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SEISMIC PROTECTION OF HIGH VOLTAGE BUSHINGS BY USING POLYURETAN SPRINGS

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Abstract

High voltage bushing structures are most vulnerable components of electrical substations during strong seismic excitation. A new low-cost seismic isolation device for high voltage porcelain electric bushings has been proposed and deliberated at the Structural and Earthquake Engineering Laboratory (STEELab) of Istanbul Technical University. The seismic isolation device consists of steel plates and four polyurethane springs. The polyurethane springs are placed between the steel plates and they are post-tensioned by means of the bolt located at the center of the device. A series of preliminary tests in which steel column was used instead of real bushing, have been conducted in the laboratory. The tests performed can be classified into three groups. Quasi-static cyclic tests are in the first group. In the second group, white noise tests, pull-back tests and hammer tests are performed to determine the damping property and vibration frequency of the device. In the last group, uniaxial shake table tests are accomplished for the isolated case and its fixed base version by using real acceleration records. The experimental results obtained from the preliminary tests indicate that the proposed seismic isolation device is able to be competent to protect the high voltage bushings from strong seismic excitation.

Keywords: High voltage equipment, bushing, earthquake, seismic isolation, low-cost isolation, polyurethane spring

1. Introduction

Due to the nature of their design, porcelain bushings have proven to be one of the most vulnerable pieces of substation equipment during earthquakes. During the earthquakes which are occurred at 1990’s, electrical substations components were heavily damaged. Such damage is difficult to repair without removing the bushing from the service. The cost of repair, including indirect costs due to interruption of the power supply, is significant. After the earthquakes, 1994 Northridge/America, 1995 Kobe/Japan, 1999 Izmit/Turkey and 1999 Chi-Chi, with direct losses are in the range of hundreds of millions of dollar for each event. For example, the combined damage inflicted upon electrical substation equipment by the Loma Prieta and Northridge earthquakes resulted in an estimated $283 million worth of losses, [1].

The main objective of this study is the seismic protection of high voltage porcelain insulators (bushings). In this direction, a base isolation device has been developed which provides the requirements in IEEE 693 [2], *Recommended Practice for Seismic Design of Substations.*

IEEE-693 defines three diverse performance ranges as *High Performance Level*, *Moderate Performance Level* and *Low Performance Level* for substation members according to importance and voltage range of the members. Some American researchers started to study about seismic vulnerability of substations at the beginning of the 2000’s, but there are very limited studies still in Europe.

Kong and Reinhorn [3] performed shake table tests of full-scaled disconnect switch with support structure. Two different base isolation system, friction pendulum system and wire rope isolators, which are located under the support structure, are used to reduce the inertial stress of the insulators. Koliou *et al.* [4] are proposed stiffening technique to reduce the seismic demand under strong seismic excitation. The main idea is the stiffening the base of the bushing to shift its fundamental frequency near the rigid base condition. Seismic tests of transformer bushing systems are performed for the cases of rigid and flexible bases. Hatami *et al.* [5] performed several tests to determine the seismic performance of transformer and its insulator. Murota *et al.* [6] performed tri-axial shaking table tests of power transformers for two isolation systems which are sliding bearings combined with rubber bearings and segmented high-damping rubber bearings. The interaction between the bushing connecting cables with the bushing in the base-isolated system is experimentally evaluated. The recent study about seismic retrofitting of a high voltage circuit breakers in Europe is performed by Alessandri *et al.* [7], [8]. They propose a base isolation system made of wire rope for high voltage circuit porcelain breakers.

A new low-cost *polyurethane seismic isolation device* (PSID) has been produced which satisfy the criterion declared in IEEE-693. The seismic isolation device consists of four polyurethane springs and two steel plates connected to each other by a traded rod. The working principle of the device is to generate large elastic rotation capability with negligible lateral displacement. The bushing system is supported on the device; therefore, its predominant vibration period is elongated.

In the scope of this study, a series of preliminary tests were conducted. The tests performed can be classified into three groups. Quasi-static cyclic tests are in the first group. In the second group, white noise tests, pull-back tests and hammer tests are performed to determine the damping property and vibration frequency of the device. In the last group, uniaxial shake table tests are accomplished for seven historical earthquakes. The experimental results are compared with the numerical ones obtained from the SeismoStruct Software [9].

The main advantages of the developed seismic isolation system against the present ones are its low-cost, no self-centering problem, high corrosion and UV resistance, no maintenance necessity in its service life, its serviceability in the large displacement demands.

The supporting steel truss may have distinct geometry and lateral stiffness. Hence it will be rational to place the isolation device between the bushing and supporting system. The proposed seismic isolation system is unique because of its significant features and the employment of polyurethane springs as well.

2. Definition of Polyurethane Seismic Isolation Device and Test Specimen

The developed PSID consists of four polyurethane springs placed between two circular steel plates which are connected at the center by a threaded rod. The lateral displacement capacity of a polyurethane spring is about 30% of its original height. The polyurethane springs are placed in the cavities on the steel plates. Depth of each cavity is 5 mm and it is aimed the shear transfer between polyurethane spring and steel plates. The post-tensioning force applied to the threaded rod is about 40 kN. Moreover, intensity of the post-tensioning force is arranged so that the polyurethane springs always remains in compression during the service life. The dimensions of PSID used in the experimental study is presented in Fig. 1. A steel column is utilized in the preliminary tests instead of a real bushing. The steel column is preferred due to its low damping property which is similar to the porcelain bushings. Damping ratio of the porcelain bushing is expressed as 2% in IEE693. Additional mass is utilized to generate the similar mass condition with the porcelain bushing.

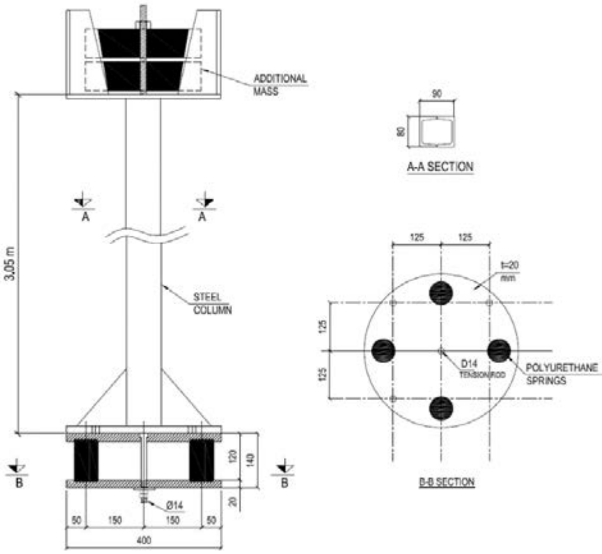


Fig. 1 – Test specimen of PSID

2.1. Quasi-Static Tests

The existing testing setup in STEELab was used in the experimental study, Fig. 2. A displacement protocol was applied on top of the steel column by using a horizontally oriented MTS servo-hydraulic actuator. To prevent potential out-of-plane deformations, two U-shaped restrainers were used in the testing setup. There is a trivial distance between the restrainers and the steel column, and grease was applied to the surface of the restrainers.

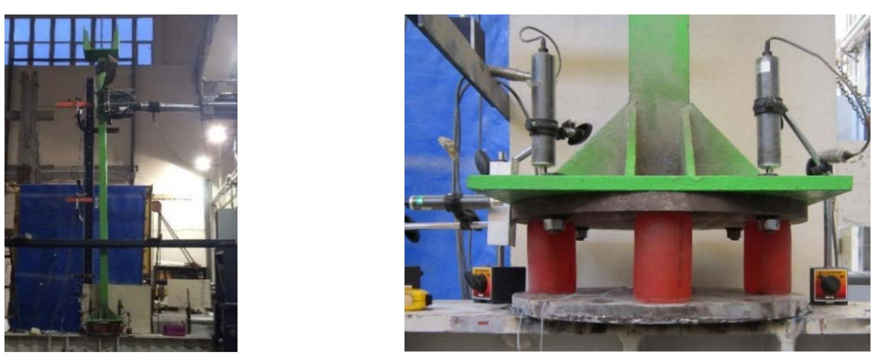


Fig. 2 – Test setup for Quasi-Static Test

Moment-rotation relation is obtained by using two displacement transducers which are located on the bottom plate of steel column. Relative horizontal displacement of PSID is measured by a horizontally oriented displacement transducer. The applied displacement protocol and the measured moment-rotation relation is given in Fig. 3. The maximum relative lateral displacement of PSID is less than 1mm. Hence, PSID has large lateral stiffness compared with the rotational flexibility.

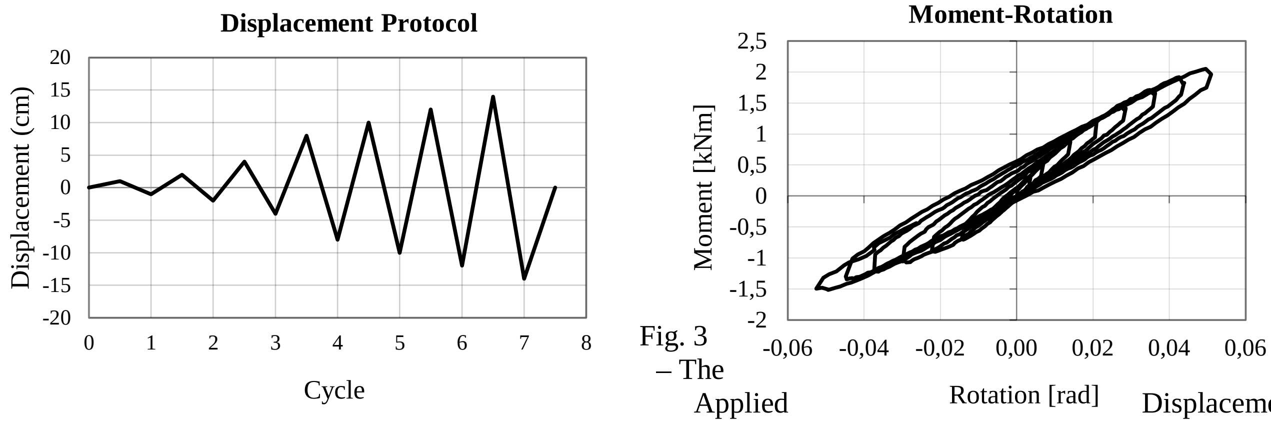


Fig. 3 – The Applied Displacement Protocol and the Measured Moment-Rotation Curve

2.2. Free Vibration Tests

Impact hammer test was applied to determine the damping ratio and free vibration frequency. Logarithmic decrement method was used to determine the damping ratio of the specimen with and without PSID. An accelerometer and a transducer were positioned at top of the column. Impact hammer tests were applied in the two perpendicular directions to evaluate the symmetry. The displacement histories and the corresponding FFTs are presented in Figs. 4 and 5, respectively.

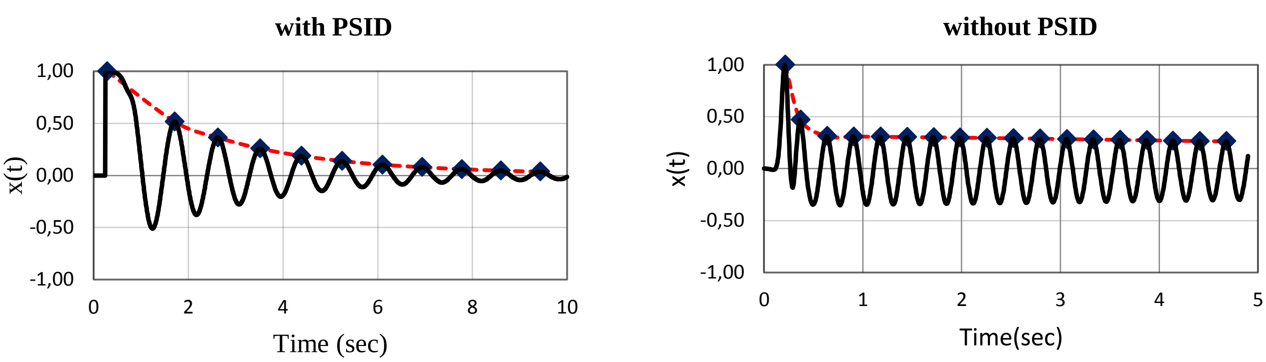


Fig. 4 – The Displacement History

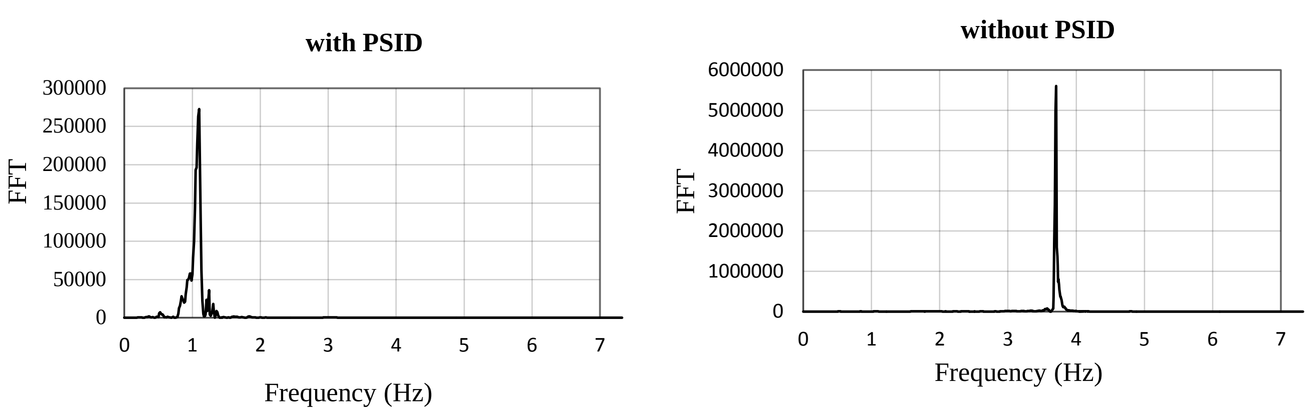


Fig. 5 – FFT Analyses

The first mode frequency and periods are determined as 1.086 Hz (0.917sec) and 3.705 Hz (0.269 sec) for the specimens with and without PSID, respectively. The damping ratio is obtained as 8.0% for the specimen with PSID while 0.2% for the fixed base specimen.

2.3. Shaking Table Tests

The uniaxial shake table facility existing in STEELab is utilized in the study. The ultimate displacement capacity of the table is ±325 mm. Test specimen was located at the center of the table. A number of displacement transducers and accelerometers were utilized to measure data on the specimen. Accelerations were recorded at the top and bottom of the specimen. Laterally and vertically oriented displacement transducers were employed on PSID to measure the shear and rotational type of displacements, respectively. The shaking table test setup and location of the measuring devices are presented in Fig. 6.

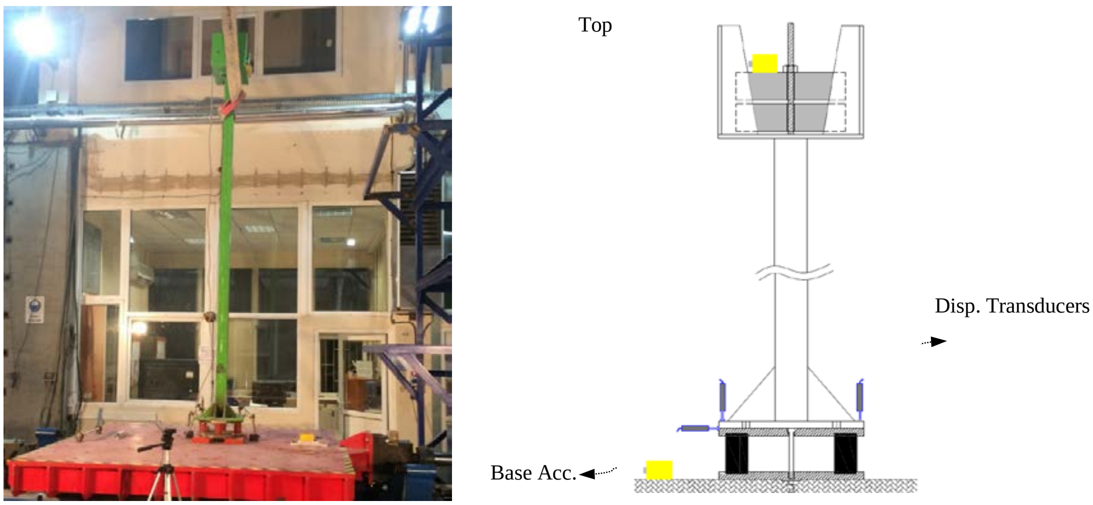


Fig. 6 – Shaking Table Test Setup

Historical acceleration records listed in Table 1 are utilized on the shaking table tests as incremental form. PGA and PGV parameters of the records are listed in the last two columns of the table. The multipliers used to scale the records are 0.25, 0.50, 0.75 and 1.00. At the end of each incremental set, white noise was applied to the specimen to detect the damages.

Period vs. elastic spectral acceleration curves of the records and the code-specified design spectra for firm (soil type Z2) - and weak (soil type Z4) - type soils according to TEC [10] are also shown in Fig. 7.

Table 1 Selected Historical Acceleration Records

Record	SYMBOL	M_s	d [km]	PGA [cm/s^2]	PGV [cm/s]
Erzincan 03/13/1992 Erzincan S.	ERZ-EW	6.90	8.97	486.6	64.3
Superstition Hills 11/24/1987 USGS 5051 P. Test Site S.	PTS315	6.60	15.99	369.8	43.9
Chi-Chi, Taiwan 09/20/1999 CWB 99999 TCU076 S.	TCU076	7.62	16.03	408.1	64.2
Chi-Chi, Taiwan 09/20/1999 CWB 99999 TCU067 S.	TCU067	7.62	28.70	318.8	66.6
Loma Prieta 10/18/1989 Hollister Diff. Array S.	HDA165	7.10	45.10	263.9	43.9
Superstition Hills 11/24/1987 USGS 9400 Poe Road S.	POE360	6.60	11.20	294.3	32.8
Duzce 12/11/1999 Bolu S.	BOL000	7.14	17.16	714.2	56.4

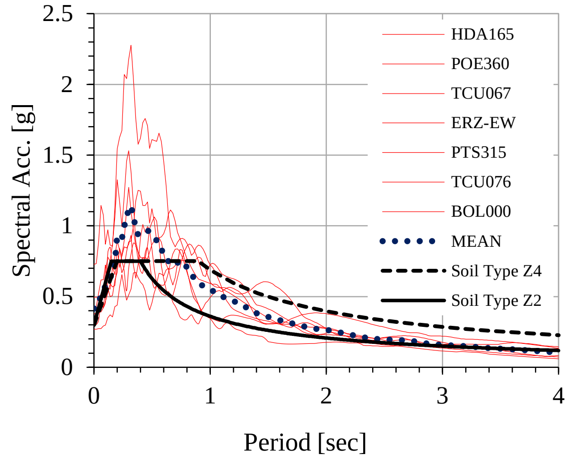


Fig. 7 – Elastic Spectral Accelerations

The specimens succeed all the historical earthquakes without any damage. The acceleration records measured at the top of the specimen are compared in Fig. 8a between the fixed base and PSID cases. The PSID system is effective to reduce the top accelerations in the ratios of 50% to 70%.

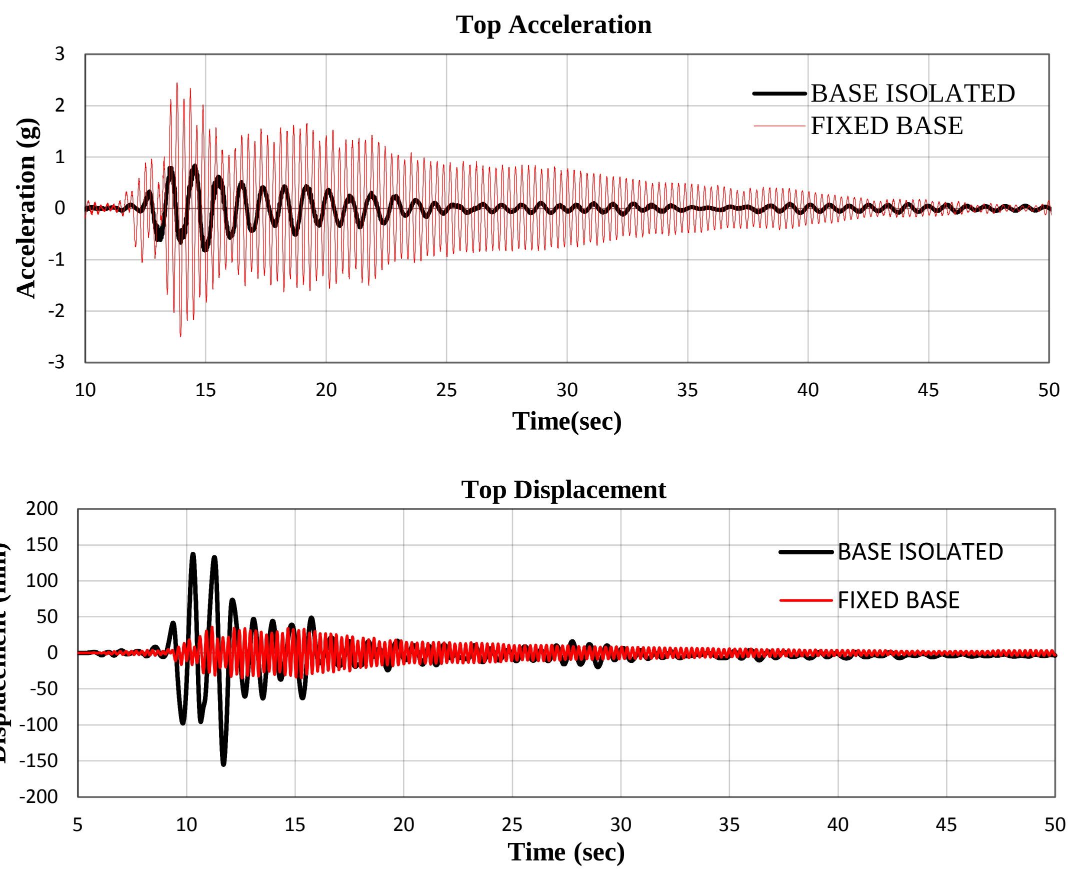


Fig. 8 – Top acceleration and displacement comparisons for BOL000 record

Maximum acceleration measured for the fixed base specimen is about 2.5g. Though, the corresponding value for PSID case is 0.83g. Top displacement comparison is given in Fig. 8b. The maximum top displacement values are 36.07mm and 155.12mm for the fixed base and PSID cases, respectively.

3. Numerical Modelling

Ramberg-Osgood behavior model is utilized to simulate the response of PSID. Non-linear static analyses are executed in SeismoStruct for the selected displacement pattern. After the refinement process, α parameter of Ramberg-Osgood model is determined as *1.50*. A satisfactory correlation is obtained between the numerical and experimental moment-rotation curves, Fig. 9.

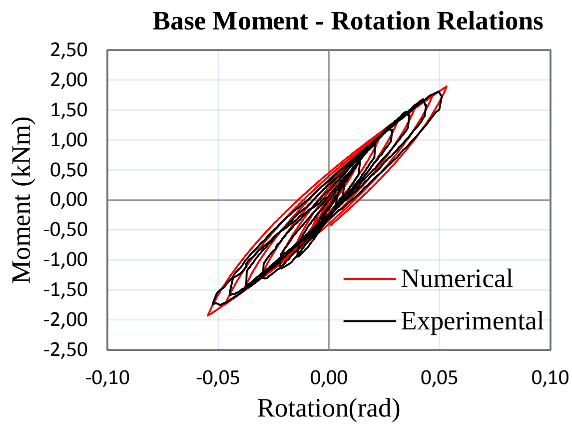
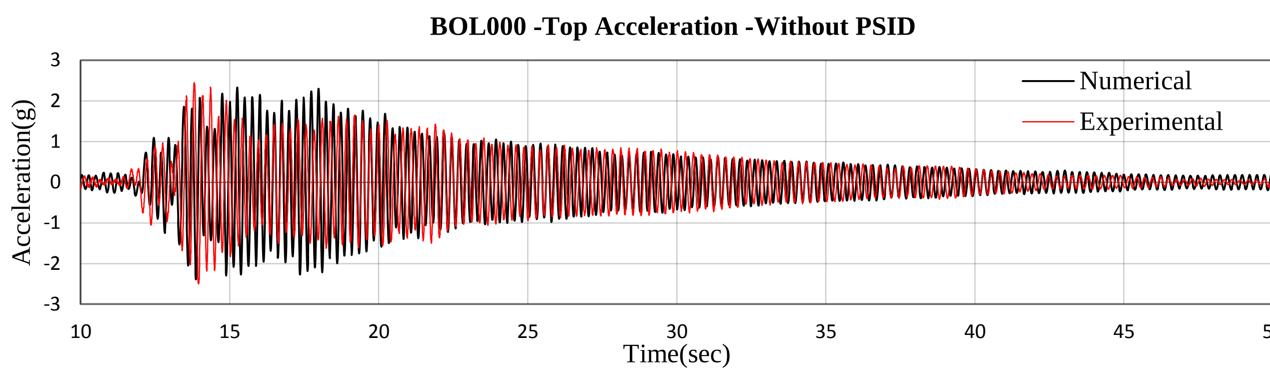


Fig. 9 – Comparison of Experimental and Numerical Moment-Rotation Relations

Numerical analyses are performed for the fixed base and the isolated specimens. Top acceleration histories obtained for BOL000 record are illustrated in Fig. 10. There is an acceptable accordance between the experimental and numerical results.



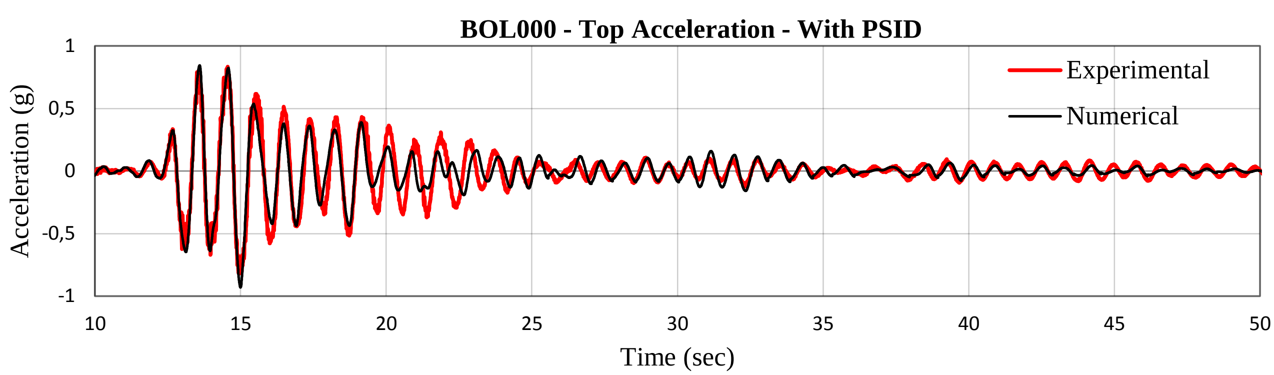


Fig. 10 – Comparison of Experimental and Numerical Top Accelerations

4. Conclusions

A novel low-cost seismic isolation device for high voltage porcelain electric bushings, which is positioned between steel sub-structure and the bushing, is developed and the preliminary tests are accomplished through the intensive experimental research. Based on the results of the study, the following results can be concluded.

1. A significant seismic performance enhancement is determined in terms of dominant frequency, damping, base shear and base moment.
2. Fundamental period (frequency) of the specimens are determined as 0.269 sec (3.71 Hz) and 0.917 sec (1.09 Hz) respectively for the fixed base and the isolated specimens.
3. PSID is effective not only on the elongation of predominant period but also providing additional damping. The equivalent viscous damping ratio determined from the test results for the isolated case is around 8%.
4. The selected acceleration records produce innumerable effectiveness ratios for the seismic isolation system. In terms of lateral top acceleration and the corresponding quantities, the ratios are between 50% to 75%.
5. The base moment which is effective on seismic design of the high voltage bushing is diminished approximately 50% to 80% compared with the fixed base occasion as it is expected. Hence, seismic safety of the bushing is increased particularly.
6. From the model calibration study, Ramberg-Osgood model parameter of α is determined as 1.50.
7. The self-centering capability of the isolation system is experienced during the shaking table tests.
8. Elongation of the predominant period will increase the effectiveness of PSID. However, it should be noted that the excessive top displacements may cause some operational problems in the electrical system.

5. Acknowledgment

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