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Influence of spatial variation of ground motions on dynamic responses of supporting towers of overhead electricity transmission systems: An experimental study

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ABSTRACT

An overhead electricity transmission system typically consists of a series of steel lattice towers supporting transmission lines (referred to herein as the *tower-line* system). Recent major earthquakes suggest that the tower-line system constructed based upon existing knowledge can be vulnerable. A tower-line system typically extends over a large region and it may be subjected to spatially varying ground motions during an earthquake event. The influence of spatial variation of ground motions is not explicitly considered in current design of the system and very limited research (particularly, experimental research) has been completed in this regard. A two-phase experimental program was conducted using an array of three shake tables to quantitatively assess the respective impact of three factors causing non-uniform excitations (namely, the wave passage effect, the ground motion coherency loss effect, and the local site effect) on dynamic response of the supporting towers. Test results show that neglecting the wave passage effect may result in underestimates of peak dynamic responses of the towers. Additionally, it is found that non-uniform ground motions with a higher degree of coherency loss tend to amplify tower dynamic responses. Furthermore, test results reveal that when the soil at the bases of adjacent towers becomes more flexible, the resulting spatially varying ground motions cause larger tower dynamic responses.

1. Introduction

Electricity transmission systems carry electrical energy at high voltages from generating power plants to electrical substations located near demand centers. A typical overhead electricity transmission system consists of conductors and ground wires supported by a series of steel lattice towers (referred to herein as the *tower-line* system). Although electricity can be generated from a wide range of sources such as hydropower, nuclear power, wind, solar and fossil fuels (coal, natural gas, petroleum, *etc.*), power plants may be located far away from electrical substations and consumers, which requires the tower-line systems to transmit the power over long distances. Inevitably, the transmission tower-line systems need to cover the regions with moderate and even high seismicity. In comparison with conventional civil structures and other lifeline groups (such as pipelines of gas and liquid fuels, telecommunication facilities, transportation infrastructures, and water supply network), the tower-line systems take on even more importance in a post-earthquake environment due to the dependencies of medical care, emergency response, community rescue and economy recovery upon electricity.

In a 1998 business survey reported by the Multidisciplinary Center for Earthquake Engineering Research (MCEER), business respondents rated electric power as the most critical lifeline, with most indicating that their businesses would need to shut down in the absence of electric power [1]. The costs associated with physical damage to utility infrastructure and loss of revenue are secondary compared to the economic impacts on the communities affected by loss of service. A 2001 Federal Emergency Management Agency (FEMA) study estimated the mean economic loss in the United States due to loss of electric power at $188 per capita per day [2]. Undoubtedly, the tower-line systems should remain fully functional after an earthquake event.

In past decades, research efforts have been made to develop improved models for seismic analyses of electricity transmission systems [3]. However, as a complex, continuous,

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electrical/mechanical system, seismic design of the tower-line system remains one of the most challenging tasks in the civil engineering design community. Recent earthquakes have highlighted the vulnerability of the tower-line systems designed according to the existing guidelines and the catastrophic outcomes from their failures. For example, during the 1992 Landers earthquake, about 100 transmission lines failed in Los Angeles [4]. In the 1994 Northridge earthquake, 85 transmission lines fell off their supporting towers and two transmission towers collapsed [4]. During the 1995 Kobe earthquake, 38 transmission lines were damaged and 20 transmission towers leaned as a result of foundation deformation [5]. In the 1999 Chi-Chi earthquake, damage of transmission lines and collapses of transmission towers were both observed [6]. During the 2008 Wenchuan earthquake, more than 20 transmission towers supporting the 110 kV transmission lines collapsed, 8 towers supporting the 500 kV transmission lines in Maotan and 2 towers supporting the 220 kV transmission lines in Maoyong were severely damaged [7].

Many effects may have contributed to the abovementioned failures in the tower-line systems; however, the influence of spatial variation of ground motions is an important factor worthy of investigation. Compared with conventional civil structures, the tower-line systems usually have much larger spans. For example, distance of adjacent towers in a typical tower-line system can be on the order of a few hundred meters. As such, seismic wave arrival time differs at the base of each supporting tower of a tower-line system. This effect, coupled with ground motion coherency loss owing to reflections and refractions of seismic waves in the heterogeneous media and the difference in local soil properties, impose spatially varying ground motions on the tower-line systems.

Studies on the effect of spatially varying excitations on dynamic responses of structures started from the 1960s. However, most research efforts in this field have been devoted to highway bridges [8,9]. Very limited research, particularly experimental work, has been completed for the tower-line systems. The objective of this research is to experimentally investigate the influence of spatial variation of ground motions on dynamic response of supporting towers in representative tower-line systems. Specifically, an experimental model consisting of four spans of transmission lines supported by three towers were constructed and tested using an array of shake tables. For comparison purpose, both uniform ground motions and spatially varying ground motions were adopted in the shake table tests. The spatially varying excitations were based upon both recorded and synthesized ground motions. The test results obtained from this investigation help generate the key knowledge for achieving more reliable seismic designs and hence improve earthquake preparedness of the tower-line systems. The following sections present descriptions of the prototype tower-line system, design and construction of the experimental model, selection and synthesis of spatially varying ground motions, test setup, instrumentation, discussion of test results and adequacy assessment of computer models of the tested system.

2. Prototype tower-line system

To capture the characteristics of typical transmission systems and best suit the need of this investigation, a prototype tower-line system was selected for construction of the experimental model based upon the following criteria: (1) the system should be in a region with seismicity; (2) span of transmission lines and configuration of supporting towers should be representative; (3) components in the system should be designed according to recent seismic design guidelines; (4) detailed design information of the system should be available for development of the experimental model.

To this end, a 500 kV transmission system in Liaoning Province, China was selected. The system extends about 88 km and is designed for the seismic events with a Peak Ground Acceleration (PGA) of 0.15 g. Fig. 1 illustrates a representative supporting tower of the system. Typical span of the transmission lines (i.e., distance between adjacent supporting towers) is 400 m while the maximum span is up to 900 m. All the supporting towers in the system have the same member configuration as SZ21 according to the Rules of Nomenclature for Transmission Poles and Towers [10]. Height of the supporting towers in the system varies from 53.9 m to 74.9 m. Given that it is less practical to consider the complete transmission system in shake table tests and also considering the seismic excitation tends to attenuate from the tower adjacent to the fault to others further away from the fault rupture, a subsystem consisting of three supporting towers and four spans of transmission lines was isolated from the entire system as the prototype for this investigation. Fig. 2 shows sketch of the prototype. As shown, the prototype transmission lines include two ground wires supported at the top of each tower and two four-core conductor lines connected to each crossarm. The ground wires and conductor lines are LGJ-95/55 and LGJ-400/35, respectively. Table 1 lists properties of the ground wires and conductor lines. In the prototype, all the three supporting towers were assumed to have the same height of 53.9 m. Fig. 3 shows elevation of each supporting tower. As shown, each tower consists of three crossarms at the elevations of 30 m, 40.6 m and 53.9 m, respectively. The supporting towers are made of Q235 or Q345 steel angles. Note that the yield strengths of Q235 and Q345 steel are 235 MPa and 345 MPa, respectively. Detailed information about sizes of the components in the towers is presented elsewhere [11].

3. Experimental model design and construction

The experimental model was tested at the laboratory of Beijing University of Technology. An array of three identical shake tables were adopted in this investigation. The interval of adjacent tables can be adjusted up to 18 m. Each table has a payload of 5 ton, the size of 1 m × 1 m, the maximum stroke of 7.5 cm, the maximum velocity of 0.6 m/s, the output frequency ranging from 0.4 Hz to 45 Hz and the output acceleration up to 1.5 g along the horizontal directions. Moreover, the lab allows to test the specimens up to 8 m high.

Fig. 1. Prototype system.