ACTIVE FAULTS IN DAM FOUNDATIONS: AN UPDATE

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SUMMARY

This paper updates the 1974 *Geotechnique* paper on the same subject by Sherard, Cluff, and Allen. Geologists and seismologists are now able to recognize the presence of, and assess the degree of activity of, faults in dam foundations far more effectively than only a few years ago, thanks to a variety of new neotectonic tools. Similarly, engineers are increasingly able to accept possible foundation displacements with a variety of innovative measures in dam design. Brief case studies of faults beneath dams are presented, and some mitigative measures are described, for Auburn Dam site (USA), Clyde Dam (New Zealand), Eastside Reservoir USA), Lauro Dam (USA), Matahina Dam (New Zealand), Ridgway Dam (USA), Seven Oaks Dam (USA), Steno Dam site (Greece), and Tarbela Dam (Pakistan).

INTRODUCTION

The purpose of this paper is to bring up to date the 1974 paper by James Sherard and the two present authors, "Potentially active faults in dam foundations" [Sherard *et al.*, 1974]. The present paper is dedicated to Sherard, who was a highly valued friend and colleague. This paper concentrates primarily on recent developments in methods of fault identification and activity assessment, rather than mitigative measures in engineering dam design.

To the authors' knowledge, there has as yet been no historic case of an operating dam being displaced by a fault during an earthquake, although there have been some "near misses." This good record of worldwide performance is particularly remarkable in view of the fact that many—if not most—dams are located in river canyons whose courses are controlled by preferential erosion along underlying faults and joints.

WHAT IS AN ACTIVE FAULT?

Not surprisingly, almost all foundations for large dams display some faults, however minor, and the geologic and seismologic challenge is to determine whether such faults are likely to rupture during the life of the structure (i.e., are they "active"?) and, if so, with what displacements, with what geometries, with what magnitudes, and with what likelihoods. Over the years, many authors have discussed various definitions of "active" and "inactive" faults. Suffice it is to say that modern geologic studies, together with vastly improved age-dating capabilities, have demonstrated unequivocally that there are *all degrees* of fault activity, and any categorization into active and inactive features is necessarily arbitrary. In worldwide dam-design practice, repeat times on faults of significant earthquakes of a few thousand years, or a few tens of thousands of years, are often used to distinguish between faults one wishes to worry about and those of no concern.

HAZARD ASSESSMENT OF FAULTS

The last few years have been marked by numerous significant improvements in fault recognition and hazard assessment techniques, particularly in improved methods of absolute age dating that have made possible meaningful probabilistic assessments that were formerly impossible. These techniques have been discussed in detail elsewhere [e.g., Yeats *et al.*, 1997] and are not repeated in detail herein, nor is a discussion of the merits of probabilistic vs. deterministic methodologies.

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Perhaps the most critical parameter of value in determining the degree of activity of a fault is its *slipe rate*, that is, its average rate of slip (usually expressed in mm/yr) over a sufficiently long time period to include several large earthquakes. This, of course, necessitates age measurements of some displaced feature or features, such as strata, stream courses, river terraces, erosion surfaces, etc. Age-dating of young rocks, which is essential to determining degree of fault activity, formerly depended almost solely on recovering organic materials which could be dated by radiocarbon methods. But a myriad of new techniques is now available and others are under vigorous development. Particularly important are novel methodologies for dating the length of time the ground surface has been exposed (e.g., a stream terrace surface), using cosmogenic nuclides. There has always been a hope that, instead of dating the rocks or surfaces offset by a fault, something within the sheared, clayey material making up the fault itself—the so-called fault *gouge*—might be able to reveal the time of the latest or earlier movements. Novel methods are being investigated and attempted, but no technique utilizing the gouge itself has as yet been proven generally applicable. A summary of available techniques and their limitation is given by Yeats *et al.* [1997, ch. 6].

THE PROBLEM OF BRANCH FAULTS

The problem of branch faults—those that are branches of a more significant "main" feature—has long plagued geologists, seismologists, engineers, and regulators. If the main fault has a sufficiently low degree of activity to dismiss it as a hazard, and if there is no indication that a branch is more active, then it is usually straightforward to put the branch fault in the same non-hazardous category as the main fault. But a more troublesome situation is that in which the main fault has a high degree of activity. Should all branch faults then be considered equally as hazardous as the main break? If so, the quandary immediately arises as to what features really *are* to be considered branches, and what kinds of displacements are to be assumed relative to those on the main fault?

In the authors' opinion, no matter how high the degree of activity of the main fault, the possibility of future displacements on a branch fault can be dismissed *if* the branch fault can be demonstrated to have an acceptably low degree of activity—for example, if it is covered and truncated by unbroken late Quaternary strata of hundreds of thousands of year age. That is, if the branch fault has not broken sympathetically with the main fault over a sufficiently long period of time, there is no reason to assume that it will do so in the near future. More difficult, however, is the not-unusual situation in which a branch fault may show no evidence of activity one way or the other—that is, there are no young strata in the local area to demonstrate whether or not they are would be broken if present. This is a situation where geologic judgment necessarily comes into play. A principal line of evidence is the geometrical relationship of the branch fault to the main fault. How close are they in attitude? Do they actually join? Could the same stress field actuate both? How conservative does one wish to be? This was the situation faced at Auburn Dam, USA, Clyde Dam, New Zealand and Steno Dam site, Greece (see below).

FAULT CREEP VS. ABRUPT FAULT DISPLACEMENT

Fault creep is gradual, continuing displacement, usually at a very low rate. This behavior is in contrast to the abrupt fault displacement causing an earthquake, which often takes place within only a very few seconds, associated with displacements of several meters and particle velocities of as much as 1 m/sec [Wallace, 1984; Heaton, 1990]. Fault creep was first recognized in 1956 on a segment of the San Andreas fault in California, USA. Subsequent careful investigation of active faults throughout the world, however, indicates that creep is a relatively rare phenomenon, even along most of the San Andreas fault. Only on one limited segment of the North Anatolian fault in Turkey, and possibly on a segment of the Xianshuihe fault in China, has continuing creep been documented, in addition to reports of two faults that cut the Bajina Basta Dam and the Lipovica Dam in Yugoslavia [Bozovic and Markovic, 1999]. In the authors' opinion, continuing fault creep is a sufficiently rare phenomenon so that it can usually been dismissed in hazard studies unless direct evidence to the contrary exists.

SEISMOLOGICAL EVIDENCE OF FAULT ACTIVITY

Another difficult problem for the geologist and seismologist is the degree to which locations of instrumentally recorded earthquakes should play a role in deciding whether rupture on a fault is credible. In actuality, not all faults on which major earthquakes have occurred historically (e.g., the San Andreas fault in California) are characterized by continuing seismic or microseismic activity along the same fault segment. And some major earthquakes have occurred on faults with very little, if any, precursory seismicity or microseismicity within the previous few years. Therefore, the presence *or* absence of seismic activity must be viewed with great caution in determining the degree of activity of a given fault, [Allen *et al.*, 1965; Yeats *et al.*, 1997]. Likewise, one should be very careful in postulating fault locations from hypocentral locations. As applied to dam foundations, it should be emphasized that, inasmuch as surface fault rupture is the hazard of principal concern, the demonstrated absence of surficial late Quaternary displacement on a fault is usually an adequate guarantee of similar behavior in the near future *regardless* of whether or not micro-earthquake epicenters are present at depth beneath the structure.

FAULTING ASSOCIATED WITH RESERVOIR-TRIGGERED EARTHQUAKES

Although there have been probably hundreds of cases worldwide of reservoir-triggered earthquakes, mostly of very small magnitudes, the authors are aware of only two instances where the triggered events are known to have been associated with unequivocal surface faulting. One of these was at Koyna, India, in association with the M = 6.3 triggered event of 1967 [Cluff, 1977], and the other at Oroville, California, USA, in association with the M = 5.7 event of 1975 [Clark *et al.*¸1976]. In both cases, rupture was along a pre-existing fault with earlier displacements of Holocene age, although in neither case did the fault actually pass beneath the dam.

It was suggested by Allen [1982] that reservoir-triggered earthquakes possibly could occur on a fault otherwise considered to be "inactive," because "the reservoir may produce a stress distribution quite unlike that which the area has experienced for many thousands of years." While perhaps theoretically possible, it must be recognized that, to date, only two out of literally hundreds of worldwide reservoir-triggered earthquake sequences have been associated with unequivocal surface ruptures. In the current opinion of the authors, the likelihood of a reservoir-triggered earthquake with significant surface displacement on a fault with proven absence of late Quaternary displacements is exceedingly remote, particularly if the associated reservoir is not deep and large.

RESPONSE TO DISCOVERY OF FOUNDATION FAULTS

When a fault of suspected displacement hazard is discovered in a dam foundation, either during initial exploration and excavation, or during reassessment at some later date, responses seem to fall into several categories: (1) If still under planning, the design of the dam may be altered and/or the dam's alignment adjusted to minimize the risk. Such was the case at Cedar Springs Dam, California, USA [Sherard *et al.*, 1974] and at Clyde Dam, New Zealand (see below). (2) Through geologic studies involving age-dating of affected foundation rocks, it may be possible to determine that the slip rate on the fault is sufficiently low, and/or the time of last movement is sufficiently great, so that no significant danger to the dam is present. That is, for all practical purposes, the fault is determined to be "dead." Such was the case at the Eastside Reservoir Project, California, USA (see below). (3) Engineering studies may indicate that the dam can safely withstand the largest expected fault displacement. Such was the case at Tarbela Dam (Pakistan), and at Seven Oaks Dam, California, USA (see below). (4) In an existing dam, modification and strengthening may be possible to reduce to risk to a low level. Such as was the case at Matahina Dam, New Zealand (see below). (5) The site may be abandoned, at least for the type of dam being planned, either before or after construction starts. Such was the case at Auburn Dam, California, USA (see below).

SELECTED CASE STUDIES

The following brief case studies represent a few that have come to the attention of the authors. There are undoubtedly many others examples worldwide that could also have been mentioned, and some of these are summarized by Bozovic and Markovic [1999]. Leps [1989] not only discusses other examples, but also presents a good discussion of a variety of defensive design measures. Dams that were specifically discussed by Sherard *et al.* [1974] are not discussed again herein.

Auburn Dam site, California, USA: Construction was started in 1967 by the U.S. Bureau of Reclamation (USBR) on what was planned to be the world's longest double-curvature thin-arch concrete dam, a 210-m-high structure across the American River 45 km northeast of Sacramento, California. Although it was recognized at the time that the predominantly pre-Cretaceous metamorphic rocks of the foundation were highly deformed and faulted, it was not considered by the USBR that any of these faults were "active," and the region's historic and instrumental seismicity was relatively low. Geologic mapping of the excavated foundation was carried out competently and in great detail, and none of the many faults therein showed evidence of youthful displacements. However, none of these faults was mantled in the dam footprint area by younger rocks that could have revealed youthful displacements if they had, in fact, occurred. In the meantime, the 1975 Oroville earthquake (M = 5.7) occurred along a member of the same fault system about 50 km northwest of Auburn, with surface displacements of as much as 5 cm [Clark *et al.*, 1976], albeit perhaps triggered by the nearby Oroville Reservoir [Toppozada and Morrison, 1982]. Furthermore, contemporary regional studies along the Foothills fault system, which included the Auburn area, had revealed unequivocal evidence of late Tertiary displacements at several localities, as well as some indications of late Quaternary displacements [Woodward-Clyde Consultants, 1977]. These studies stimulated subsequent neotectonic investigation of faults close to the Auburn area itself, which revealed several instances of surface fault ruptures of less than 100,000-year age, including one at a trench locality only 800 m from the dam excavation. Literally dozens of trenches were excavated across these faults. Although there was considerable controversy about the interpretation of the exposures in these trenches and their relevance to the faults within the dam footprint, a number of outside consultants (including, independently, both authors of this paper) agreed that fault movements beneath the dam were possible during a maximum earthquake, with displacement estimates ranging from 2 cm to about 1 m. As a result, and also taking into account reservations expressed by the U.S. Geological Survey and the California Division of Mines and Geology, the Auburn Dam project was cancelled after many hundreds of millions of dollars had already been expended on major foundation excavation and concrete dental work. There was simply not sufficient confidence that a concrete thin-arch dam could safely withstand even small foundation displacements.

Clyde Dam, New Zealand: Clyde Dam is a 102-m-high concrete gravity dam across the Clutha River, New Zealand, completed in the early 1990's. The nearby Dunstan fault had long been recognized as extending at least 60 km north from the dam area, with Holocene-active segments within 3 km of the dam itself [Beanland, *et al.*, 1986]. The Dunstan fault was the principal feature guiding the design of the dam for seismic shaking, with a M = 7-7.5 earthquake assumed to occur on it with an average frequency of about once in 8,000 years. The main fault did not extend directly into the dam foundation, but several apparent branches were mapped nearby. During preliminary exploration for the dam, but before construction started, the River Channel fault was identified in the deepest part of the foundation, and, although its trend was roughly perpendicular to that of the Dunstan fault, and it could be followed for only some 780 m, it was deemed credible that it could move in sympathy with a major earthquake on the Dunstan fault. The reasoning was apparently related to its proximity to the Dunstan fault and to its wide shear zone within the foundation [Hatton *et al.*, 1991]. Furthermore, the Dunstan fault is a thrust fault with complicated near-surface fracturing, and elsewhere along its trace are many minor faults within 2-3 km that have demonstrable late Quaternary displacements [Beanland *et al.*, 1986]. Others pointed out that the strain field near the termination of a major active fault may be very complicated, so the perpendicular orientation of the River Channel fault might not in itself rule out possible sympathetic movement [Nelson, 1984]. The New Zealand Geological Survey estimated that up to 20 cm of slip could occur on the River Channel fault in sympathy with a major earthquake on the Dunstan fault. The design of the dam was therefore modified by including an appropriately located slip joint directly above the fault, with a rubber-sealed, steel-sheathed wedge plug, 100-m high, to accommodate as much as 2 m of strike slip and 1 m of dip slip movement on the River Channel fault [Hatton *et al.*, 1987; 1991]. The intent was "to keep the joint water tight during normal operation and to limit the flow in the event of fault displacement" [Hatton *et al.*, 1987]. The powerhouse, sluice intake, and spillway were also relocated to avoid the fault and slip joint. .

Eastside Reservoir Project, California, USA: Currently nearing completion, the Metropolitan Water District's Eastside Reservoir Project, near Hemet, California, is the largest ongoing dam construction project in the U.S. It involves three embankment dams enclosing a formerly dry valley. The dams are founded largely on metamorphic and igneous rocks of more than 100-million-year-old age. The Project is located at a closest distance of 8 km from the highly active San Jacinto fault—a major member of the San Andreas fault system—but no Holocene faults are known to be present in the reservoir area itself. The largest dam (West Dam) is some 3300 m long and 87 m high, but its construction involved excavation below grade as much as 25 m to unweathered bedrock, except for 3 relatively narrow and still deeper ancient channels filled with highly consolidated Quaternary alluvium. Several relatively minor faults were exposed, not unexpectedly, in the ancient metamorphic bedrock of the foundation, but one of these was found to extend into the adjacent channel-filling sediments, with a maximum vertical separation of about 5 cm in the old alluvial deposits [Metropolitan Water District, 1996]. In a series of 11 fault-crossing trenches, the fault was followed in the old alluvium—sub-parallel to the ancient channel—for about 320 m, at which point the fault was truncated by an overlying unbroken younger alluvial unit. Fortunately, within the younger alluvial unit several beds were capped by ancient soils whose ages could be estimated on the basis of diagnostic pedogenic features. Based on these features, it was possible to infer that the latest displacement on the fault took place more than 200,000 years ago. A number of vertebrate fossils in the sequence also supported a relatively great age for the old alluvium. On the basis of the age of the most recent faulting event, as well as the relatively small displacements involved, it was judged that the fault created no concern for the safety of the Project.

Lauro Dam, California, USA: Lauro Dam, part of the USBR Cachuma Project, is a 42-m-high dam within the city of Santa Barbara, California. When the foundation was excavated in 1951, a fault was recognized within the dam footprint that juxtaposed alluvial fan deposits against Miocene sedimentary rocks. Only limited geologic work was carried out at that time, but in 1998 an extensive exploration program was initiated, including 2 trenches and more thorough geologic mapping, in order to determine the degree of fault activity and its possible displacement capability [Anderson, 1999]. Although the trenches and excavations at the site reaffirmed the presence of the fault, analyses of regional geologic data studies were necessary to determine the critical hazard-assessment parameters. The foundation fault appears to be part of the 50-km-long Mission Ridge-Arroyo Parida-Santa Ana fault system, with predominantly left-lateral strike-slip displacement. Uncertainties are high with regard to slip rate and slip-per-event, although the length of the fault suggests significant displacements are possible. Anderson [1999] concluded that " . . . , the maximum surface displacement in the foundation of Lauro Dam could be as high as 2 m. Assuming a slip rate of 1 mm/yr, the annual probability of 1 m or more of surface rupture through the embankment and outlet works of Lauro Dam could be higher than 0.002/yr." The need, if any, for possible mitigative measures has not yet been decided upon.

Matahina Dam, New Zealand: Faulting at Matahina Dam, an 80-m-high embankment structure on the Rangitaiki River of the North Island of New Zealand is described in detail by Mejia *et al.* [1999] and Freeman *et al.* [this volume]. When the dam was constructed in the 1960's, several prominent faults parallel to the river trend were observed and mapped in the mid-Quaternary sedimentary foundation rocks exposed in the core trench. Although carefully mapped, none of these faults was observed to displace the overlying valley-fill alluvium. It was only later recognized—after completion of regional geologic studies elsewhere in New Zealand—that these faults comprised the northernmost splays of the Alpine fault system, one of the world's longest and most active regional strike-slip faults. This realization, together with the fact that the dam was slightly damaged by the very nearby Edgecumbe earthquake of 1987 (M = 6.3), albeit on a different fault system, led to a re-assessment of the dam's earthquake safety. An intensive geologic study of the neotectonics of the fault system was undertaken within some 40 km of the dam, which included a number of trench excavations and was aided by the fact that several Holocene volcanic ash deposits in the damsite area could be confidently identified and dated. These studies led to the conclusion that at least some of the fault splays underlying Matahina Dam were highly active and could be expected to suffer oblique displacements of up to 3 m with an estimated exceedence probability of between 1/6000 and 1/11000 annually [Woodward-Clyde Consultants, 1996]. Engineers judged that the dam could not safely withstand a displacement of this magnitude, partly due to the somewhat brittle nature of the existing core. It was deemed impractical either to remove the dam or completely to replace it, so an innovative mitigative solution was devised in which the downstream shoulder of the dam was excavated, a leakage-resistant filter and transition zone constructed within the dam, and a thick rock buttress was placed on the downstream face of the dam to guarantee that, even if the integrity of the core was compromised during a future fault displacement—however unlikely—flow would be impeded to the extent that no excessive downstream flooding would result [Mejia *et al.*, 1999]. As part of the strengthening program, a cutoff trench for the new filter zone was excavated some 100 m downstream of the original core trench. As expected, several faults were observed in the underlying bedrock in this new trench, some of which undoubtedly corresponded to faults mapped in the original core trench nearby. Three of these faults, however, were now observed to displace the overlying basal valley-fill alluvium, with displacements as great as 1 m. The latest movement on one of the faults could be dated as between 3,690 and 10,600 years, B.P. [Woodward-Clyde Consultants, 1998; Freeman et al., this volume]. This documentation of very youthful faulting was, in a sense, satisfying, in that it confirmed the wisdom of having concluded that the faults had a high degree of activity and truly represented a risk to the integrity of the former dam.

Ridgway Dam, Colorado, USA: Ridgway Dam, a USBR embankment structure across the Uncompahgre River in southwestern Colorado, was completed in 1987. Some debate still exists, however, concerning the probability of surface faulting through the foundation, and it represents an interesting case of the relative importance of geologic vs. seismologic data. During excavation, the Cow Creek fault was discovered in the right abutment and outlet works area, but trench exposures revealed that the fault did not break overlying glacial outwash of middle Pleistocene age (>130 ka)[Ake *et al.*, 1997]. Nevertheless, the Cow Creek fault, as well as others in the vicinity, is debatably associated with minor seismicity that largely post-dates reservoir impoundment. An interesting probabilistic analysis was carried out, based on a logic-tree analysis and the recorded seismicity, which tentatively suggests that surface displacements of several tens of centimeters might occur with recurrence intervals on the order of a thousand years. Many assumptions are necessarily involved, including an exponential recurrence curve truncated at magnitude 6.3 (i.e., no "characteristic" earthquake), and use of the Wells and Coppersmith [1994] regression relationships, with uncertainties. Any displacement during the project life is, needless to say, difficult to rationalize with the local geologic evidence of no surface displacement in more than 130,000 years. In this case, it is argued that, since the current seismicity commenced with the initial reservoir filling, the late Quaternary geologic history of the Cow Creek fault may be irrelevant to the reservoir-triggered events [Jon Ake, personal communication]. Studies are continuing.

Seven Oaks Dam, California, USA: Seven Oaks Dam is a U.S. Army Corps of Engineers (USCE) project, envisaged initially primarily for flood control, that is currently nearing completion in the canyon of the Santa

Ana River 18 km east of San Bernardino, California. The curved embankment structure will be 168 m high. It was fully recognized from the outset that the damsite was located between two major strands of the highly active San Andreas fault—the South Branch (the principal and most recently active strand) 2 km to the south, and the North Branch less than 1 km to the north. An earthquake of about magnitude 8 on the South Branch was assumed to occur during the life the structure, and although the North Branch is also "active," its slip rate was found to be 1 or 2 orders of magnitude less than that of the South Branch. Since the damsite is virtually within the San Andreas fault zone, the question of active faults in the foundation arose early in the planning stage. One the authors (CRA) recommended to the USCE in 1984 that the dam be designed "on the assumption that as much as 4 feet (1.2 m) of surficial displacement in any direction could take arbitrarily beneath the facility," as cumulative slip on one or more faults. The dam and its appurtenant structures are so designed, with a wide core, transition zones, and drains. When excavation commenced, it quickly became clear that several significant faults did, in fact, cut the foundation, including one fault beneath and parallel to the core that showed evidence of displacement of the valley-fill alluvium. A detailed field study [Sadler and Rasmussen, 1991] confirmed that three sequential valley-fill units were cut by the fault, with the amount of offset (a few centimeters) decreasing up-section. Although no datable materials were obtained, several features suggested that the fault may have moved within the past 35,000 years. Sadler and Rasmussen [1991] recommended that the fault "should be considered capable of moving in the near future," and estimated that slip during a single event "may approach 20 cm of oblique right-slip movement." The length of the fault as a continuous feature is now known to be at least 1.4 km, and exploration still continues in the attempt to determine its total length. Seven Oaks Dam is an example of a situation where both intense shaking and foundation faulting are recognized as being very credible—if not likely—during the life of the project. Nevertheless, in this light, engineers are satisfied that the dam and appurtenant structures have been designed and constructed with adequate seismic safety margins.

Steno Dam site, Greece: Steno Dam was a planned 185-m-high double-curvature thin-arch dam to be built across the gorge of the Arakhthos River in northwestern Greece [Gilg *et al.*, 1987; Pedro and Azenedo, 1988], although the dam has not yet been built, apparently for economic reasons. A conspicuous fault—the Steno fault—underlay the deepest part of the gorge, and alternative sites or dam types were not deemed practical. The Steno fault is not itself a major feature and did not display evidence indicating late Quaternary displacements. However, other "main" mapped faults nearby were thought to have a reasonably high degree of activity. At least one, shown as an "active" thrust fault by King *et al.* [1993], is some 30 km in length, and many other similar active faults characterize northwestern Greece. A microearthquake study of the dam region located many events, but Kiratzi *et al.* [1987] concluded that the activity "indicates deformation over a broad volume of the crust rather than along well-defined faults." Although the Steno fault was thought to be "a secondary fault" to the main nearby faults, it was judged on the basis of the regional neotectonic history and historical seismicity of earthquakes up to magnitude 6.5 that "displacements on the Steno fault cannot be excluded, but they would be limited to some decimeters only." [Gilg *et al.*, 1987]. The dam was designed with such a displacement in mind, mainly by introducing a complicated system of grooved slip joints to create adequate "fexibility" to the structure to withstand the estimated foundation displacements. Subsequently, the entire dam and abutments were successfully tested under simulated earthquake displacement loads in a sophisticated model constructed at the Laboratorio Nacional de Engenharia in Portugal. Details of the proposed design and the model testing are given by Gilg *et al.* [1987] and Pedro and Azevedo [1988].

Tarbela Dam, Pakistan: During the initial exploration for Tarbela Dam—the world's largest embankment structure—it was discovered that the valley alluvium of the Indus River, upon which the dam rests, was considerably thicker on one side of the 2-km-wide valley than on the other. This variation was associated with a steep buried bedrock escarpment, and in the initial planning, it was argued that this escarpment might represent simply a buried steep bedrock wall of the highly incised glacial Indus River, or perhaps a featured scoured by glacial ice itself . Upon detailed drilling, however, it turned out that the 200-m-high escarpment was actually overhanging [see Yeats and Hussein, 1989, Fig. 7], and the rock properties were such that it could not have existed as a freestanding slope. Thus it was argued that the buried escarpment must represent, at least in part, a fault contact. And since the abutting gravels are post-glacial in age, the fault would have to have a relatively high degree of activity. Subsequently, it was mapped as the Darband fault [Calkins et al., 1975], and its mapped length and segmentation length were used to suggest a maximum earthquake on it of M = 6.5, using regression techniques similar to those later summarized by Wells and Coppersmith [1994]. Similar regressions were also used to suggest a maximum displacement on the fault of about 1 m during such an event. Engineers judged that the nature and thickness of the dam's core, transition zones, and drains would allow the structure safely to withstand such a displacement.

CONCLUSIONS

- There is no standard definition of what constitutes an "active" fault, which reflects the geologic reality that *all degrees* of fault activity do, in fact, exist. Any distinction between active and inactive faults is necessarily arbitrary.

- In worldwide practice, faults in dam foundations that are estimated to have ruptured on the average of once in every few thousand, or every few tens of thousands of years, have typically been considered worthy of engineering consideration.

- At least some engineers appear to be gaining confidence that, with innovative new techniques, dams of virtually all types can be designed to accommodate moderate foundation fault displacements without major failure.

- Owing to advances in the ability to obtain absolute ages on geologic materials, mainly through new geochemical techniques, degrees of fault activities can now be estimated far better than only a few years ago. A critical parameter in both probabilistic and deterministic assessments is long-term *fault slip rate*.

- Field studies of faults in dam foundations demand the expertise of geologists trained and experienced in neotectonic studies. Classical geological maps, however competently done, often have only limited relevance to earthquake hazard assessments.

- Seldom are adequate field exposures available in the dam footprint area itself to characterize fully the neotectonic environment of a proposed dam. It is virtually always necessary to carry out such studies, including trenching of suspect faults, throughout a much wider area than that of the dam footprint—typically extending over many tens of kilometers.

- Seismologic studies of earthquakes in dam areas can play an important role in safety evaluations, particularly in establishing seismic shaking parameters such as maximum ground accelerations and velocities to be expected. But field geologic efforts are nevertheless critical in estimating the likelihood of surface fault rupture through a dam foundation. The abundance *or* absence of microearthquakes may have little relevance to the probability of large local earthquake associated with surface fault rupture.

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