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NONLINEAR SYSTEMS SUBJECTED TO MULTIPLE SEISMIC EXCITATIONS MATCHED TO THE SAME SPECTRUM: NUMERICAL PREDICTIONS VERSUS SHAKING TABLE TESTS

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Abstract. *The paper summarizes the results of an extensive study conducted at the University of California, Berkeley. A test article representative of a piece of high-voltage substation equipment was studied on a shaking table. It consisted of a support structure and an insulator installed on its top. The support structure was constructed from a HSS with well-separated natural frequencies in both horizontal directions. A porcelain insulator typically used on a 230-kV system was used in the study. A set of four wire ropes was used as a seismic isolation for the system. Two installation cases were considered in the study: (1) fixed base and (2) isolated by wire ropes. As required by the latest draft of IEEE693, a number of component tests was conducted to evaluate the performance of the wire ropes. Based on the results of component testing, detailed numerical models of the seismically protected equipment were generated. Each equipment configuration was subjected to seven time histories matched to the same IEEE693 spectrum. Four of them were modified from historical records and matched to the IEEE693 spectrum in the time domain. The other three excitations were synthetic strong motions matched to the same spectrum. The main objective was to evaluate the variability of the seismic response of the equipment subjected to seven time histories matched to the same response spectrum.*

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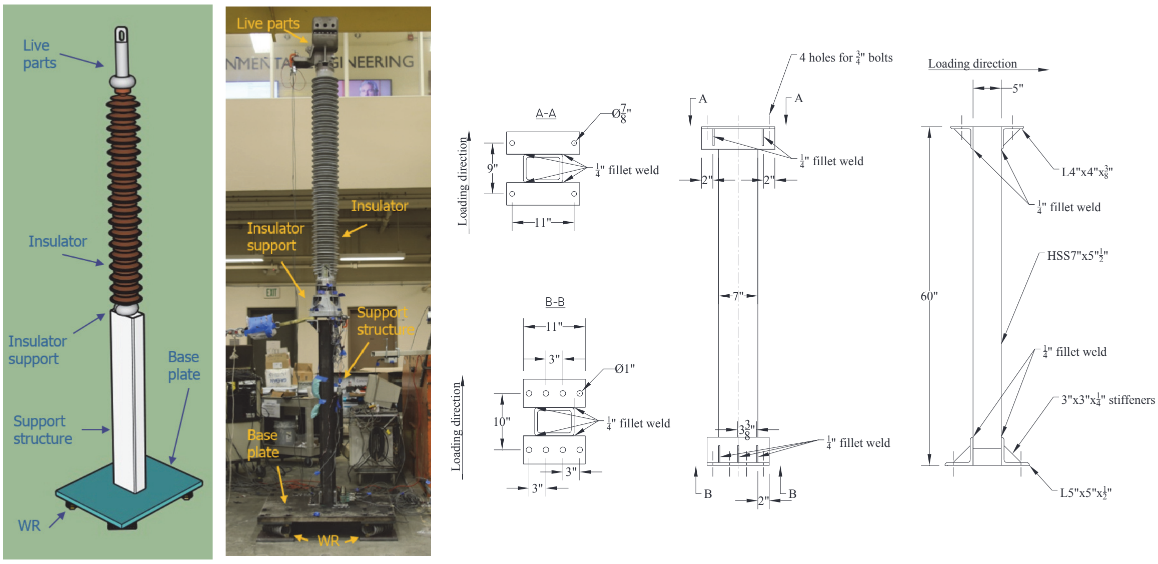
1 INTRODUCTION

The main objective of the study described in this paper is to develop an accurate finite element model and compare a seismic qualification by analysis of high-voltage (HV) substation equipment to that by testing. Sample equipment that had been seismically isolated by means of wire ropes (WRs) was used in this study. The paper follows the requirements of the newly introduced Annex W (IEEE P693/D15) [1], that provides guidance on the seismic qualification by analysis.

This paper summarizes the results of a research project that is currently being conducted at the University of California, Berkeley. The project is conducted in two phases. In the first phase, a new set of time histories for IEEE693 seismic testing and seismic qualification by analysis were developed [2]. The set consists of (a) three strong motion crustal records; (b) a strong motion record from a subduction zone earthquake; and (c) three synthetic strong motions. The spectra of historic records were spectrally matched to 5% damped IEEE693 spectra in time domain. Three synthetic strong motions were generated and spectrally matched to the same target spectra. In the second phase, the newly developed IEEE693 time histories were verified in numerical simulations of seismically isolated equipment and testing on a uniaxial shaking table. The shaking table is a high-performance earthquake simulator with a long-stroke and high velocity capabilities. The time histories were imposed back-to-back and the test results were compared to the numerical simulation results.

2 COMPONENT TESTS AND RESULTS

Sample HV equipment consisting of a base plate, support structure, seismic isolators (Wire Ropes), an insulator and live parts is presented in Figure 1.



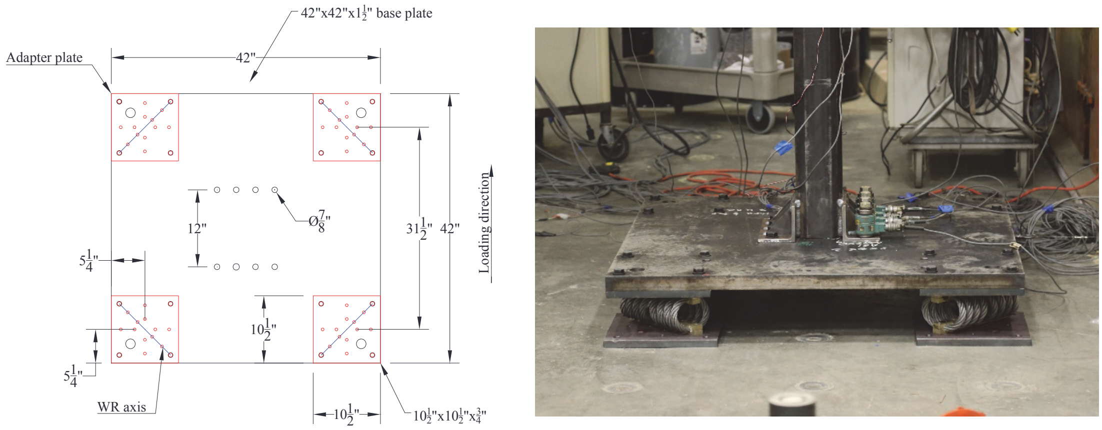
a) Schematic 3D drawing

b) As assembled

c) Details of support structure

Figure 1: Details of HV equipment.

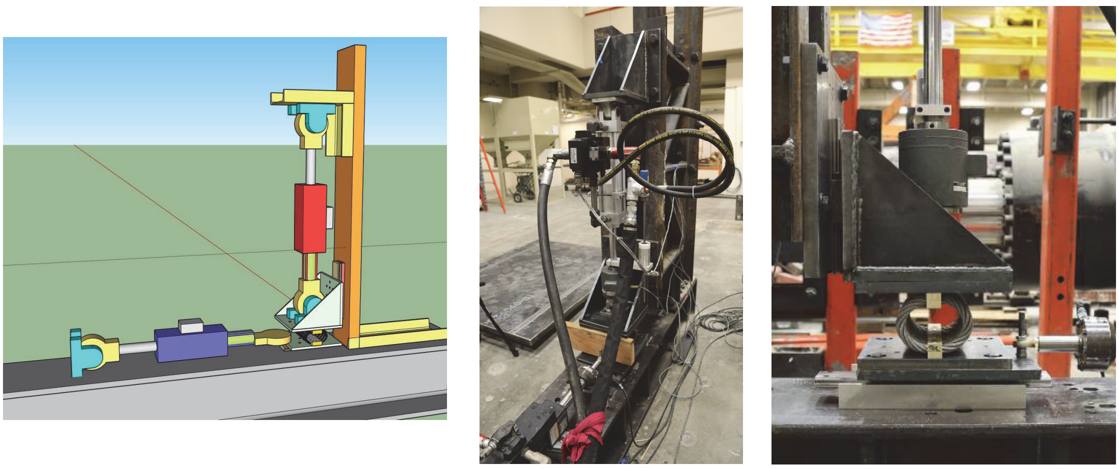
Four WRs were installed at 45 degrees to the direction of loading as presented in Figure 2. To follow Annex W [1] a set of component tests was conducted to expand the manufacturer data associated with this particular type of WRs. The data furnished by the manufacturer was limited to monotonic loading in one direction only. This typical set of data was lacking information in regard to the following: (1) cyclic performance vs. monotonic; (2) tension data in cyclic loading; (3) ultimate capacity; (4) repeatability of data from one component to another; (5) cyclic performance with applied vertical load (dead load of the system) and many others. To address these issues extensive component tests following Annex W [1] were conducted on two WRs. Due to the size limitations of the paper only some of the most important results are discussed in this paper.



a) Drawing of base plate b) Photo of base plate with 4 WRs

Figure 2: Details of base plate and WR installation.

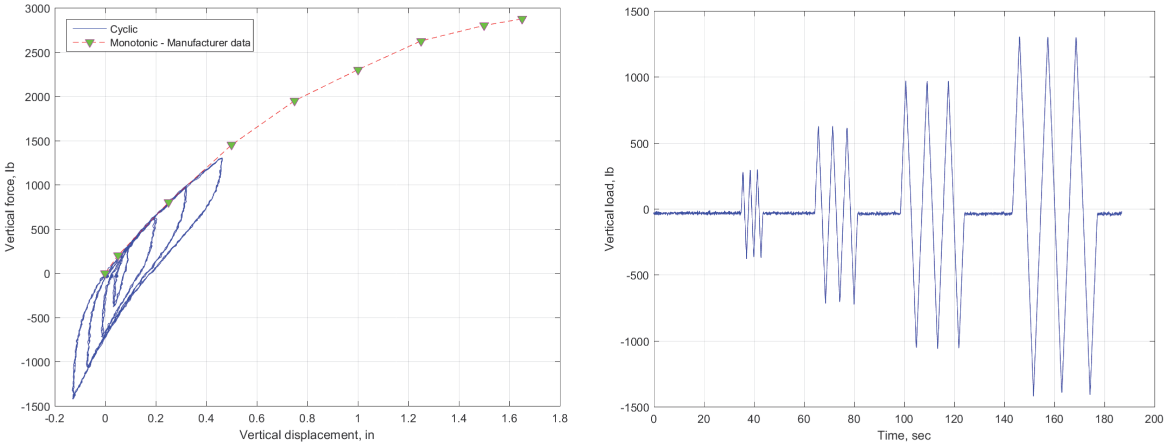
The tests were conducted in a specially designed and constructed 2D testing machine as presented in Figure 3. The machine is capable of simultaneously applying both vertical and horizontal loads. The actuators were controlled from a displacement or force feedback depending on the test objectives.



a) Schematic 3D drawing b) Global view c) Zoomed view (an example of WR testing in 0 degree orientation is shown)

Figure 3: Details 2D testing machine for component testing of WRs.

Typical results for cyclic testing in a vertical direction are presented in Figure 4a. The vertical load was applied in groups of three cycles with incrementally increasing amplitude as presented in Figure 4b. The horizontal actuator placed under displacement control to keep shear displacement at zero. As shown in Figure 4a, the compression test results closely match the data obtained from the manufacturer. The latter data was limited to monotonic compression-only test data that does not provide information on the force vs. displacement relationship in tension. The cyclic test data addresses this shortcoming and reveals the fact that the WR's performance in both tension and compression is nonlinear as shown in Figure 4a. The WR is much stiffer in tension and this needs to be accounted for in numerical modeling. From the areas of the cycle loops amount of dissipated energy per each cycle was estimated.

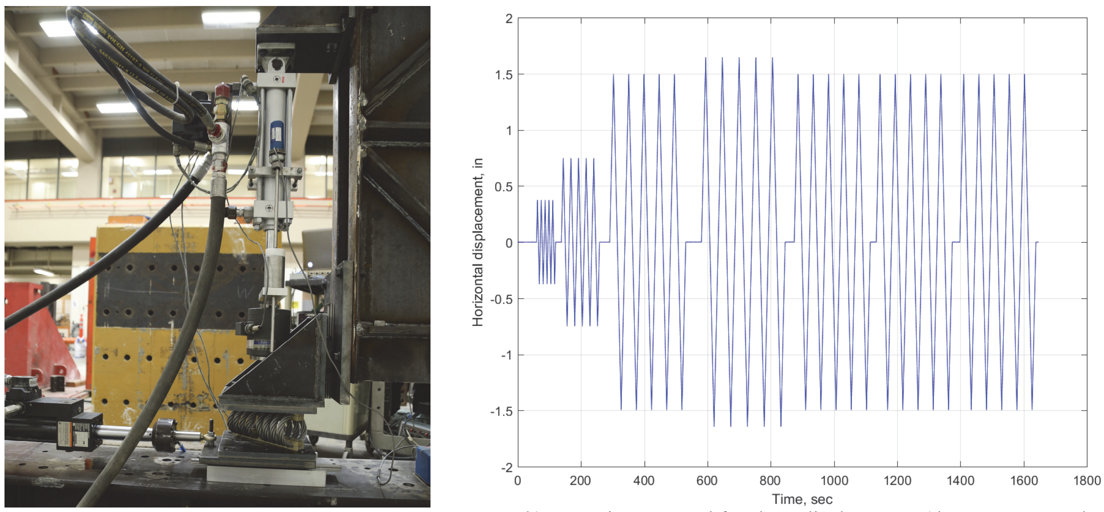


a) Force vs displacement

b) Testing protocol for vertical load

Figure 4: Cyclic loading in vertical direction.

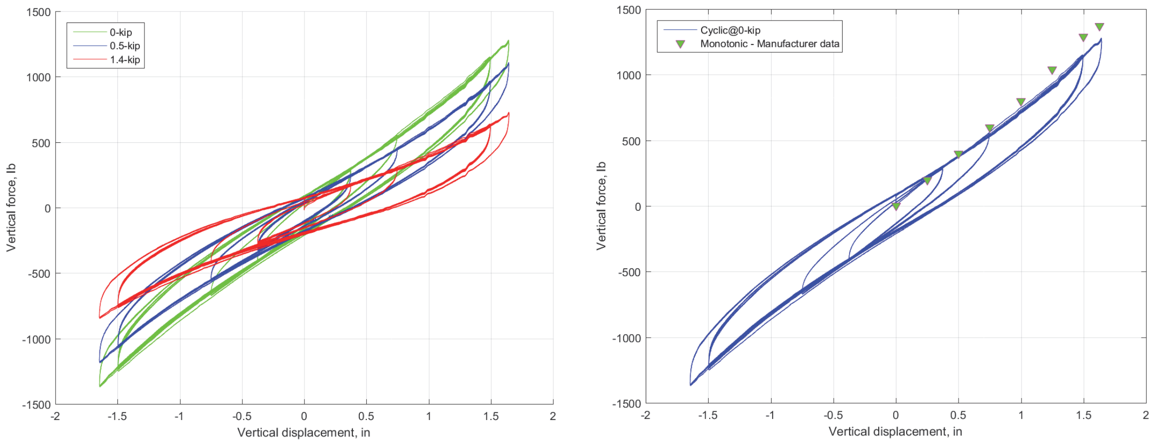
In the next stage of component testing, the WR's performance was evaluated at different vertical pre-load values. For each pre-load value the WRs were tested in 0, 45, and 90 degree orientations. The pre-load values of 0 lbs, 500 lbs, and 1400 lbs were considered. As a typical example the results for the 45 degree orientation are presented in Figure 5 and Figure 6.



a) WR under testing

b) Testing protocol for shear displacement (the same protocol was repeated for each pre-load value)

Figure 5: Component tests in shear loading with different pre-load values (45 degree orientation of WR).



a) Three pre-load values   b) Comparison to manufacturer data at 0-kip pre-load

Figure 6: Force vs displacement for 45 degree orientation of WR.

It is worthy to note that the 0, 45 and 90 degree directions can have different performance curves which is important for proper modeling of their performance in 3D analysis or shaking table tests. Since a uniaxial shaking table was deployed in this study, the results for the 45 degree orientation were used for the subsequent modeling.

Although the cyclic test data at 0-kip vertical pre-load is closely correlated to the data supplied by the manufacturer as shown in Figure 6b, the situation is different for other non-zero pre-load values as presented in Figure 6a. The manufacturer's data overestimated the stiffness that can lead to significant underestimates of the maximum displacements in the horizontal direction.

3 NUMERICAL MODELING AND VERIFICATIONS BY SYSTEM LEVEL TESTS

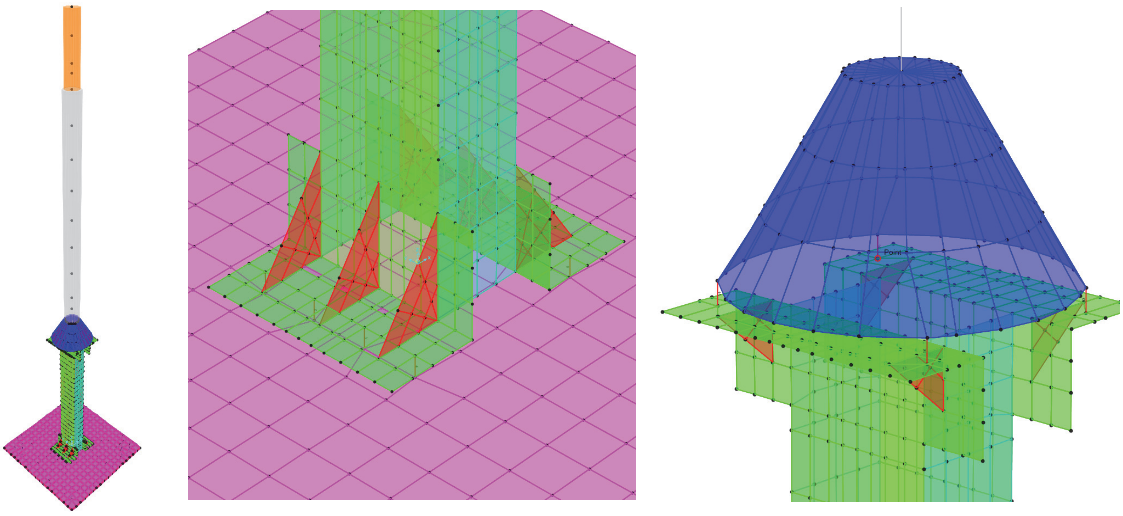
Table 1 lists all major components of the HV equipment studied in the paper. Weights of the majority of the components were measured and the weight of the base plate was estimated. The total weight of the fully assembled equipment was estimated at around 1500 lbs. Since the dead load of the equipment was evenly distributed between four WRs, each of them was pre-loaded with a load of about 400 lbs.

Item	Material	Weight, lbs	Note
Base plate (with top WR adapter plates)	A36 steel	844	Estimated
Bottom WR adapter plates	A36 steel	94	Measured
WR	SS cable	8	Measured
Support structure	A36 steel	216	Measured
Insulator support	Aluminum	50	Measured
Live parts	Aluminum	40	Measured
245 kV porcelain insulator (high strength)	Porcelain	363	Measured

Table 1: Material data of the major components and their weights.

A detailed finite element model was generated based on the information obtained from the component tests and the material data and weights listed in Table 1. The final model is presented in Figure 7. The SAP2000 [3] software package was used for FE modeling and simulations. The base plate, the support structure, and the insulator support were modeled by shell elements. The insulator and the life parts were modeled as frame sections. The WRs were modelled as non-linear links.

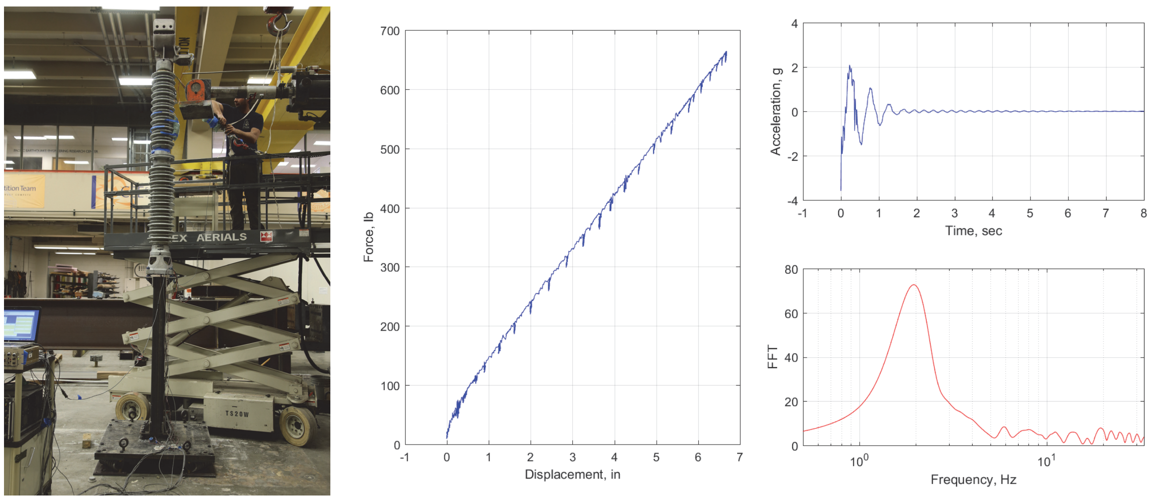
To calibrate the FE model, both fixed base and seismically isolated configurations were tested in stiffness and snap-back tests. In these tests the specimen was slowly loaded (with a horizontal pull) at the terminal location, and the load was suddenly was released at about 650 lbs maximum load. The horizontal displacement was monitored at the load application point. In addition, strain gages at the bottom of the porcelain insulator and accelerations on top of the equipment and on top of the support structure were monitored. The accelerometers were installed in both horizontal directions.



a) Global view   b) Zoomed view of support structure at base plate (bottom)   c) Zoomed view of support structure at insulator support (top)

Figure 7: Details of FE model of the equipment.

As a typical example, the results of the equipment seismically isolated by the WRs are presented in Figure 8.



a) Global view   b) Stiffness test results   c) Acceleration and FFT in snap-back test

Figure 8: Stiffness and snap-back test results for assembled equipment with WR isolators.

As shown in Figure 8b, the force versus displacement relationship is nonlinear especially at the very beginning of loading. The WRs introduced significant damping into the system and as such, the system's large amplitude vibrations decayed after about three cycles (as presented in Figure 8c, top). The Fast Fourier Transform (FFT) also shows the presence of large damping (as shown in Figure 8c, bottom).

The model was calibrated based on the stiffness and subsequent snap-back tests with the FE model vs. specimen comparison results presented in Table 2.

F_1, Hz	Tip disp., in	Tip force, kip	Eff. stiffness, kip/in	Data source
4.88	1.43	0.65	0.455	FEA: fixed based[§]
4.88	1.38	0.65	0.471	Test: fixed base[†]
1.95	6.56	0.65	0.099	FEA: isolated base[§]
1.95	6.52	0.65	0.100	Test: isolated base[†]

[†] Snap-back and stiffness test results; [§] results for elastic FE model

Table 2: Results of the FE model calibration.

4 NUMERICAL SIMULATIONS

Seven time histories developed earlier [2] were used as excitation functions at the bottom of the equipment. A complete list of the time histories is presented in Table 3. A special effort was made to ensure that spectra of all time histories stay within 15% strip above the IEEE693 High Performance Level spectra [4] as presented in Figure 9a.

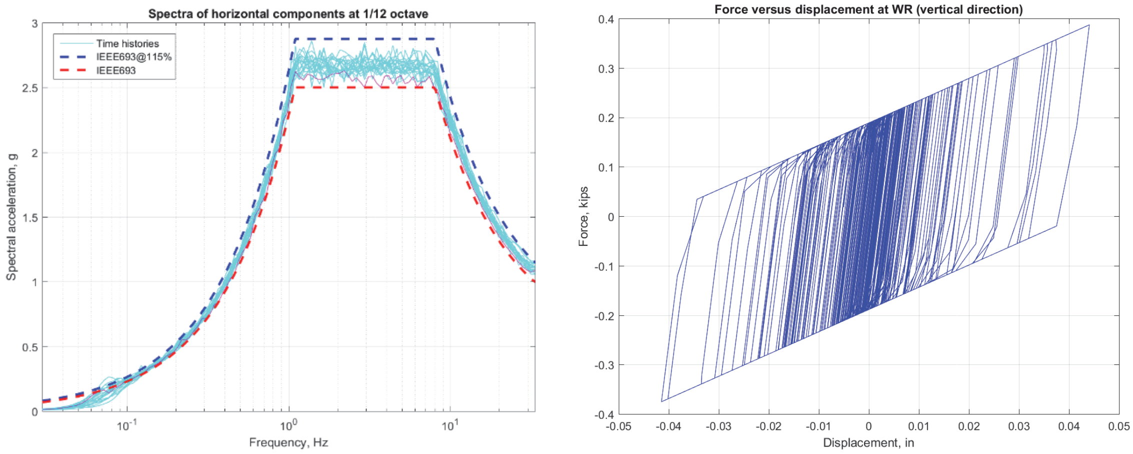
Since the shaking table testing was limited to uniaxial excitation only, X-component of each IEEE-693 compatible time history was utilized in the numerical simulations. The wire rope was modelled by multilinear model with kinematic hysteresis loop available in SAP2000 [3]. A typical result for numerically calculated force versus displacement diagram at the WR location (in the vertical direction) is presented in Figure 9b.

Seed motion, if any	EQ type	Name of IEEE693-compatible time history	Time history number in Figure 10
Landers, CA (1992)	Crustal	TestQke4IEEE5-1a	1
El-Centro, CA (1940)	Crustal	TestQke4IEEE5-1b	2
Chi-Chi, Taiwan (1999)	Crustal	TestQke4IEEE5-2	3
El Mayor-Cucapah, Mexico (2010)	Crustal	TestQke4IEEE5-3	4
CONSTITUCIONS/N4598 Chile, February 27, 2010	Subduction	TestQke4IEEE5-4	
NA (synthetic)	NA	TestQke4IEEE5-5	5
NA (synthetic)	NA	TestQke4IEEE5-6	6
NA (synthetic)	NA	TestQke4IEEE5-7	7

Table 3: List of the newly developed IEEE693-compatible time histories used in the study.

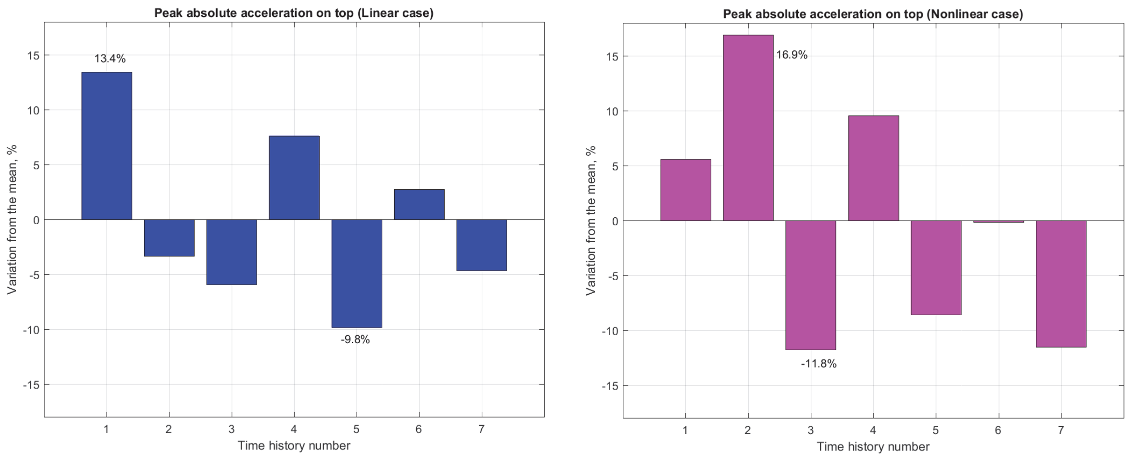
The peak accelerations on the top of the equipment are presented in Figure 10. The fixed base case is shown in Figure 10a and the nonlinear case with WRs between the base plate and the ground are presented in Figure 10b.

The following were concluded from results presented in Figure 10. First, the variation of the elastic results is limited by about 24% from the lowest valley to the highest peak. The peak accelerations have larger variation for the nonlinear case and it is close to 30% from the lowest valley to the highest peak. Second, the largest variation in both elastic and nonlinear cases occurs for the time histories with non-stationary character (No. 1-4 in Table 3 and Figure 10). These time histories were developed from seed historic records by spectral matching in time domain. In case of this numerical model, the synthetic time histories (No. 5-7 in Table 3 and Figure 10) did not represent the most conservative approach for evaluation of seismic performance of high-voltage substation equipment by analysis (peak accelerations are less than the mean). The situation can be different for other equipment tested or analyzed.



a) Spectral accelerations of all time histories b) Nonlinear case with WRs

Figure 9: Time histories used in study and force vs displacement diagram at WR (nonlinear case).



c) Fixed base (elastic case) d) Nonlinear case with WRs

Figure 10: Peak acceleration on top of the system for linear (fixed-base) and nonlinear (isolated by WRs) cases.

5 SHAKING TABLE TESTING

The equipment isolated by the wire ropes was tested on a long-stroke high-velocity shaking table at Structures Laboratory (Civil and Environmental Engineering Department of the University of California, Berkeley). Only uniaxial excitation in X-axis was imposed on the system. Each time history from Table 3 was run three times to estimate variability between the runs and its effect on the system response. Therefore, twenty one shaking table tests were performed on the system. All runs were conducted at 50% of scale (anchored at 0.5g PGA).

The global view of the equipment installed on the shaking table is presented in Figure 11. The specimen was extensively instrumented with accelerometers, position transducers, and strain gages as presented in Figure 11.

The test response spectra are presented in Figure 12a. A mean and a mean plus one standard deviation for all these runs are shown in the same figure. While the shaking table was over performing in the high frequency range, a variability between the runs in vicinity of the lowest resonant frequency of the equipment (1.95 Hz) was relatively small and remained within -4% and +6% strip as presented in Figure 12b.

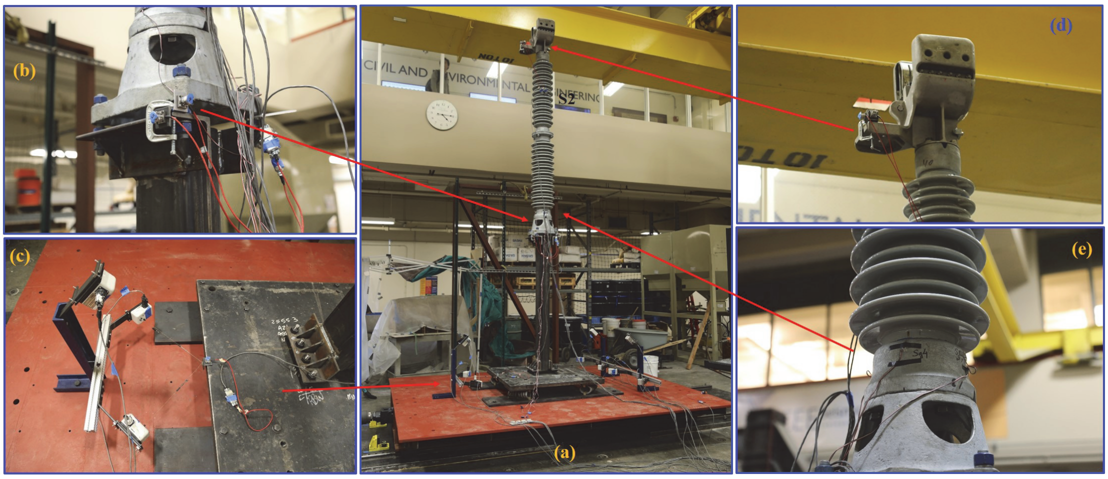
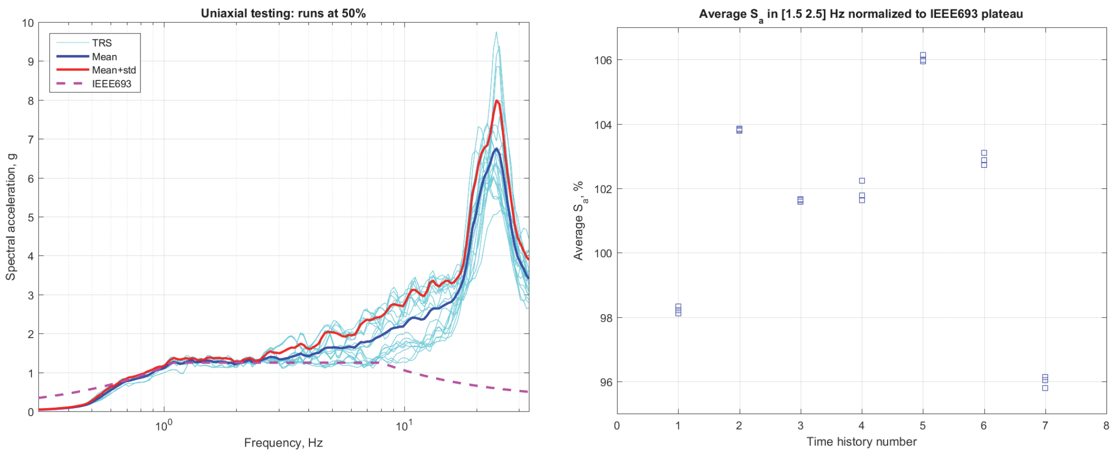


Figure 11: (a) Global view of the equipment on the shaking table and instrumentation details: (b) – accelerometers on top of the support structure, (c) 3D displacements of the base plate were estimated from triangulation at three points with one of the typical installation presented here, (d) accelerometers on top of the equipment, (e) – strain gages at the bottom of the porcelain insulator.



a) Spectral accelerations of all time histories

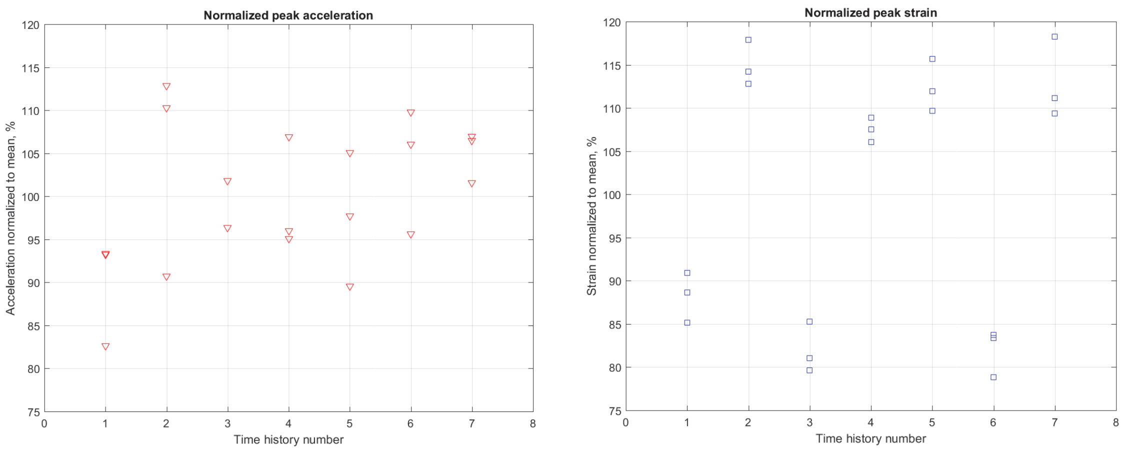
b) Variation of S_a in vicinity of resonant frequency remained within -4% and +6% strip

Figure 12: Test response spectra (TRS).

The peak accelerations on top of the equipment are presented in Figure 13a. It varies from about -17% to about +13%. Hence, it remains within 30% variability strip that is close to the theoretical variability estimated earlier. In opposite to that, the strain variability is much larger as presented in Figure 13b. The normalized strain for all runs varies from about -22% to

+18% of the mean. Therefore, it varies within 40% strip. It worthy to note that the porcelain insulator is the most vulnerable component of the tested system and, as such, the peak strain at the bottom of the insulator is the most representative parameter defining seismic the system's response to the seismic demand.

In an earlier study [5], the failure strain of the porcelain insulator was closely correlated to the cantilever strength rating provided by the manufacturer. It worthy to note that the insulator is from high-strength porcelain insulator category and is rated at 2750 lb cantilever strength. During this experimental program, the mean strain was at about 8% of failure strain for this type of porcelain insulator. The low system's response might be related to the large damping of the system introduced by the wire ropes. The performance of the system with fixed base will be investigated later in the upcoming tests of the project.



a) Normalized peak accelerations (top) b) Normalized peak strain (bottom)

Figure 13: Summary of peak acceleration of top of equipment and peak strain at bottom of insulator.

The following conclusion was made based on the results of the experimental program. Although the variability of the peak acceleration was close to the theoretical prediction, this result greatly depends on the performance of a shaking table and can increase for poorly tuned shaking tables and/or in shaking on 3D earthquake simulators. The peak strain at the bottom of the insulator (representing one of the major demand parameters) varies in a greater range than the acceleration on top of the equipment. Therefore, for future comparative studies, is it suggested to use the peak strain variability to estimate variability of the system's response to the seismic demand.

6 CONCLUSIONS

The following conclusions were made based on the results of the extensive component testing program.

- Although the cyclic shear test data at zero pre-load is closely correlated to the data supplied by the manufacturer, the force vs displacement diagrams are quite different for other non-zero pre-load values. The manufacturer's data is overestimating the stiffness that can lead to significant underestimates of the maximum displacements in the horizontal direction.

- The compression test results closely match the data obtained from the manufacturer. The latter data was limited to monotonic compression-only test data that does not provide information on the force vs. displacement relationship in tension. The cyclic test data reveals the fact that the WR's performance in both tension and compression is nonlinear. The WR is much stiffer in tension and this needs to be accounted for in numerical modeling.

The following conclusions were made based on testing of fully assembled fixed-base and isolated-base systems (snap-back testing).

- Overall stiffness and the lowest dominant frequency of the fully assembled test specimen (in both base-fixed and base-isolated cases) closely matches the stiffness of the corresponding numerical model.
- The snap-back test of the isolated base specimen reveals the fact that the dominant frequencies of the system have significantly different damping values associated with them. The large amplitude vibrations have low frequency with very high damping. The small amplitude cycles have higher frequency and very low damping.

The following conclusions were made based on the numerical simulations.

- The variation of the elastic results is limited by about 24% from the lowest valley to the highest pick. The peak accelerations have larger variation for the nonlinear case that is close to 30% from the lowest valley to the highest pick.
- The largest variation in both elastic and nonlinear cases occurs for the time histories with non-stationary character. These time histories were developed from historic records by spectral matching in time domain. In case of this numerical model, the synthetic time histories did not represent the most conservative approach for evaluation of seismic performance of high-voltage substation equipment by analysis (peak accelerations are less than the mean). The situation can be different for other equipment tested or analyzed.

The following conclusion was made based on the results of the experimental program.

- Although the variability of the peak acceleration was close to the theoretical prediction, this result greatly depends on a performance of a shaking table and can increase for poorly tuned shaking tables and/or in shaking on 3D earthquake simulators. The peak strain at the bottom of the insulator (representing one of the major demand parameters) varies in a greater range than the acceleration on top of the equipment. Therefore, for future comparative studies, is it suggested to use the peak strain variability to estimate variability of the system's response to the seismic demand.

7 ACKNOWLEDMENTS

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