ELECTRICAL SUBSTATION EQUIPMENT DAMAGE DATABASE FOR UPDATING FRAGILITY ESTIMATES

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SUMMARY

A database has been created that contains data related to damaged and undamaged electrical substation equipment collected from 60 230-kV and 500-kV substations in twelve California earthquakes. At sites where instrumental records were available, peak ground accelerations and spectral values based on the records were included. At other locations, where no instrumental recordings were available from the site, simulated ground motions based on event specific attenuation relations were used to determine peak ground accelerations and spectra. Data were summarized by earthquake, substation, and equipment type. Probabilities of failure were calculated by dividing the number of damaged components by the total number of components of that type for each earthquake and substation. Data were compared with opinion-based fragility curves and recommendations were made for modifying the existing curves. This paper gives examples of existing opinion-based fragility curves and proposed fragility curves for 500 kV Westinghouse live-tank SF6 circuit breakers and 230 kV horizontal-break disconnect switches.

INTRODUCTION

The reliable operation of an electrical power grid after an earthquake is of great importance to both consumers and utilities. Significant damage to the electrical power transmission system can lead to costly repairs and replacements for the utility and possibly long service interruptions, which may in turn result in business losses for utility customers that are unable to function at full capacity. Furthermore, loss of power immediately after an earthquake can disrupt emergency response and recovery operations for the affected region. While power systems are designed to be redundant by providing alternate routes for power delivery through the use of switches, as was shown in the 1994 Northridge earthquake, damage to key equipment and substations can cause outages over very large regions [Schiff, 1995].

The power transmission and distribution systems in California have been built over many decades and utilize equipment that was designed and installed under varying seismic criteria. Some of the older equipment that was designed to much lower seismic standards is particularly vulnerable to seismic loading. To mitigate the negative impacts of system disruption, utilities are continually developing and revising plans to replace the most vulnerable equipment with newer equipment built to new seismic standards. In addition they are retrofitting existing equipment, modifying practices for installing new equipment, and developing improved methods for seismic qualification of new equipment.

A key element of any mitigation plan is the establishment of priorities based on, at minimum, equipment function, importance, and vulnerability. The performance of substations and transmission systems can be modeled to identify likely sources of power outages and estimate restoration times [Eidinger et al., 1995; Matsuda et al., 1991]. To assess system performance, the utility establishes performance expectations that are defined in terms of levels of service and restoration times. A model of the system is subjected to a specified earthquake in which sophisticated ground motion models are used so that each substation experiences levels of shaking that take into account distance from the hypocenter and site characteristics. The effect on the system is

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portrayed in terms of damage tables, which operators of the system then use to estimate how long it will take to return the system to the expected level of performance. This restoration time is compared with acceptable restoration times and a determination is made as to whether the outcome is satisfactory or if mitigation measures need to be taken. By modeling the system with and without more reliable components, the effects of retrofits, equipment replacements and other mitigation strategies can be assessed.

Development of failure probabilities for use in these models is difficult, since for many types of components insufficient damage data exist to perform meaningful statistical analyses. Often damage reports are missing key information such as failure mode or the total number of undamaged components. In addition, complex factors such as equipment interaction and local variations in ground motion can be difficult to identify and quantify. Still, analysis of substation equipment damage in past earthquakes is an important step in establishing levels of acceleration that cause equipment failure, modes of failure and component weaknesses that lead to failure. These data, combined with expert opinion, can be used to develop or update fragility curves for use in the system reliability models.

The goal of this project was to compile substation equipment data from California earthquakes and summarize the damage statistics so that they could be used to improve existing substation equipment fragility estimates. Data were summarized by earthquake, site, and equipment type, and probabilities of failure were computed. Comparisons were made with existing fragility relationships, resulting in proposals for modifying the relationships for some types of equipment.

DATABASE DESCRIPTION

Using an existing database as the starting point, data related to ground motions, damaged equipment, and undamaged equipment were collected from 60 substations in 12 California earthquakes. Equipment that is documented in the database is owned by Pacific Gas & Electric, Los Angeles Department of Water and Power, Southern California Edison and the California Department of Water Resources. The majority of data relates to equipment operating at 220/230 kV and 500 kV. A summary of the earthquakes and substations represented in the database is found in Anagnos [1999a].

The types of equipment included in the database are circuit breakers, circuit switchers, transformers, disconnect switches, lightning arresters, wave traps, coupling capacitor voltage transformers, current transformers, and bus supports. A standardized equipment classification system developed in 1993 by a group of experts from several California utilities (referred to here as the Utilities Working Group (UWG)) was the basis of the classification system used in this study. The classification system, modified in this study to simplify some categories, refers only to equipment with voltage of 220 kV and higher and is organized so that equipment with similar performance characteristics are grouped together. For example, live tank circuit breakers have large tanks mounted on top of porcelain insulators, whereas dead tank breakers have the tank at the base. As a result, live tank circuit breakers tend to be more vulnerable to seismic motion than dead tank circuit breakers. Thus dead tank circuit breakers are in different equipment classes than live tank circuit breakers. All data in the database are assigned a UWG class; however, in the database more complete descriptions may be available. For example information about the support frame or the anchorage may be included in a comment field.

Data is organized into an Excel 97 spreadsheet with 68 fields of data (some of which are only sparsely populated). Data include ground motion (PGA and selected spectral values), characteristic soil type at the substation, type of equipment, any attributes that uniquely characterize that piece of equipment such as support structure or installation method, type of damage, time to restoration and, in a few cases, indications of interaction. In cases where no instrumental recordings were available from the site, simulated ground motions based on event specific attenuation relations were used to determine spectra (Somerville and Smith, 1999). A detailed description of the database and summary damage statistics are found in Anagnos [1999b].

EXISTING SUBSTATION EQUIPMENT FRAGILITY CURVES

The UWG developed standardized failure-mode descriptors for each class of equipment. In addition for each failure mode, fragility curves were developed based on a review of available data combined with the experts' understanding of the behavior of different components based on their visits to many substations after previous earthquakes. The failure modes have been defined to be mutually exclusive and progressively more disruptive and expensive to repair. For example, in Table 1, the mode "3 porcelain columns failing" is a more severe failure mode than "head porcelain damage". It is assumed that larger ground motions are needed to trigger more severe failure modes. Fragility curve parameters have been developed to reflect this relationship between severity of ground motion and severity of failure mode. The UWG curves have been updated somewhat since 1993, as additional information has become available due to observations from more recent earthquakes or from modeling and testing programs. These opinion-based curves are currently being used to model the reliability of transmission networks in California.

The fragility curves developed by the UWG are defined by four parameters: minimum peak ground acceleration for the onset of damage, and PGA at the 16th, 50th and 84th damage percentiles. An example of parameters and failure modes for a 500 kV Westinghouse live tank SF6 circuit breaker are found in Table 1. Fragility curves were created by combining two Normal distributions: $N(m, \sigma_1)$ for probabilities less than 0.5 and $N(m, \sigma_2)$ for values greater than 0.5. The median (m) of both Normal distributions is the 50th percentile node. The values of σ_1 and σ_2 are determined by assuming that $m - \sigma_1$ = 16th percentile and $m + \sigma_2$ = 84th percentile. Damage probabilities were set to zero for all PGA values less than the assumed minimum needed for the onset of damage.

Table 1 Failure Modes and Fragility Nodes for 500 kV live tank Westinghouse SF 6 Circuit Breakers (CB72): Existing and Proposed

	Fragility Nodes			
Failure Mode	Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
Existing Parameters				
head porcelain damage	0.15	0.25	0.35	0.50
1 porcelain column fails	0.15	0.15	0.30	0.45
2 porcelain columns fail	0.15	0.25	0.35	0.45
3 porcelain columns fail	0.15	0.30	0.40	0.50
Proposed Parameters				
head porcelain damage	0.03	0.05	0.15	0.20
1 porcelain column fails	0.03	0.07	0.18	0.24
2 porcelain column fails	0.03	0.09	0.21	0.28
3 porcelain columns fail	0.03	0.11	0.24	0.32

DATA COMPARISONS AND PROPOSED NEW FRAGILITY CURVES

In this study, if a phase has a separate piece of equipment associated with it, such as one phase of a circuit breaker, it is considered as a separate item of equipment. Thus, for earthquake damage purposes, a circuit breaker would consist of three equipment items rather than one. A transformer bank consisting of three single-phase transformers would be considered as three pieces of equipment while a three-phase transformer would be considered as a single piece of equipment. While this is not how the industry defines a piece of equipment, this definition does have its advantages for the purposes of damage estimation. For example, the number of phases damaged can impact the cost of repair and the time to restore equipment to service. Sometimes different phases are connected differently to other equipment; for example the length of or amount of slack in the bus drop may be different. By representing damage by phase, failures due to interaction may be more readily identified. Using damage data for each phase of equipment allows for the development of fragilities for each phase. Simple models then can be developed to combine the probabilities of failure of each phase to estimate the probability that one, two or three phases will be out of service.

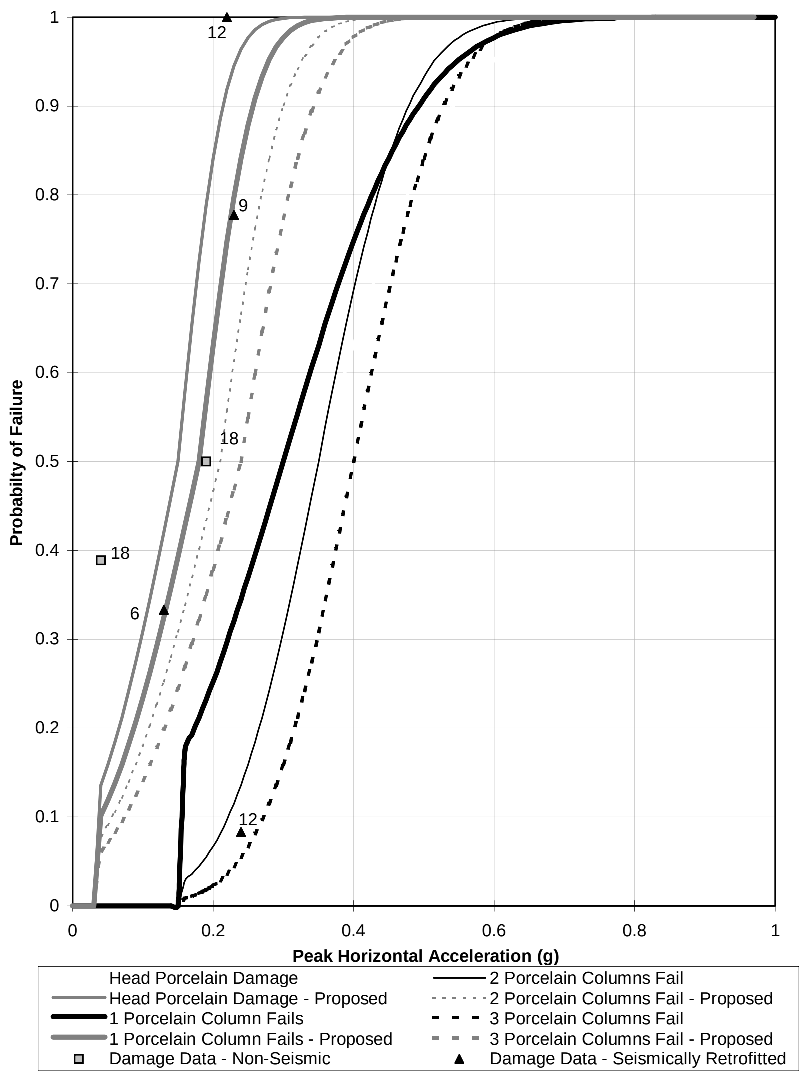

Figure 1: Comparison of 1993 UWG fragility curves with damage data and proposed fragility curves for 500 kV Westinghouse live tank circuit breakers (CB72).

For each earthquake and substation, failure probabilities were computed by dividing the number of damaged components by the total number of components for each UWG equipment class found at a site. It should be emphasized that ground motions were only recorded or simulated for one point within the multi-acre substation site. Variations in site conditions over the substation area could cause different parts of the site to experience different levels of motion. This serves as one source of inherent uncertainty that is built into the calculation of failure probabilities.

Since in most cases, failure mode is not indicated in the database, the computed probabilities of failure do not include information about failure mode. Failure probabilities were plotted along with existing fragility curves for each equipment class. Due to the lack of information about failure mode, comparisons with the existing fragility curves are useful only in making generalized statements as to whether the curves are reasonable. If the fragility curves seem to be too high or too low, the whole suite of curves is adjusted to better reflect trends in the data. With their current limitations, the data are not useful in fine tuning individual failure mode curves.

Figure 1 shows damage data for 500 kV Westinghouse live tank SF6 circuit breakers (CB72). The data represents the performance of 75 phases (25 circuit breakers), at five different substations in four earthquakes (San Fernando, Morgan Hill, Loma Prieta, and Northridge). Equipment from the Metcalf substation are represented in both the Morgan Hill and Loma Prieta earthquakes. The number next to each data point indicates the total number of phases used to calculate the failure probability. Each phase of the CB72 consists of three tall porcelain columns supporting heavy interrupter heads. At three substations (Vincent, Metcalf, and Moss Landing) the columns had been seismically strengthened with internal prestressing tendons. The seismically strengthened circuit breakers are represented by triangles in Figure 1. The support systems for circuit breakers may vary from substation to substation, and different support types have different stiffnesses. The support system will filter the ground motion and alter the way in which the circuit breaker responds. While the circuit breakers themselves may be identical, the periods of vibration of the mounted equipment might be very different. Therefore plotting all of the CB72's on one graph as if they are identical can be somewhat misleading.

The original fragility curves are the four curves plotted on the right side of the graph in Figure 1. The proposed (new) curves are to the left of the original fragility curves. The original curves fall well below five out of the six data points. The nodes for the proposed curves are summarized in Table 1. The proposed fragility curves have been adjusted so that the median failure probability occurs at a lower peak ground acceleration, and the minimum acceleration to cause damage has been reduced from 0.15 g to 0.03g. While it would be ideal to develop separate fragility curves for seismically strengthened CB72's, at this time there is insufficient data to distinguish the performance of the strengthened and unstrengthened circuit breakers.

Figure 2 compares data with existing and proposed fragility curves for 230 kV horizontal-break disconnect switches. The parameters for the existing and proposed curves are summarized in Table 2. The existing curves are represented by solid lines and the proposed curves by dashed lines. Disconnect switches are difficult to compare because they can be mounted on different types of frames and different types of post insulators, which can have a significant affect on performance.

Several data points on this figure that deviate significantly from the existing UWG fragility curves deserve additional explanation. While all of the disconnect switches at Pardee were damaged (solid triangle), 75 phases required realignment only. A second data point plotted for Pardee (square), represents the damage probability if only those disconnect switch phases that were severely damaged are counted. The damage probability calculated from San Mateo data is based on incomplete information, since there were an unknown number of disconnect switches at the site. This damage probability is unrealistically high since it does not include the all of the undamaged disconnect switches in the ratio of damaged to total switches. Aside from these few anomalous points, the data indicate that for accelerations less than 0.25g this type of equipment has performed well.

Disconnect switches at several substations in the Northridge earthquake, as well as at Devers in the North Palm Springs and Olinda in the Whittier Narrows earthquakes performed particularly well. At Sylmar, 24 phases were mounted on heavily braced frames. These had been sine-beat tested indicating that they were more modern switches. On average, these performed less well (6 damaged, 18 undamaged) than the phases on less stiff support structures (12 damaged, 120 undamaged). At Rinaldi, the database indicates that some of the units were seismically qualified. The database provides little insight for the other substations.

The proposed curve for the failure mode "misaligned contacts" produces higher probabilities of occurrence than the existing curve. The justification for this is that misaligned contacts are not necessarily obvious to an engineer during a post earthquake reconnaissance visit. Often disconnect switches are mounted high up on frames or overhead racks and the contacts are quite far from the engineer who is on the ground. Because of this, this failure mode may be easily overlooked and there is a sense that the damage data underestimate the number of misaligned contacts. Additional data, and special attention to this failure mode in future post-earthquake reconnaissance investigations, will be needed to more accurately estimate the parameters of this curve.

Table 2 Failure Modes and Fragility Nodes for 230 kV Horizontal-Break Disconnect Switches (DS3): Existing and Proposed

	Fragility Nodes			
Failure Mode	Minimum (g)	16th Percentile (g)	50th Percentile (g)	84th Percentile (g)
Existing Parameters				
misaligned contacts	0.20	0.30	0.50	0.70
broken porcelain	0.30	0.50	0.70	0.90
Proposed Parameters				
misaligned contacts	0.10	0.25	0.35	0.50
broken porcelain	0.30	0.50	0.80	1.10

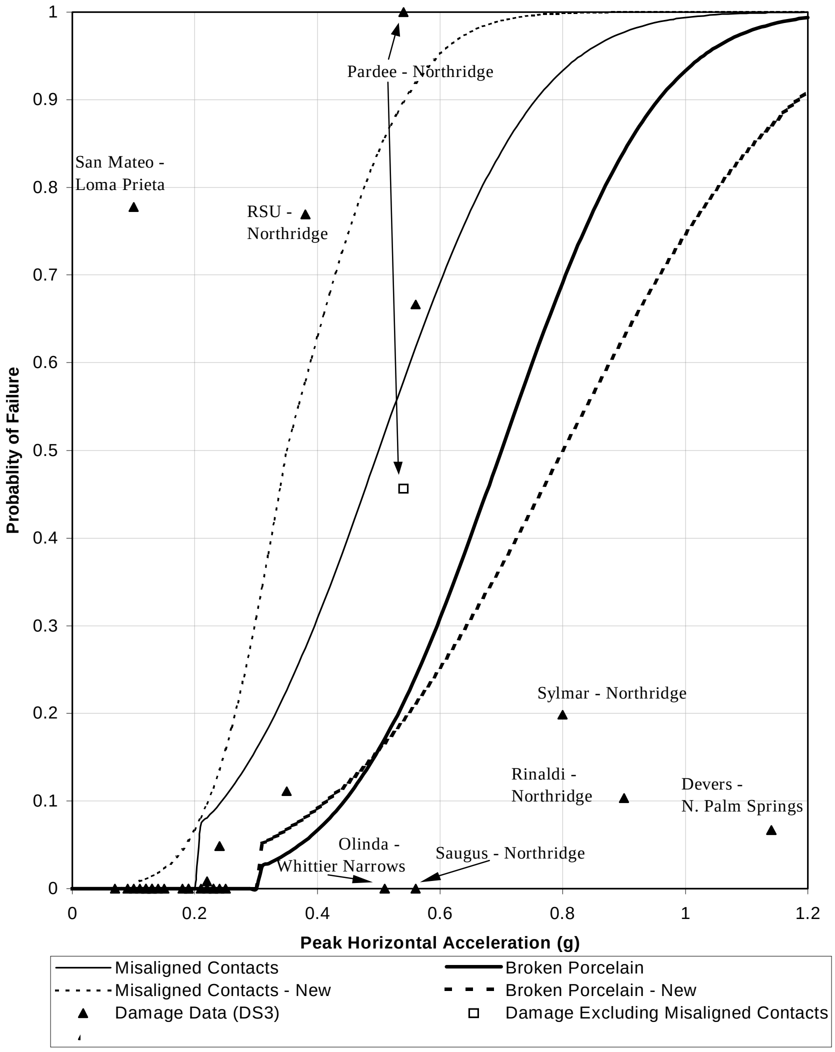

Figure 2: Comparison of 1993 UWG fragility curves with damage data and proposed fragility curves for 230 kV horizontal disconnect switches (DS3).

CONCLUSIONS

Systematic collection and analysis of performance data for electrical substation equipment is needed so that electrical power system performance can be accurately modeled. The database discussed in this paper provides the most comprehensive set of data currently available for use in developing or modifying substation equipment fragility curves. The database has a number of limitations that currently constrain the analysis. These include: limited information on failure modes, missing information about undamaged equipment, the use of simulated ground motions, ground motions that are only recorded at one location at a substation, inability to account for variations in support stiffnesses, incomplete information about equipment interaction, and incomplete information about functionality. Newer equipment that has been installed since the 1994 Northridge earthquake is not included in the database, though one possible source of performance data for newer equipment is the results of seismic qualification tests. Use of seismic qualification data should be investigated.

While all of these factors add to the uncertainty associated with calculating probabilities of failure, the failure probabilities calculated from the data have been useful in assessing how well the existing models reflect historical damage observations. For most of the components in the database, adjustments have been made to the fragility curves developed by the UWG in 1993 to better fit those curves to the data. No formal statistical analysis has been performed. Instead, judgement has been used to adjust the parameters that define the curves.

One of the reasons that damage data has been incomplete in previous earthquakes, is that utilities place a much higher priority on bringing a system back on-line after an earthquake than on performing reconnaissance. Since many of the substations have no permanent staff at the site, those who are performing reconnaissance may arrive at a site after repair crews have already completed their work. Repair crews may have been the only ones to have seen the substation in its damaged state. Often repair crews simply replace a component with a spare, making it difficult to determine the extent of damage that occurred to the component that has been removed. A typical reconnaissance report based on a visit to the site would not be adequate to document the damage in the case just described. Sometimes it is possible to piece together details about the failure mode and mechanism through interviews with repair personnel. This requires detailed follow-up and possibly multiple visits to the site.

A number of suggestions can be made about how to collect data in future earthquakes so as to capture the maximum amount of information for performance modeling. A first step would be to keep accurate inventories of what exists at each site. With the use of GIS systems and the Internet, it should be possible to provide inventory printouts and line drawings of substations to remote locations. Inventories should include a variety of characteristics that could be used to classify the type of equipment, as well as installation data. Secondly, it is important to collect information about components that performed well. Calculation of failure probabilities requires knowledge of the total number of components at the site. Thirdly, if possible, it is important to document the failure mode. Fourthly, it is helpful to know if the equipment is still operational. Equipment that is damaged but operational will not cause the system to stop functioning. Usually utilities Finally, one piece of data that is often missing the length of time it took to repair a component. This type of information is useful in developing estimates of the time needed to bring the system back to the expected performance level.

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