LONGITUDINAL RESPONSE OF POWER TRANSMISSION TOWER-CABLE SYSTEM TO TRAVELING WAVE

Q.C. Liu[1] M.G. Yue [2] and D.S. Wang[3]

[1] *China Communications Construction Company WuHan Harbour Engineering Design & Research Co.,Ltd, Wuhan China*
[2] *State Key Laboratory of Costal and Offshore Engineering, Dalian University of Technology, Dalian China*
[3] *Institute of Road and Bridge Engineering, Dalian Maritime University, Dalian China*
Email: ymg2008@126.com

ABSTRACT :

Based on the established model of power transmission tower-cable system, seismic response is analyzed with time history method. Seismic response to traveling wave is compared with uniform wave, the results indicate that: traveling wave excitation can increase, as well as decrease, the seismic response of power transmission tower-cable system which depends on both traveling wave velocity and ground motion characteristics; traveling wave excitations increase the cable's axis force to a large extent, which will decrease gradually and approach to the case of uniform excitations as velocity increasing; traveling wave strongly magnified cable's displacement response in longitudinal and vertical direction, especially the latter term under excitations of near-fault ground motions; traveling wave velocity has great affection on the seismic response of power transmission tower-cable system.

KEYWORDS: power transmission tower-cable system; seismic response; traveling wave excitation; uniform excitation; near-fault ground motions; traveling wave velocity

1. INTRODUCTION

High voltage power transmission line is the important component of power system, once it is destroyed, there may be great economic losses and affections on society. Along with the economic development and the strategy execution of power transmission from West to East, some power transmission towers have to be built in intensive seismic zone. Although wind is the controlling load in present designation of power-transmit tower, many transmission tower systems are still seriously destroyed in earthquake, such as Kobe earthquake in Japan (Yin R.H. 2005) and Chi-Chi earthquake in Taiwan (1999). Because of particular dynamic characteristics and seismic response of power transmission tower-cable system, many of them are destroyed seriously in earthquake and result in great losses, so earthquake may be the controlling load in intensive seismic zone. For large-span structures, excitation varies along the longitudinal axis of the wave propagation path in terms of arrival time, amplitude and frequency content, a fact primarily attributed to the wave passage effect, the loss of coherency and the effect of local site conditions (Ghobarah A., Lin J.H., Fan L.C., Zhang Y.H. and Zhao C.H.). The spatial variability of ground motion has become significant for the seismic design of such structures. In earthquake, wave propagation will also take place in the cable which has characteristics of small original stress, large deflection and strong geometry nonlinearity (Li H.N. 1997). Large-scale movements of cable in vertical direction will cause discharge or short circuit account for too small space between cables, even tensile failure may be caused by large tension stress.

So, it is not sufficient only taking uniform excitation or single tower into consideration in seismic design. In this paper, model of tower-cable system is established and wave propagation effect is taking into consideration in nonlinear seismic response compared with uniform excitation.

2. FINITE ELEMENT MODEL AND EXCITATIONS

2.1 Finite Element Model (Yue M.G. 2005)

The model of tower-cable system is presented in Fig. 1. The tower's height is 57m with span of 300m and with 4 layers cable. The top cable is ground wire with 2 GJ-80 wires and the 3 bottom layers cable is fire wire with 8 LGL-400 wires of each. The tower is modeled by beam element with 7 lumped masses in series. The cable is modeled by truss element without compression bearing capacity, and the affection of original stress and large-scale deflection are considered. The cable has 30 elements in each span and the vertical deflection is 5m in span center. The tower bottom is encastred and the soil-structure interaction is neglected. The damping takes 3%. The main parameters of the model are listed in Table 1.

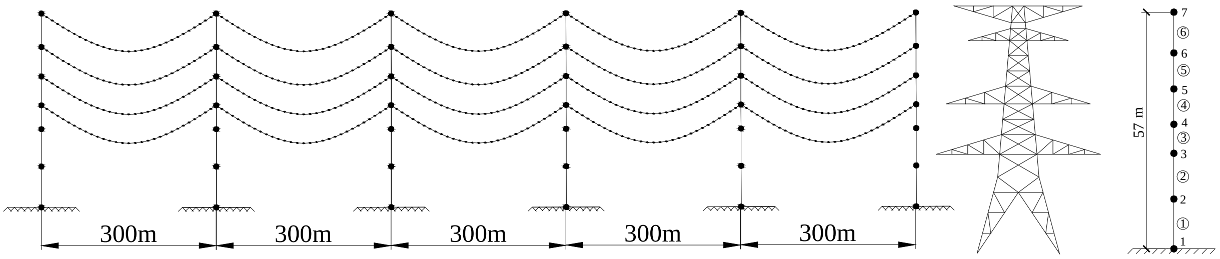

Fig. 1 Finite Element Model of Power Transmission Tower-cable System

Table 1 Main parameters of tower-cable system

Node	Number	1	2	3	4	5	6	7
	Height (m)	0	12	23	30	38.5	47.17	57
	Mass (kg)	/	14800	11760	12657	8632	6893	3084
Element	Number	1	2	3	4	5	6	--
	Sectional area (m^2)	0.0497	0.0497	0.0363	0.0248	0.0150	0.0079	--
	Moment of inertia (m^4)	2.3172	1.0569	0.4548	0.2235	0.0869	0.0245	--
	Polar moment of inertia (m^4)	3.6613	1.6689	0.7186	0.3531	0.1263	0.0345	--
Cable	Sectional area: 454.6mm^2, Mass: 1626kg/km, Failure stress: 29kg/mm^2, Young's modulus: 800kg/mm^2							

2.2 Earthquake Excitations

In this analysis, 8 recorded earthquake waves are used, 6 of which is near-fault record from Chi-chi earthquake and the other 2 records are El Centro and Taft. All the near-fault records are component that perpendicular to the fault (east-west direction). The peak ground acceleration is adjusted to 0.3g according to 'Code for seismic design of buildings GB 50011-2001' (Chinese seismic code). The primary parameters of these records are listed in Table 2.

Table 2 Parameters of records

Records	PGA (g)	PGV (cm/s)	PGD (cm)	Distance to fault (km)	PGV/PGA (s)
TCU052	0.348	159.0	184.42	0.06	0.46
TCU054	0.148	59.4	59.42	5.92	0.40
TCU068	0.566	176.6	324.11	0.49	0.31
TCU075	0.333	88.3	86.45	1.49	0.27
TCU076	0.303	62.6	31.47	1.95	0.21
TCU102	0.298	112.4	89.19	1.79	0.38
El Centro	0.313	29.7	13.04	--	94.89
Taft	0.178	17.5	8.84	--	98.29

3. SEISMIC RESPONSE UNDER TRANVELING WAVE EXCITATIONS

3.1 Longitudinal Modals of Tower-Cable System

Modal analysis step, which takes the original stiffness consideration, must be carried out after static step under gravity load. As the cable is very flexible element in the model, many micro-vibration modals appear in modal analysis. In order to removing the affection of finite boundary, 10 principal modals of middle span in longitudinal direction are extracted (Fig. 2). The dark lines are deformed shape and the light lines denote the original model. In Fig. 2, the first 6 modes are mainly caused by wire vibration while the tower vibration is involved in the last 4 modes. From the comparison of vibration periods of the system's 10 principal modals with the first 6 periods of the single tower (Table 3), it is concluded that the system's periods are much larger than the single tower because the cable's vibration, and the tower's fundamental period is increased from 0.39s to 0.55s.

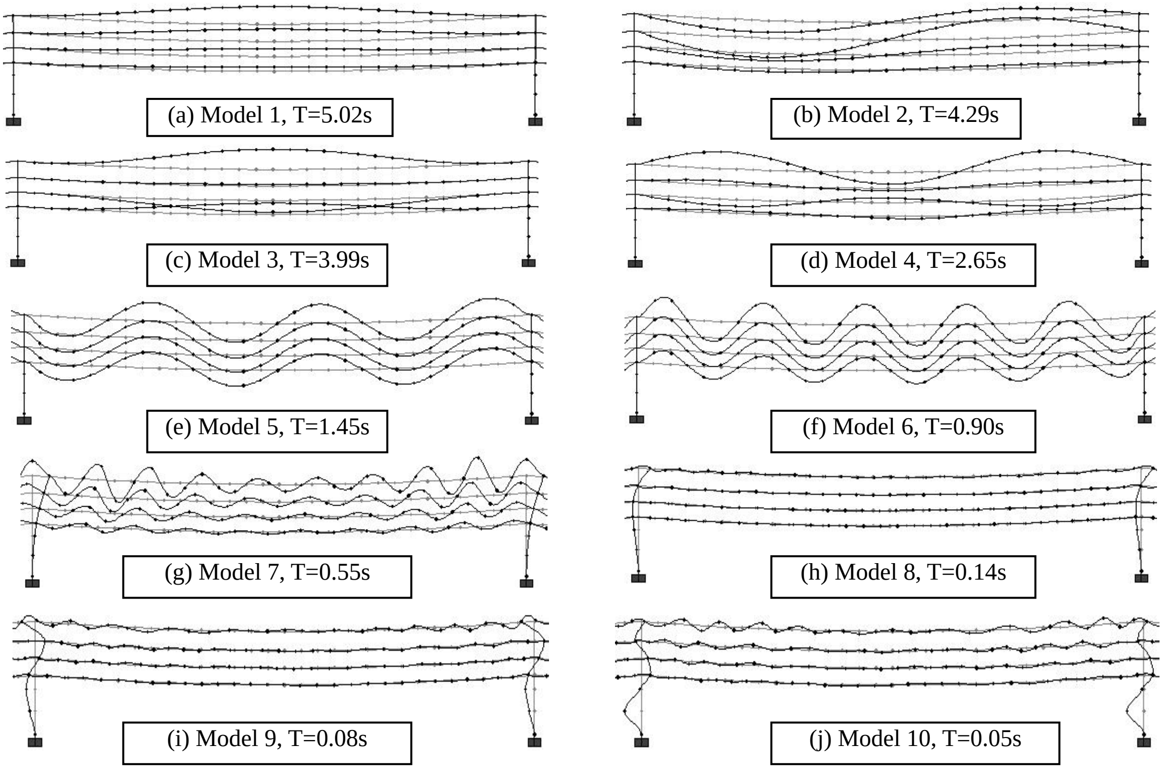
(a) Model 1, T=5.02s
(b) Model 2, T=4.29s
(c) Model 3, T=3.99s
(d) Model 4, T=2.65s
(e) Model 5, T=1.45s
(f) Model 6, T=0.90s
(g) Model 7, T=0.55s
(h) Model 8, T=0.14s
(i) Model 9, T=0.08s
(j) Model 10, T=0.05s

Fig. 2 Ten modals of the tower-cable system in longitudinal direction

Table 3 Vibration periods (s)

Model	1	2	3	4	5	6	7	8	9	10
Tower-cable system	5.02	4.29	3.99	2.65	1.45	0.90	0.55	0.14	0.08	0.05
Single tower	0.39	0.15	0.08	0.05	0.04	0.03	--	--	--	--

3.2 Seismic Response of Tower

In order to study the affection of traveling wave, comparison of the system's seismic response is carried out between uniform excitations and traveling wave excitations. Response ratio of the system (including moment ratio, shear force ratio and drift ratio), which defined as ratio of response under traveling wave excitation to response under uniform excitation, is presented in Fig. 3~Fig. 5, in which average value is for near-fault waves and maximum value is for El Centro and Taft.

Traveling seismic wave excitation can increase, as well as decrease, the seismic response of the power transmission tower-cable system which depends on both traveling-wave velocity and ground motion characteristic. When wave velocity is 300m/s, shear force of the tower at bottom increased 50% under excitations of El Centro and Taft which represented far-field wave, and small increment also happened in moment at bottom and drift at top nodes. But for near-fault waves, shear force raised about 4 times, and increment in moment at bottom is more than 1 times and drift at top is slightly less than one times. So there are great differences in tower response for near-fault and far-fault field. As the velocity increased to 600m/s or 900m/s, there are no much differences in tower response between near-fault field and far-fault field, except for shear force at bottom and drift at lower joint. So, the tower's seismic response will decrease with wave velocity increasing. As to 1200m/s, tower's response to traveling wave excitation is less than which to uniform excitation on the whole. Shear force and moment at bottom will reduce to 50% for El Centro and Taft, and drift at top will reduce to about 40%. The corresponding terms for near-fault waves is 80% and 50% respectively. So, tower's response for near-fault wave is higher than which for El Centro and Taft at higher velocity.

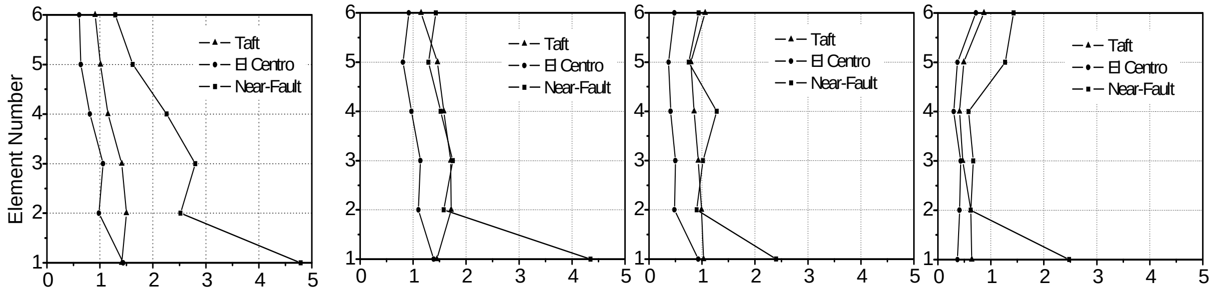

Fig.3 Distril ower shear force ratio

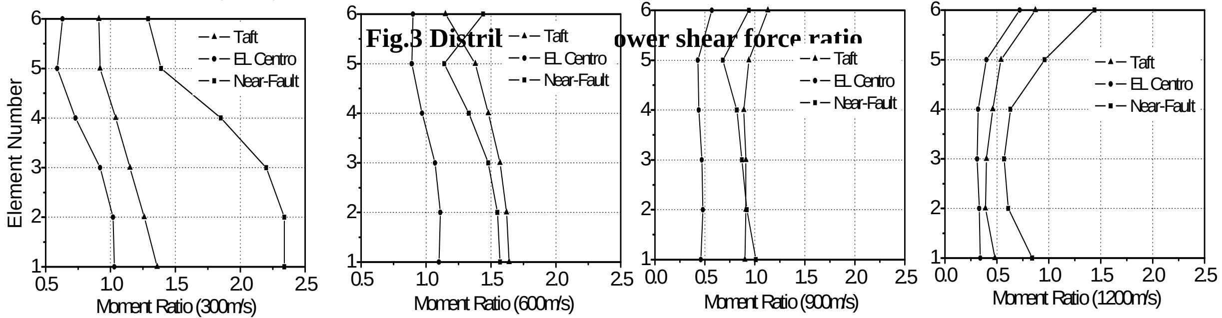

Fig. 4 Distrib tower moment r

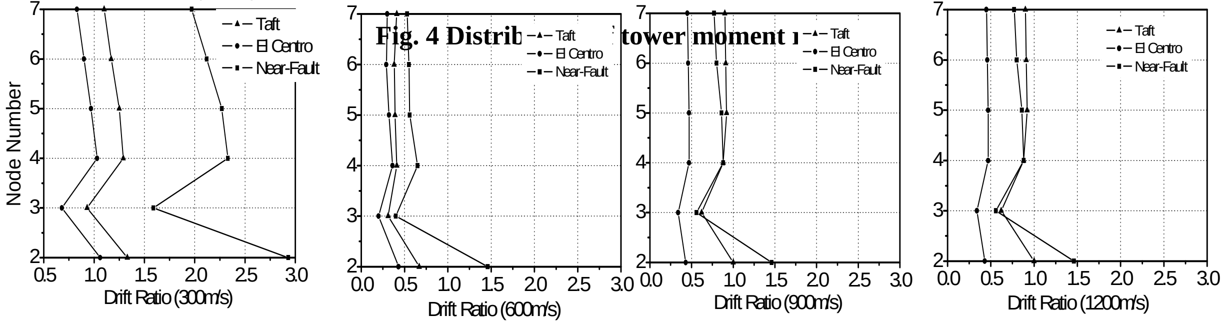

Fig. 5 Distribution of tower drift ratio

For uniform excitation, seismic response ratio of tower under near-fault wave is close to which under El Centro and Taft wave (Yue M.G. 2005). While for traveling wave excitation, seismic response of tower may be depended on wave velocity to a certain extent. When velocity is low (300m/s for example), near-fault wave can enhance tower's response intensively. As a whole, when velocity varies from 300m/s to 1200m/s, the range of variation in tower response ratio is about ±50% for El Centro and Taft, and the range is more wider for near-fault wave.

Considering the uniform excitation is equivalent to infinite velocity of traveling wave, seismic response of tower to El Centro and Taft is also calculated for velocity of 3000m/s, 6000m/s and 15000m/s. In order to saving paper length, only moment ratio of tower is presented in Table 4. The moment ratio approaches to 1.0, especially for Taft. As a result, the model is approved to be rational.

Table 4 Moment ratio of tower for different wave velocities

Node Number	3000m/s		6000m/s		15000m/s	
	El Centro	Taft	El Centro	Taft	El Centro	Taft
7	\	\	\	\	\	\
6	0.75	1.09	0.90	1.07	0.97	1.00
5	0.48	1.02	0.81	1.02	1.06	1.02
4	0.44	1.00	0.78	0.98	1.15	1.00
3	0.48	1.03	0.80	0.97	1.20	1.03
2	0.54	1.08	0.80	0.98	1.23	1.08
1	0.59	1.12	0.81	0.99	1.24	1.12

3.3 Axial Force of Cable

Seismic response of cable is also analyzed under traveling wave excitation, and comparison with uniform excitation is also presented. Axial force of cable to near-fault wave is nearly the same all through cable length, so we can conclude that axial force is uniformly distributed along cable. In order to illuminate affection of traveling wave on cable's axial force, axial force ratio of traveling wave excitation to uniform excitation is studied and axial force ratio at span end is given as example (Fig. 6). Average value is for near-fault waves and maximum value is for El Centro and Taft.

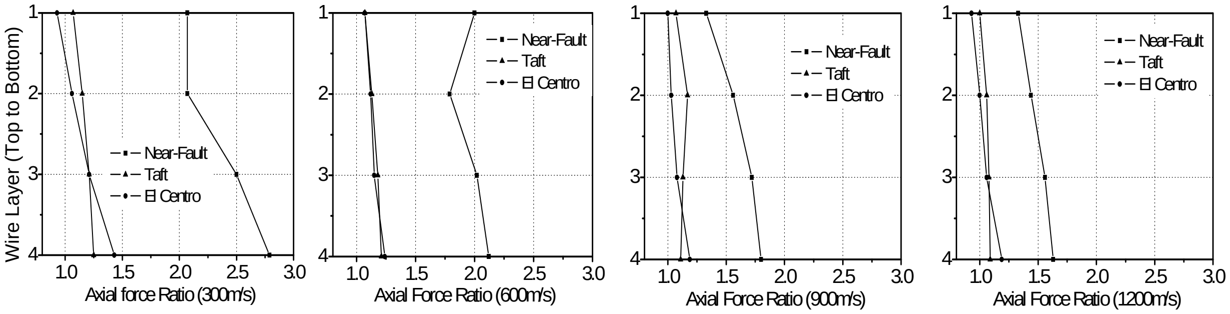

Fig. 6 Axial force ratio of cable

The above Figure indicates that axial force of cable is increased by traveling wave to a large extent. Especially for near-fault wave, increment in cable axial force is more than one times when wave velocity is low (300m/s~600m/s), the corresponding increment is about 25%~50% for El Centro and Taft. The increment in cable's axial force under traveling wave excitation becomes slow as wave velocity increasing, and cable response will approach to uniform excitation for infinite velocity.

3.4 Displacement of Cable

Seismic displacement of cable is also compared between traveling wave and uniform wave. Only longitudinal displacement of cable at 1/4 span and vertical displacement of cable at span center are given in Table 5 and Table 6 respectively, more details see reference (Yue M.G. 2005).

Longitudinal displacement of upper layer cable is a bit larger than the lower layer for traveling wave, and so is it for uniform wave. Under uniform excitation, cable's longitudinal displacement is nearly uniformly distributed along cable length. But for traveling wave, longitudinal displacement at 1/4(3/4) span is larger than span center. The trend of cable's longitudinal displacement is similar to cable's axial force, that is: cable's longitudinal response is intensively magnified by traveling wave, especially for near-fault wave at lower velocity, displacement reaches to 27~35cm for top layer cable and 19~30cm for bottom layer cable at 1/4 span, and the corresponding term for uniform wave is only 11cm and 3cm. The cable's response under traveling wave excitation approaches to uniform wave excitation as wave velocity increasing.

Table 5 Longitudinal displacement of cable at 1/4 span (cm)

Wave	Layer Number	Traveling Wave				Uniform Wave
		300m/s	600m/s	900m/s	1200m/s	
Near-Fault	1	35.1	27.1	15.8	11.3	11.0
	2	30.9	21.8	14.0	10.2	7.1
	3	30.4	20.1	13.0	9.6	4.3
	4	30.1	19.0	12.4	9.3	2.5
El Centro	1	14.3	17.6	9.8	8.5	13.0
	2	13.6	13.8	8.3	7.3	8.4
	3	13.1	11.0	7.3	6.7	5.1
	4	12.8	9.1	6.9	6.8	3.0
Taft	1	11.4	12.8	12.5	8.3	9.0
	2	10.1	10.4	9.8	7.2	5.7
	3	10.0	9.3	7.8	6.4	3.7
	4	10.3	8.4	7.2	6.1	2.1

Annotation: The layer numbering is from top to bottom.

Table 6 Vertical displacement of cable at span center (cm)

Wave	Layer Number	Traveling Wave				Uniform Wave
		300m/s	600m/s	900m/s	1200m/s	
Near-Fault	1	493.1	326.0	194.7	157.1	0.8
	2	525.9	341.1	195.2	158.0	0.3
	3	561.2	357.3	195.7	158.6	0.2
	4	594.3	372.3	196.3	159.1	0.2
El Centro	1	53.5	33.9	24.2	18.6	0.5
	2	56.8	34.8	24.4	18.6	0.2
	3	61.6	35.6	24.5	18.6	0.1
	4	65.8	36.3	24.7	18.6	0.1
Taft	1	115.7	63.0	43.4	32.7	0.4
	2	115.3	63.3	43.1	32.5	0.1
	3	117.5	63.6	43.0	32.2	0.1
	4	120.7	63.9	42.8	32.1	0.1

Annotation: The layer numbering is from top to bottom.

Vertical displacement of cable at bottom layer is larger than which at top layer for traveling wave, while it is opposite for uniform wave. Cable’s seismic response at vertical direction to traveling wave is much higher than which to uniform wave, and response at span center is more intensive than which at 1/4(3/4) span obviously. Take velocity of 1200m/s, smallest vertical response, as example, vertical displacement is 158cm at span center and 105cm at 1/4 span for traveling wave, and average value for El Centro and Taft is 25cm at span center and 20cm at 1/4 span. So, vertical displacement of cable for traveling wave is 5 or 6 times higher than that for uniform wave. Under uniform excitation, cable’s vertical displacement is no more than 1cm at span center and 7cm at 1/4 span for all the input waves. When velocity is 300m/s, cable’s upward displacement can reach to 5m~7m for traveling near-fault wave, nearly equal to deflection of cable under gravity.

4. CONCLUSION

By the user of finite element model of power transmission tower-cable system, seismic response of tower and cable is analyzed account for traveling wave and uniform wave excitation. We can conclude:
1) Comparing uniform wave, traveling wave can increase, as well as decrease, seismic response of power transmission tower-cable system which depends on both traveling-wave velocity and ground motion characteristic. When velocity is low, seismic response of tower is magnified by traveling wave to a certain extent, which is disadvantage for lower portion of tower.
2) Cable's axial force is increased by traveling wave to a large extent especially for near-fault wave. Axial force can increase more than one times at lower velocity (300m/s~600m/s), and which will approach to uniform excitation as velocity increasing.
3) Cable's displacement response is intensively magnified by traveling wave, especially for near-fault wave, vertical displacement can reach to 5m~7m.
4) Wave velocity has a great affection on seismic response of power transmission tower-cable system, so it is very important to assure the wave velocity in practical.
Only traveling wave effect is considered in this paper, further more studies on coherent effect and local site effect are still needed.

ACKNOWLEGMENTS

Thanks for the support of National Natural Science Foundation of China (59978025) and Key Seismic Technique Research and Demonstration of Large and Important Buildings, Sub-topics of 'Eleventh Five-Year National Scientific Support Plan' (No. 20070106110141014).

REFERENCES

Yin Ronghua, Li Dongliang and Liu Gelin etc. Seismic damage and analysis of power transmission towers. *World Earthquake Engineering*, 2005, **21: 1**, 51-54 (in Chinese)
National Center for Research on Earthquake Engineering in Taiwan, Disaster investigation report of 921 Chi-Chi earthquake. *Taipei*, 2001
A. Ghobarah, T.S. Aziz and M. El-Attar. Response of Transmission Lines to Multiple Support Excitations. *Engineering Structures*. 1996, **18: 12**, 936—946
Lin Jiahao, Zhong Wanxie and Zhang Yahui. Seismic analysis of long span structures by means of random vibration approach]. *Journal of Building Structures*, 2000, **21: 1**, 29-36 (in Chinese)
Fan Lichu, Wang Junjie and Chen Wei. Response characteristics of long-span cable-stayed bridges under non-uniform seismic action. *Chinese Journal of Computational Mechanics*, 2001, **18: 3**, 358-63 (in Chinese)
Zhang Yahui, Li Liyuan and Chen Yan etc. Wave passage effect on random seismic response of long-span structures. *Journal of Dalian University of Technology*, 2005, **45: 4**, 480-6 (in Chinese)
Zhao Canhui. The Asynchronous excitation model for the seismic response analysis of long-span bridges. *Journal of Southwest Jiaotong University*, 2002，**37: 3**, 236-40 (in Chinese)
Li Hongnan and Wang Qianxin. Dynamic characteristics of long-span transmission lines and their supporting towers. *China Civil Engineering Journal*, 1997, **30: 5**, 28-36
Yue Maoguang, Wang Dongsheng and Li Hongnan etc. Response of power transmission tower-cable system subjected to near-fault ground motions. *Earthquake Engineering and Engineering Vibration*, 2005, **25: 4**, 116-25 (in Chinese)
Yue Maoguang, Wang Dongsheng and Li Hongnan etc. Cable's seismic response of the tower transmission tower-cable system. *14th Structure Engineering Conference of China*, **third volume**, 2005, 175-80 (in Chinese)