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Design Solutions to Accommodate Faulting in Foundations of Critical Structures

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ABSTRACT

In planning for dam and hydropower projects with high earthquake hazard, good practice calls for appropriate investigations to help assure developments are not located on or immediately adjacent to active faults. However, such hazards might only become evident late in design or during construction when project features are fixed and hazard avoidance is not an easy option. Two examples are described where active faults were identified in foundations of critical structures resulting in design solutions to enable satisfactory project performance should fault displacement occur during operation. One concerns a dam and long tunnel system in the Himalayas and the other involves locks and dams at the Pacific end of the Panama Canal Expansion. Both are constructed within seismically active settings, though during preliminary design foundation faults were not considered active. Engineering and construction measures are described including analytical methods used in design development. In addition to comparison with other case histories, discussion summarizes current best practices to accommodate faulting in foundations of critical structures.

Introduction

Several excellent papers have been written on the subject of active faults in the foundations of critical structures, such as dams, which include discussion of the explicit hazard posed by active faults, how this has been addressed at various projects, and the standards of care that should be expected on projects faced with such issues (e.g. Sherard, 1967; Allen and Cluff, 2000; Amos and Gillon, 2007; Wieland et al., 2008 a, b; Sêco e Pinto, 2013). It is the intent of this paper to add to this body of knowledge by introducing some new case histories. Two projects in particular are described: one is a hydropower project in Pakistan with a dam and long tunnel system and the other involves the new locks and dams at the Pacific end of the Panama Canal Expansion Project. Although both projects are constructed within seismically active settings, foundation faults were not considered active during preliminary design phases.

Wieland et al. (2008 a, b) point out that a principal emphasis in dam earthquake engineering has often typically been on management of ground shaking at a given project site and the influence that this has on the foundations, on design, and on performance and safety of structures. In contrast, the potential for surface fault rupture or block movements in a dam foundation is sometimes less in focus, even though it is universally and implicitly understood that any movement of a fault in a dam foundation would be the most dangerous loading that could

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influence the safety of a dam. This apparent neglect is observed in the fact that code requirements in many countries and engineering efforts in design of dams (or other critical civil works) tend to concentrate on mitigation of the effects of severe ground shaking as opposed to foundation rupture by fault movement. In some cases perhaps it may be mistakenly thought that hazard avoidance has already taken place and that the site selection process has included elimination of any candidate sites where active faults could exist. However, the following are some important considerations why this hazard must be treated with due care:

- The presence of active faults cannot always be properly recognized or understood before construction starts and therefore decisions might have to be made whether to abandon a site already under development (e.g. Auburn Dam in California perhaps) or whether to engineer acceptable mitigation measures. In some cases other factors have come into play (such as economic, political) resulting in an unbending commitment to a given site;
- There is a trend towards making use of more marginal, less favourable sites for development;
- In a tectonically active region, there might be very few suitable locations free of active faulting or the proposed project footprint may be so large (or linear, such as the Panama Canal) that one cannot escape intersecting the trace of an active fault;
- Sites are being developed in regions where advanced knowledge of the skills needed to identify and properly characterize fault activity (e.g. palaeoseismicity) may be lacking.

A summary of dams located at sites with active faults is provided in Table 1 which is includes information in various published papers (Wieland et al., 2008 a, b; Amos and Gillon, 2007). The information has been updated to include some new examples – Nauseri Dam (Neelum-Jhelum Project, Pakistan) and Borinquen Dams (Panama) described in this paper, and Karahnjukar Dam (Iceland). Indicated on the table are those dams where features were designed to accommodate fault movement in foundations.

Table 1. Dams at Sites with Active Faults or Features Capable of Movement

Name of Dam	Country	Description
San Andreas Dam	USA, Ca	27-m-high embankment; damaged but survived 1906 San Francisco earthquake
Karori Dams	New Zealand	24 and 20-m-high concrete gravity dams built on Wellington Fault, 1908 and 1911
Hebgen Dam	USA, Mt	26-m-high concrete-core earthen embankment dam; built 1914; damaged in 1959 Hebgen Lake earthquake
*Morris Dam	USA, Ca	Concrete gravity, 75-m-high; constructed 1934
*Aviemore Dam	New Zealand	Composite dam (concrete and earthfill, 56- and 49-m-high respectively); constructed 1962-68
*Matahina Dam	New Zealand	Zoned rockfill, 80-m-high. Constructed 1967. Damaged in 1987 earthquake, followed by repairs with design improvements
*Cedar Springs Dam	CA, USA	76-m-high zoned earth-rockfill; constructed 1972
Tarbela Dam	Pakistan	143-m-high zoned fill dam; completed 1974. Subsequently discovered to be sited on an active fault capable of 1-1.5 m of displacement
*Clyde Dam	New Zealand	Concrete gravity, 100-m-high; constructed 1983
*Karahnjukar Dam	Iceland	198-m-high concrete faced rock fill with concrete toe wall 39-m-high with joint to accommodate fault movement; completed

		2006
*Sirvan (Barzoo)	Iran	Concrete arch; 2007
*Borinquen Dams	Panama	Zoned rock fill dams, various heights; under construction as part of Panama Canal Expansion project
*Nauseri Dam	Pakistan	56-m-high composite dam (gravity and zoned rock fill); under construction; active faults also cross tunnels
*Rudbar Lorestan Dam	Iran	Concrete gravity 158-m-high; yet to be constructed
*Rogun Dam	Tajikistan	Zoned embankment, originally planned 335-m-high; yet to be constructed
*Steno Dam	Greece	Concrete arch; yet to be constructed

*Designed with features to accommodate fault movement in foundation

Case History – Nauseri Dam, Pakistan

The Nauseri Dam is being developed by WAPDA of Pakistan as part of their 970-MW Neelum-Jhelum Project, located near Muzaffarabad. The dam will divert water from the Neelum River to a lower branch of the Jhelum River through a 32.5-km-long tunnel system and underground powerhouse complex. Geological investigations were conducted in support of feasibility studies completed by 1995 followed by detailed design ending in late 1997. The project was put on hold for ten years until late 2007 when a construction contract was signed. In May 2008, a joint venture of engineering companies was contracted to serve as the Consultant for design review/update and construction supervision.

It was soon recognized that the earlier designs had short-comings, including the fact that the original seismic design parameters were unquestionably too low. The effects of the catastrophic M 7.6 earthquake which afflicted the region on 8 October 2005 endorsed this. Subsequently, a comprehensive seismic hazard evaluation was conducted in accordance with international practices to develop more realistic seismic design parameters (NJC, 2010), with the results prompting redesign of the main structures. In addition, a major regional fault, known as the Main Boundary Thrust (MBT), was found to pass through the dam foundation – Figure 1. Although this was known to the earlier consultants, it had been assumed to be inactive with no potential for surface rupture.

The MBT is a major feature of the Himalayan region, extending some 2500 km from Assam in the east to beyond the Indus in the west. In the dam site area, it cuts obliquely across the Neelum River on the right abutment of Nauseri dam. The actual position of the fault zone and its physical characteristics were not yet properly defined at the start of construction in 2008. Therefore methods used in neotectonics and paleoseismic investigations were followed to gather evidence of most recent movement and to aid estimation of slip-rate. Unfortunately it was not possible to categorically rule out potential for future movement on the MBT at the site, particularly since recent displacement on this fault system had been documented elsewhere in the region. Therefore, it was not only prudent but also in keeping with industry practice to consider the fault capable of displacement during the lifetime of the project and to design critical project features accordingly.

The following fault parameters were derived from the investigations (NJC, 2010):

- Slip rate: 2.5 mm/yr to 5 mm/yr.
- Fault Dip: Regionally known to vary from 50° (from horizontal) to nearly vertical. At the dam site, dip is about 80°-85° to the northeast.
- Sense of movement: thrust/reverse with the hanging-wall (up-thrown side) on the northwest or right side of the river valley.
- Maximum in-plane vertical movement is assumed to be ~ 3 m, with possibility of some oblique slip; no evidence of coseismic movement on MBT in 2005 earthquake event (which occurred on the Muzaffarabad Fault).
- Width of rupture zone is ~ 3 m, a highly disturbed zone 10 to 30-m-wide, and the total width of affected zone > tens of meters.

Design Development

Various concepts were evaluated designed to accommodate anticipated maximum displacements and severe shaking. Structures also had to be designed for very high ground motions: MCE event magnitude 7.7, PGA= 1.16g. Principal solutions considered included: 1). Relocation of the dam to another stretch of the river where the dam would not be overlying a fault capable of movement; not accepted because of commitment to this site. 2). Provision of an engineered joint in the concrete dam, similar to measures at Clyde Dam in New Zealand or Kárahnjúkar Dam in Iceland. This alternative was dropped for reasons including introduction of an untested slip joint, uncertainties in location and nature of foundation rupture, and need for more space/wider river section to accommodate a longer dam. 3). Design of a composite dam with a zoned embankment section (rockfill with clay core) spanning the fault zone and a concrete structure to accommodate the gated spillway and other features. This concept was adopted – Figure 1.

The fill section was designed to accommodate the maximum offset interpreted for the underlying fault. Design details followed previously accepted practices in such situations, including:

- Widening the core and specifying core materials that assure the best ductility possible with a high failure strain to mitigate potential fracture of the core; special conditioning and beneficiation may be required.
- Thick filter and transition zones with flaring of the filters; specification of cohesionless materials.
- Provision of generous freeboard in the fill section and a widened crest.
- Careful quality control regarding material selection, moisture content during placement, and proper compaction (especially against the concrete dam section – a *critical* location).

Design analyses included: 1). Sliding analyses of the dam including examination of failure modes through the foundation; non-linear 2-D stress analyses in upstream-downstream and in cross-valley directions; particular focus on post-earthquake condition and performance (including fragility to aftershocks); assessment of tensile stresses to evaluate potential cracking in concrete sections, in the dam foundation, and in the core of the embankment section. 2). 3-D FEM models to analyse stresses in the concrete dam and integral spillway with various model sizes ranging from local (individual bays) to global (entire dam and spillway); to evaluate seismic behaviour of dam and foundations, identify critical regions affecting dam safety, development of concrete and reinforcement design, verification of seismic performance.

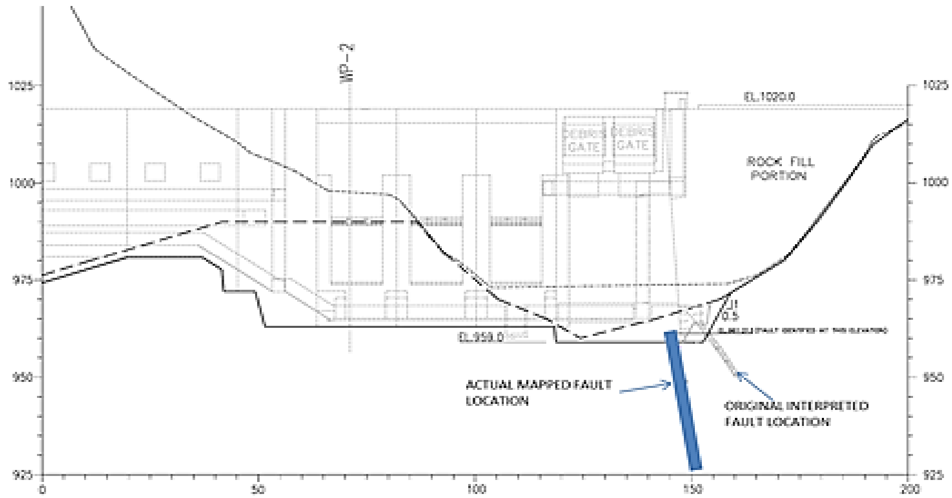

Figure 1. Neelum-Jhelum Project: Nauseri Dam Section showing location of MBT Fault

However, during excavation for the dam, the actual trace of the MBT was unexpectedly found to be not entirely beneath the fill section and that an edge of the concrete super-structure would overlie the fault. Various innovative subsurface foundation treatment options were examined that could help direct any potential fault movement into the fill and away from the concrete part of the dam. The most feasible and realistic given the existing contract provisions would be construction of a release plane or preferred plane of slip, such as a slurry wall or row(s) of bentonite-filled drill holes. The design intent is to construct a feature to help minimize potential damage to the concrete structures in case of movement along the fault during a seismic event. The adopted method involves drilling two rows of closely-spaced vertical holes beneath the rockfill section of the dam to intersect the fault at a depth of about 25-40 m below the foundation surface. The 10- to 15-cm-diameter holes are backfilled with thick bentonite slurry. It is intended that in the event of movement on the MBT, the rows of holes would act as a preferred slip plane. Because of the low permeability backfill, the plane would not become a line of preferred seepage.

The design methodology and analyses used in developing these details are described in detail in Dickson et al. (2013) and included: 1). 2-D FEM analyses to explore the results of simulated movement of the MBT and respective effects on the concrete structures with/without the release plane. 2). Rigid body analyses examining fault movement and effects and with/without a release plane. The results indicated that the release plane would be effective and would significantly improve performance of the concrete structures by directing fault movement into the more deformable embankment portion of the dam. Without it there would be serious damage to the concrete structures, but with the release plane it is expected there would only be minor damage that would be acceptable.

Case History – Borinquen Dams, Panama Canal Project

The four Borinquen Dams (1E, 1W, 2E, and 2W) are part of the Third Set of Locks Panama

Canal Expansion Project, and are designed to allow access and navigation through the new Pacific Post-Panamax Locks (Pacific Locks). Because these dams will retain Gatun Lake and upstream waterways of the Panama Canal, they have been designed and constructed to achieve a high level of reliability. The Borinquen Dams have a total combined length of about 5.3 km – see Figure 2. Dams 2W and 2E abut the Pacific Locks complex structures.

Figure 2. Location of Borinquen Dams at Pacific Locks

The dams are zoned rockfill central core embankments up to approximately 35-m-high. Design and construction has had to take into account challenging foundation conditions, the tropical environment, high seismic hazard, and stringent performance requirements. The foundations of the dams involve several active fault crossings, complex geologic contacts, and weak claystone/siltstone units prone to slaking. The unique nature of tropical environments also presented challenges for construction, including unusual behaviour of the tropical residual soils, heavy precipitation, and a long wet season. The high seismic activity in the area led to demanding seismic performance requirements in the contract documents for the design-build contractor to follow.

Seismic Performance Requirements

These included: 1). Seismic dam deformations should not compromise the ability of the structure to retain Gatun Lake, lead to any overtopping, or require emergency response that impedes the operation of the Canal. 2). Embankment zones must remain functional, not be disrupted by seismic deformations, and accommodate fault displacements. 3). The dams and abutments must withstand the 1,000-year earthquake ground motions without any damage that requires emergency response and repairs that impede operation of the Canal. 4). The dams and abutments must withstand 2,500-year earthquake ground motions without release of Gatun Lake or overtopping.

Fault Displacement

The Borinquen Dams are required to be designed to accommodate the fault displacements of between 1.0 and 3.0 m of strike-slip fault offset and 0.5 meters of thrust slip and normal slip fault offset. Within 50 m of active fault locations, the thickness of the core and chimney filter/drain/transition zones had to be at least 1.5 times the horizontal fault displacement component. The thickness of the blanket/filter/drain/transition zones had to be at least 1.5 times the vertical fault displacement component. The core of the dams is designed to accommodate these fault displacements without piping.

Seismic Design

The design of the Borinquen Dams considered two levels of design earthquake: 1,000-year return period design earthquake (about 0.72 g, PGA) and 2,500-year return period design earthquake (0.97 g, PGA). The primary controlling earthquake is a crustal event occurring on the Pedro Miguel-Limon Fault System producing an earthquake of moment magnitude (Mw) 7.1.

Embankment Seismic Deformation Analysis

The key considerations regarding earthquake-induced deformation of the dam are loss of freeboard that could lead to uncontrolled release of the Gatun Lake and overtopping due to seiche, and deformation of the drain/filter system that could lead to malfunction of the filter and drainage system. The following progressive seismic deformation analysis process was implemented for the Intermediate and Final Design of the Borinquen Dams:

> Step 1 - Decoupled Seismic Deformation Analysis: Two-dimensional finite element seismic response analysis were performed using QUAD4M (Hudson et al., 2003) to calculate peak accelerations and effective cyclic shear strain for the 2,500-year return period design earthquakes. Seismic deformations were evaluated using Newmark (1965) sliding block and Makdisi and Seed (1977) methods with the acceleration data calculated in the seismic response analysis. Design ground motions and foundation conditions controlling the seismic performance of the dams were identified based on the seismic response and displacement analyses.
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> Step 2 - Coupled Seismic Deformation Analysis: For the final design stage, 2-D finite difference seismic analysis with elasto-plastic material models were performed using FLAC, ver6.0 (Itasca, 2008) to refine the evaluation of seismic deformation for the controlling foundation and ground motion identified in Step 1.
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> Step 3 – Evaluation of Analysis Results Using Case Histories: Results of the decoupled and coupled seismic deformation analyses performed in steps 1 and 2 were assessed using empirical correlations developed based on published seismic performance data of rockfill dams.

The results of the analyses completed in steps 1 and 2 were evaluated to verify compliance with seismic deformation requirements. The performance requirements for the 1,000-year return period motion were checked using the results of the 2,500-year return period earthquakes. The liquefaction potential under seismic conditions was evaluated using SPT-based methods recommended for granular soils, and the index property based method recommended for fine grained soils. Initial stress state of the dams and foundation was computed using SEEP/W analysis results for the Long-Term Steady Seepage condition. Appropriate seismic boundary conditions were implemented at the sides and bottom of the dam-foundation model to model the half space. To determine the proper acceleration inputs at the base of the analysis model, a deconvolution analysis was performed.

Conclusions

Good practices as summarized in Wieland et al. (2008) have been evaluated and incorporated into the design of new dams where active faults occur in their foundations. Our work entirely supports these principles. It is recommended that, for any dam project located in a seismo-tectonically active area, comprehensive site investigations must be carried out before commitment to any given site, including paleoseismic and neotectonic studies as necessary. In addition, careful attention must be paid to interactions under dynamic loadings between differing structures (e.g. concrete-fill interfaces) and between structures and their foundations, including understanding areas of potential cracking, and post-earthquake earthquake conditions and safety. Where strong ground motions are expected, analytical techniques should consider both linear and non-linear methods.

- Foundation faults capable of rupture are the most important condition to be identified as early as possible by qualified experienced experts;
- Alternative dams sites should be sought and the hazard avoided if at all possible, if such features are recognized;
- If this is not possible, then well-designed embankment dam solutions can be considered incorporating defensive measures and design processes as used on the Panama Canal Borinquen dams and for the Nauseri Dam Project.

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