AN ASSESSMENT OF THE EARTHQUAKE RESISTANT DESIGN
OF ELECTRICAL POWER TRANSMISSION FACILITIES

by

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SYNOPSIS

Following the San Fernando earthquake, an assessment was made of the
earthquake resistant design of typical damaged equipment and facilities located at
the Sylmar Converter Station, which is the southern terminus of the 800-kv DC
Pacific Intertie between Oregon and Southern California. This assessment was
made to verify analytical procedures for predicting the response of complex electri
cal equipment to strong earthquake ground motion, and to develop criteria for
design modifications and for improved specifications for the procurement of new
equipment. A comprehensive engineering review was then made of the electrical
power transmission facilities of the Bonneville Power Administration to establish
the modifications needed to increase the earthquake resistance of the transmission
system facilities, and to develop a comprehensive implementation plan. This paper
summarizes the basic approach and discusses examples of equipment that required
design modification.

INTRODUCTION

Earthquake Damage to Sylmar Converter Station

The damage assessment report (1) contains more than 250 photographs and
descriptions of observed damage to 80 equipment items at the Sylmar converter
station. Inside the valve hall the current divider and anode reactor hangers failed,
and the dividers and anode reactors fell and impacted on the valves. Major damage
occurred to heavy items of equipment with high centers of gravity such as lightning
arresters, air power circuit breakers, harmonic filter capacitors, AC filter
reactors, power factor capacitors, and valve damping resistors. There was
widespread damage due to weld failures.

Dynamic structural analyses, using ground motions estimated from the strong
motion records from nearby stations, determined the stress levels and identified
the failure modes of the equipment. The predicted response or failure mode and
the factors of safety are compared with the observed behavior in Table 1.

Of the items analyzed, three did not fail during the earthquake and were found by
the analyses to have a factor of safety greater than one based on estimated ground
motions from the San Fernando earthquake. One item had a calculated factor of
safety slightly greater than one but failed. The remaining items had computed

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factors of safety well below unity and failed. Computed factors of safety for various items were in general agreement with the observed results. It was concluded that the analysis procedure could be used to predict the response of similar equipment at other facilities when subjected to earthquake ground motion.

Factors Contributing to Equipment Failure

An examination of the results of the response predictions as well as the observed behavior indicates five factors which contributed to equipment failure at Sylmar: (1) an extremely strong earthquake motion, (2) amplification of motion due to dynamic response, (3) three-dimensionality of ground motion, (4) lack of reserve strength of brittle materials, and (5) weak equipment to foundation connections.

SEISMIC REGIONALIZATION

Seismic risk and earthquake ground motion criteria for the Bonneville Power Administration service areas were obtained in four steps as follows: (1) definition of significant epicentral areas, (2) prediction of intensity of motion in epicentral areas and selection of an attenuation relationship, (3) delineation of seismic risk areas or zones, and (4) definition of earthquake ground motion for each seismic risk/zone in the form of response spectra.

Definition of Significant Epicentral Areas

The first step in the development of a seismic regionalization map was to identify those areas in the region that historically have experienced the largest and most frequent earthquakes. By associating this record with the geology and tectonic structures of the region, the significant epicentral areas were defined and the maximum earthquakes that can reasonably be expected to occur in each epicentral area were predicted(2).

Potential epicentral areas of Magnitude 7 earthquake or larger are shown in Figure 1. Similar maps were drawn for potential epicentral areas in which maximum earthquake Magnitudes of up to 6.5 and 5.0 were predicted.

Selection of Attenuation Relationships

In order to establish zones of different seismic risk, Modified Mercalli (MM) intensity values were assigned to the epicentral areas indicated in Figure 1 and to similar figures describing epicentral areas for lower Magnitudes. Attenuation curves for each epicentral area were also developed from actual experience records and from attenuation with distance relationships obtained from the published literature (3)(4). These curves were then used to define attenuated (MM) intensity curves at distance from the epicentral areas. For example, the attenuation curves for the Puget Sound area are shown in Figure 2. Assuming an epicentral (MM) intensity of X for a Magnitude 7.4 earthquake in the Puget Sound epicentral area, a distance of 110 miles is indicated for the Intensity VIII isoseism. Referring to Figure 1, this would indicate that Portland, Oregon could experience Intensity VIII ground motion for a Magnitude 7.4 earthquake occurring near Olympia in the Puget Sound epicentral area. Using this procedure a composite map of seismic intensity was developed extending from epicentral areas throughout the entire Pacific Northwest.
Delineation of Seismic Risk Areas

The composite intensity map was regionalized into three zones for the purpose of assigning earthquake design levels to the large number of power transmission facilities located within the area covered by this map. The three zones (Figure 3) correspond to three peak ground acceleration levels, as determined from generally accepted relationships between Intensity (MM) and peak ground acceleration\(^5\). Zone A is based on an upper bound peak horizontal ground acceleration of 0.12g, Zone B is 0.24g, and Zone C is 0.36g.

Definition of Earthquake Ground Motion.

A study of soil characteristics in the general region of the BPA Service Area reveals the need to account for site dependent characteristics for specific locations where ground motion time histories or response spectra are to be specified. Generalized response spectra, Figure 4, were developed from an analysis of several soil profiles. The response spectra are normalized to 0.10g. Figure 5 gives the envelope spectra and it was used as the basis for ground motion input, scaled to the appropriate peak acceleration for a given site. Although this is considered adequate for a general assessment of power transmission facilities located in a large geographic area, a more detailed study of a given location would be warranted for critical facilities whose response is sensitive to input variations.

BASIS FOR REDESIGN OF EXISTING FACILITIES

The classification of electrical equipment and support structures was in three phases: (1) data collection phase, (2) analytical investigation phase, and (3) classification phase.

In the data collection phase, information concerning foundation construction, support structure, equipment construction, and equipment installation was reviewed. The soils data, available test information, and seismic requirements were combined with the equipment and support information in a data summary for each item of equipment. In the analysis phase, the equipment and supports were modeled in a manner consistent with the general overall configuration to obtain an estimate of the natural frequencies. A preliminary analysis was made using the applicable response spectrum, damping, and mathematical model to obtain an estimate of the stresses in the major components. In the classification phase, the resulting stresses or internal forces were compared to the established criteria, and factors of safety were computed\(^6\).

Analysis Procedure

In general, most electrical power equipment can be placed in one of the model classes illustrated in Figure 6. As far as feasible, each equipment/support unit, including its foundations, was treated as a discrete structure. For these typical cases it was assumed that connecting power cables or bus do not impose significant loads or restraint on the units under investigation. If the existing installation made this assumption invalid, a more extensive analysis was performed which included the bus and power cable, their support structure, and the dynamic interaction of the interconnected units.
For many items of equipment a simple approximate calculation yielded the fundamental frequency of vibration, accelerations, and stresses at critical points in the model. For items which have either a complex configuration, interconnection with other equipment, poor connection details, or nonlinear response, more refined mathematical models were used.

**Damping Estimates**

Damping (expressed as percent critical damping) in electrical power equipment generally ranges from 0.5 percent to 7.0 percent. The only reliable method of determining damping is by actual testing of equipment as installed. Estimates of damping values, based upon testing of typical equipment configurations are: steel or aluminum supported equipment (working stress range): 1 percent; insulator stacks: 2 percent; insulator supported equipment frames: 1-2 percent; foundation-soil interaction (estimate including both internal and radiation damping): 5-10 percent.

**Directional Factors**

Both vertical and horizontal response was considered in the analysis. The combination of vertical and horizontal response which gives the most severe combination of stress was used. The horizontal earthquake component was oriented to provide maximum stresses in the structure. For analysis of complex items three-dimensional time history input was used.

**Equipment Within Buildings**

Items of equipment located on or within a structure, and whose mass is small compared to the structure mass, were analyzed using a response spectrum computed from the time history response of the structures at the point of attachment of the equipment.

**Modification Methods and Materials**

Four basic methods of increasing the seismic resistance level of equipment/support combinations were used depending on type of equipment and function, as shutdown time was also a consideration: (1) change of natural frequency, increase damping, or shock isolation, (2) reinforce existing support structure, (3) install new structural supports to brace existing structures, and (4) replace existing support structure with redesigned structures. The last three methods may stiffen the structures sufficiently to change their natural frequencies, and it was necessary, therefore, to reinvestigate the structure’s seismic response after the design modifications were introduced.

**EXAMPLES OF DESIGN MODIFICATIONS**

Four examples of design modifications will be given here to illustrate four different solutions—the first example, a lightning arrester, shows the use of a design detail (a spring) that changes frequency and redistributes moments and reduces the moment at a critical point. In the second case, capacitor racks are made earthquake resistant by providing stiff support elements. In the third case, the structural support of air power circuit breakers is replaced by a yielding (elasto-plastic) support to absorb energy by hysteretic damping. In the fourth case, the
air power circuit breaker is placed on an isolation platform to attenuate the effect of input accelerations.

**Lightning Arrester**

Figure 5, scaled up to correspond to 0.12g ground acceleration, was used for the response spectra at the ground surface describing the input at the base of the lightning arrester located in a substation in Zone A. Figure 7 shows a view of the equipment, the corresponding schematic representation, and the proposed modification. The bases are fixed. Allowable moment resistance is 120 kip-inches at the porcelain base; the other bases are bus supports of very large section modulus. A spring was introduced at the porcelain base (detail shown in Figure 7(a)), and a three-dimensional analysis of the model was performed. (Two percent of critical damping was assumed.) At the arrester base the results were:

<table>
<thead>
<tr>
<th></th>
<th>y-direction</th>
<th>x-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without spring</td>
<td>137 kip-in.</td>
<td>161 kip-in.</td>
</tr>
<tr>
<td>With spring</td>
<td>72 kip-in.</td>
<td>94 kip-in.</td>
</tr>
</tbody>
</table>

For an allowable moment of 120 kip-in. the design modification was considered to be satisfactory.

**AC Fifth Harmonic Filter Capacitor Racks**

These racks are three-dimensional moment resisting frames which could fail either at the aluminum welds or at the porcelain supports. There is also a possibility of overturning. The input is represented by Figure 5, scaled up to 0.12g to correspond to a location in Zone A. A complete redesign of the frame, porcelain support, and concrete foundation for each capacitor rack would essentially require replacement of the system. The alternative solution, shown in Figure 8(a,b), consisted of a braced frame system external to the group of 12 capacitor racks. The independently constructed peripheral and overhead bracing system is connected to the capacitor racks with insulator diagonals providing a second level support (eliminating cantilever action) and changing completely the structural configuration. The capacitor racks supported at the bases and the top were then reanalyzed showing considerable reduction in forces and moments at critical points.

**Air Power Circuit Breakers--Scheme 1**

The input for this group of electrical equipment is Figure 5, scaled up to 0.24g ground acceleration, to correspond to a location in Zone B. The circuit breakers have a fundamental frequency range of 1-3 Hz and are very fragile due to the fact that the porcelain is stressed during normal operating conditions, and superimposed forces from earthquake excitations would cause serious damage. Structural redesign changing the porcelain elements could also change the electrical characteristics, and, therefore, design changes external to the electrical units were necessary. In this scheme, shown in Figure 9, a three-phase group is shown placed on a rigid platform supported on commercially available elasto-plastic elements that yield at a preset constant force, as shown schematically in Figure 9(a). The support trusses can be repositioned after motion has occurred due to an earthquake. A flexible bus drop-in is used to accommodate relative motions. The results of an analysis, using the Olympia 1949 record (0.30g peak acceleration) as input, show a base
moment reduction from 200 kip-in. to 140 kip-in. when the yielding support is used. The allowable moment at the base of the circuit breakers is 150 kip-in. Since the Olympia strong motion record describes an input more severe than the Zone B level of Figure 3, the proposed design modification is adequate for this zone.

Air Power Circuit Breakers--Scheme 2

A second group of circuit breakers have their foundation integral with the porcelain isolators. The input for this group of electrical equipment is Figure 5, scaled up to 0.36g ground acceleration, to correspond to a location in Zone C. In this case an isolation platform is interposed between the ground and the circuit breakers, and the platform is supported by the pendular devices shown schematically in Figure 10. The pendular supports reduce the natural frequency of the system to 0.2 to 0.3 Hz and the peak response is attenuated to 0.1g. Relative motions in excess of 20 in. should be anticipated during a strong earthquake. In order to stabilize the platform against wind, friction plate dampers (not shown) are added in the horizontal directions. There is considerable experience in shock isolation of military systems for the effects of ground shock from nuclear weapons, and pendular support hardware and isolation platforms can now be readily designed to attenuate input accelerations.

SEISMIC SPECIFICATIONS FOR NEW EQUIPMENT

Equipment that has not yet been procured can be designed to be earthquake resistant if seismic resistance requirements are provided to the manufacturer along with functional requirements. As an example, an outline of a simple specification is given here.

Operational Requirements. The design shall be such that the apparatus and its supporting structures shall suffer no damage nor loss of function and shall remain operational during and following the seismic event.

Seismic Environment. (Peak ground acceleration and response spectra should be specified.)

Design Specifications and Factors of Safety. (Standard specifications for steel and aluminum should be specified.) For porcelain, add: the rated strength of porcelain elements shall not be less than three times the working stress. No increase in working stress for porcelain elements shall be permitted for seismic loads acting alone, or in combination with the design dead and live loads.

Dynamic Analysis. The manufacturer shall perform a dynamic analysis which considers all critical directions of response. The analysis shall be based upon the seismic environment defined in this specification. If time motion records are used for the analysis, these records shall yield response spectra which are equal to or greater than the response spectra given in this specification for comparable damping in the region defined by the essential natural frequencies of the equipment. The analysis shall indicate the natural frequencies and damping used, experimental test results, the safety factors computed for probable modes of failure, and the maximum deflections, shears, moments, and forces at all critical points in the apparatus and supporting structures.

Foundations and Supporting Structures. The foundations and/or supporting structures shall be considered in the dynamic analysis.

Responsibility of the Manufacturer. (Review by the buyer should not relieve the manufacturer of responsibility.)
CONCLUSIONS

Design modifications of existing electrical power transmission facilities to resist earthquakes have been determined to be feasible. Design details and construction procedures are within the state-of-the-art, and the modifications may be scheduled without disruption of the power supply. The inconvenience of construction modifications to achieve earthquake resistance is insignificant compared to the potential damage and the ensuing power disruption when electrical facilities are exposed to a strong earthquake. New equipment and facilities can be designed to resist ground motions that are predicted for a given region, such as the Bonneville Power Administration Service Area, provided equipment procurement specifications, as well as building design criteria, include provisions for earthquake resistant design.

REFERENCES


<table>
<thead>
<tr>
<th>Item Analyzed</th>
<th>Observed Behavior</th>
<th>Behavior Indicated By Analysis</th>
<th>Estimated Factor of Safety*</th>
</tr>
</thead>
<tbody>
<tr>
<td>230-kv air blast circuit breaker (APCB)</td>
<td>Bending failure</td>
<td>Bending failure</td>
<td>0.1 to 0.6</td>
</tr>
<tr>
<td>Valve hall-structure</td>
<td>Not overstressed</td>
<td>Not overstressed</td>
<td>&gt;2.0</td>
</tr>
<tr>
<td>Valve hall-current divider hangers</td>
<td>Impact failure</td>
<td>Impact failure</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Valve and valve platform</td>
<td>No struct. failure</td>
<td>No struct. failure</td>
<td>4.0</td>
</tr>
<tr>
<td>Unbraced capacitor racks for ac (Welds Porcelain)</td>
<td>Weld failure</td>
<td>Failure</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Bending failure</td>
<td>Bending failure</td>
<td>0.6</td>
</tr>
<tr>
<td>Braced capacitor rack for sixth-harmonic dc filter yard</td>
<td>Marginal Connection failure</td>
<td>Marginal Tensile failure</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base</td>
<td></td>
</tr>
<tr>
<td>1300-bli line-to-ground lightning arrester</td>
<td>Bending failure</td>
<td>Bending failure</td>
<td>-1.0</td>
</tr>
<tr>
<td>High-pass filter reactor in ac filter yard</td>
<td>Did not over-turn</td>
<td>Marginal</td>
<td>1.3</td>
</tr>
<tr>
<td>Odd-harmonic filter in ac filter yard</td>
<td>Overturned</td>
<td>Should overturn</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*Based on estimated ground motions from the San Fernando earthquake
Figure 8(a). Plan, external brace frame structure for capacitor racks.

Figure 9. Typical three-phase APC/CT isolation yielding platform concept.

Figure 9(a). Yielding support isolation concept.

Figure 10. Typical three-phase APC/CT isolation pendular platform concept.

Figure 10(a). Pendular isolation concept.