch dams adhere closely to Billington's more generalized observations on the development of structural engineering in the 20th century. But first, in order to relate Billington's views to the particular nature of Eastwood's approach to dam design, some historical background is in order.

THE MASSIVE AND STRUCTURAL TRADITIONS

Dam design can be divided into two basic traditions extending back hundreds of years.[9] The first, and most common, is the massive tradition oriented toward building up such massive quantities of material in a dam that the horizontal thrust of the water in the reservoir is insufficient to move or dislodge the structure from its foundations. The massive tradition is exemplified by earthen or masonry dams of huge proportions erected in accordance with the dictum "more is better." Beginning with dam builders in ancient Egypt and Mesopotamia, the massive tradition represented a simple and logical response to the problem of water storage technology: assemble a large quantity of material in order to insure safety. If a dam washed away, builders would learn that more material was necessary in order to insure structural integrity. Eventually, the massive tradition led to the development of several basic types of earthen, rock and masonry designs that proved their stability through actual construction and long term service. Because massive dams rely solely upon their weight for stability they are usually called gravity dams in recognition of how the force of gravity acting upon the structure's mass is what provides resistance against hydrostatic pressure.

By the mid-nineteenth century European engineers were using mathematical formulas to determine the proportions of masonry gravity dams in an effort to develop a more "rational" method of design for these

8. In discussing the work of the great Swiss bridge engineer Robert Maillart (arguably the greatest of all structural artists), Billington notes that the conflict between mathematical complexity and interest in choice of structural form "would engage Maillart over his entire career, and the power of his designs both scientifically and visually would grow as he went further and further from the mathematical tradition which was increasingly dominating the profession [in the 1920s and 1930s]." *Id.* at 215.

9. N. Smith, A History of Dams (1972); Schnitter, *Roman Dams*, 3 Water Supply & Mgmt. 29 (1979); Schnitter, *The Evolution of the Arch Dam*, 19 Water Power & Dam Construction 34 (1976) (for basic history of early dam construction).

types of structures.[10] Beginning with the Furens Dam in France in the 1860s and continuing with prominent structures such as the Gilleppe Dam in Belgium, the Vrnwry Dam in England, and the New Croton Dam outside of New York City, by the early twentieth century the masonry gravity dam became recognized as the "design-of-choice" for large municipalities and wealthy manufacturing interests.[11] The use of mathematical formulas helped rationalize the design of gravity dams, but structures of this type still required large quantities of material (as befit the massive tradition) and thus were quite expensive.

In addition to solid masonry structures and their antecedents formed out of concrete, the massive tradition includes "fill" dams composed of loose earth, rock or a combination of these two materials. Earthfill and rockfill dams invariably contain huge quantities of construction material and they assume the form of giant sloped mounds large enough to resist the horizontal thrust exerted by water stored in a reservoir. Obviously, earth and loose rock are susceptible to erosion and this limit s their desirability in dam construction projects. However, they often are extremely inexpensive materials that can be located so near a potential dam site they comprise the most economical material for a project. Modern earthen and rockfill dams are not irrationally designed, but the proportions employed for these types of structures primarily are determined by empirically-based experiences rather than a seemingly rigid application of mathematical theory.[12] In many ways, earthfill and rockfill dams exemplify why dam technologies that rely upon excessive size are best characterized as being part of a massive tradition.

In contrast to the massive tradition, the structural tradition of dam design relies upon the shape of a dam rather than mere size in order to insure stability. Although far less common than massive dams, structural dams date back to Roman times and have been built in many parts of the world.[13] In the simplest variant, structural dams rely upon a curved up-

10. The famous "profile of equal resistance" that presented a mathematically rational means for designing masonry gravity dams was first proposed by the French engineer M. De Sazilly in 1853; it was first implemented by M. Delocre for the Furens Dam in France in the 1860s. Smith, *supra* note 9, at 197–200. *See* E. Wegmann, The Design and Construction of Dams 1–45 (3d ed. 1911) (for subsequent development of this profile). The term "equal resistance" derives from the concept of equalizing the compressive stresses at the upstream face of the dam when the reservoir is empty with the compressive stresses at the downstream edge of the dam when the reservoir is filled. The profile (or cross-section through the dam) developed in response to this criteria takes on a characteristic triangular shape with a height-to-width ratio of approximately 3 to 2.

11. Wegmann, *supra* note 10, at 63–209 (for descriptions of these dams).

12. *E.g.* W. Creager, J. Justin & J. Hinds, 3 Engineering for Dams 222–23 (1945) ("precise and highly mathematical methods of design or analysis of earth dams are seldom justified because we know in advance that the assumptions which must be made are sufficiently wide so that no precision is justifiable").

13. Schnitter, *Roman Dams, supra* note 9; Schnitter, *Evolution of the Arch Dam, supra* note 9; Schnitter *The Evolution of the Buttress Dam,* 26 Water Power & Dam Construction (1984) (for a well synopsized history of structural dams).

stream shape, or arch, for stability. Gravity dams can be built along a curved alignment but such curved gravity dams do not necessarily rely upon their curvature in order to resist hydrostatic pressure. For example, the famous Hoover Dam across the Colorado River is curved in plan but its cross-sectional profile is so thick the dam could stand safely even if built without any upstream curve. Consequently, the 726-foot high Hoover Dam is a curved gravity dam and should not be considered part of the structural tradition.[14] In contrast, the 78-foot high Kebar Dam built in 13th century Persia (present day Iran) is built with a maximum cross-sectional profile capable of safely supporting a gravity design only about 50 feet in height.[15] Consequently, the Kebar Dam is a true arch dam exemplifying the structural tradition because its curvature is mandatory in order to achieve stability under full hydrostatic load.

Early arch dams such as Kebar and the seventeenth century Elche Dam in Spain were built empirically and without any theoretical analysis to help determine the appropriate thickness of the arch.[16] In the early nineteenth century the French mathematician Louis Navier developed a simple formula (often called the "ring formula" or the "cylinder formula") that could help engineers determine suitable arch thickness depending upon hydrostatic pressure (i.e. the depth of water in a reservoir) and the curvature or arc of an arch.[17] It appears likely that Navier's theory was used by the French engineer Francois Zola in designing the 130 foot-high Zola Dam near Aix-en-Provence in the 1840s; the theory was certainly utilized in designing the 64-foot- high Bear Valley Dam built in southern California in the 1880s.[18] As a result, by the end of the 19th century the use of rational, mathematically-based design methods had been brought into the realm of the structural tradition.[19]

The other primary variant within the structural tradition is the buttress dam. In basic form, buttress dams do not constitute designs with cross-sectional profiles that remain constant across the length of the dam. Instead, buttress dams use a series of discrete thick walls (or buttresses) that absorb the hydrostatic pressure and allow the overall quantities of material in the dam to be reduced.[20] Primitive buttress dams consist of simple masonry designs which have been strengthened by the erection of buttress walls along the downstream face. But to achieve substantial re-

14. Schnitter, *Arch Dams*, *supra* note 9 (describing the Hoover Dam as a "massive curved gravity structure").
15. *Id.* (for description and illustration of the Kebar Dam).
16. Smith, *supra* note 9.
17. *Id.*
18. Smith, *supra* note 9, at 181–83, 207–08; Schnitter, *The Evolution of the Arch Dam*, *supra* note 9, at 36–38.
19. Schnitter, *Evolution of the Arch Dam*, *supra* note 9.
20. Schnitter, *The Evolution of Buttress Dams*, *supra* note 13.

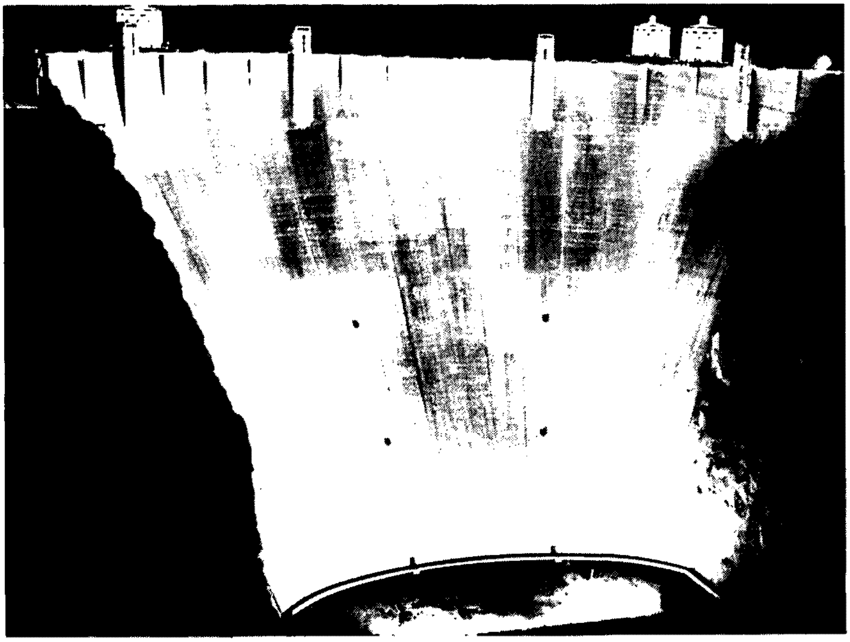

Figure 1: The downstream side of the curved gravity Hoover Dam (completed 1935). The conservative proportions of this 726-foot high structure exemplify the massive tradition of dam design. Note how its appearance contrasts with the downstream side of the Littlerock Dam. [Source: Prints and Photographs Division, Library of Congress]

ductions in the amount of material required, buttress dams usually use designs with an inclined upstream face. This upstream face forms a barrier that holds back the water in the reservoir; in turn, the upstream face is supported by buttresses carrying the hydrostatic forces down to the foundations. By inclining the upstream face into the reservoir, it is possible to reduce the amount of concrete or masonry necessary for overall structural stability. If the buttresses are used to support a flat slab that forms the upstream face, then the design is known as a "flat slab buttress dam." If, instead, the upstream face is formed by a series of arches that are supported on the buttresses, then the design is referred to as a "multiple arch dam."

The multiple arch dam represents a particularly efficient form within the structural tradition because it uses both the arch and the buttress principle in its design. The use of discrete buttresses allows the amount of material within the body of the dam to be reduced significantly, while the use of arches for the upstream face allows this part of the design to be built with a minimum amount of material. Small examples of multiple arch dams using stone masonry were built in Spain in the eighteenth

century, but the blossoming of multiple arch dam technology needed the development of reinforced concrete construction techniques in the late nineteenth and early twentieth centuries.[21]

The massive and structural traditions of dam design have existed for centuries and attracted the interest of a wide range of builders. Although some engineers have prepared designs within both traditions, it is more typical for an individual (or engineering bureaucracy) to devote their professional energies to erecting structures within a single tradition. As a consequence, an engineer skilled and knowledgeable in the practice of one tradition may be quite unsuited to rendering a valid, unbiased assessment of a design developed out of another tradition. As we shall see, John Eastwood became an impassioned advocate of the structural tradition in dam design and this ultimately brought him into conflict with John R. Freeman, a prominent advocate of the massive tradition. The two engineers believed each other to be responsible for promulgating designs which were either unsafe, uneconomical, or both.[22] In truth, the roots of their antipathy for one another came from the fact that each approached issues of dam design from different perspectives, different traditions and from different self interests.

EASTWOOD AND THE MULTIPLE ARCH DAM

Born in Minnesota in 1857, John Eastwood attended the University of Minnesota as an engineering student before heading West to work on railroad construction in the early 1880s.[23] In 1883, he set up shop as a civil engineer/surveyor in Fresno, California and for the next 29 years worked in the heart of the state's Central Valley. During the 1880s and early 1890s, he undertook a variety of jobs ranging from the city engineer for Fresno to surveyor for lengthy lumber flumes in the Sierra Nevada mountains.[24] Eastwood's interest in water storage extended from his work as chief engineer for the San Joaquin Electric Company in the mid-1890s when, under his direction, the company built a sophisticated hydroelectric power system that transmitted 11,000 volt alternating current to Fresno over a transmission line 34 miles long. At the time operations began in April 1896, this

21. Smith, *supra* note 9, at 118–20 (for description of several small buttress dams built by Don Pedro Bernardo Villareal de Berriz); Garcia-Diego, *The Chapter on Weirs in the Codex of Juanelo Turriano: A Question of Authorship*, Technology & Culture 217 (1976) (for description of a sixteenth-century multiple arch dam design).

22. Jackson, *supra* note 1, at 330–424.

23. *Id.* at 151–70. The primary source of material on Eastwood's life is the John S. Eastwood Papers at the Water Resources Center Archives, University of California, Berkeley, CA. These papers are divided into a series of numbered folders that refer to either a specific project or a particular file. Hereafter, material from folders in the Eastwood Papers will referenced as JSE, WRCA.

24. *Id.* at 151–70.

constituted the longest commercial power system in the world.[25] Unfortunately, the company's plant depended upon a steady flow of water in the North Fork of the San Joaquin River to power its turbines. Because the company initially could not afford to build a large dam for storing spring flood waters, operation of the plant was hindered severely by a drought that hit central California in the late 1890s. This drought ultimately forced the San Joaquin Electric Company into bankruptcy in 1899, and Eastwood retained no financial interest in the reconstituted San Joaquin Light and Power Corporation that took over the insolvent system.[26] Eventually the new company became a very profitable component of the San Francisco-based Pacific Gas and Electric Company and proved the viability of Eastwood's pioneer electric power project.[27] Although blocked from participating in the long term economic success of the San Joaquin facility, Eastwood did not lose interest in either hydroelectric power technology or the subject of dam design.

During the first decade of the twentieth century, Eastwood planned a new hydroelectric power system for the main stem of the San Joaquin River. Today known as Big Creek, this development is operated as part of Southern California Edison Company's power grid and provides a generating capacity of almost one million horsepower.[28] Eastwood's development of the reinforced concrete multiple arch dam resulted directly from efforts to devise an inexpensive means of storing water for the Big Creek system.[29] Eastwood had no desire to repeat the experience of the drought-plagued San Joaquin Electric Company, and he set out to develop a dam type that would minimize construction costs. To accomplish this, he sought a design that would reduce the amount of material necessary for stability. Perforce, he became an advocate of the structural tradition of dam construction.

25. Low, *The Fresno Transmission Plant*, 2 J. Electricity 79 (1896).

26. Jackson, *supra* note 1, at 209–11.

27. F. Fowler, Hydroelectric Power Systems of California and Their Extensions into Oregon and Nevada 454–58 (1923) (for the financial history of the San Joaquin Electric Company); C. Coleman, P. G. and E. of California: The Centennial Story of the Pacific Gas and Electric Company (1952) (for description of the later success of the San Joaquin Light and Power Company).

28. D. Redinger, The Story of Big Creek (1949); W. Myers, Iron Men and Copper Wires: A Centennial History of the Southern California Edison Company (1983) (for more on the Big Creek power system).

29. Henry E. Huntington Collection in the Henry E. Huntington Library, San Marino, CA. Within the Huntington Collection there are a few specific documents in file No. 11/7/(2) providing evidence of Eastwood's development of a multiple arch buttress dam design for use at Big Creek. *E.g.* J. Eastwood, Report on the Comparative Cost of Plant Showing the Advantages of the Use of Buttressed Dams (Aug. 3, 1906). *See* Dams (circa 1907) (unpublished report, in JSE, WRCA, No. 21; for evidence of Eastwood's desire to build multiple arch dams at Big Creek).

Figure 2: View showing the multiple arches that form the upstream face of John S. Eastwood's Big Bear Valley Dam (completed 1911). The vignette on right shows Eastwood circa 1912 [Source: Eastwood Papers, Water Resources Center Archives, Berkeley, California]

Because of financial uncertainties caused by the Panic of 1907 and because of corporate machinations surrounding the management and control of the Pacific Light and Power Corporation, Eastwood was prevented from implementing his innovative multiple arch dam technology at Big Creek.[30] However, in 1908, he was given the opportunity to design and build the 64-foot-high Hume Creek Dam as part of the Hume-Bennett Lumber Company's new logging plant in the Sierra Nevadas about 50 miles east of Fresno.[31] Completed in 1909, this structure was the world's first reinforced concrete multiple arch dam. In 1910, he began work on the 92-foot high Big Bear Valley Dam in southern California to be used by irrigation farmers to increase crop production in the Redlands/San Bernadino region.[32] These first two dams were important structures for the

30. Whitney, Dollars and Genius Built Southern California (circa 1970) (unpublished manuscript; a copy of this document is on file at the Water Resources Center Archives, Berkeley, CA). *See* Jackson, *supra* note 1, at 217–69. Actual construction of the initial Big Creek system was undertaken by the Boston-based engineering firm of Stone & Webster (using Eastwood's plans) in 1912–1913. H. Johnston, The Railroad the Lighted Southern California (1966).

31. Eastwood, *Hume Lake Dam*, 23 J. Electricity Power & Gas 398 (1909). *See* JSE, WRCA, No. 12.

32. Eastwood, *The New Big Bear Valley Dam*, 3 W. Engineering 458 (1913). *See* JSE, WRCA, No. 1.

people and organizations that commissioned Eastwood to build them, but they were not the types of projects that attracted widespread attention. However, in late 1911, he began working on a project for the Great Western Power Company that brought his dam design work to the attention of the national civil engineering community.[33]

In the early 20th century the Great Western Power Company was a major competitor of the Pacific Gas and Electric Company (P.G.& E.) in northern California.[34] During the 1920s, the two companies eventually merged together, but in 1911, Great Western sought to expand its system on the North Fork of the Feather River (about 100 miles north of Sacramento) in order to compete better with P.G.& E. As part of the new Feather River system, the company planned to build a large storage dam at a reservoir site known as Big Meadows in order to regulate water flow through a series of hydroelectric power plants along the lower part of the river. Originally, the company planned to build a concrete gravity dam at this important reservoir site, or at least this had been the hope of engineering consultant John R. Freeman. Freeman was a graduate of the Massachusetts Institute of Technology and a prominent hydraulic engineer who had advised Boston, New York City and Los Angeles on the design and construction of their municipal water supply systems. In addition, Freeman had served as president of the American Society of Mechanical Engineers and as vice-president of the American Society of Civil Engineers.[35] Although well connected with the New York financial community, Freeman discovered that his influence upon the corporate leadership of the Great Western Power Company seriously waned when H.H. Sinclair, an experienced California-based electric power entrepreneur, became vice-president in charge of the firm's California operations in 1909.[36] Much to Freeman's chagrin, in early 1911 Sinclair gave Eastwood responsibility for developing a multiple arch design for the Big Meadows site.[37]

Within this article it is impossible to recount the full story of the controversy involving Eastwood, Freeman and the Big Meadows Dam.

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33. Jackson, *supra* note 1, at 341.

34. Coleman, *supra* note 24, at 211–24, 267–76 (for history of the Great Western Power Company).

35. John Ripley Freeman, 98 Transactions Am. Soc'y of Civil Engineers 1471 (1933) (for Freeman's obituary with a description of his professional career).

36. Sinclair's experience with California's electric power industry dated back to the early 1890s when he served as vice president for the Redlands Electric Light and Power Company, a firm which later became a key component of the Southern California Edison Company. *See* Henry Harbinson Sinclair Papers, Henry E. Huntington Library, San Marino, CA. (for evidence of Sinclair's difficulties with Freeman). *See also* John Ripley Freeman Papers (MC51), Institute Archives and Special Collections, Massachusetts Institute of Technology, Cambridge, MA (for evidence of Freeman's disagreements with Sinclair).

37. *The Big Meadows Dam*, 27 J. Electricity Power & Gas 287 (1911). *See* JSE, WRCA, No. 18 (for evidence of Eastwood's extensive involvement in planning and building the Big Meadows Dam).

However, two aspects of the events surrounding Eastwood's attempts to build the Big Meadows Dam are relevant to issues addressed in this article: 1) How Eastwood responded to technical criticisms of his design that were made on the basis of mathematical analysis, and 2) Freeman's ability to use non-technical arguments (or what he termed "psychological" concerns) to force abandonment of Eastwood's half-built multiple arch design in favor of a massive earthfill structure. Each of these topics will be considered separately within the context of Eastwood's overall career and the development of twentieth century dam engineering.

THE ROLE OF MATHEMATICAL THEORY

The first issue concerns how Eastwood used mathematical theory in his design method and how practical experience and observation of structural behavior affected the form of his subsequent design. Eastwood's most obvious and immediate use of mathematical formula came in determining the thickness of the arches that enclosed the space between the buttresses. To calculate the thickness of the arches at various elevations within the dam, Eastwood used the formula developed by Navier in the 1820s known as the cylinder formula.[38] Using this formula, the thickness T of an arch under hydrostatic pressure is equal to the pressure P multiplied by the radius R of the arch divided by the allowable stress Q, or:

$$T = P \times R / Q$$

With concrete having an ultimate strength of about 3,000 pounds per square inch (psi), Eastwood determined that concrete could easily withstand stress equaling ten percent of this ultimate strength, thus providing an allowable stress Q of 300 psi. With Q held at a constant, and with hydrostatic pressure P constant for any given depth of water, Eastwood was able to vary the arch thickness T in direct proportion to the radius R of the arch.[39] Taking the distance between the buttresses to be a constant, any variation in the radius R necessarily changes the arc encompassed by the arch. For example, with a distance of 20 feet between buttresses, a radius R = 10 feet will create an arch with an arc of 180 degrees (or a semicircle). As R becomes larger, the arch will necessarily become flatter and the arc will decrease.

In using the cylinder formula, engineers have long understood that it represents an idealized model that only approximates conditions

38. Schnitter, *The Evolution of the Arch Dam*, *supra* note 9, at 36.

39. Eastwood, *The Ultimate Dam*, 3 W. Engineering 175 (1913); Eastwood, *The Eastwood Multiple-Arched Dam*, 33 J. Electricity Power & Gas 49 (1914); Eastwood, *The Multiple-Arched vs. the Single-Arched Dam*, 38 J. Electricity 149 (1917). *See* Jackson, *supra* note 1, at 486–546 (providing a complete discussion of Eastwood's method of design).

within actual structures. For example, to be completely accurate the cylinder formula requires that the foundations supporting the arch be absolutely rigid and unyielding. Although this condition is unattainable in practice, reinforced concrete and hard rock foundations are usually sufficiently rigid that the formula retains much of its validity despite discrepancies between theoretical assumptions and actual conditions. Another limitation of the cylinder formula that has caused many engineers to question its value as a predictive mathematical model relates to the formula's inability to consider the effect of structural deformation (sometimes called "rib-shortening") and temperature changes on the distribution of stresses within the arch. To cope with such effects in analyzing arch stresses, by the early twentieth century engineers were using the elastic theory of arches to provide a mathematical means of calculating the stresses created by rib-shortening and temperature changes [note: sometimes these two type of stresses are jointly referred to as secondary stresses].[40] Use of the elastic theory indicates an increase in stresses for arches with very flat arcs. In other words, to reduce rib-shortening and temperature stresses to a minimum, the elastic theory directs engineers to use an arch with an arc of 180 degrees. The flatter the arch, the greater the effect of secondary stresses; consequently, arches with an arc of 120 degrees will (at least according to the elastic theory) always be more stressed than comparable arches with an arc of 140 degrees. This is significant because there can be good economic reasons, such as reduced costs for concrete and reduced costs for wooden formwork, that might lead an engineer to use a flat arch despite being informed by the elastic theory that flatter arches induce higher stresses.

While the Great Western Power Company was considering the advisability of using a multiple arch dam for Big Meadows, Eastwood evaluated the effect of secondary stresses upon his arch designs. Utilizing the elastic theory, he determined that the effect of rib-shortening and temperature changes could be minimized by the use of deep arches encompassing an arc of over 140 degrees.[41] Eastwood understood that his multiple arch dams employed relatively thin arches for the "water face" [i.e. the barrier that held back the reservoir] and he wanted to be certain that his arch designs were strong enough to resist any forces that might cause them to crack or collapse. Consequently, when the seemingly sophisticated elastic theory indicated that deep arches could reduce stresses that might precipitate cracking, Eastwood incorporated this design feature into his plans for the Big Meadows Dam.

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40. I. Baker, A Treatise on Masonry Construction 670–703 (10th ed. 1909) (chapter 23 is devoted to the subject of analyzing arches which are considered to support their loads "by virtue of the internal stresses developed in the material"). *See* Cain, *The Circular Arch Under Water Loads*, 85 Transactions Am. Soc'y of Civil Engineers 233 (1922).

41. J. Eastwood, Discussion of Temperature Stresses in the Multiple Arch Dam (Oct. 1912) (unpublished report making specific reference to the tenth edition of Baker, Treatise on Masonry Construction, as a source for Eastwood's method of analysis; JSE, WRCA, No. 12).

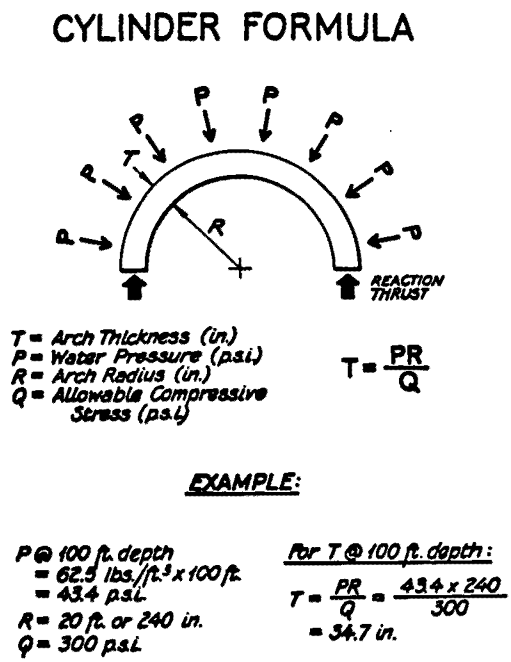

Figure 3: Illustration showing how the cylinder formula can be used in arch design. [Source: Courtesy Richard K. Anderson from D. C. Jackson Collection]

When Eastwood continued his dam design career after working on the Big Meadows project, he remained committed to using deep arches as a way to reduce the deleterious effect of secondary stresses. In fact, with his Los Verjels Dam (completed in late 1913), he employed arches with an arc of over 144 degrees, the deepest of any of his structures.[42] For his next commission (the Kennedy Dam erected in 1914) he adopted a new structural tactic to eliminate secondary stresses in the arches.[43] Rather than merely rely on a deep arch as a means of countering such stresses, Eastwood devised a "three-hinge" design that would allow the arches to adjust themselves (by minute internal rotation) in response to any rib-shortening or temperature stresses that might cause cracking. At the time, "three-hinge" designs were becoming popular among reinforced concrete bridge engineers as an innovative way to reduce uncertainty in stress analysis.[44] Eastwood picked up on this trend and in 1914 began adapting it for

42. Eastwood, *Los Verjels Dam: A Multiple Arch Structure*, 5 W. Engineering 7 (1914).
43. Eastwood, *The Kennedy Dam*, 5 W. Engineering 407 (1915).
44. *E.g. A Three-Hinged Concrete Arch Bridge Over the Danube at Eringen*, 47 Engineering News 35 (1902) (for one of the earliest references to three-hinged arch technology).

his dam designs.[45] The three-hinge arch appeared to offer an ideal way of counteracting the effect of secondary stresses and in 1915 Eastwood employed the feature as a key part of his 150-foot-high Mountain Dell Dam design for Salt Lake City.[46] However, he soon abandoned the technology and moved toward the use of rigid [i.e. non-hinged] arches with very shallow arcs. In fact, during the final years of his career he developed designs with arches as shallow as 100 degrees in apparent defiance of the elastic theory. To understand why Eastwood changed his approach to arch design, we must consider how he perceived the relation of mathematical theory to actual construction experience (or practice) in his effort to develop more sophisticated, and useful, dam designs.

First, it is significant that almost all engineers (aside from Eastwood) who advocated use of multiple arch dams in the 1920s relied upon the elastic theory and considered the use of 180-degree arcs as mandatory if arch stresses were to be minimized.[47] Billington's comment about the engineering profession's slavish devotion to mathematical formulas after World War I is extremely accurate in regard to how most engineers approached the process of multiple arch dam design. In retrospect, what is most disconcerting about this phenomenon is how many engineers could turn a blind eye to practical, in-the-field observations that were not compatible with conjectures indicated by mathematical theory. In this context, Eastwood distinguished himself as being responsive to how his designs actually functioned in the real world, regardless of what mathematical analysis might predict.

This duality between theory and practice can be most clearly appreciated when analyzing why Eastwood dropped his use of three-hinge arches, despite the advantages this technology seemed to offer in countering the effect of secondary stresses. Specifically, during final construction of the Mountain Dell Dam, a thin coating (or wash) of cement was applied to the upstream face of the structure's three-hinge arches. This cement coating provided a smooth surface for the upstream face but was not intended to serve any structural purpose. Presumably, when the three-hinge arches would rotate in response to temperature and other rib-shortening stresses, small vertical cracks would appear in the cement coating and provide evidence of the hinges' movement. However, such cracking did not

45. JSE, WRCA, No. 14; and JSE, WRCA, No. 35 (these files describe two unbuilt designs prepared by Eastwood in 1914–15 that used three-hinged arches).

46. *High Multiple-Arch Concrete Dam for Salt Lake City Water Supply*, 80 Engineering-News Record 455–57 (1918); Cannon, *The Mountain Dell Dam*, 3 Monthly J. Utah Soc'y of Engineers 223 (1917).

47. *See* Jakobsen, *supra* note 4. *See also* E. Wegmann, Design and Construction of Dams (8th ed. 1927) (this edition of Wegmann's book contains a special section on designing multiple arch dams written by Fred Noetzli).

occur. In fact, Fred Noetzli, a multiple arch dam designer and advocate of the elastic theory, noted in 1927:

> It was found [during a 1925 inspection] that in the seven years of operation of the [Mountain Dell] dam and reservoir none of the hinges had moved a sufficient amount to break the thin coating of cement wash, except for a distance of one to two feet from the crest of the dam down. The hinges were painted with asphalt and probably offered relatively little resistance to rotation due to deformation of the arches. It appears, therefore, that the deformation of the arches was too small to break the cement coating.[48]

Amazingly, Noetzli's observation did not lead him to question the validity of relying upon the elastic theory when designing arches for multiple arch dams. Instead, he declined to use the actual physical behavior of a functioning structure as a rationale for modifying his reliance upon mathematical theory in the dam design process. Despite undeniable indications that rib-shortening and temperature stresses were negligible in the arches of multiple arch dams (otherwise the cement wash on the face of the Mountain Dell Dam would have exhibited cracks), Noetzli continued to advocate the use of 180 degree arches as a means of countering the supposed secondary stresses revealed by the elastic theory.

In contrast to Noetzli's reaction, by late 1916 Eastwood expressed dissatisfaction with the elastic theory based on "the result of experience and many trials."[49] In response to adherents of the elastic theory who claimed that high arch stresses existed in many multiple arch dams, Eastwood defended his design method by stating: It is undoubtedly the proper procedure to fit theory to practice but the factors of the theory must be based on the actual physical conditions as they are in practice or else theory will lead us astray.[50]

After constructing three-hinge arches as part of the Kennedy and Mountain Dell Dams and then observing their actual performance, Eastwood came to appreciate several variances that existed between theoretical assumptions and physical realities in relation to the structural performance of his designs. These variances included such conditions as: a) the hydrostatic loadings on the arches are not uniform because the upstream face of most multiple arch dams are built on a slope; b) the supports for the arches (i.e. the buttresses) are not rigid and inelastic, but are similar in elasticity to the arches themselves; and c) with the reservoir filled, the

48. Wegmann, *supra* note 42, at 482.

49. Letter from J. Eastwood to P. Downing (Sept. 27, 1916) (JSE, WRCA, No. 4; discussing limitations of the elastic theory).

50. *Id.*

upstream side of the arches are saturated with water which causes the arches to expand in volume (just as a slice of bread will expand in size if soaked in water); this expansion will consequently help counteract any rib-shortening stresses caused by the hydrostatic loading.[51] The precise technical significance of the factors listed above need not be explicated in this article. However, what is important to realize is that the ability of the elastic theory to accurately determine arch stresses is very much affected by variance in these factors.

Rather than adhere to the dictates of seemingly advanced mathematical theory or attempt to assess quantitatively the inaccuracy of the elastic arch theory, Eastwood chose another approach to the problem of dam design. As such, he opted to use the relatively simple cylinder formula and design thin arches that provided relatively good compatibility with the theoretical assumptions underlying this formula. When the elastic theory led to conclusions incompatible with the actual structural performance of his dams, he did not hesitate to reject the universal validity of this theory in favor of the less complicated cylinder theory. The cylinder formula may not have been absolutely accurate in its ability to predict stresses within multiple arch dams, but Eastwood recognized that it could provide good estimates that were more than sufficient to insure structural safety.

Eastwood sought to forge a logical, but oftentimes misunderstood, middle ground between highly abstract, academic approaches to structural design and engineering based upon practical field experience. After being confronted with numerous studies that seemingly showed his designs to be unsafe or unstable, he drafted a memo entitled "Limitations to Formulae" in the early 1920s in which he denigrated the notion that mathematical theory could always provide exact answers to structural problems involving the physical environment.[52] Recognizing how mathematical formulas could only provide answers that were relatively accurate, Eastwood aptly compared this situation with the newly-popularized theories of Albert Einstein by observing: "Einstein is right! All lines are curves and all things mundane are relative."[53] Eastwood's pragmatism produced stable dams but ran counter to the notion that engineers could, and should, precisely calculate stresses in man-made constructs. Consequently, his design methods represented a challenge to the idea that mathematical formulas can establish beyond cavil the magnitude of all stresses

51. *Id.*; and Letter from J. Eastwood to W.S. Post (March 27, 1917) (Carroll Dam Folder, Box 8, Ed Fletcher Collection, Special Collections, University of California, San Diego) (describing in detail Eastwood's thoughts on why the elastic theory did not provide accurate results when used to calculate arch stresses in multiple arch dams).

52. J. Eastwood, Limitations to Formulae (circa 1922) (JSE, WRCA, No. 45; unpublished report).

53. *Id.*

within a structure. Rather than claim that the limitations of such formulas stripped them of any validity, he championed the idea that careful consideration of how theory related to physical reality would lead to the true ideal of scientific design.

Unfortunately for Eastwood, engineers generally have moved away from his practical approach to dam design in the decades since his death. The divergence was well demonstrated in the late 1960s, when the Bechtel Corporation, a major American engineering firm, analyzed the safety of Eastwood's 1924 Littlerock Dam in southern California.[54] This modern, "scientific" engineering firm utilized a special mathematical methodology of its own to analyze the stresses in the buttresses of multiple arch dams. On the basis of this simplified, yet seemingly precise, investigation the firm determined that dangerous stresses would exist at the upstream face of the buttresses at times when the reservoir was filled.

These stresses were calculated to be so great as to precipitate possible collapse if the buttresses were placed under the loading of a full reservoir. Based upon this analysis the firm proposed a complicated means of "strengthening" the buttresses with external steel cables, all the while conveniently forgetting that for more than 40 years the reservoir frequently had been filled with no damage resulting to the structure.[55] In this context, a comparison between Noetzli's and the Bechtel Corporation's approach the problem of analyzing stresses in multiple arch dams is illuminating.

Noetzli may not have fully appreciated the implications of the Mountain Dell Dam's non-moving hinges, but at least he refrained from attacking the safety of the design based upon his interest in promoting the value of mathematical analysis over practical insight. However, by the 1960s a major engineering firm chose to ignore the 40 year performance history of the Littlerock Dam in deference to mathematical analysis which indicated the existence of supposedly dangerous buttress stresses; this predilection to consider the results of mathematical analysis to be somehow sacrosanct ultimately led to a bitter court battle focused around the issue of whether or not the Littlerock Dam represented an imminent threat to public safety.[56]

54. Bechtel Corporation, Littlerock Dam Safety Study (Jan. 1968) (copy available in the records of the Littlerock Creek Irrigation District, Littlerock, CA). *See* Jackson, *Controversy in Concrete: The Littlerock Dam (1918–1977)*, Proc. Am. Soc'y of Engineering Education 471 (1982); and D. Jackson, Great American Bridges and Dams, at 74–78 (1988) (providing detailed discussion of engineering issues surrounding the operational history of the Littlerock Dam).

55. Bechtel, buttress strengthening page ref.

56. Based upon the 1968 Bechtel Corporation report, the California Division of Safety of Dams took legal action to force revocation of the state permit that allowed the Littlerock and Palmdale Irrigation Districts to store water behind the Littlerock Dam. The decision to prevent the state from revoking the storage permit without complying with the requirements of the California Environmental Quality Act (CEQA) is recorded in Citizen's Committee to Save the Littlerock Dam, Inc. v. Robie, c184 269 (Superior Court, County of Los Angeles, Apr. 20, 1977).

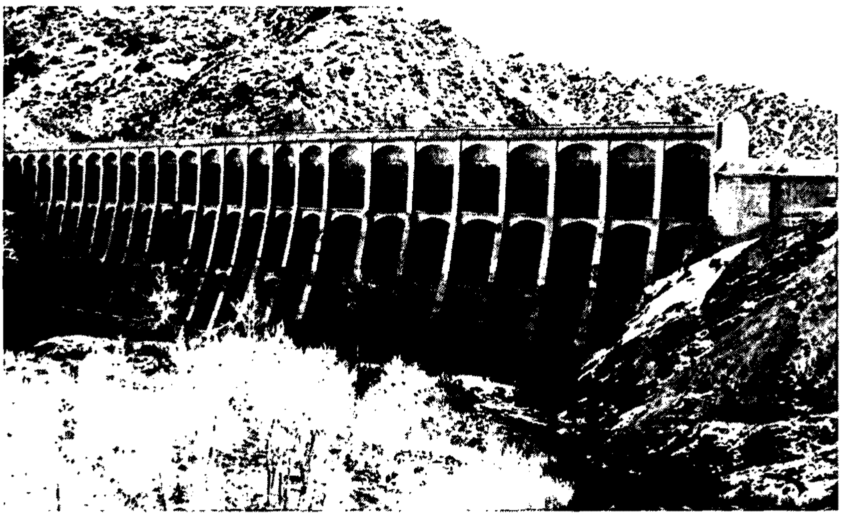

Figure 4: View showing the buttresses that form the downstream side of the Littlerock Dam (completed 1924). With a maximum height of 170 feet, it stands as Eastwood's tallest dam. [Source: D. C. Jackson Collection]

THE "PSYCHOLOGY" OF THE MULTIPLE ARCH DAM

As discussed previously, the Big Meadows Dam first prompted John Eastwood to confront the theoretical possibility of using the elastic theory of arch analysis in his search to discover better ways of designing multiple arch dams. In contrast, when John R. Freeman sought to convince the Great Western Power Company to abandon construction of Eastwood's half completed dam, he primarily drew upon non-technical, non-mathematical arguments to influence the corporation's decision making process. Whereas Eastwood focussed his creative energies on the technical and mathematical issues that surrounded the process of dam design, Freeman discerned a dramatically different approach to the subject involving arguments which were difficult, if not impossible, to counter with strictly technical counter arguments.

After H. H. Sinclair became vice-president of the Great Western Power Company, Freeman exercised little control over planning for the Big Meadows Dam.[57] However, this situation changed in February 1912 when Edwin Hawley, president of the company and the person responsi-

57. Executive Committee of the Great Western Power Company, Relating to Construction [of] Permanent Dam and Method of Future Expenditure (May 20, 1910) (unpublished report, Sinclair Papers, *supra* note 36; for evidence of Freeman's lack of influence within the Great Western Power Company).

ble for bringing Sinclair into the firm, passed away. In his place Mortimer Fleishhacker, a San Francisco banker who recently had become involved with Great Western because of his control over San Francisco's City Electric Company, assumed the presidency. Fleishhacker held no special relationship with either Sinclair or Eastwood, and within a few weeks after Hawley's death Freeman began a campaign to gain Fleishhacker's confidence and force abandonment of Eastwood's Big Meadows design.[58]

This campaign extended over the next several months with Freeman claiming that while he "fully believe[d] in the multiple arch principle for many sites . . . [he had] doubts about [Big Meadows] being the best place [for it]."[59] Although he expressed concern over technical matters such as "imperfect theories of stress" that related to the cylinder formula, Freeman's most devastating attack on the multiple arch concept did not rely on technical arguments *per se*.[60] After making a one-day visit to the construction site in August 1912 Freeman began castigating Eastwood's design because of its visual appearance. Referring to undefined "popular apprehensions and misapprehensions," Freeman hypothesized how the general public might react to the distinctive appearance of multiple arch dams with the assertion:

> [T]he psychology of [the multiple arch dam's] airy arches and the lace curtain effect of Eastwood's stiffening props [between the buttresses] is not well suited to inspire public confidence.[61]

Freeman's perspective in arguing against the multiple arch dam derived directly from his adherence to the massive tradition of dam design, a tradition which placed little emphasis on conserving the amount of construction material required for a structure. Freeman reported that he had "repeatedly informally urged [the Great Western company] . . . to build a big massive lump of a dam." because he considered dams to be a technology in which the appearance of bulk was a natural and desirable feature, regardless of whether or not this bulk served any useful purpose.[62] Because Eastwood's design seemed to present an "airy" appearance, Freeman went so far as to recommend formally to the company that they consider "lessen[ing] the apparent height of the slender buttresses... [by placing a] fill of loose fragments of rock and gravel" along the downstream side of the dam where it would serve no structural purpose.[63] Interestingly, he defended the value of such a costly action purely on the

58. Letter from J. Freeman to A.W. Bullard (Feb. 23, 1912) (Freeman Papers, *supra* note 36).
59. *Id.*
60. *Id.*
61. Letter from J. Freeman to A. Davis (Sept. 30, 1912) (Freeman Papers, *supra* note 36).
62. *Id.*
63. Letter from J. Freeman to H.P. Wilson, secretary of the Great Western Power Company (Sept. 30, 1912) (Freeman Papers, *supra* note 36).

grounds of "diplomatic or psychological reasons."[64] Thus, Freeman advocated an expensive alteration of the appearance of Eastwood's Big Meadows Dam simply so that it would look like a massive earthfill dam. As he put it in October 1912:

> [P]lainly, it is worthy of some considerable expenditure beyond that necessary to satisfy engineers... in order to satisfy the more or less ignorant public... [who would] regard [Eastwood's] dam not from a technical standpoint, but by comparison with the solid gravity type of masonry or earth."[65]

Eastwood made a valiant attempt to defend the integrity of his design, but Freeman's attack on the "psychology" of the multiple arch dam found an audience with Fleishhacker and other corporate leaders of Great Western.[66] Apparently these businessmen were more inclined to listen to the highly respected Freeman than to an engineer who had spent most of his career in the remote hinterland of Fresno. In March 1913, the Great Western Power Company officially abandoned Eastwood's multiple arch design, despite having already expended hundreds of thousands of dollars on its construction.[67] In its place they chose to build a completely new, and much more expensive, massive earthfill dam.[68] Officially, the company's decision to change plans was justified in terms of minor foundation problems that led them to opt away from a daring new design.[69] However, any foundation problems that might have affected Eastwood's design would have been equally (or more) troublesome for a gravity masonry or earthfill dam. At the root, Eastwood's design was abandoned because of Freeman's success in castigating its unorthodox appearance as being ill-suited to the proper image of the Great Western Power Company, an appeal that struck a resonant chord in the corporate hierarchy.

After the debacle at Big Meadows, Eastwood entered a period in which he had to scramble intensely in order to obtain even small-scale design commissions; in fact, it was not until the early 1920s that he began to work on projects that approached the scale of Big Meadows. Meanwhile,

64. *Id.*

65. Letter from J. Freeman and A. Noble to H.P. Wilson (Oct. 17, 1912) (Freeman Papers, *supra* note 36; this letter was officially signed by both Freeman and Alfred Noble, a prominent New York City-based consulting engineer, but it was written almost entirely by Freeman).

66. J. Eastwood, Description and General Specifications of the Big Meadows Dam (circa Oct. 1912) (unpublished report); J. Eastwood, Non-Technical Description of the Big Meadows Dam (circa Oct. 1912) (unpublished report); Letter from J. Eastwood to M. Fleishhacker (Feb. 13, 1913) (JSE, WRCA, No. 18).

67. Jackson, *supra* note 1, at 382–84.

68. *Raising the Big Meadows Dam, Plumas, Cal.*, 3 Modern Irrigation 42 (1928) (describing earthfill dam built at Big Meadows).

69. Jackson, *supra* note 1, at 330–424 (for a complete analysis of all aspects of the Big Meadows controversy).

Freeman continued to gain influence in the engineering establishment as he ascended to the presidency of the American Society of Civil Engineers in 1923–24.[70] Throughout the final 20 years of his career Freeman remained a staunch proponent of massive gravity dams and refused to consider multiple arch dams as worthy of serious attention.[71] Without question, Eastwood's long-term success in promoting his dams was seriously impeded by Freeman, and this opposition derived from the latter engineer's personal and professional interest in advocating the massive tradition as a superior method of dam design.[72] Most remarkably, in light of his scientific training at the Massachusetts Institute of Technology, Freeman did not hesitate to brandish the most non-technical, "unscientific" arguments in order to stop construction of a dam design that did not adhere to a tradition and style of his own choosing.

CONCLUSION

The purpose of this article is not merely to rescue the good name of John S. Eastwood and bring his career greater public attention. Nor is it oriented toward getting people to think that multiple arch dams comprise the only type of water storage technology that should ever be built. As a technology, multiple arch dams have their limitations, and in the latter 20th century the economics of building such labor-intensive structures has not been particularly compelling. However, in terms of assessing Eastwood's accomplishments it is important to understand that everyone of his 17 dams constituted the least expensive design for a project (there is no evidence that any of his designs were ever underbid) and that none of his designs ever failed in any manner which caused loss of life or property.[73]

Given both the inability of the engineering establishment to accommodate Eastwood's design method with a more mathematically oriented approach to structural design and the manner in which engineers such as Freeman castigated Eastwood's dams on the grounds of visual appearance, a few comments on the ethics of technological safety are in order. As a society we are eager to live in a world where our physical safety is never threatened and where people responsible for technological mis-

70. Eastwood, *supra* note 32.

71. J. Freeman, Summary of Recommendations Regarding Future Extensions of Water Supply for the City of San Diego, Cal. 81–82 (May 16 and 22, 1924) (a copy of this report, which provides evidence of Freeman's long-standing disinterest in multiple arch dams, is on file at the Water Resources Center Archives, Berkeley, CA).

72. Letter from A.G. Wishon, General Manager of the San Joaquin Light and Power Corp., to J. Eastwood (Mar. 29, 1922) (JSE, WRCA, No. 48; containing Wishon's observation that "it is a tremendous undertaking to sell the idea [of multiple arch and single arch dams] to the financier who slips behind your back and consults a man like John R. Freeman").

73. Jackson, *supra* note 1.

haps are held legally responsible for their miscalculations. This is all well and good. But how do we decide how safe is safe? And how do we judge the potential benefits of a new technology that may foster unforeseen problems as well as anticipated benefits. We usually perceive the "ethics of safety" in terms of unscrupulous individuals trying to foist an unsafe product off on an unsuspecting public. But what about the ethics of having someone declare a new technology to be unsafe when, in fact, it is just as safe as the technologies it is attempting to supplant.

Eastwood faced a difficult challenge in simultaneously defending the suitability of his designs from both the realm of excessively rigorous mathematics and from the realm of "psychological" intuition. In several instances, he proved capable of withstanding his opposition and his dams were able to provide successful, long-term service as water storage structures. But in other cases, most notably at Big Meadows, he succumbed to the forces of conservative hydraulic design and failed to implement his projects for the benefit of potential clients. The reasons for his failure to win design commissions never related to economic inefficiency. Rather, they concerned the perceived weakness of his designs as determined by seemingly precise (but in fact erroneous) mathematical analysis or by non-rational considerations related to visual appearance.

The larger lesson to be drawn from Eastwood's experiences is that the scientific and "rational" nature of modern technology is not always as absolute as we might like to think. Regardless of our desires, safety remains a relative value that only has meaning in terms of how people choose to evaluate a wide range of factors and influences. Engineering "experts" used to bolster legal arguments in technically-oriented court cases may bring huge amounts of knowledge and experience to a problem, but this background cannot insure the cogency or validity of their professional opinions. A key insight to be gleaned from Eastwood's work in promoting multiple arch dams is that society, and the legal system, cannot afford to relinquish responsibility over the technological decisionmaking process to experts without appreciating the traditions and technical prejudices that may color their view of what is safe and/or acceptable. Dams may appear to represent a simple, straightforward technology in which all engineers can agree on a few basic mathematical principles that govern the design process. But the history of the multiple arch dam, replete with concerns over visual appearance, "psychology" and the truthfulness of advanced mathematical theory, provides compelling testimony to the contrary.