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MODAL STUDY OF TRANSMISSION CONCRETE POLES FOR HEALTH MONITORING

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Abstract

Prestressed concrete poles are unique structures extensively used in the power transmission system across southeastern regions of the United States. Their vibration characteristics are critical to the stability of these pole structures. These characteristics also represent essential information for the development of a vibration-based monitoring technique to ensure sustainable power supply and public safety. This paper reports an investigation on modal behaviors of the concrete poles. Field impact tests were conducted on simply-supported, suspended and clamped poles with wireless sensors and traditional contact accelerometers attached. Finite element analysis was carried out to validate the experimental eigenvalues of the pole vibration. Modal sensitive parameter study and FE updating were then implemented on concrete poles. The paper also offers a basic roadmap for designing a health monitoring strategy that involves logistics unique to the power transmission industry. This study is part of a preparatory work for future research to develop a health monitoring system for the transmission infrastructure.

INTRODUCTION

The spun-cast prestressed concrete pole is a unique RC structure widely used to support the power transmission lines in the southeastern areas of the United States. It is fabricated using the centrifugal casting method, yielding a significantly denser concrete, as well as increasing the strength-to-weight ratio. As support structures in the electric transmission grid, the vibration characteristics of these concrete poles are critical for the reliability of sustained power supply. There are few published literatures about the prestressed concrete pole vibration. Lantrip [1] and Chen [2] reported modal tests and FE analysis works on several poles, but there are still great research needs. Recently, power industries put forward concerns about the stability of transmission grids under extreme loading conditions, such as blasting effects [3]. In order to investigate structural dynamic response under extreme loading, it is essential to first understand structural vibration characteristics of these poles. These characteristics can also form the basis for developing a health monitoring strategy for power transmission grids.

This paper reports research results from a series of tests on modal behaviors of concrete poles. Modal testing was conducted by impact excitation to seek eigensolutions of the pole vibration. Modal analysis was also executed through finite element modeling. The influences of some physically significant parameters on modal characteristics of concrete poles were numerically investigated. Basic FE model tuning technique of the pole structure for later research on damage detection has been implemented. A roadmap for designing a health monitoring system to electric transmission grids under extreme events is briefly introduced here. The proposed vibration-based monitoring technique with remote sensing is expected to be effective for the detection of damage present in the power transmission structures.

MODAL TESTING OF PRESTRESSED CONCRETE POLES

Understanding the modal behaviors of concrete poles is the fundamental task for further research on the structural dynamic responses under extreme loading, and for the development of the vibration-based health monitoring system for transmission grids. Full-scale modal testing was conducted to solve the eigen-problems of representative spun-cast prestressed concrete poles in this study.

Testing Program

Modal testing is an experimental technique that involves measuring the frequency response functions (FRF) of a structure. The FRFs represent the inherent dynamic properties of a system in forms of natural frequencies, mode shapes, and damping factors. Modal testing, using impact excitation, can obtain the FRF that contains necessary information about a system. In this study, impact modal testing was conducted on two prestressed concrete poles (Table 1), where the poles in the CP3 and CP4 tests were embedded at the same depth (1.50 m), and were determined by the common power industry construction practice. The test procedure included using a fixed response location (output from the sensor) and several moving force excitation points (input from the hammer). Testing configurations include suspended, simple-supported, and direct-embedded poles (Figure 1). The equipment consisted of accelerometers, a data acquisition system, and an instrumented hammer. A triaxial MEMS wireless sensor (Figure 2) was attached side by side with a traditional contact accelerometer in the modal testing.

Table 1. Tested specimens

Designation	Tested pole	Boundary condition
CP1	A 28.95 m height isolated concrete pole	Simple-supported
CP2	A 10.67 m height isolated concrete pole	Suspended
CP3	The same 10.67 m pole used above	Embedded with soil as back-fill
CP4	The same 10.67 m pole used above	Embedded with gravel as back-fill

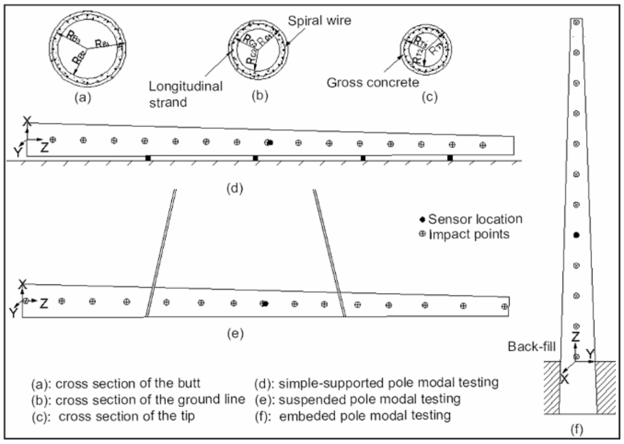


Figure 1. Modal testing set-up

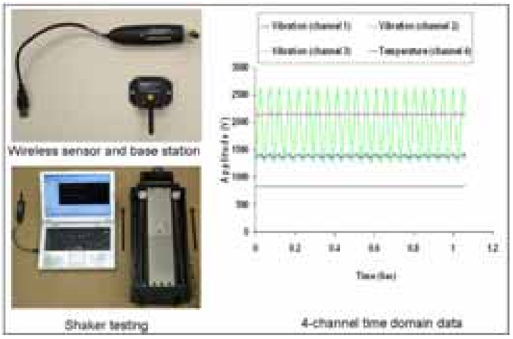


Figure 2. Wireless sensor used in the modal testing

Test Results

The frequency transfer functions were processed to extract the modal parameters such as natural frequencies and corresponding mode shapes. The identified eigen-frequencies of the pole vibration are listed in Table 2. Figure 3 gives the representative mode shapes of two different test configurations. Mode shapes from CP1 and CP4 are not shown here since they are similar to those of CP2 and CP3.

Table 2. Identified natural frequencies

Designation	Frequency	Description
CP1	2.51 (Hz)	1st bending mode of simple-supported 28.95m pole
	8.13(Hz)	2nd bending mode of simple-supported 28.95m pole
	13.87(Hz)	3rd bending mode of simple-supported 28.95m pole
CP2	13.37(Hz)	1st bending mode of suspended 10.67m pole
	36.33(Hz)	2nd bending mode of suspended 10.67m pole
	69.66(Hz)	3rd bending mode of suspended 10.67m pole
CP3	3.30(Hz)	1st bending mode of soil back-filled embedded 10.67m pole
	15.28(Hz)	2nd bending mode of soil back-filled embedded 10.67m pole
	39.36(Hz)	3rd bending mode of soil back-filled embedded 10.67m pole
CP4	3.30(Hz)	1st bending mode of gravel back-filled embedded 10.67m pole
	15.18(Hz)	2nd bending mode of gravel back-filled embedded 10.67m pole
	39.46(Hz)	3rd bending mode of gravel back-filled embedded 10.67m pole

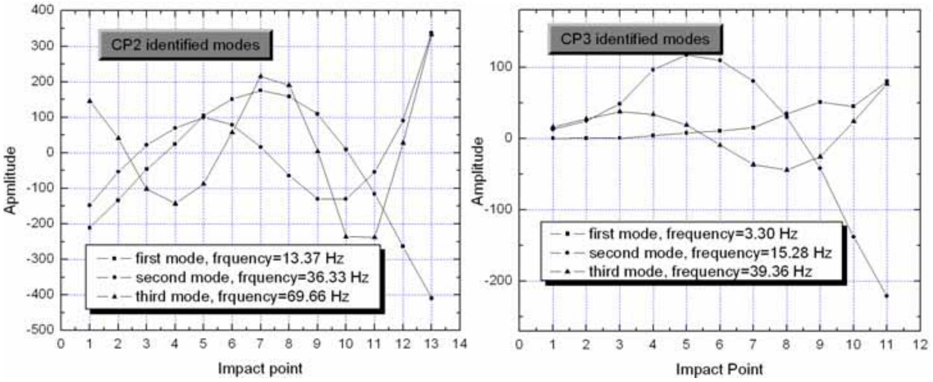


Figure 3. Representative vibration mode shapes

FE MODELING OF TRANSMISSION CONCRETE POLES

The influences of physically significant parameters on modal characteristics of concrete poles were numerically examined. FEM updating technique was implemented to the 10.67 m concrete pole. It is anticipated that damage assessment will be based on updating the finite element model in the later developed transmission structure health monitoring system.

Numerical Investigation of Sensitive Parameters

The 28.95 m concrete pole in test CP1 was numerically analyzed. Material properties and geometry information for the original model are listed in Tables 3 and 4. Concrete and prestress strands were respectively modeled using solid elements (SOLID65) and truss elements (LINK8), whereas the spiral wires were smeared into concrete by their volume ratio along the length of the pole. Nonlinear static analysis and modal analysis were conducted sequentially so as to include prestress effects into eigen-solutions of the pole vibration [4].

Table 3. Material properties

Material	Young's Modulus	Density	Poisson's ratio	Constitutive law
Concrete	37.70 (Gpa)	2403.84 (kg/m^3)	ν_c=0.20	Multi-linear σ-ε f'_c=75.86 (Mpa)
Prestress strand	200.00 (Gpa)	7852.56 (kg/m^3)	ν_s=0.27	Bilinear σ-ε f_{pu}=1724.14 (Mpa)
Spiral wire	200.00 (Gpa)	7832.69 (kg/m^3)	ν_w=0.27	Bilinear σ-ε f_y= 448.28 (Mpa)

Table 4. Geometric Data

Portion	Length (m)	Cross section diameter (m)			Wire volume ratio (%)
1	H_1=3.51	D_{B1}=0.80	D_{B2}=0.61	D_{B3}=0.73	u_1=0.59
2	H_2=24.54	D_{G1}=0.74	D_{G2}=0.55	D_{G3}=0.66	u_2=0.28
3	H_3=0.91	D_{T1}=0.28	D_{T2}=0.14	D_{T3}=0.21	u_3=0.78

Modal analysis was performed with varied prestressing forces in order to investigate the frequency sensitivity to prestress level. The resulting correlation between the change in prestress level and the corresponding natural frequencies is shown in Figure 4 (a), which indicates that prestress is not a very sensitive parameter. Previous studies [5, 6, 7, 8] explained prestress effect on natural frequencies. Generally speaking, within the scope of small deformation analysis of prestressed concrete structures, when nonlinearity of concrete material as well as the cracking issues are ignored, prestress effects on eigen-solutions are insignificant, especially for modal analysis, which usually deals with lower modes due to experimental restrictions.

Concrete strength sensitivity was studied by adjusting the concrete modulus of elasticity, which was obtained through Equation (1) [9]. The correlation between change of concrete strength and natural frequencies of pole vibration is shown in Figure 4 (b). It is found that eigenfrequencies deviate approximately within 13% range with the varying concrete strength from -40% to 30% of its original value (75.86 Mpa) in the same trend for all studied modes.

$$E_c = (3.32\sqrt{f_c^{'}} + 6895)(w_c / 2320)^{1.5}\,(Mpa) \qquad (1)$$

where: E_c (Mpa) is concrete modulus of elasticity, $f_c^{'}$ (Mpa) is concrete compressive strength, and w_c (kg/m^3) is concrete density.

To study the effects of boundary conditions, linear springs (COMBIN14) were added to the original FE model at the location of the supports. It is found that, for the same mode shape, the natural frequency increases with the increase in the spring stiffness (k) (Figure 4 (c)). For example, the fundamental frequency at k=1750.00 kN/m is 5.60 Hz while at k=175.00 kN/m is 3.10 Hz. Different spring stiffness represents different boundary conditions, which, to some degree, introduces changes in mode shapes.

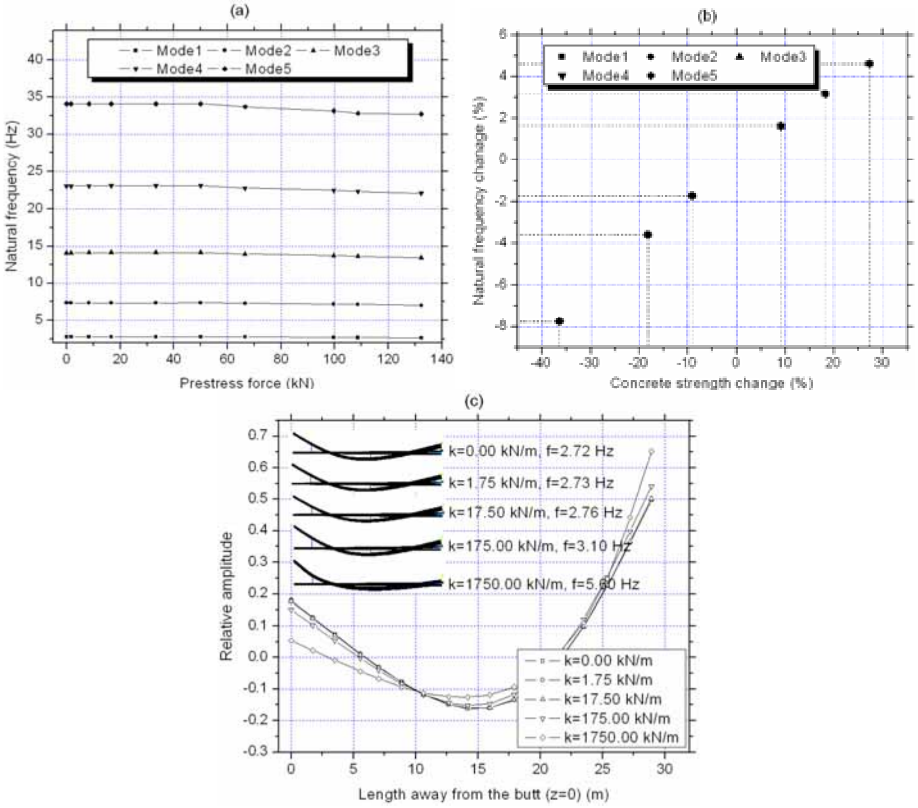


Figure 4. Influence of sensitive parameters on natural frequencies: (a) prestress force; (b) concrete strength; (c) boundary stiffness

FE Model Updating of the Concrete Pole

The 10.67 m concrete pole was selected for FEM verification and updating through manual tuning of the physical-meaning-bearing parameters. According to the foregoing discussion, prestress effects are insignificant for small deformation elastic scope analysis; therefore, it is not always advisable to model prestress strands and concrete separately. The pole was instead modeled by using tapered beam elements (BEAM189). Considering the fact that prestress is usually helpful at reducing concrete cracks, its effects could be included in the models by updating the material elastic constant of the beam elements for the purpose of health monitoring.

Updating the FE model is an optimization process, among, which manual tuning the physical-meaning-bearing parameters, is one of the simple and straightforward approach. Based on the suspending modal testing results (CP2), the original model first went through concrete material property updating. This resulted in a valid FE model for the concrete pole itself. The resulting model was further updated to converge to the CP3 data, which gave the baseline model for the same pole in the direct embedment boundary condition. The latter procedure was achieved by specifically tuning stiffness of the soil springs, which were modeled by no-mass spring elements (COMBIN14). Since the bury depth to width ratio of the studied pole was, approximately, within the range of 0.5-4, the models developed for rigid caisson foundations [10] were chosen for these springs. The damping was not considered in this study. The updated results of these springs were expected to represent the boundary condition (combination effects of property, bury depth, consolidation of backfill material, and surrounding soil condition). These iterative updating processes would not stop until the objective minimization of discrepancies between the updated FE results and experimental data, in the form of both natural frequency and mode shape, were realized. The resultant correlation between experimental data and updated FEM analysis are shown in Table 5 and Figure 5.

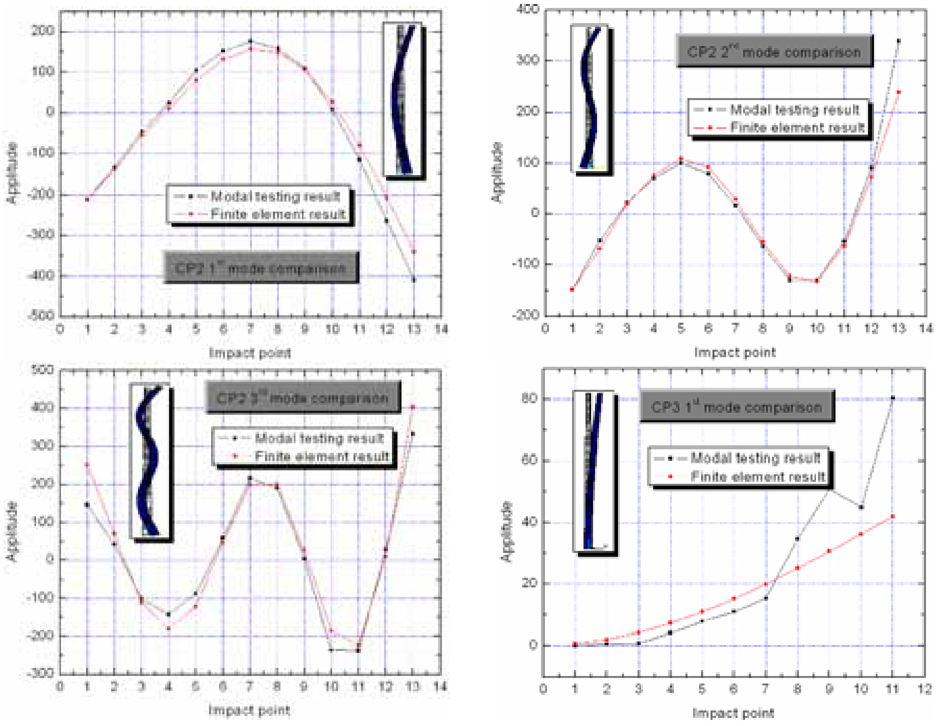
Table 5. Comparison between test results and FE model updated calculations

Test	Mode	Measured frequency	FEM Results	Difference	MAC
CP2	1st bending	13.37 (Hz)	13.38 (Hz)	0.07%	0.99
CP2	2nd bending	36.33(Hz)	36.22 (Hz)	0.30%	0.96
CP2	3rd bending	69.66 (Hz)	69.96 (Hz)	0.43%	0.96
CP3	1st bending	3.30 (Hz)	3.14 (Hz)	4.85%	0.93
CP3	2nd bending	15.28 (Hz)	15.36 (Hz)	0.52%	0.99
CP3	3rd bending	39.36 (Hz)	39.37 (Hz)	0.03%	1.00

The maximum frequency difference is the first mode of CP3 (4.85%). This may be caused by the deficiencies of the testing in determining the first mode vibration. All modal assurance criterion (MAC) values in Table 5 obtained from Equation (2) indicate good coherence between experimental and numerical results. These give confidence to the validity of the updated FE model.

$$MAC(\phi_a,\phi_e)=\frac{\left|\phi_a^T\phi_e\right|^2}{\left(\phi_a^T\phi_a\right)\left(\phi_e^T\phi_e\right)} \qquad (2)$$

where: ϕ_a and ϕ_e are the FE and experimental mode shape vectors, respectively.



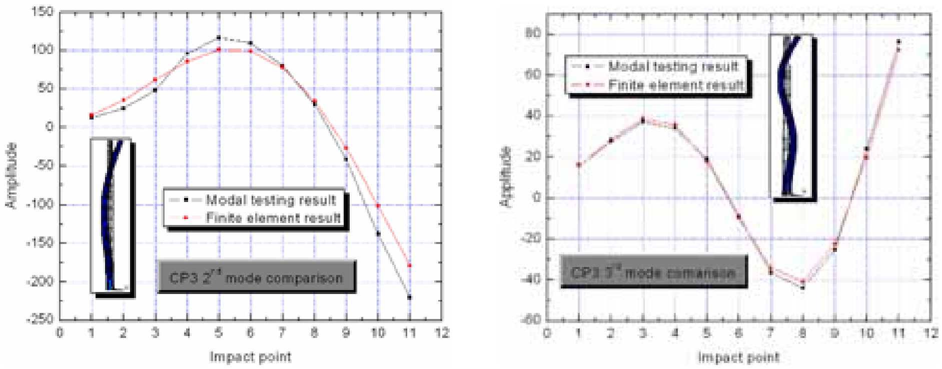


Figure 5. Mode shape comparisons between tests and updated FE models

HEALTH MONITORING OF TRASMISSION POLES

Damage scenarios were observed during the ongoing research of blasting effects on electric grids [11]. The following strategy is a preliminary concept to develop a health monitoring system suitable for critical transmission poles. It is based on the fact that changes in structural dynamic properties can be used as damage indicators on the global scale. The main idea is to explore the observable variation in modal parameters (natural frequencies, mode shapes, etc.) before and after the presence of structural damage.

The framework of the anticipated health monitoring system is shown in Figure 6. Taking advantage of the wind-sensitive characteristic of electric grids, ambient loading can be treated as excitation to the monitored structure. Considering the unique safety distance requirement, the remote sensing technique is to be used to obtain structural response. Special work is required to study the electromagnetic field effects on the wireless sensing system. Suitable modal identification techniques will be utilized to analyze measured data. Sensitive geometric and/or material properties will be chosen to verify the prototype model, as well as to tune the baseline FE model into the target model for the possible damaged structure. Confidence of the updating can be ensured by minimizing residues between measured modal parameters and their counterparts from the FE model. Damage assessment can be conducted by comparing the baseline model and the target FE model through the physical-meaning-bearing parameters. The evaluation requires an index to judge the damage threshold. This criterion, unique to the transmission structures, is part of the work to be completed in the near future.

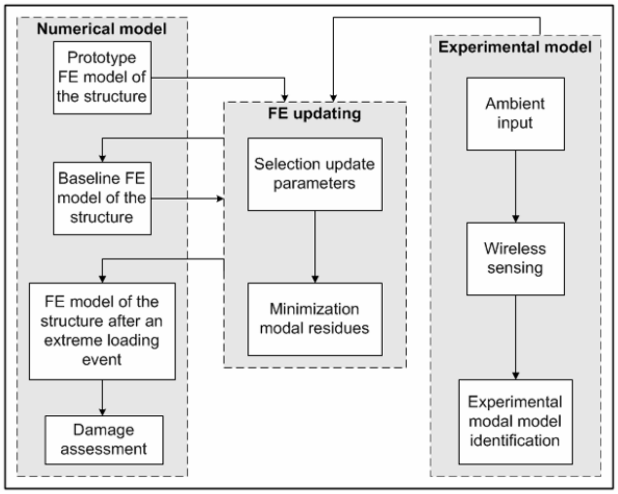


Figure 6. Framework of the health monitoring strategy

CONCLUSION

Early damage detection of electric grids is an approach to ensure power supply safety under extreme events. Modal based structural health monitoring strategy for transmission poles has been preliminarily explored in this paper. Through modal testing, basic characteristics of concrete pole vibrations were studied. Eigenfrequencies and mode shapes of concrete poles under different boundary conditions have been obtained. FE updating technique has been successfully implemented on a transmission pole. Numerical investigation of physical-meaning-bearing modal-sensitive parameters indicates that the prestress effect is insignificant for the elastic eigensolutions to prestressed concrete structures. The health monitoring strategy for electric grids was schematically described. Further work based on this roadmap will be carried out.

REFERENCES

[1]. Lantrip, T.B., ‘Identification of Structural Characteristics of Spun Prestressed Concrete Poles Using Modal Testing Methods’, M. S. Thesis, University of Alabama at Birmingham, 1995.

[2]. Chen, S.E., Ong, C. K. and Antonsson, K., ‘Modal Behaviors of Spun-Cast Pre-Stressed Concrete Pole Structures’, Proceeding of IMAC – XXIV, Saint Louis, Missouri, USA, February 2006.

[3]. Conner, E., Dai, K. S. and Chen, S.E., ‘A Comprehensive Blast Plan for Transmission Structures Due to Mining Induced Blasts’, Proceedings of the IMAC-XXV, Orlando, Florida, USA, February 2007.

[4]. SAS IP, Inc., ‘Release 10.0 Documentation for ANSYS’, 2005.

[5]. Dallasta, A. and Dezi, L., ‘Prestress Force Effect on Vibration Frequency of Concrete Bridges—Discussion’, ASCE Journal of Structural Engineering 122 (4), (1996): 458–458.

[6]. Deak, G., ‘Prestress Force Effect on Vibration Frequency of Concrete Bridges—Discussion’, ASCE Journal of Structural Engineering 122 (4), (1996):458–459.

[7]. Jain, S.K. and Goel, S.C., ‘Prestress Force Effect on Vibration Frequency of Concrete Bridges—Discussion’, ASCE Journal of Structural Engineering 122 (4), (1996): 459–460.

[8]. Hamed, E. and Frostig, Y., ‘Natural Frequencies of Bonded and Unbonded Prestressed Beams–Prestress Force Effects’, Journal of Sound and Vibration, 295 (2006): 28–39.

[9]. Nawy E. G., ‘Prestressed Concrete: a Fundamental Approach’, 4th Edition, Pearson Education, Inc., 2003.

[10]. Gerolymos, N. and Gazetas, N., ‘Winkler Model for Lateral Response of Rigid Caisson Foundations in Linear Soil’, Soil Dynamics and Earthquake Engineering, 26(2006): 347-361.

[11]. Chen, S.E., Dai, K. S., Conner, E., and Qi, W. Y., ‘Mid-term Research Report: Study of Blast-Loading Effects On Transmission Structures’, Department of Civil and Environmental Engineering, University of North Carolina at Charlotte, February 2007.