CORPS OF ENGINEER EARTHQUAKE ENGINEERING RESEARCH PROGRAM FOR DAMS

by

William E. Roper [1]

ABSTRACT

This paper summarizes the ongoing research work at the Corps of Engineers in the area of earthquake engineering for Dams. This seven year $20 million program involves twenty-one specific work unit efforts and a number of public and private sector partners. The program is managed at the Corps' Waterways Experiment Station. The scope of the program is presented and a selected number of specific work unit areas are reviewed. The program addresses both the geotechnical and structural aspects of dams and related facilities.

KEYWORDS: Earthquake engineering; dams; earthquake; laboratory testing; research; seismic loading; seismic signal

1. INTRODUCTION

The Earthquake Engineering (EQEN) Research Program is the only federally funded program focused on seismic safety of dams and is one of the highest priorities in the Corps R&D program. Most Corps dams were built at a time when earthquake engineering was in its infancy; seismic hazards were not recognized or were poorly understood, and our understanding of them is still changing. The Corps has more than 200 dams and 73 intake towers located in seismic zone 2 or greater (80 percent of the U.S.), most of which would expose downstream populations to mortal hazard in the event of failure to contain their reservoirs (see figure 1). Many of these dams and all of the 73 intake towers would be judged seismically inadequate using current methods of evaluation. Remediation of all of these structures would cost more than a prohibitive $20 billion. Expensive remediation can be avoided in many cases by reevaluating the structures using improved methods of engineering analysis that clearly discriminate between safe and unsafe structures. The cost of remediation of the unsafe structures can be substantially reduced by improved, more cost-effective remediation techniques. A focused, aggressive, coordinated effort of theoretical development, physical modeling, and experiment is required to develop and validate the needed engineering tools.

The program is developing well-verified, practical engineering tools to assess the safety of dams and reservoir control structures (such as intake towers, spillways and gated outlet works), and to remediate dams and control structures found to be unsafe. These tools include advanced field-investigation techniques, physical modeling of the failure processes of the dam-reservoir-foundation systems during earthquakes, cost-effective remediation techniques for dams with deficient seismic stability, and verification of behavior of roller-compacted concrete during earthquakes so that we can use this cost-effective construction process of remediation of seismically susceptible dams and for new construction.

The primary EQEN payoff is avoiding remediation costs for dams that today are judged unsafe only because of the inadequacies in current assessment techniques, and, when remediation is required, avoiding over-construction. Using the tools developed in this research program, the Corps will realize: $100M reduction in remediation costs for each intake tower found to be safe with new methods; a $200M savings for each concrete dam and $50M for each embankment dam found to be safe with more advanced analytical methods. In addition, field

---

[1] Director, Civil Works Research and Development, US Army Corps of Engineers, Washington, DC

investigation costs will be reduced from $500K to $200K per dam (overall projected cost avoidance of more than $50M for the 200+ dams at risk), and there will be reduced uncertainty in seismic damage to dams and increased safety for all Corps dams.

2. RESEARCH PROGRAM PURPOSE

EQEN focuses on the seismic safety of reservoir dams--the Corps' most critical structures from a potential loss of life perspective. Expensive remediation actions are planned for many Corps dams. These actions are necessarily conservative to overcome shortcomings in the current state of the art in earthquake engineering. The EQEN was proposed as a seven-year, $20M R&D effort focused on eliminating inadequacies in present seismic safety evaluation knowledge. Budget restructuring has extended the time length and cost of the program. There is no other national program at this time to develop seismic safety evaluation criteria for our critical Civil Works structures. This program offers the potential for vast cost savings in seismic remediation efforts by performing focused research to ensure that safe dams are not remediated, and dams that are unsafe are remediated as quickly and efficiently as possible.

Even once a logical line of reasoning has been developed to solve the problem, the solution involves a great deal of uncertainty, and may be tentative because of new knowledge provided when earthquakes occur, or because a major state-of-the-art advance may necessitate revisions. To compensate for these shortcomings, we attempt to make design decisions that we hope are sufficiently conservative. The problem is compounded by the fact that most Corps dams were built at a time when earthquake engineering was in its infancy. The problem becomes even more difficult to solve if remediation is required. Examples of these problems were encountered in the seismic safety evaluations for Barkley Dam, Folsom Dam (see figure 2), Sardis Dam, Success Dam, Seven Oaks Dam, and Olmsted Locks and Dams.

The EQEN Program was thus developed to provide a focused research program to improve our ability to assess the seismic safety of our unique Corps Civil Works projects. The cost of partial failure of even one facility will be much greater than the cost of the proposed program. Conversely if even one Corps dam did not need remediation as a result of improved criteria, the cost savings would exceed the program outlay.

2.1 SCOPE OF THE CHALLENGE

At least thirty-nine U.S. States have significant seismic hazard posing a life-safety risk. Consequently, most of our existing dam projects are subject to some degree of seismic hazard and were designed and built at a time when this hazard was not well understood. The Corps has identified at least 200 reservoir dams and 73 intake towers as potentially subject to significant levels of earthquake shaking. With the large levels of uncertainty inherent in present seismic safety evaluation procedures and the consequent need for conservatism, several of these dams and all of the intake towers would be found in need of remediation.

In order to assess the seismic safety of our Corps reservoir dams, we need to be able to reliably predict the ground motions for design, and the amount of damage these ground motions will cause to our projects. Although there have been advancements over the last three decades, the present state-of-the-art in earthquake engineering falls far short of our needs. Consequently, every time the Corps faces a serious seismic safety evaluation, the study turns into a research project that takes a long time and requires experimentation in the laboratory, in the field and on the computer.

Civil Works research in earthquake engineering has led to the ability of the Corps to remediate seismically unsafe dams instead of direct dam replacement. Research activities associated with recently completed remediation at Sardis Dam in Mississippi, for example, results in economic savings of more than $200 million for replacement of a main portion of the dam and averted more than $600 million for replacement of the entire dam and potentially averted more than $60 billion in losses if the dam failed.

2.2 RESEARCH STRATEGY

The EQEN cooperates with and draws from the basic and applied research elements provided by other Corps R&D efforts, other federal agencies, and academic and professional experts, and extends and integrates these elements with in-house work to address Corps seismic safety issues. EQEN is formulated to contain a balance of short-term work units design to address immediate questions related to currently used methods of analysis, and longer-term efforts to provide better methods with stronger theoretical foundations and greater validation. The program was developed by a combination of input from field offices, OCE Technical Monitors and earthquake engineering researchers.

The program content was formulated through discussions of problems encountered in seismic safety evaluations of Corps projects and an examination of shortcomings in each step of the evaluation process. The program thus forms a matrix with the steps in the solution process applied to the reservoir dam structures of concern. The structures of concern in reservoir dam safety are embankment dams, concrete dams and outlet works. The steps in the solution process are a) defining the earthquake ground motions, b) determining the site characteristics, c) assessing the damage these motions will cause to the site, and d) designing appropriate remediation if needed. Through these efforts, the EQEN Program was established as a multi-year approximately $20M effort. The program will also leverage existing research facilities to push the state-of-the-art in carrying out their research (see figure 4).

As a result of this program, we want to have better estimates of the earthquake ground motions to use in design and we want to be able to predict more accurately and quantitatively the amount of deformation and damage these ground motions will cause to our facilities. If remediation is found necessary, we want to have effective, efficient options to select from and practical tools to design and implement a remedial action.

The elements required to do this are developed from the solution process: 1) evaluation of the seismic hazard, 2) site characterization and conceptualization, 3) modeling the material behavior and computing the expected damage. The development of effective, economical remedial measures puts even greater demands on steps 2 and 3, since the materials are now complex composites, possibly requiring a three dimensional analysis to evaluate. It is the underlying plan of this research program to provide practical products from each work unit that work together to achieve the advancement in the state-of-the-art we seek.

3. GEOTECHNICAL WORK UNITS

The geotechnical work units address the steps involved in solving a seismic problem for embankment dams: earthquake ground motions, site characterization, liquefaction-deformation-damage assessment, and remedial measures.

3.1 EARTHQUAKE GROUND MOTIONS

Knowledge of the behavior of ground motions advances with each new earthquake and breakthroughs in basic research by seismologists. The ground motion work units will maintain cognizance of these advances and translate the aspects important for engineering analysis into usable tools to provide ground motion input for analysis in the form needed as computational ability advances. These work units are thus closely coordinated with the development of structural and geotechnical numerical models.

3.2 SITE CHARACTERIZATION

Present methods of site characterization rely mainly on individual borings to provide key information about stratigraphy, velocities and penetration resistance. The work units in this area propose to 1) develop improved geophysical techniques to link together borehole information, and to directly measure soil parameters needed for analysis, and 2) resolve the present controversy regarding interpretation of Becker Hammer measurements widely used in liquefaction evaluation of gravelly soils, and possibly develop a new in situ testing tool that is more amenable to direct analysis, so that the translation of field information to inputs needed in numerical analysis is as seamless as possible.

3.3 LIQUEFACTION-DEFORMATION-DAMAGE

The present procedures for assessing liquefaction potential and post earthquake stability rely almost exclusively on empirical correlations between penetration resistance and cyclic and residual strength. These procedures do not provide a basis for quantitatively predicting deformations and assessing damage. Advances have been made in developing more fundamental constitutive models and numerical dynamic analysis codes that can solve large-deformation problems. To advance beyond present procedures it is proposed to perform a combination of physical and numerical modeling research to:

* Critically examine the shortcomings of existing Seed procedures through two focused series of centrifuge experiments which will provide direct observation of underlying mechanisms of behavior of liquefying materials and the deformations that result (Figure 3 Centrifuge Facility). These tests will provide quantitative measurement of residual strength and poorly understood "correction factors": such as K_{sigma} and K_{alpha}; simplified guidance for controlling foundation features necessary to experience large deformations; an improved method of interpreting more traditional laboratory test results; measurement of the actual damage that deformations cause to internal structures such as filter and core zones; and a full-scale performance data base against which various numerical models can be tested.

* Critically examine the present state of development of fundamental constitutive models and large deformation numerical dynamic analysis codes to provide guidance for choosing among them in the short term, and to select the most promising for development, verification, simplification for practical use in the long term. To resolve remediation problems, this effort must work towards a three-dimensional analysis capability.

3.4 REMEDIATION

Efforts to advance remediation guidelines have been slowed by the cost of full scale field testing and the difficulty in generalizing results since remedial actions are very site specific. The centrifuge (Figure 3) gives us the opportunity to perform these full scale tests on a wide variety of remediation geometries to test our ability to compute their effectiveness. It is proposed to perform such a series of centrifuge tests, and later in the program, to design a test to examine the actual state-of-stress and density field that exists in remediated soils, since this stress history plays a major role in the future cyclic behavior of the soil. These efforts, combined with lessons learned from actual remediated sites should provide a basis for improved guidance so that we only remediate as much as actually needed.

4. STRUCTURAL WORK UNITS

The structures work units are designed to develop the necessary analytical tools and corresponding guidance to predict the dynamic response of concrete dams and outlet works from elastic behavior to the development of failure mechanisms. The understanding of the dynamics of the structural response will allow the determination of the ultimate capacity of these critical structures. The work units necessary to develop these products are divided into the areas of concrete dams, outlet works, and earthquake analysis tools.

4.1 CONCRETE DAMS

This work will focus on determining dynamic ultimate capacity of conventionally place and roller-compacted concrete dams. These work units will address the nonlinear behavior and failure mechanisms of the different types of dams as well as include component tests, scale model tests, and tests of existing structures.

4.2 OUTLET WORKS

This work focuses on determining the ultimate capacity of intake towers and the ductility of other than lightly reinforced concrete members. One major work unit will determine the ductility of lightly reinforced structures. The other work units will focus on other aspects on nonlinear behavior and failure mechanisms of these reinforced concrete structures.

4.3 COMPUTATIONAL TOOLS

These efforts will develop numerical tools to support the dams and outlet works areas. These work units will product time-domain numerical analysis tools compatible with the nonlinear materials models, and postprocessing tools to aid in the interpretation and understanding of output from time-history and response spectrum analyses. Other work units will support the appurtenant structures to the outlet works and dams. These work units will address dynamic earth pressures on walls and the dynamic response of piles.

4.4 INTAKE TOWERS

Existing Corps inake towers of outlet works of dams were designed using the seismic coefficient methods which incorrectly estimates demands placed on an intake tower during a major earthquake. The success of these lightly reinforced concrete towers in resisting failure is dependent upon the magnitude of the earthquake loads and the structural details controlling the nonlinear dynamic response and failure mechanisms of a specific tower (see figure 4). Currently available analysis tools and engineering guidance for intake towers do not properly include these factors.

The research effort will concentrate on evaluating the inherent ductility of existing intake towers. The initial effort will include a survey of existing intake towers to examine their location hazard and the variation of structural parameters. Primarily, the research effort will be a computational and experimental effort to generate a valid structural model representative of those found in the population of existing intake towers. It will include an examination of the performance of reinforcing bar details (lap lengths, development lengths, bond forces, and joint details), substructure experimentation (compression, shear, and moment effects), model tower experimentation (failure mechanisms and bridge/tower interaction), and perhaps nondestructive and destructive testing of a full-scale prototype tower.

5. COORDINATION

Partnering and cooperative research programs are an essential element of the EQEN Program. Current joint efforts include:

* Collaborative studies with NIST, TVA, NSF, DOE, and Japan through UJNR

* International contacts - Japan, China, Turkey, UK, Canada, and Panama

* Corps, FHWA, NCEER - Highway Seismic Research Programs funded by FHWA, executed by NCEER, leverages Corps funding for reinforced concrete and retrofit research.

* Corps, NIST researcher cooperation at NIST Building and Fire Research Laboratory

* Corps, NSF, Quest Structures, Inc. - Full-scale shaking experiments at Donjian Dam (see figure 5) China (1992) for subbottom absorption studies; Planned experiment in 1998 at another concrete arch dam in China.

* Corps, NSF/Quest Structures, Inc./USBR - Geophysical seismic reflection coefficients measured at seven concrete dams in cooperatively funded subbottom absorption study.

6. CONCLUSIONS

The Earthquake Engineering Research Program addresses both the geotechnical and structural aspects of water resources facilities with participation by other federal and state agencies and academic and professional experts. The activities include:

(1) Geotechnical: Development of a) criteria for selecting three-dimensional design earthquake ground motions and characterizing earthquake input required for the design of new and remediation of existing water resource facilities; b) cost-effective, reliable methods to determine site characteristics relevant to seismic performance; to determine, in three dimensions, the extent of potentially liquefiable materials subject to ground failure; and to determine, in three dimensions the adequacy of remedial actions such as ground improvement construction; c) reliable, nonlinear analysis methods to predict the capacity of earth structures to resist damage when subjected to seismic stresses and large, earthquake-induced deformations, and d) development of innovative, least cost, yet reliable remedial measures to strengthen embankment dams and their foundations if necessary.

(2) Structural: Development of a) methods of analysis to predict the extent of damage and ultimate capacity of conventionally placed and roller-compacted concrete dams and reservoir control structures subjected to strong earthquake ground motions, b) least cost remedial measure to strengthen these dams and structures if necessary; c) a material model for predicting nonlinear structural response caused by cracking and large displacements in concrete materials; d) methods for structure-reservoir-foundation interaction analyses that included hydrodynamic effects of the reservoir, uplift pressures beneath the dam, and interaction of the concrete dam with the surrounding rock foundation.

(3) The R&D results from EQEN form the basis for input to Corps guidance documents (ETL, EC, EM), and are put into practice in ongoing seismic safety evaluation projects as results on improved procedures become available. In addition to technical reports and professional papers, the R&D results in improved software, data bases and the aviablity of user manuals to all Corps District offices. In some cases this occures directly and in other cases it is through special projects such as CASE and CAGE. The R&D results form input to workshops seminars, conference presentations and training courses such as PROSPECT courses. For example, more than 100 copies of the Corps shear wave velocity data bases have been distributed to Corps offices, universities, and private industry. This data base provides key input properties for preliminary screening analysis of site response to earthquake ground motions.

7. ACKNOWLEDGMENTS

The author gratefully acknowledges the information and support provided by Dr. Mary E. Hynes, EQEN Program Manager, at the US Army Corps of Engineers Waterways Experiment Station.

8. REFERENCES

Earthquake Engineering Research Program Review Report, US Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, April 1997

Assessment of Earthquake Engineering for Dams and Related Facilities, Civil Engineering Research Foundation, Washington, DC August 1995

US Army Laboratory of the Year Award Report, Corps of Engineers Waterways Experiment Satation, Vicksburg, MS, January 1996

Seismic Hazard Map

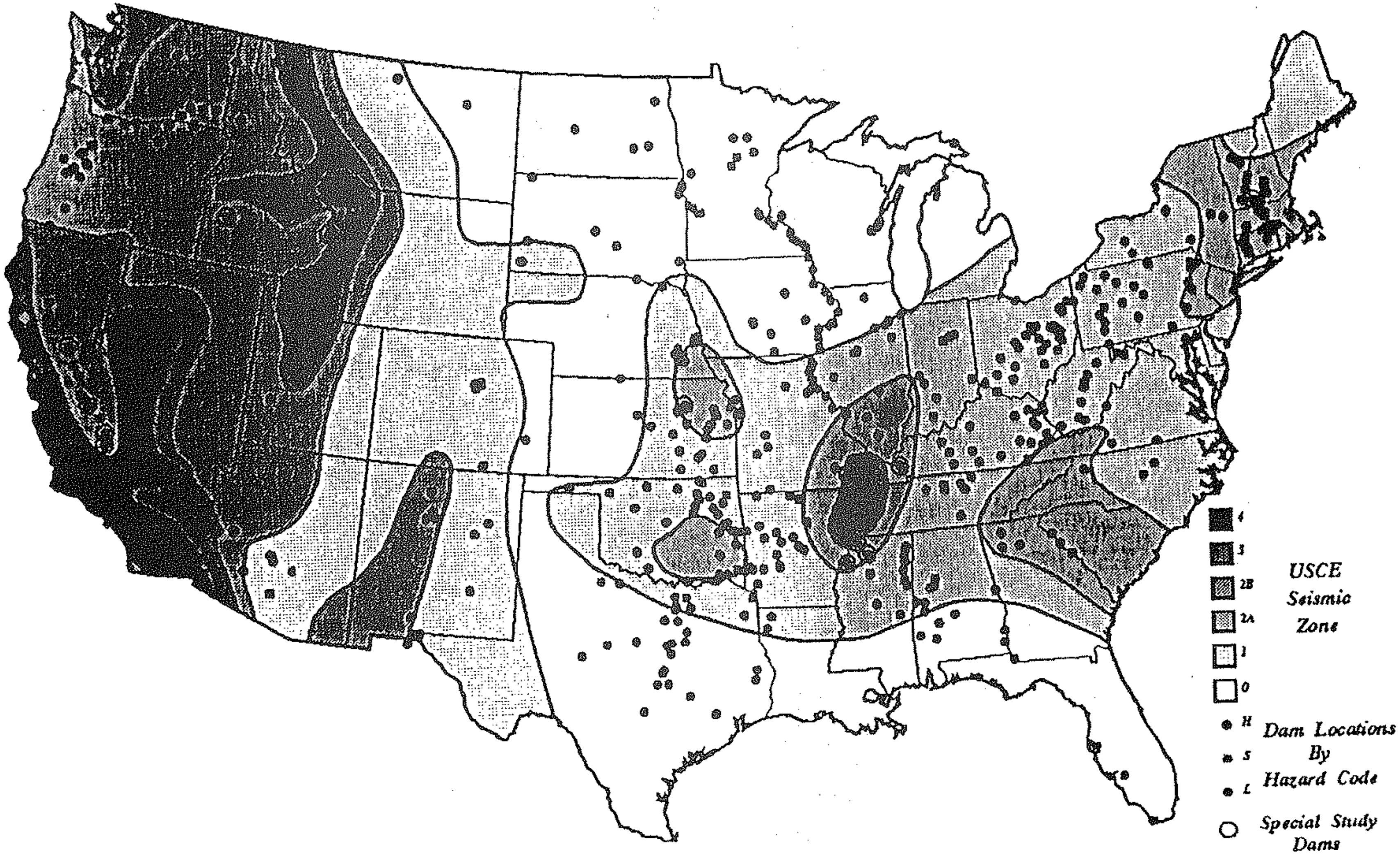


Figure 1. Seismic Risk Zones and Dam Locations

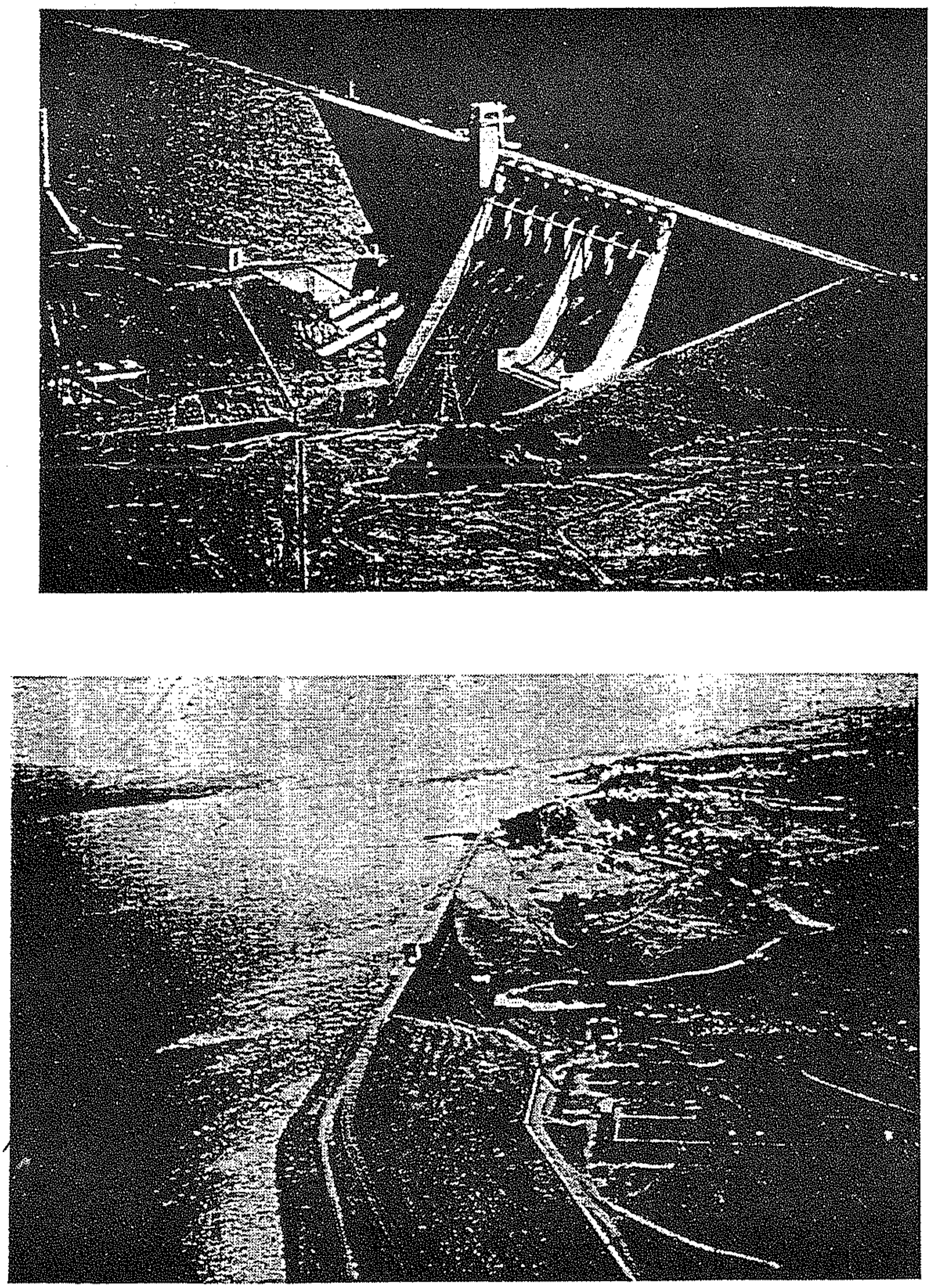
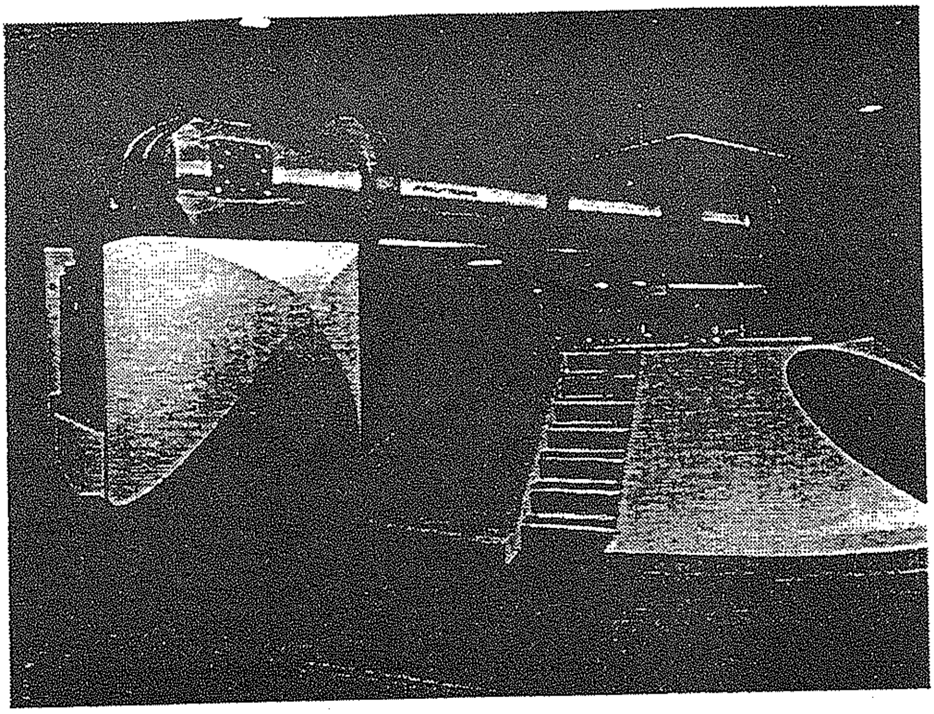


Figure 2. Ariel Views of Folsom Dam and Reservoir



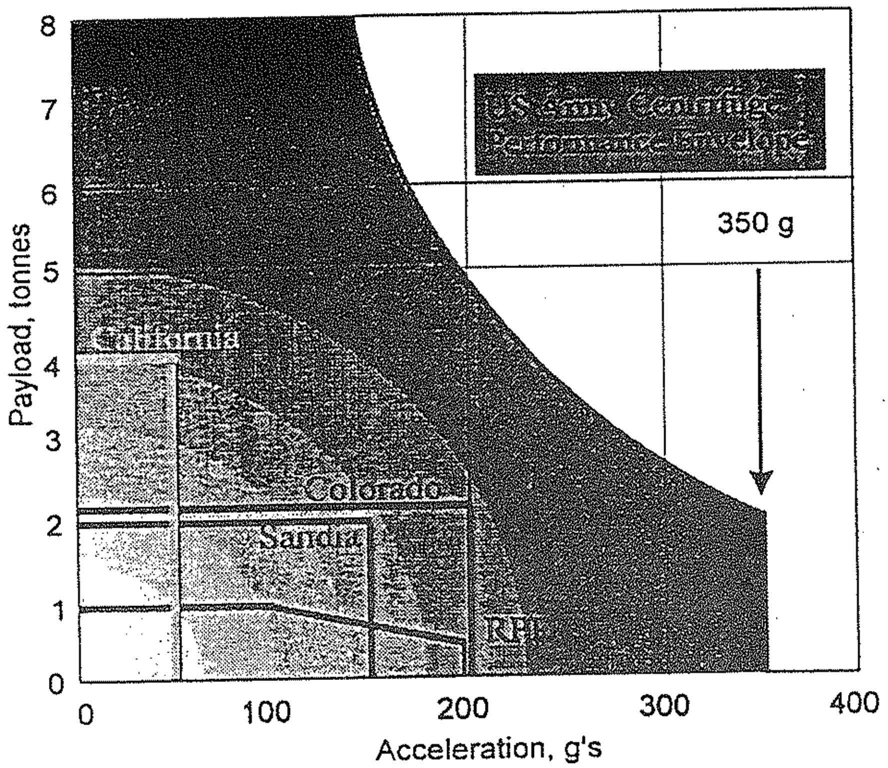


Figure 3. Corps of engineers Geotechnical Centrifuge and Performance Characteristics

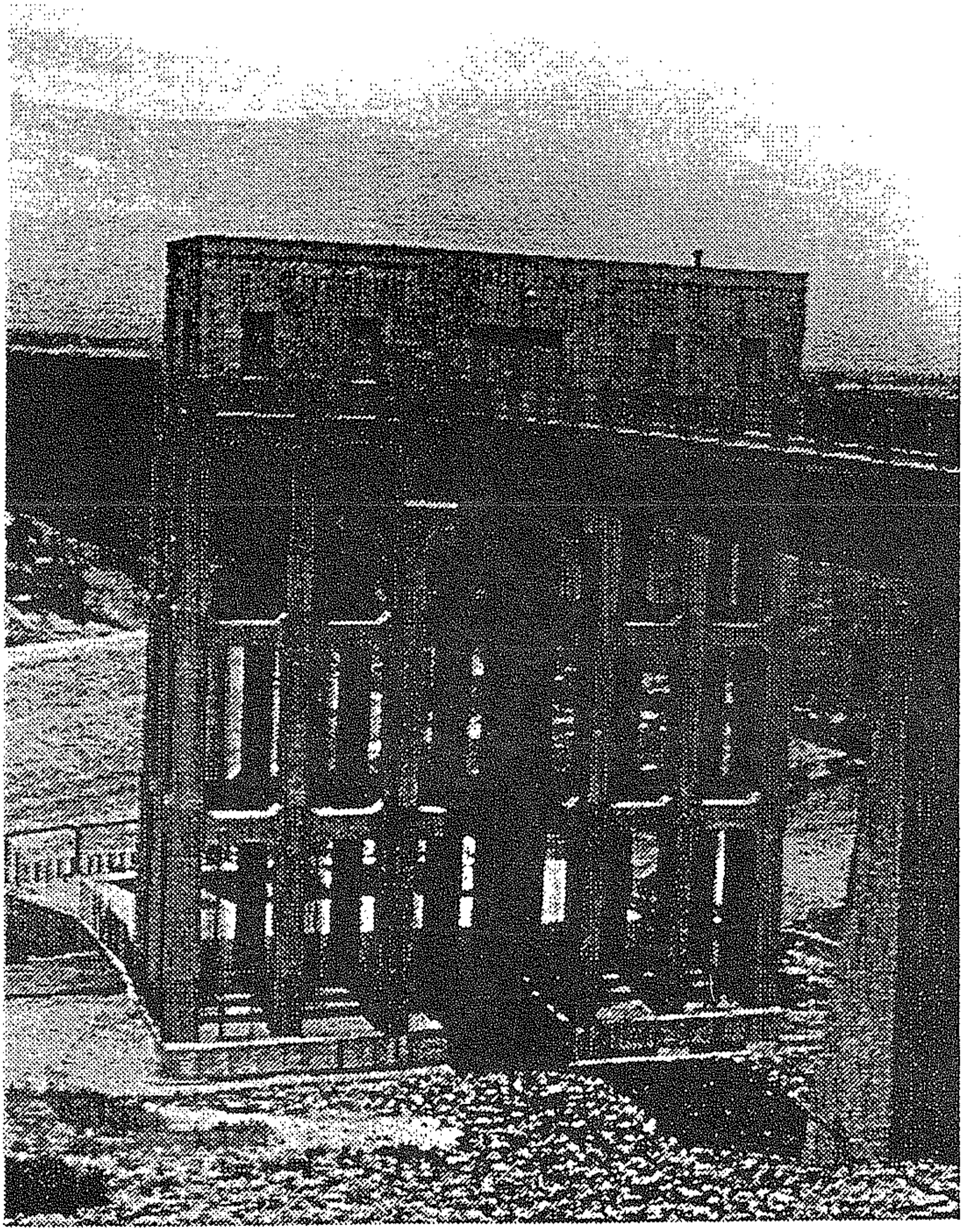


Figure 4. Intake Tower Structure of Prado Dam

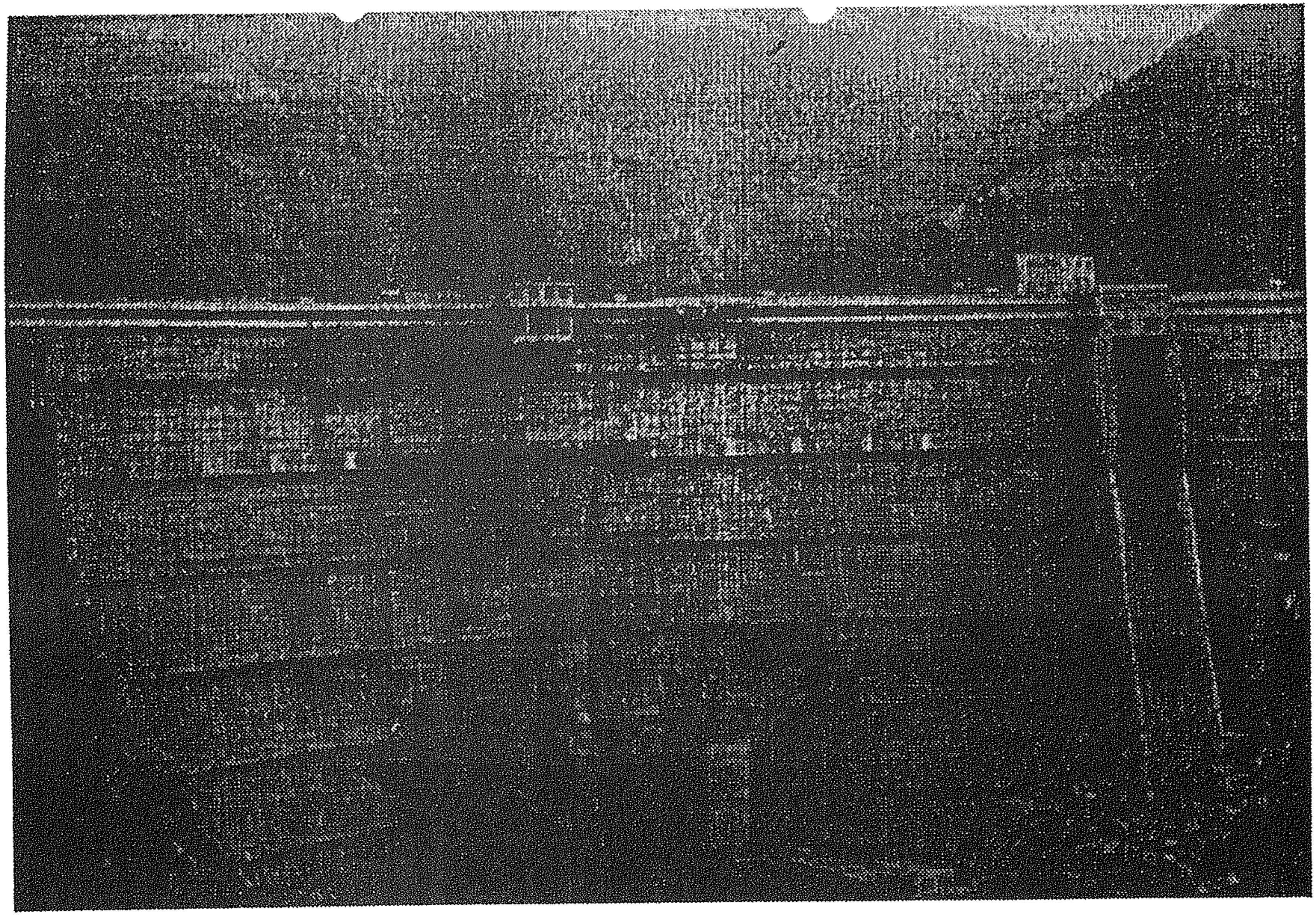


Figure Donjian Dam and Spillway in the Peoples Republic of China