ANALYTICAL-EXPERIMENTAL DYNAMIC ANALYSIS OF THE EL CENTRO POWER PLANT UNIT NO. 4 STEAM GENERATOR UNDER THE EFFECTS OF THE OCTOBER 15, 1979 IMPERIAL VALLEY EARTHQUAKE

G. Lopez (I)
Y. Makimoto (II)
T. Mii (III)
K. Mitsuhashi (IV)
B. Pankow (V)
Presenting Author: G.A. Lopez

SUMMARY

This paper describes experimental and analytical dynamic seismic analysis of the Imperial Irrigation District's Unit No. 4, located in El Centro, California, under the effects of the October 15, 1979 Imperial Valley Earthquake. The experimental work consisted of a shake table study using a scale acrylic model of the support structure and the boiler, which included the representation of non-linerarities due to gap effects. The analytical work involved a simulation study using a three-dimensional linear finite element structural model coupled with a lumped parameter soil representation, and accounted for soil-structure interaction. Results of these studies and their correlation with the actual earthquake damages are presented.

INTRODUCTION

The El Centro Power Plant is located at approximately 26 km from the epicenter of the earthquake that rocked the Imperial Valley on October 15, 1979. As a result of this earthquake, with a magnitude of 6.6, the plant's Unit No. 4 boiler suffered some minor structural damage. The damage, however, did not interfere with the normal operation of the unit; service was restored within two hours of the event. The ground motions at the site were accurately recorded and documented by the U.S. Geological Survey (U.S.G.S.), Ref. 1.

The event coincided with a then beginning development effort by the authors to develop reliable and practical dynamic seismic analysis procedures applicable to the routine design of boiler structures. Dynamic seismic analysis, the norm in other major areas such as nuclear power plant or chemical plant design, had not so far been adopted by the boiler industry as a routine analysis tool. The literature on this subject is rather scarce, although

---

(I) Senior Engineer, Riley Stoker Corporation, Worcester, Mass., U.S.A.

(II) Research Engineer, Mitsui Engineering & Shipbuilding, Tamano, Japan

(III) General Manager, Mitsui Engineering & Shipbuilding, Tamano, Japan

(IV) Assistant Manager, Mitsui Engineering & Shipbuilding, Tamano, Japan

(V) Manager, Riley Stoker Corporation, Worcester, Mass., U.S.A.

some of the available works (Refs. 2 & 3) have covered its main analytical aspects quite comprehensively. Previous efforts had not included, however, experimental confirmation of the selected modeling approaches, nor the effects of soil-structure interaction.

In this context, the availability of high-quality ground motion records of the above mentioned earthquake presented an exceptional opportunity for correlating the results of a simulation analysis, with the damages caused to the actual structure by the earthquake.

DESCRIPTION OF THE EL CENTRO UNIT NO. 4

Structural Characteristics

El Centro Unit No. 4 is an oil and gas fired, top supported steam generator. The structure was designed for a seismic lateral loading of 0.2 of the gravity loads, using the conventional pseudo-static force method. The main, structurally distinct, components of the unit are the steam generator (boiler), the support structure, the foundation and the adjacent turbine building (Figure 1).

The steam generator is suspended from its support structure by an array of vertical suspension rods. The internal boiler structure consists mainly of tube walls, which provide axial and shear stiffness. The walls are tied at various elevations by horizontal moment frames, or buckstays, which provide transverse restraint to the wall tubes against furnace pressures, while also serving as seismic load resisting elements. Seismic guides, located around the boiler at the buckstay elevations, provide lateral restraint to the boiler against lateral displacements. These guides typically consist of short cantilevered beams, with one end attached to either the buckstays or the support structure, and the other free to move vertically and axially between lateral stops, with a typical gap of 1.6 mm on each side.

The support structure is a 29 m tall, bolted steel braced frame. It consists of a box formed by four main vertical braced frames, located around the boiler, two lateral unbraced auxiliary frames, and two smaller rear frames. Horizontal trusses at various elevations carry the horizontal floor loads into the main vertical frames.

A continuous, raft-type foundation, consisting of an eleven foot deep reinforced concrete box with internal walls, extends under both the boiler support structure and the adjacent turbine building. The turbine building and the support structure are not structurally connected in any way other than by the common foundation mat. The foundation rests on deep alluvial deposits, consisting mainly of clays with layers of loam and fine sand.

Earthquake Damages

As a result of the earthquake, some of the bracing members of the main vertical frames and the suspension level horizontal trusswork buckled; the permanent transverse deflection in some of these members reached approximately 10 cm. In addition, most of the seismic guides suffered some degree of permanent deformations, either by bending or localized buckling. Dye-penetrant tests of the welds at the boiler walls showed no signs of cracks, indicating that the damage was confined to the seismic guides themselves. Figures 2 and 3 show a buckled bracing member and a bent seismic guide, respectively. Some piping and equipment damages also occurred, but their investigation was beyond the scope of this work. The equipment damages and the analytical study of the equipment response were treated in Reference 4.

MODELING CONSIDERATIONS

The nature of the boiler suspension system and seismic guide arrangement present significant modeling complexities. The main consideration when selecting the modeling approach was to be able to obtain the detailed response of the support structure; the response of the boiler was only of interest at its points of interface with the structure. The authors considered the internal response analysis of the boiler to be in itself sufficiently complex to warrant specific treatment in future efforts.

While it was considered essential that the model be as realistic as possible, practical considerations forced some simplifications. The large number of suspension rods made it impractical to model every one individually; therefore, they were modeled using a reduced set of rods of equivalent properties. Another simplification involved the modeling of the turbine building. Due to the lack of detailed data regarding its structure, only a very coarse representation of it was possible. This was found acceptable because the boiler structure and the turbine building are not connected, except through the foundation.

An area which needed particular attention was the modeling of the boiler-structure interface. Because of the seismic guide gaps, the boiler-support structure system is dynamically non-linear. For practical reasons, however, it was desirable to use a linear representation. To determine if a linear model would be sufficiently accurate, the dynamic effects of the seismic guide gaps were studied experimentally.

EXPERIMENTAL STUDY

Test Model Description

The experimental study was conducted on a scale model of the boiler and the support structure, subjected to base excitation on a shake table. The experimental model, Figure 4, was made of acrylic resin, to a scale of approximately 1/25 of the actual structure.

The model of the support structure, standing 1170 mm and weighing 8 kg, consisted of prismatic and laminar elements representing the main structural members and horizontal trusses, respectively. The boiler was modeled using plates for the boiler walls, and beams to simulate the buckstays; weighted bars represented the boiler mass. The boiler model, with a height of 900 mm and a weight of 4 kg., was suspended from the support structure by four rods. The boiler seismic guides were all included in the model, and were built so that they could be modified or removed for the testing of different gap effects.

As input to the shake table, artificial waves were generated that simulated the north-south component of the ground motions. The digital to analog synthesis process accounted for the natural frequency scaling of the model and resulted in ten waves that had, accordingly, higher frequency and shorter duration than those of the actual earthquake. The maximum amplitude of the artificial waves was 0.9 g and their duration was approximately 3 seconds. Figure 5 shows the response spectra for both the artificial seismic waves and the actual ground motion.

Study of Seismic Guide Gap Effects

The effects of the seismic guide gaps on the dynamic response of the test model were evaluated by studying the model behavior under various gap conditions, and then simulating the same response using a finite element representation of the test model to perform detailed response calculations. The finite element model consisted of a three-dimensional representation of the support structure, coupled with a rigid body-lumped mass representation of the boiler. The experimentally and analytically calculated natural frequencies of the test model are shown in Table 1. By modifying the seismic guide settings in the test model, the coupled boiler-support structure response was studied for the following seismic guide conditions:

1 - FREE TYPE	:	Sesimic guides removed
2 - FIXED TYPE	:	Sesimic guides with no gap
3 - GAP TYPE I	:	Seismic guides with 2 mm gap
4 - GAP TYPE II	:	Seismic guides with 0.05 mm gap

The response accelerations of the test model to the seismic wave input were recorded at various locations. From these, the model acceleration transfer functions were calculated and compared for the four different seismic guide conditions listed above. Figures 6 and 7 show the transfer functions at the top of the structure and top of the boiler, respectively. It can be seen from these curves that, for the range of frequencies of interest, below 30 hz, the response for GAP TYPE I approximates that of the free type. Also, for the same frequency range, the response for GAP TYPE II is equal to or lower than that of the fixed type.

The ratio of gap size, d, to relative displacement D, was used as the criterion to establish a vibration type classification. After studying the value of this ratio for the test model, it could then be determined whether the response of the structure for the modes of interest could be indeed approximated by a linear representation, i.e. FIXED TYPE. Table 2 shows the vibration type classification as a function of the d/D ratio values calculated for the test model of the boiler and support structure. The values of D were obtained as the average of the relative displacements between the boiler and support structure, at each seismic guide level. The response was calculated for the FREE TYPE condition using the finite element model, excited with the spectrum shown in Figure 5.

Application of the Test Results

To correlate the response of the actual structure, with that of the experimental model, the d/D ratios were calculated for the analytical model escribed below, with FREE TYPE seismic guide conditions. The d/D ratios or the most significant modes, listed on Table 5, were found to be less han 0.25.

Since it was shown for the test model that for d/D ratios of 0.25 the esponse approximates FIXED TYPE conditions, it was concluded that the seisic guide gaps could be neglected for the purpose of determining the overall esponse of the coupled boiler-structure system. This simplification, howver, implied that the response loads on the seismic guides themselves could ot be directly obtained from the overall system analysis. While the present ork did not include a detailed analysis of seismic guides loads, the authors ecognize the need for follow-up work, in which the seismic guides are analzed in detail, accounting for their non-linear nature.

ANALYTICAL SIMULATION

Having discussed in previous sections the principal problems associated with modeling the system, the main characteristics of the model of the actual structure used in the analytical response analysis are briefly described below:

The model of the boiler support structure consisted of beam and truss finite elements. Nodes were placed at all main joint locations and in coincidence with the boiler seismic guides. All vertical bracing was included, while the horizontal trusses were simplified to avoid non-essential degrees of freedom in the analysis. The seismic guides were modeled using beam elements with the proper end reaction releases, to simulate the horizontal shear-only restraint offered by the guides.

The boiler model was limited to a lumped mass-rigid element representation. The masses, placed at the seismic guide location, reflected the boiler mass distribution.

The continuous, box-type foundation lent itself to a rigid body representation, with nodes at the column bases under the boiler, and at the corners under the turbine building. The soil was modeled by springs representing the soil's translation and rotation stiffnesses. Because the analysis was to be done in the time domain, only the frequency independent static stiffness coefficients were used. Based on the results of a free field site response analysis, the soil shear modulus was reduced 5% for horizontal deformation and 40% for vertical deformation from its static value, to calculate the stiffness coefficients.

The dynamic response of the model was calculated in the time domain by the modal superposition method. Table 5 shows the natural frequencies and predominant direction of motion of the five most significant modes included in the analysis. The model was subjected to a base excitation consisting of the three components of ground acceleration, applied simultaneously. From the free field soil response analysis, mentioned previously, it was found that variation between the ground motions at the surface and those at the base of the foundation, located at a depth of 3.3. m were negligible. Thus the surface ground accelerations were applied to the model without modification due to depth variation.

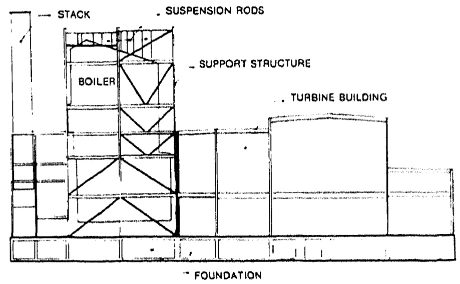

FIGURE 1 UNIT NO. 4 GENERAL ARRANGEMENT

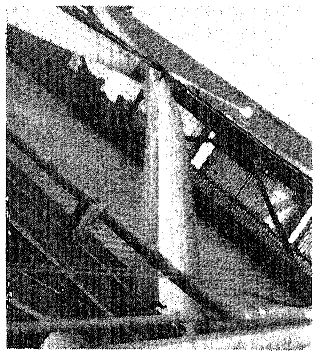

FIGURE 2 BUCKLED DIAGONAL

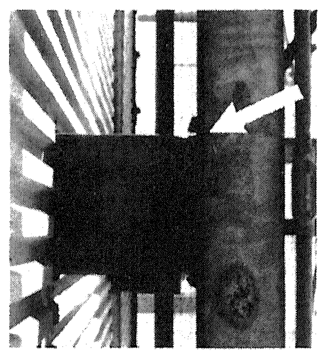

FIGURE 3 DAMAGED SEISMIC GUIDE

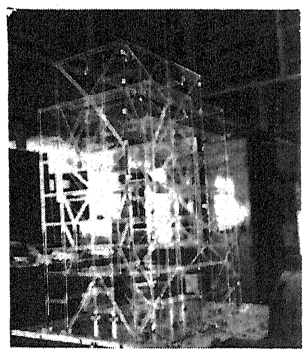

FIGURE 4 TEST MODEL

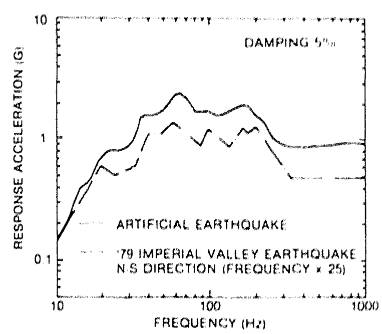

FIGURE 5 RESPONSE SPECTRA OF SEISMIC INPUTS

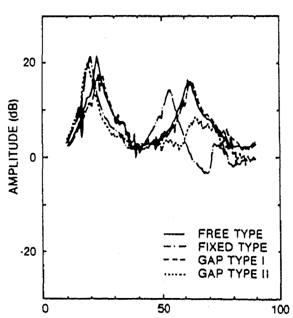

FIG. 6 TRANSFER FUNCTIONS OF SUPPORT STRUCTURE

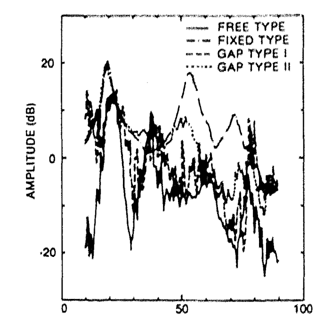

FIG. 7 TRANSFER FUNCTIONS OF BOILER

TABLE 1 COMPARISON OF EXPERIMENTAL AND CALCULATED FREQUENCY

(Unit: Hz)

	Mode	Experimental Value	Calculated Value
FREE TYPE	1st Bending Mode in N-S Direction	23	26
	2nd Bending Mode in N-S Direction	63	60
FIXED TYPE	1st Bending Mode in N-S Direction	20	23
	2nd Bending Mode in N-S Direction	54	58

TABLE 2 VIBRATION TYPES OF GAP EFFECTS

SUPPORT STRUCTURE	FIXED TYPE	FIXED TYPE with Gap Damping	FREE TYPE with Gap Damping	FREE TYPE
	GAP TYPE II 1st Mode (d/D = 0.25)	—	GAP TYPE II 2nd Mode (d/D = .83) GAP TYPE I 1st Mode (d/D = 10)	GAP TYPE I 2nd Mode (d/D = 33)
BOILER	FIXED TYPE	FIXED TYPE with Gap Damping	FREE TYPE with Transmission of Energy	
	GAP TYPE II 1st Mode (d/D = 0.25)	GAP TYPE II 2nd Mode (d/D = 0.83)	GAP TYPE I 1st Mode (d/D = 10)	2nd Mode (d/D = 33)

note d: gap size
D: average relative displacement

TABLE 3 RATIOS d/D FOR EL CENTRO UNIT NO. 4
NOTE: GAP SIZE d = 1.6 mm

Mode No.	Main Vibration Direction	Average Relative Displacement D (mm)	Ratio d/D
1	N-S	76.0	0.020
2	E-W	44.0	0.036
3	N-S	6.5	0.250
4	N-S	23.0	0.070
5	E-W	7.9	0.200

N-S North-South Direction E-W East-West Direction

TABLE 4 ANALYTICAL MODEL NATURAL FREQUENCIES

Mode	Frequency (Hz)	Direction (Fig. 8)
1	.91	N-S
2	.92	E-W
3	1.72	Vert.
4	2.08	Torsion

TABLE 5 RATIO OF CALCULATED AXIAL LOAD TO BUCKLING LOAD FOR BRACING MEMBERS ON REAR MAIN FRAME
(c = % of critical damping)

Level (From bottom to top)	Axial Load/Buckling Load				
	C=10	C=15	C=20	C=30	C=40
1	1.19	0.99	0.83	0.77	0.67
2	1.42	1.22	1.00	0.93	0.81
3	0.95	0.79	0.67	0.62	0.54
4	1.46	1.27	1.00	0.93	0.82
5	2.23	1.87	1.38	1.28	1.11
6 (1)	2.67	2.43	1.83	1.70	1.49
7	2.74	2.73	1.64	1.54	1.29

(1) Level where bracing was permanently buckled.

The method of analysis required that uniform damping be applied to all modes, precluding the use of different soil and structural damping ratios. This limitation is usually overcome by computing a theoretical composite damping value that accounts for the relative modal contributions. In this study, because it was desired to approximate the actual building response, rather than to produce conservative design loads, damping was chosen as a parameter and given arbitrary values, from 0 to as high as 40%. The results for high damping values agree best with the observed effects of the earthquake, suggesting a highly damped response of the actual structure. Table 5 lists the ratio of actual load to critical buckling load, P/Pcr, for the bracing members of the rear main frame; the bracing in the 6th level of this frame had suffered a large permanent deformation during the earthquake.

CONCLUSIONS

The main aspects of the analytical modeling and experimental verification of a suspended boiler and its support structure were discussed, although the authors recognize the need for further investigation into the detailed modeling and analysis of boiler internals.

Soil structure interaction effects were taken into account. It should be noted, however, that the combination of soil and foundation characteristics of the El Centro Unit No. 4, which made their simplified lumped parameter representation feasible, is uncommon. In general, the modeling of soil structure interface will be more complex.

Finally, this effort showed that dynamic analysis can be practically implemented and can reasonably predict earthquake loads on suspended boiler support structures, even under the constraints of standard analysis techniques.

REFERENCES

1. A.G. Brady et. al., "The Imperial Valley Earthquake, October 15, 1979. Digitation and Processing of Accelerograph Records", U.S. Department of the Interior Geological Survey, Open File Report 80-703.

2. K. Shiraki and S. Nakazawa, "Study on the Aseismic Design of Boilers and Structural Steels", Technical Review, Sept. 1968, pp. 184-195.

3. T.Y. Yang and M.I. Baig, "Seismic Analysis of Fossil Fuel Boiler Structures", ASCE Journal of the Structural Division, Dec. 1979, pp. 2511-2527.

4. R.C. Murray et. al., "Equipment Response at the El Centro Steam Plant During the October 15, 1979 Imperial Valley Earthquake", NUREG/CR-1655, Oct. 1980.