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Earth Dams at Nuclear Power Plants
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SYNOPSIS

Many of the nuclear power plants under operation or construction use earth dams to impound cooling water for the safe shutdown of the plants in an emergency. The U.S. Nuclear Regulatory Commission reviews the licensee's design and analysis of the dams associated with the nuclear plants. An example of an earth dam including its unusual design features such as a high phreatic surface and a zoned blanket drain, safety analyses, and performance monitoring is given. Where well established procedures have been properly implemented during design, analysis, and construction, and when supported by field monitoring and periodic inspections, the dams have not only performed adequately, but have enhanced public confidence in their integrity and in the overall safety of the associated power plants.

INTRODUCTION

There are 85 nuclear power plants (148 units) operating, under construction or proposed for construction in the United States; 28 of these plants obtain emergency cooling water required for safe shutdown of the plant from impoundments formed by earth dams. To determine whether any of these dams constitutes a hazard to people or property, it is essential to consider the possibility that the integrity or function of these dams might be endangered by overtopping, seepage, slope failure, settlement, erosion, sediment accumulation, cracking, earth movement, earthquakes or other conditions that might exist or occur in the vicinity of the dam. Therefore, federal regulatory practices require that these dams be designed and operated according to high standards.

Generally, the most critical time in the life of a reservoir is during its first filling, when the design assumptions are checked against actual field performance. However, many dams may become weaker with advancing years and such weakening due to progressive deterioration of a dam or its foundation may become apparent only after many years of operation. Therefore, periodic inspection and analysis of performance data of dams associated with nuclear power plants are considered essential to ensure early detection and remedy of any adverse conditions.

SAFETY EVALUATION AND INSPECTION

Analyses of these dams generally include an evaluation of factors of safety against slope failure under both static and dynamic loading conditions. The static loading conditions normally analyzed include (1) end of construction, (2) steady state seepage, and (3) sudden drawdown. Under dynamic loading conditions, the dams are analyzed for the safe shutdown earthquake (SSE) combined with assumed steady-state seepage through the dam with a reservoir water level corresponding to a 25-yr flood. The effects of combining the operating basis earthquake (OBE) with the reservoir water level corresponding to the standard project flood are also commonly investigated.

Dynamic analyses of several dams associated with nuclear power plants have been performed using finite element analysis techniques, when such analyses were considered warranted. The results of these analyses have helped in the evaluation of the susceptibility of embankment and foundation materials to liquefaction effects. In some cases, permanent displacement analyses, originally proposed by Newmark (1965) and modified by others (Ambraseys and Sarma, 1967; Sarma, 1975), have been performed to estimate the movement of embankment slopes due to a design earthquake.

Performance monitoring of these dams is considered essential to ensure that they remain functional and impound the required quantity of cooling water for safe-shutdown of the nuclear plants in the event of an emergency. In many cases, seepage tests are conducted after the initial filling of the dam to estimate the rate and quantity of water loss due to seepage from the storage volume of the impoundment. Evaporation effects are also considered.

A periodic inspection program for earth dams to detect erosion, riprap deterioration, slumping, gully, excessive seepage, or any abnormal condition is generally established soon after completion of construction.

Failure of a dam that impounds the emergency cooling water or provides flood protection for a nuclear power plant could endanger plant safety systems, possibly leading to a radiological release to the environment that could affect public health and safety. Therefore,
design and construction of earth dams at nuclear power plants require a high degree of professional engineering attention. Several of these dams have unusual features and unique design loads that make their design and analysis site-specific. An example of such a dam is given below, showing the details of the dam geometry, its unusual design features, safety analyses, and performance monitoring as reported in public documents by the applicant for a license to operate a recently constructed nuclear power plant.

TYPICAL EXAMPLE

Dam Geometry and Materials

Figure 1 shows the cross section of an earth dam that was constructed in 1977 to impound the emergency cooling water for a nuclear power plant. The dam is a homogeneous, rolled earthfill structure built within a cove of a nearby lake. At its maximum cross section, the dam is approximately 75 feet high, measured from the prepared foundation surface located at about 25 feet below the lake bottom. The base of the embankment is approximately 470 feet wide at the same cross section. Each face of the dam is sloped at 3 to 1 (horizontal to vertical) from the 35-foot wide crest down to the toe.

The dam contains about 536,000 cubic yards of compacted earth fill obtained from two borrow areas. The embankment material consists of silty sand derived from saprolites. The crest, and the upstream and downstream faces of the dam are protected by riprap stones extending from abutment to abutment and underlain by a 12-inch thick layer of filter material. A zoned blanket drain in the downstream side of the dam extends to the one-fourth point of the base width, as shown in Fig. 1.

Salient Features of the Dam

One salient feature of the dam is the unusually high phreatic surface. The normal pond elevation upstream of the dam is 571 feet whereas the normal lake level on its downstream side is at elevation 569.4 feet, a difference of only 1.6 feet. The unusually low difference in the normal water levels on the two sides of the dam is due to the location and function of the dam. The dam impounds a pond within a cove of the lake; the lake provides the normal cooling water supply, whereas the pond provides the emergency cooling water for shutdown of the plant. The normal pond level upstream of the dam was determined by the quantity of cooling water required for a 30-day supply for emergency cooling of the plant.

Another unusual characteristic of this dam is the zoned blanket drain mentioned earlier. Since the normal phreatic surface is at a significantly higher elevation than the drain, the drain does not serve any function under normal conditions. However, in the case of a sudden drawdown of the lake to el. 550.0 feet due to the loss of the lake water for any reason, the drain will serve to lower the phreatic surface at a faster rate. The stability analysis of the dam under rapid drawdown conditions considers this feature.

The adequacy of the freeboard of the dam considered expected settlement based on consolidation test data on the embankment materials. The total estimated static settlement of the 75 feet high section of the dam was about 26 inches for the reservoir empty condition. Most of this settlement was expected to occur during construction, with an estimated post-construction settlement of only about 2 inches. To maintain the design freeboard, the dam crest was overbuilt two feet above the finished design elevation at the maximum dam section; the overbuild was proportional to the fill height at other sections.

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Fig. 1. Cross Section of an Earth Dam

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Stability Analysis

The static stability of the dam was analyzed for the following loading conditions: 1) end of construction (before pond filling); 2) steady state seepage (maximum pond level upstream, minimum lake water level downstream); and 3) sudden drawdown due to either the loss of the lake downstream or the loss of the pond upstream. The dam was found to have adequate safety margins against failure under these static design loading conditions.

The dynamic stability of the dam was investigated to consider two significant effects of an earthquake, namely, (1) the estimated strength loss (liquefaction) of the materials comprising the dam, and (2) the inertia forces acting on the mass of the dam. The analysis considered (1) a combination of SSE and reservoir water level corresponding to a 25 year flood; and (2) a combination of an OBE with a standard project flood level.

The safety factor against liquefaction effects on the dam was determined to be adequate, using the computer program QUAD4, a finite element analysis technique (Idriss, et al. 1973).

The permanent (plastic) movement within the dam was estimated using the modified Newmark sliding block model (Franklin & Chang, 1977; Margnati, Ill, et al. 1980, Makhist and Seed, 1977). The modified Newmark method considered the amplifying characteristics of the foundation-embankment system rather than treating the dam elements as rigid bodies. This analysis showed that the permanent (plastic) movement of the dam during a postulated SSE with a peak bedrock acceleration of 0.15g was insignificant (approximately 1 inch).

Performance Monitoring

Instruments were installed and monitored to evaluate dam performance during construction; monitoring will be continued throughout its lifetime. Typical instrumentation include piezometers at representative cross sections and at different levels to monitor the phreatic surface within selected material layers in the embankment. Surface monuments on the crest of the dam are used to monitor post-construction settlements. The piezometric data and the settlement data obtained to date (1983) from the instrumentation installed on the dam have verified that the dam is functioning as expected. For example, the phreatic surface elevations were estimated for the static conditions with the upstream pond level at el 571.0 and the downstream lake level at el 569.4. The recorded measurements of phreatic elevation agree reasonably well with the estimated values. Similarly the measured settlements at different locations of the dam were generally found to be in reasonable agreement with the predicted values.

A seepage test was carried out after the pond was initially filled. During a 60-day monitoring period, the seepage rate was determined to range from 20 to 28 gpm, which was considered insignificant in view of the total storage volume of the reservoir at the normal pond level.

Inspection

Periodic inspections of the dam and pond are being performed under the direction of qualified engineers, experienced in design, construction and operation of similar water control facilities. A detailed inspection report is prepared after each inspection to document the inspection findings and recommend any necessary remedial measures.

During the inspection in late 1981, localized erosion areas were noticed in three small regions along the shorelines of the pond. The total area of these eroded regions was about 0.3 acre. As a result of the findings of this inspection, remedial measures were taken to 1) remove vegetation from the slope protection, 2) repair erosion areas around the pond, and 3) remove debris such as tree limbs, leaves, stones, etc. from the area around the intake structure. No significant erosion has been reported since the affected areas were repaired and grassed. Continued maintenance of the dam and the surrounding shorelines of the pond based on the results of future inspection findings will likely reduce potential hazardous conditions and enhance the overall safety of the dam.

CONCLUDING REMARKS

For earth dams that provide emergency cooling water or flood protection for nuclear power plants, high standards are appropriate for the details of design and construction because of the potential for a radiological hazard to the environment. In cases where well established procedures have been properly implemented during design, analysis, and construction and are supported by field monitoring data, such dams have not only performed adequately, but have enhanced public confidence in their integrity and in the overall safety of associated power plants.

Recently, increased attention is being focused on probabilistic risk assessment techniques to characterize uncertainties and establish probability models for evaluating soil and rock parameters associated with geotechnical and dam engineering. Also, improved methods are being developed for the prediction and evaluation of induced vertical and horizontal movements in dams and embankments under seismic loading. Development of these procedures and a better understanding of the associated phenomena are likely to lead to improved and credible designs and to more reliable performance predictions in the future.

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The details of the dam described in this paper are taken from the Safety Analysis Report documents supplied by the licensee to the NRC staff for its review. This information is docketed in the NRC's Public Document Room in Washington, D.C. The opinions expressed in this paper are those of the authors and are not necessarily those of the license applicant or the U.S. Nuclear Regulatory Commission.

REFERENCES


