Dynamic Seismic Analysis of the El Centro Steam Plant, Unit No. 4

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Summary

The Lawrence Livermore National Laboratory (LLNL) performed a dynamic seismic analysis of Unit 4 of the El Centro Steam Plant in El Centro, California, for the U. S. Nuclear Regulatory Commission. Built in 1968, Unit 4 is an oil-fired steam driven turbine-generator that was designed to resist a static lateral force equivalent to a 0.2 g horizontal acceleration. However, the unit's structural and mechanical systems sustained only minor damage during the October 15, 1979 Imperial Valley earthquake that produced an estimated 0.5 g peak horizontal ground acceleration (0.6 g vertical) at the site. LLNL's seismic analysis was done to estimate the equipment response analytically.

Detailed results of this analysis as well as licensing implications are discussed in NUREG/CR-1665 [1].

The LLNL analysis consisted of the following steps:

- Review and summarize available design and construction information such as structural geometry, equipment locations and characteristics, and design criteria.
- Visit the site to inspect the structures and damage caused by the October 15, 1979 Imperial Valley earthquake.
- Develop a lumped-mass model of Unit 4, including the mass effects of major equipment items and soil-structure interaction, and determine the fundamental mode shapes and modal frequencies.
- Perform a dynamic analysis of the model using the actual time histories of the October 15, 1979 Imperial Valley earthquake recorded near the plant.
- Estimate structural accelerations and displacements.
- Generate in-structure response spectra at locations of major equipment items.
- Estimate fundamental frequencies for selected equipment items.
- Estimate the accelerations that equipment experienced.

This paper presents a summary of the analysis and results.

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*This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

1. Introduction

On October 15, 1979, at 4:16:55 p.m. (PDT) an earthquake shook the Imperial Valley of California. The earthquake had a Richter magnitude M_L of 6.6. The epicenter was on the Imperial Fault, 5 km south-east of the El Centro Steam Plant. There was no loss of life in this sparsely populated agricultural area, but there was some property damage and extensive damage to irrigation facilities.

When the earthquake occurred, only Units 3 and 4 of the four-unit nonnuclear El Centro Steam Plant in El Centro, Calif., were operating. The operating units tripped off line when station power was lost because of a short circuit. Units 3 and 4 were restored to service within 2 hr.

There was some minor damage to the facility; however, the two operating units safely shut down with no known malfunctions of electrical control and instrumentation equipment during or after the earthquake [1,2]. The most notable damage occurred at Units 3 and 4, which developed leaks in the cooling water piping for the hydrogen cooler and the exciter cooler. The leaks occurred in locations weakened by corrosion. The piping is made of 3- and 4-in. diameter welded carbon steel pipes with some threaded and unthreaded couplings. By expedient plugging of leaks, Unit 3 was kept in service. Because the load was abnormally low for several hours, Unit 4 was removed from service at 9:40 p.m. that evening to make repairs.

At the request of the U.S. Nuclear Regulatory Commission, the Lawrence Livermore National Laboratory (LLNL) performed a dynamic seismic analysis of Unit 4 of the El Centro Steam Plant to analytically estimate structural and equipment response. Laboratory representatives visited the site to become familiar with the plant layout and to gather information for modeling and analyzing the structure and equipment. Built in 1968, the oil-fired Unit 4 was designed to resist a static lateral force equivalent to 20% of the dead and live load. The unit's structural and mechanical systems sustained only minor damage during the earthquake, which produced an estimated 0.5 g peak horizontal ground acceleration (0.66 g vertical) at the site. A photograph of the plant is shown in Fig. 1.

Since the purpose of this report is to estimate reserve capacity in equipment, conservative assumptions usually made in the analysis of nuclear power plants were eliminated whenever possible so that lower bound estimates would result. Estimated response indicates that the structure and equipment experienced accelerations higher than those originally specified in the design. A comparison of the lower bound estimated responses to the design values provides a conservative estimate of the inherent reserve capacity that may be inferred for these types of equipment.

2. Structural Model

The seismic response of the turbine building and its associated structures was determined using a normal mode time history method of analysis for a linear elastic model composed of equivalent vertical beam members with masses lumped at floor levels. A schematic representation of the analysis model is shown in Fig. 2. Each model mass point represents the mass of the floor, boiler, and equipment at the respective level and a proportionate share of the mass of the walls and columns between each level. All masses are lumped at the respective floor levels of the structure. Each mass point has six degrees of freedom. The turbine building and the boiler support tower structural steel are interconnected and monolithically cast within concrete shear walls.

The gap between the boiler and its lateral seismic restraints was not modeled. In a design analysis of the turbine or boiler structure this omission would generally underestimate the actual building accelerations. However, for the purposes of equipment capacity estimates, we expect that this omission will lead to a lower bounding estimate of the equipment capacity.

The material damping is taken as 10% of critical damping for the concrete portions and 7% for the steel portions--the value recommended for highly stressed elements in NUREG/CR-0098 [3]. Note that the structure as a whole was not damaged; however, the use of these high damping values will lead to a low estimate of the equipment acceleration, and, by implication, its capacity.

3. Soil-Structure Interaction

To account for soil-structure interaction, the soil was treated as an elastic half-space, and soil springs and damping were developed using the formulations in reference [4]. The resulting six springs, three translational and three rotational, were attached to the center of rigidity at the mid-plane of the base slab.

In performing soil-structure interaction analyses, the large calculated damping ratios for the soil are frequently of concern. This is especially true when using modal superposition methods with frequency-independent soil parameters. As indicated in reference [5], when the soil damping gets very high, the response approaches that of the fixed-base case.

For this analysis, the responses of the centers of gravity of the base mat and operating floor were compared for the fixed-base case and the flexible-base case, which uses composite modal damping incorporating the high damping ratios calculated (see Table 1).

Parameter studies were conducted using an arbitrary 40% cutoff on composite modal damping. Based on these studies, it was decided that the calculated values were reasonable, therefore useful, except in the case of damping for the vertical direction where logic constraints of the software necessitated a maximum input value of 100% damping.

4. Seismic Input

The time history input was obtained from records of the October 15, 1979 Imperial Valley earthquake for U.S. Geological Survey Station No. 5165 [6]. Since the three components of the records were properly timed-phased, all three were simultaneously applied in the analysis.A ground motion duration of 20 s with a 0.01 s time step was used for this analysis.

5. Peak Accelerations and Response

The maximum accelerations and response for the main equipment floors are shown in Table 2. Note that the floor accelerations in the turbine building decrease as elevation increases. This behavior results from the soil springs, which cause an increase in the participation of higher modes compared to the fixed-base analysis.

The maximum predicted base shear values are relatively close to the design base shears determined from reference [7]. The two shears are compared in Table 3.

The maximum absolute differential displacement of the turbine building relative to the pedestal is 0.7 in., which is less than the design gap of 1 in. This result agrees with the fact that no damage was observed at the building-pedestal interface.

To estimate equipment response, in-structure response spectra nodes were selected and considered to be rigidly attached to the center of rigidity at each elevation in the model. Acceleration time histories and response spectra were generated at each node. Then, for each direction, a fundamental frequency and damping ratio were estimated for each of the 41 equipment items considered. The frequencies were either calculated, estimated by engineering judgment, or estimated by comparison to similar equipment for which frequencies were determined by analysis or test. Damping values were estimated for elastic response. Equipment acceleration responses were determined from the various in-structure response spectra. In general, the equipment acceleration responses varied from 0.5 to 1.8 g in the N-S direction, 0.4 to 1.2 g in the E-W direction, and 0.4 to 1.55 g in the vertical direction.

6. Conclusions

We concluded that the turbine building dynamic model with highly damped soil springs reasonably reflects the forces induced in the building during the earthquake. This conclusion is evidenced by:

- The low level of damage observed at the plant.
- The close relationship of the design to predicted base shears.
- The low displacement at the turbine pedestal.

In drawing conclusions about structural response, it is difficult to relate the static loading design criterion (a static lateral load equivalent to 20% of the dead as well as the live load) to an earthquake loading characterized by a particular peak ground acceleration. However, for this particular earthquake and structure the triaxial time history gives base shear values in close agreement with the original design values.

The forces experienced by the plant equipment were on the order of 2 to 9 times greater than the 0.2 g specified design load. This would seem to imply a reserve seismic equipment capacity of about 200%. However, it is difficult to verify this value without knowing the actual lateral load the equipment could withstand. One can only conclude that nuclear power plant equipment similar to that in Unit 4 and anchored as well should perform equally well during a similar earthquake.

References

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TABLE 1. Summary of soil springs and damping.

Direction	Damping ratio % of critical	Direction	Damping ratio, % of critical
N-S translation	94.5	Rotation about E-W axis	77.8
E-W translation	89.2	Rotation about N-S axis	68.6
Vertical translation	152[a]	Rotation about vertical axis	48.8

[a] 100% was used in the dynamic analysis.

TABLE 2. Maximum structural accelerations for main equipment floors in units of g

Elevation, ft	Peak ground Acceleration 0.49 (N-S)	0.35 (E-W)	0.66 (Vertical)
Turbine building			
998.7	0.51	0.37	0.36
983.0	0.51	0.38	0.37
969.0	0.52	0.39	0.39
949.0	0.55	0.40	0.40
Turbine pedestal			
969.0	0.52	0.38	0.39

TABLE 3. Base force comparison.

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Direction	Design	Predicted
E-W	1800[a]	1389
N-S	1800[a]	1752
Vertical	Unknown	1024

[a] Estimated shear (0.2 x weight) based on reference [6].

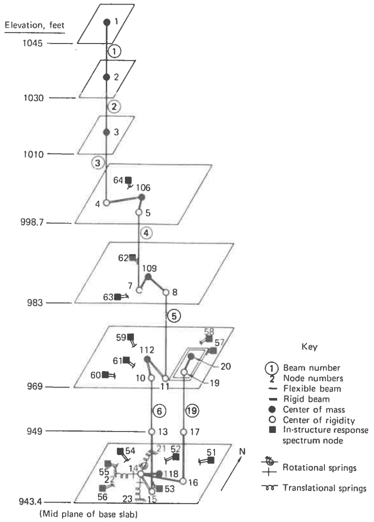

Fig. 1. View of the El Centro Steam Plant looking at the south side of Unit 4.

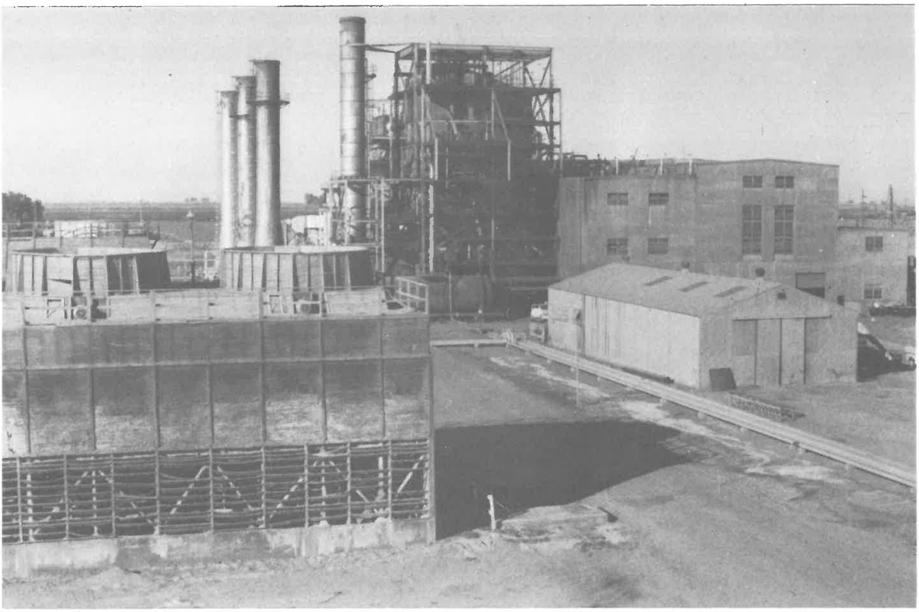

Fig. 2. Lumped-mass and beam model of the El Centro Steam Plant, Unit 4. Note the separate turbine pedestal beam, the translational and rotational soil springs, and the different locations at certain elevations of centers of gravity and rigidity.