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A UTILITY'S APPROACH TO SEISMICALLY HARDENING EXISTING HIGH-VOLTAGE ELECTRICAL TRANSMISSION SUBSTATION EQUIPMENT

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SUMMARY

The Bonneville Power Administration (BPA) is responsible for the Pacific Northwest high-voltage electrical transmission line system. This transmission system extends throughout the States of Oregon, Washington, Idaho, and Western Montana with major inter-tie connections to California, Montana, and Canada. A majority of the transmission system was construction before the mid-1970's.

In 1994, BPA implemented a long-term seismic mitigation program to address the seismic vulnerability of their existing high-voltage electrical transmission line system. The mitigation program includes assessment of seismic vulnerabilities present in the existing transmission line system. The system components surveyed in the assessment include transmission, substation, and communication towers, substation equipment, and buildings critical to the operation of the power system.

This paper discusses the strategy currently employed by BPA for mitigating seismic deficiencies of existing electrical substation equipment. The issues and challenges of addressing seismic mitigation inside existing substation facilities are presented. In addition, to the author's knowledge, there are currently no consensus guidelines for seismic anchorage of existing substation high-voltage electrical equipment, such as transformers and reactors. The design criteria currently utilized by BPA is presented.

INTRODUCTION

Since 1994 the Bonneville Power Administration (BPA) has been conducting an on going seismic mitigation program. BPA is a United States Federal Power Marketing Agency for the U.S. Department of Energy. BPA operates a electrical high-voltage transmission line system throughout the states of Oregon, Washington, Idaho, and Western Montana. The BPA electrical transmission gird is interconnected to California to the South, Montana to the East, and Canada to the North. BPA's transmission system consists primarily of 115 kV, 230 kV, and 500 kV facilities. The majority of the 115 kV and 230 kV

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facilities were built before 1965. The 500 kV transmission line system was developed from 1965 through the mid-1980's. BPA's facilities include high-voltage substations and transmission lines, telecommunication sites, and support buildings. A seismic design policy was initially implemented in early 1970. The majority of BPA's existing facilities were designed to meet the 1970's seismic criteria, (based on 0.2g static requirements) which are significantly less than BPA's new seismic policy requirements. As a consequence, BPA has a mitigation program to seismically harden existing facilities.

The infrequent occurrences of significant earthquakes that can potentially damage high-voltage facilities within BPA's service region have made it difficult to initiate a seismic mitigation program. In addition, BPA's ability to fund the seismic mitigation program has been difficult due to the limited funds in a competitive electric power environment.

BPA's seismic mitigation program includes the following components:

1) Identify ***earthquake hazards,***
2) Establish ***seismic design criteria*** for new facilities,
3) Assess ***seismic vulnerability*** of facilities,
4) Prioritize and schedule ***mitigation*** efforts,
5) Prepare and practice ***emergency response plan***.

Earthquake Hazards

Pacific Northwest historical earthquake data has only been recorded for approximately the last two hundred years. Based on this information it was believed that maximum magnitude earthquakes for the region were in the range of 5 to 7. Little information was available for the Pacific Northwest about the potential for great subduction zone and shallow intra-crustal earthquakes. In the mid-1980's, understanding of the subduction earthquake potential for the Pacific Northwest was recognized. Currently seismologists estimate the region is susceptible to magnitude 9 earthquakes.

Off the Pacific Northwest coast is the Cascadia Subduction zone. This is where large pieces of the Pacific Ocean floor, namely the Juan de Fuca and Gorda plates, are sliding under the North American plate. The Cascadia subduction zone extends from northern California to southern British Columbia. Seismologists have discovered evidence that shows there have been occurrences of massive earthquakes along this subduction zone. Sea floor continent collisions have generated the largest known earthquakes, such as in Alaska (1964) and Chile (1960). It is estimated that the subduction interface (Megathrust) earthquakes have a return period of 100 to 1000 years and with average of 300 - 500 years. The most recent event or set of events occurred about 300 - 400 years ago. This type of earthquake has potential for earthquake magnitudes in the range of 8 to 9.

A subduction zone earthquake can be devastating because of its potentially long duration (minutes) of strong ground shaking at low frequency content. The Pacific Northwest subduction zone is unique in that it is not currently as active as other known subduction zones. Studies of modern coastal uplift and subsidence indicate that the Cascadia subduction zone is currently locked and accumulating strain.

There is also the potential for deep inter-plate earthquakes between the subducting Ocean plate and the North American plate, as well as shallow intra-crustal earthquakes within the North American plate. Significant inter-plate earthquakes have occurred in 1949 (Olympia, M7.1), 1965 (Tacoma, M6.5), 1999 (Satsop, M5.8), and 2001 (Nisqually, M6.8 and Satsop, M5.0). Significant shallow intra-crustal earthquakes occurred in 1993 (Scotts Mills, M5.6 and the Klamath Falls, M's 5.9 and 6.0), 1995

(Robinson Point, M5.0), and 1996 (Duvall, M5.3). It is thought that the 1872 earthquake (M7) near Lake Chelan in central Washington was also a shallow seismic event.

Seismic Design Criteria For New Facilities
New facilities are designed to meet the requirements of current seismic design codes and standards. Buildings supporting the operation of the power grid are design with the International Building Code [1]. Substation high-voltage equipment is designed with IEEE Standard 693 [2]. Facilities and substation equipment designed to meet the seismic requirements of current codes and standards will help BPA to protect life, limit damage to property, and minimize utility system function interruption.

Seismic Vulnerability
High-voltage electrical transmission line systems have been and will continue to be subjected to significant earthquakes. In the US, the State of California experiences significant earthquakes that result in damage to high-voltage electrical transmission line facilities. The seismic performance of these facilities has demonstrated the vulnerable components of a power transmission line system. The earthquake response of power system support buildings (such as control houses, maintenance buildings and offices) is similar to that of the "engineered" building population. The design of buildings to current codes provides adequate resistance to earthquake loads. Generally, telecommunication facilities used to support electrical transmission line systems have shown good earthquake performance. Worldwide performance of transmission line and substation wire support structures have been very good. Damage to these structure types have been limited to foundation failures caused by landslides, ground fracture, and liquefaction.

The level of damage to high-voltage electrical substation equipment is directly related to the voltage level. Worldwide experience has shown slight damage at 115 kV and below; moderate damage at 230 kV; and significant damage at 500 kV and above. Porcelain components (brittle material) of high-voltage electrical substation equipment are very susceptible to earthquake damage. Failures have also resulted from rigid bus and/or tight (inadequate slack) flexible aluminum rope connections between substation equipment. Experience has shown the following high-voltage substation equipment to be vulnerable to seismic events: disconnect switches (broken porcelain), transformers (broken porcelain, bushing seal failure, and triggering of protective relays), live tank circuit breakers (broken porcelain and seal leakage), instrument transformers (broken porcelain), and unrestrained batteries (spilled acid and cracked cell cases).

Mitigation
Existing facilities built before 1994 were targeted for seismic mitigation. BPA identified critical facilities within its high seismic hazard region as first priority for implementation of its seismic mitigation program. BPA conducted seismic walkdowns of these existing facilities to identify substation equipment to be hardened. The highest priority was assigned to the anchorage of power transformers and reactors. Other substation equipment within these facilities were anchored, braced and restrained to prevent sliding and overturning. Critical substation components were identified to have their electrical interconnections modified to flexible connections to account for seismic response between the high-voltage electrical substation equipment.

BPA's efforts to date include the following seismic mitigation activities: anchorage of power transformers (rail and pad mounted) and reactors, addition of supplemental structural bracing for transformer accessories (radiators, conservators, and surge arresters), anchorage of station service transformers, and restraining batteries to their racks and installing battery spacers. BPA has evaluated emergency power engine-generator fuel lines for flexibility and added vibration isolator supports for seismic stops. In addition, emergency substation equipment storage facilities have been evaluated and, if necessary, strengthened. A building structure that housed spare bushings was seismically upgraded.

Emergency Response Plan

An emergency response plan is an important component of a seismic mitigation program. Yearly review of the plan's components and company practice of earthquake exercises that implement the plan are critical to the restoration of the power system after a major seismic event.

EXISTING SUBSTATION EQUIPMENT

The seismic performance of high-voltage electrical substation equipment has been identified by BPA as a critical seismic mitigation component to ensure post-earthquake operations of the transmission line system. New electrical equipment installed in BPA substation facilities are required to be qualified in accordance with IEEE Std. 693-1997 [2] to withstand a minimum level of strong ground shaking. When installed, the equipment is anchored to the foundation, by welding or bolting, for the demands recorded during the seismic qualification.

However, a majority of the electrical equipment installed prior to 1994 was not subject to the seismic qualification levels of IEEE Std. 693-1997 [2]or typically anchored to the supporting foundation. As part of the seismic mitigation program, BPA developed a design methodology for seismically anchoring existing high-voltage electrical substation equipment. The performance objective for the anchorage is to limit business interruption time to one week or less following a major earthquake.

The following discussion addresses the anchorage design of existing high-voltage power transformers currently employed by BPA. Because of the importance of power transformers to the operation of a high-voltage transmission grid and the long replacement lead-time for this equipment, it is critical existing equipment be seismically hardened. It is hoped the anchorage design methodology presented will assist other utilities with anchorage of existing power transformers.

Design Criteria

Existing substation electrical equipment is anchored to resist lateral loads that produce both overturning and sliding demands at the equipment base. The anchorage is designed to resist a peak horizontal ground acceleration of 0.5g in addition to a simultaneous vertical ground acceleration of 0.4g (i.e. 80 percent of the horizontal ground acceleration). As an alternative, if available, site-specific data can be used to determine the peak ground accelerations for anchorage design.

Typically the in-service mass (weight) of the electrical equipment is known, however the location of the center of gravity (c.g) may not be available. The weights of transmission power transformers vary with voltage level and whether the transformer is a single or three-phase unit. BPA has successfully designed seismic anchorage for a wide range of transformer sizes and weights. The range of transformer weights include the following: 115kV units = 890 kN to 1340 kN (200,000 to 300,000 pounds); 230kV units = 1340 kN to 2700 kN (300,000 to 600,000 pounds); and 500kV units = 1800kN to 3100 kN (400,000 to 700,000 pounds). Unless the c.g. location is readily available, the plan location of the c.g. is assumed to be located at the geometric centroid of the transformer. Furthermore, it is also assumed that the vertical location of the c.g. is at 2/3 of the overall transformer height. See Figure 1 for assumed location of the transformer c.g. and application of horizontal and vertical demands.

The calculated anchorage demands are considered ultimate strength demands, not service level forces. The anchorage component nominal capacities are calculated using load and resistance factor design

(LRFD) with a strength reduction phi factor, ϕ, of 1.0. A phi factor of 1.0 is justified when considering the following:

1. Horizontal Ground Accelerations: Using a peak horizontal ground acceleration of 0.5g is conservative for the BPA transmission system service region. The largest 0.2 second spectral acceleration for the 2% in 50 year event provide by the 2002 United States Geological Survey maps for the BPA transmission system is 1.65g. Using ASCE 7-02 [3] to estimate the peak ground acceleration assuming a typical soil class of S_D (stiff soils), the peak horizontal ground acceleration is calculated to be 0.44g. Therefore, using 0.5g for the design horizontal acceleration results in a minimum effective load factor of 0.5/0.44 = 1.14 or an effective capacity reduction factor of 0.88.

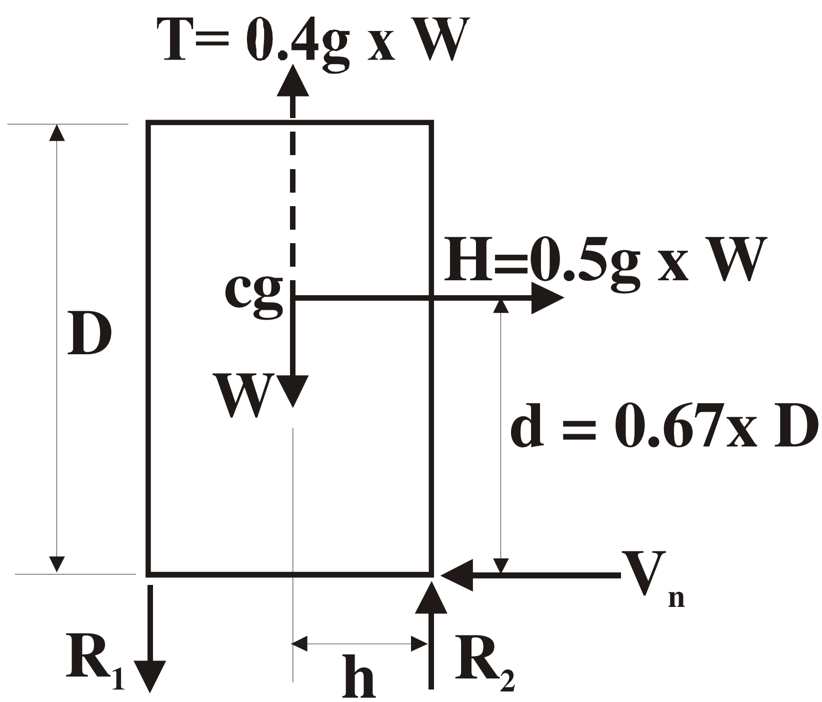


Figure 1, Transformer Forces and Reactions

2. Ductile Anchorage Components: The anchorage components typically include such items as bent steel plates (ASTM A36), adhesive anchors and ductile undercut anchors. Nominal energy dissipation is anticipated to occur in the anchorage components through rod elongation during a major earthquake.

Anchorage of the unit is designed to provide an ultimate factor of safety of 1.5 for both global unit overturning and sliding. Global overturning is satisfied when:

$$\frac{M_{OT}}{M_{RESIST}} \leq 1.0$$

where,

$$M_{OT} = 1.5\ x\ H\ \ x\ d\,;\ M_{RESIST} = (W - T)\ x\ h;\ T = 0.4\ x\ W$$

Global sliding is satisfied when:

$$\frac{1.5\ x\ H}{V_N} \leq 1.0$$

where,

V_N = *Nominal Unit Base Shear Capacity*

Anchorage Strategies

Anchoring of existing equipment in operational high-voltage electrical substations can be challenging. Due to the sensitivity of the electrical substation equipment and nature of the energized working environment, design and construction restraints may dictate the anchorage strategy employed. Typical constraints within an energized substation include limited electrical overhead clearance and the inability to reroute or move existing substation equipment or utilities. In addition, BPA requires the anchorage assemblies be installed while substation equipment is fully energized in order to limit utility interruption time.

Quite often the best location for anchoring a transformer is at the lifting lug or rigging attachment points. The lifting lug points are ideal anchorage points since they are designed for significant loads applied during movement of the transformer. However, the presence of nearby electrical conduits, valves or other appurtenances may preclude the use of lifting lugs points. With the exception of grounding wire, conduit and other electrical components generally cannot be rerouted to accommodate the installation of anchorage assemblies.

Anchorage Assemblies

Anchorage assemblies are custom designed for each of the high-voltage transformers to accommodate the unique combination of attachment points and field installation constraints. Anchorage assemblies are typically a built-up assembly of steel plates and hot-rolled sections.

The preferred method of anchoring existing transformers is bolting to the electrical substation equipment and mechanical expansion or adhesive anchors into the foundation. Anchorage assemblies can also be welded to electrical substation equipment, however, the use of welds is limited. Welding too close to the electrical equipments oil tank may result in gas bubbles from the introduction of heat during welding. Gas bubbles in the cooling oil can effect the substation maintenance routine of gas measurements in the transformer oil for determining potential transformer problems. If welding is to be performed in areas that can generate gas bubbles, the transformer can have gas measurements taken before and after the welding to establish a gas bubble content level for future maintenance checks. Also welding on certain areas of a transformer can damage internal control wires if located within the weld area, and internal surfaces. Welding to thick plates and plates that extend away from the tank wall is acceptable, but only with extreme caution.

Pad-Mounted Transformers

Anchorage solutions for pad-mounted transformers are shown in Figures 2, 3, and 4. Anchorage assemblies are designed to resist all the reaction loads (uplift, shear, and bending moment) at a single point or a combination of assemblies are designed to resist different load components. Figures 2a and 2b show an anchorage design to resist all the reaction load components. The disadvantage of this concept is that the dimensions for the anchorage assembly need to be very accurate to fit between the lifting lug and the concrete pad, which can vary for each lifting lug location. The anchorage assembly shown in Figures 2c and 2d also resist all the load components but has the advantage of accommodating varying dimensions between the transformer attachment point and the concrete pad. The anchorage units shown in Figures 2e and 2f use a combination of assemblies to resist different reaction loads. The vertical telescopic assemblies are designed to resist the uplift loads, while the plate assemblies shown in Figure 1f are used to resist shear loads. Installed anchorage solutions are typically limited by the dimensions of the concrete pad relative to the transformer placement, the locations of the lifting lugs, the design of the transformer case/tank, and access to potential anchorage locations.

Figure 3 shows anchorage assemblies that do not connect to the transformer lifting lugs. The transformer shown in Figures 3a, 3b, and 3c had restricted access to the lifting lugs. To accommodate this field condition, a combination of diagonal braces and shear plates were used to anchor the transformer. The diagonal braces are weld to the transformer tank stiffener. Prior to installation of the braces, the transformer manufacturer was consultant to determine the feasibility of welding at these locations. The vertical tank components contain electrical control wires, however wires were not located in the area the diagonal brace were attached. By contrast, Figures 3e and 3f show an anchorage assembly with a vertical support that is bolted to a protruded vertical tank stiffener. In addition, shear plate assembles were also provided to resist the horizontal loads.

Figure 4 shows additional anchorage concepts used for pad-mounted transformers. Figures 4a and 4b show anchorages designed for bolting to the transformers rather than welding to the lifting lugs as shown in Figure 2.

Some transformers are better suited for the installation of anchorage clips as shown in Figure 4c. The number of clips required to anchor one transformer can be significant. The clip anchor bolts are designed for the additional tensile load due to the prying action of the clip plates.

The transformer anchorage shown in Figure 4d required an extension to the concrete pad. In general, this option may not be feasible due to confined space around the transformer or because of restricted workspace due to the transformer appurtenances (such as radiators). Figures 4e and 4f show an anchorage concept with the anchor assembly bolted to the side of the concrete pad and welded to the transformer lifting lugs. In general, extreme caution must be used when excavating within a substation yard or under transformer radiators since substations have numerous buried electrical conduits and oil containment piping systems.

Rail-Mounted Transformers

Anchorage concepts for rail-mounted transformers are shown in Figure 5. Rail-mounted transformers are typically more difficult to anchor since the steel components are usually heavy and the working space is more confined. Typical anchorage concepts include diagonal- and V-braced systems installed below the transformer to resist the overturning moments and horizontal shear loads. When designing rail-mounted transformer anchorage it is important to check that there is a load path between the transformer carriage and the anchorage assemble. Figure 5b illustrate where the transformer base-plate required welding to the transformer carriage in order to provide a load path from the anchorage assemble to the carriage frame.

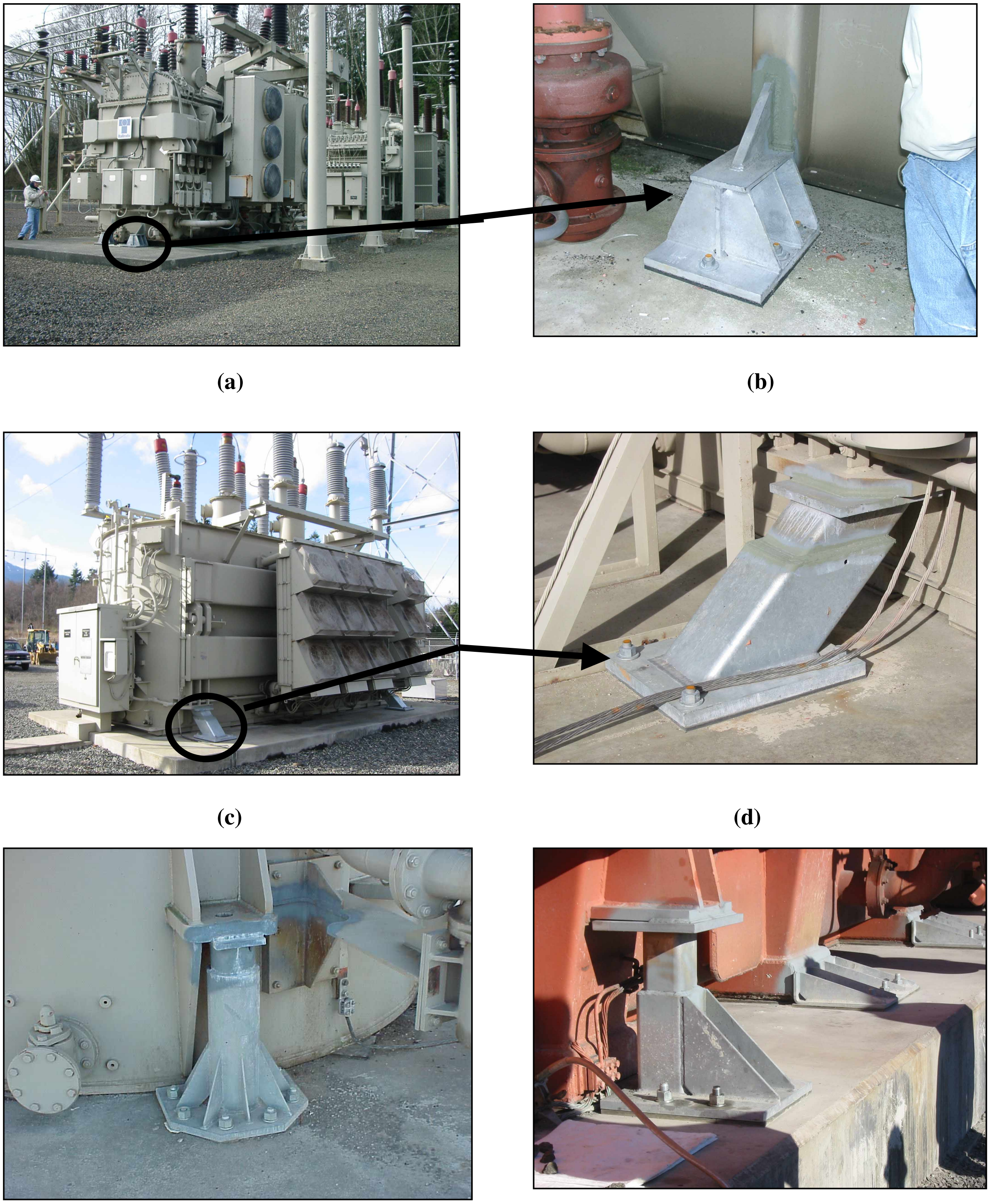
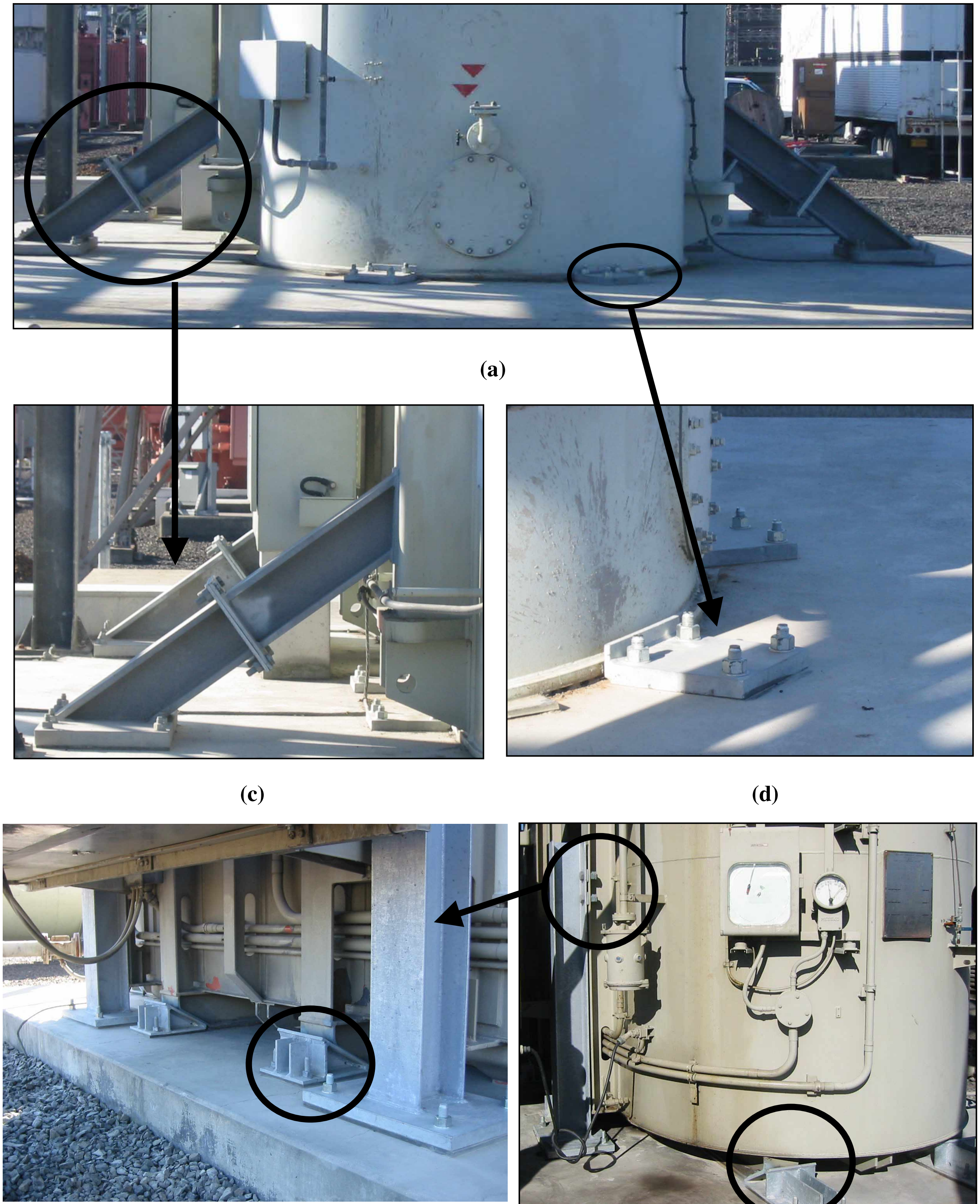


Figure 2, Typical Pad-Mounted Transformer Anchorage Assemblies



(a)

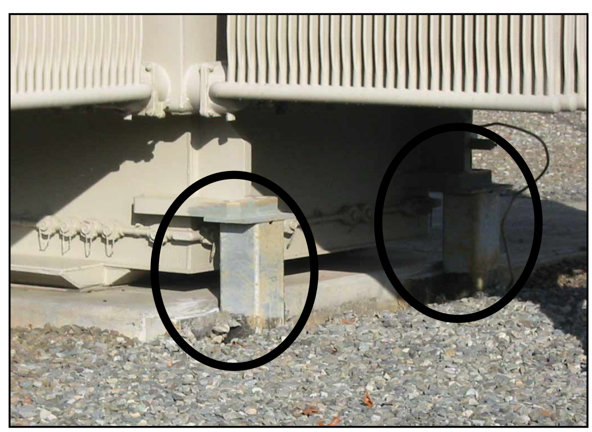
(c) (d)

(e) (f)

Figure 3, Unique Pad-Mounted Anchorage Concepts

(a) **(b)**

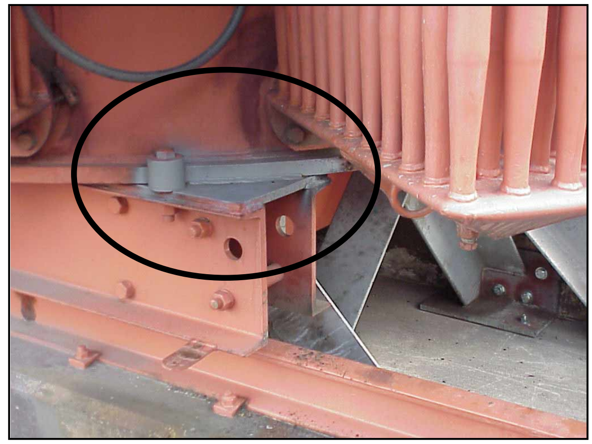
(c) **(d)**



(e) **(f)**

Figure 4, Additional Pad-Mounted Transformer Anchorage Assemblies

(a)

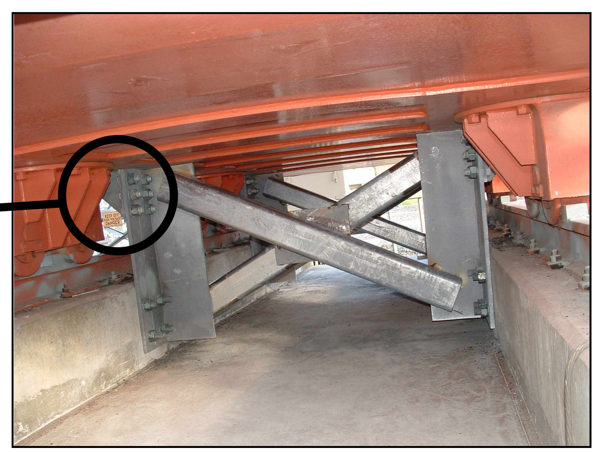


(b)

(c)

(d)

(e)



(f)

Figure 5, Typical Rail-Mounted Transformer Anchorage Assemblies

(a)

(b)

(c)

(d)

(e)

Figure 6, Pedestal-Mounted Transformer Anchorage Solution

Pedestal-Mounted Transformers

This is a unique situation were the rail-mounted carriage is removed and the transformer is placed directly onto the concrete pedestal foundation. This type of transformer installation required a very unique anchorage solution. An anchorage solution for a pedestal-mounted transformer is shown in Figure 6. As can be seen by Figures 6a through 6f many different anchorage components were utilized to provide a reliable load path.. A limited number of adequate anchorage attachment locations required using several anchoring components. Figures 6a, 6b, and 6d show vertical tension members for resisting overturning moments. Figures 6a and 6b also show shear plates assemblies for resisting horizontal loads. Figure 6e shows an anchorage designed to resist shear load only. Not shown in Figure 6e is a horizontal strut that is connected to the member anchored to the pedestal wall and butted up against the transformer base-plate.

As demonstrated by the anchorage assemblies presented for existing transformers, the mitigation solutions typically require custom design for each transformer. Due to differences in field conditions and variety of transformers contained within the BPA inventory, anchorage assemblies are typically not transferable from one unit to another. Where ever possible the anchorage concepts are use on different transformers, but this is typically not feasible.

CONCLUSION

This paper discussed the seismic mitigation approach used by the BPA to harden its high-voltage electrical substation equipment. Worldwide earthquake performance of high-voltage electrical transmission line systems has demonstrated the vulnerability of high-voltage electrical substation equipment components. This is particularly true for existing facilities installed before adequate seismic design criteria was available to the industry.

It is costly to replace existing high-voltage electrical substation equipment for seismic mitigation. As existing equipment is replaced with seismically qualified equipment, utility high-voltage transmission line systems will become more reliable. In the interim, utilities can implement a long-term seismic mitigation program for hardening critical components by anchoring and bracing equipment, and by adding flexible connections (jumpers) between substation equipment installed in existing facilities.

High-voltage power transformers are the critical component of which a utility cannot operate their power system if this equipment is damaged during a major earthquake. Transformers have a long lead-time for replacement. New power transformers should be designed and installed based on adequate seismic criteria. Existing power transformers should be anchored to minimize seismic damage. A few anchorage concepts have been presented. The authors hope that these concepts will be helpful to other utilities when designing anchorage for critical power transformers.

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