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# Seismic response of pile groups supporting long-span cable-stayed bridge subjected to multi-support excitations

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ABSTRACT

Long-span cable-stayed bridge is one of the main structures for highways and railways crossing wide rivers. Seismic response of an integral 1:70 scaled model for a long-span cable-stayed bridge was studied with multi-functional shake tables. The bridge model includes synthetic soil, pile groups and long span cable-stayed bridge structure. Seismic responses of pile groups supporting bridge structural systems of different stiffness, namely the floating system, the elastically constrained system and the supporting pier system are studied considering the seismic soil-pile-structure interaction (SSPSI). The accelerations, bending moments and displacements of piles supporting pylons, auxiliary piers and transition piers are discussed. The wave passage effect on pile foundation supporting long-span cable-stayed bridge is studied by tests for the first time. Results showed that compared with the floating system and the elastically constrained system, the bridge girder of long natural period has larger impact on pile foundations in the supporting pier system under uniform excitations. When subjected to non-uniform excitations, different seismic load generates from the superstructure and acts on the substructure. As a result, seismic response of pile foundation supporting long span bridge under non-uniform excitations is different from that under uniform excitations. The wave passage effect has little influence on seismic response of piles in the floating system and the elastically constrained system. However, in the supporting pier system, with shear wave velocity decreased from infinity to 1000 m/s, the Fourier amplitudes of pile accelerations, bending moments and relative displacements at 3.50 Hz decreased dramatically. The peak bending moments at the head of piles supporting auxiliary piles decreased about 50%.

## 1. Introduction

Earthquakes have caused great fatalities and damage to human beings [1]. A great many of buildings and bridges have been damaged by earthquakes. Pile foundation, which is applicable under various geological and loading conditions, has been widely adopted in supporting high-rise buildings, bridges and other structural systems situated in soft soil area [2,3]. Damage to pile foundation is concerned with ground earthquake response and vibration performance of structures. To study seismic response of pile foundation, physical model tests considering soil-pile-structure interaction have been conducted using 1 g and ng shaking tables.

In terms of geotechnical engineering, Dou et al. [4] increased soil body force by 100 times using hydraulic gradient similitude technique and investigated single pile response under earthquake loading. Taking the piles used for Inchon Grand Bridge as prototype, Yang et al. [5] evaluated dynamic p-y curves for a single pile with different flexural stiffness under various conditions of the acceleration frequency and amplitude in dry and saturated dense sand. Aldimashki et al. [6] tested the response of a single pile that embedded in a horizontally stratified soil subjected to earthquake loading. Durante et al. [7] carried out a comprehensive experimental research, with and without pile caps and/or superstructures. Different pile head conditions and masses at the top of the single degree of freedom system excited by various input motions were tested with the device of an oscillator connected to a single or a group of piles embedded in a bi-layer deposit. In terms of pile groups, Chau et al. [2] studied 2 × 2 end-bearing concrete piles supporting a single-story steel structure. Suzuki et al. [8] tested on a 3 × 3 pile group supporting a foundation with and without a superstructure set in a dry sand deposit. Saha et al. [9] tested on a 3 × 3 pile group supporting a single storey bare frame structure and concluded that the design forces for both the column and pile may be underestimated significantly if

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soil-foundation-structure interaction was not considered. Hokmabadi et al. [10] tested on a 4 × 4 end-bearing piles supporting 5-, 10-storey, and 15-storey structures set in soft soil. It was concluded that the seismic soil-pile-structure interaction (SSPSI) amplifies the maximum lateral deflections of the structures in comparison with the fixed-base structures.

The aforementioned researches simplified the superstructure to single degree of freedom (SDOF) oscillator or used over simplified structure to model bridge structure. In terms of structural engineering, pile foundation supporting long span bridge are often simplified, or even assumed as rigid foundation. Johnson et al. [11] carried out shaking table tests on a quarter-scale, two-span reinforced concrete bridge (the prototypical span lengths were 37 m). Saiidi et al. [12] carried out shaking table tests of a 1/4 scaled model for an assumed bridge in a region of high seismicity (a non-skewed four-span continuous bridge, 130 m long). Zong et al. [13] carried out shaking table tests of a 1/100 scaled model for Wuhan Two-Seven Yangtze River Bridge (cable-stayed bridge, 1732 m long with main span length of 616 m). Li et al. [14] carried out shaking table tests of a 1/40 scaled model for Taizhou Yangtze Highway Bridge (suspension bridge, 2940 m long with main span length of 1080 m). The aforementioned bridge models were fixed on shake tables directly. No piles or soils were included in the bridge models. The soil-structure interaction was not taken into consideration.

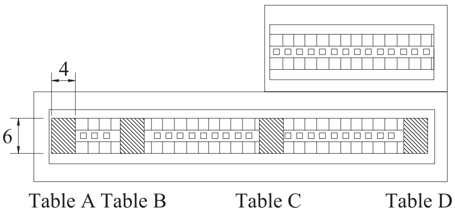
From the researches above, it can be found that in terms of structural engineering, the foundations of bridges are often simplified with equivalent springs and dashpots, or even assumed as rigid foundation. In terms of geotechnical engineering, however, only soils and piles have been a major concern, and superstructures have been ignored or oversimplified [15–17]. It is necessary to develop a model dealing the superstructure and the foundation with the same level of importance [18]. Furthermore, it has been found in structural engineering that the wave passage effect, which means that the long span structure is excited asynchronously at different supports, has great impact on superstructure of long span bridges [13,19,20]. Yan et al. [21] concluded from shaking table tests on free field that wave passage effects caused by earthquake should be considered in study of seismic response of long-shape field. Since in terms of geotechnical engineering, pile group foundations supporting different components of long span bridges are often treated as independent components, while in terms of structural engineering, pile groups are often assumed as rigid foundation, wave passage effect on pile foundation supporting long-span structure cannot be studied. To study the wave passage effect on pile group foundation supporting long span bridge, a bridge model including both superstructure and substructure should be fabricated.

A series of shaking table tests of an integral 1:70 scaled model for a long-span cable-stayed bridge were leaded and organized by Sun et al. [22]. The bridge model includes synthetic soil, pile groups and long span cable-stayed bridge structure. The present study is to investigate seismic responses of pile groups supporting long-span cable-stayed bridge considering the seismic soil-pile-structure interaction (SSPSI). Three different bridge model systems, namely the floating system, the elastically constrained system and the supporting pier system, which are of different stiffness are tested. The wave passage effect on pile foundation supporting long-span cable-stayed bridge is studied by tests in detail for the first time. The accelerations, bending moments and displacements of piles supporting pylons, auxiliary piers and transition piers are discussed.

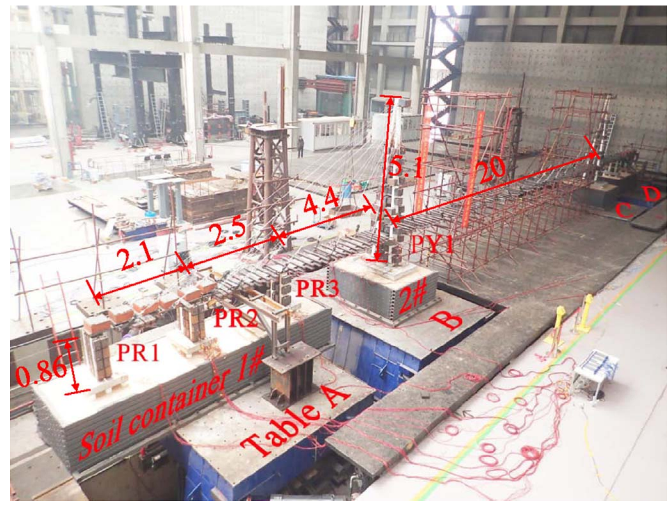
## 2. Prototype and test model

### 2.1. Shake table system

The Multifunctional Shake Table system at Tongji University was used to conduct the model test. The shake table system at Tongji University is one of the largest shake table systems in the world. Fig. 1 shows the layout of the shake table system. The system is composed of two trenches and four shake tables. The lengths of the two trenches are 70 and 30 m, respectively. Table 1 lists the performance specifications of each table [14]. The four shake tables are moveable along the two trenches and can be installed in any order. The bridge model was supported on four shake tables in the long trench.




(a) Shaking tables




(b) Bridge model

**Fig. 1.** Layout of the bridge model (Unit: m).

### 2.2. Bridge prototype

The bridge model was designed based on an assumed prototype in soft soil area. The arrangement of the spans is 150 m + 176 m + 310 m + 1400 m + 310 m + 176 m + 150 m, with an overall length of 2672 m (Fig. 2a). The bridge includes 304 (38 × 4 × 2) stayed cables and the longest one is about 750 m. The cables were made of galvanized steel wire having diameter of 7 mm.

**Table 1**
Performance specifications of shake tables.

| Item | Table A and D | Table B and C |
|---|---|---|
| Table size | 6 m × 4 m | 6 m × 4 m |
| Maximum specimen mass (kg) | 30,000 | 70,000 |
| Degree of freedom in control | 3(longitudinal, lateral and yaw) | 3(longitudinal, lateral and yaw) |
| Stroke (mm) | ± 500 (x-axis, y-axis) | ± 500 (x-axis, y-axis) |
| Velocity (mm/s) | ± 1000 (x-axis, y-axis) | ± 1000 (x-axis, y-axis) |
| Acceleration (g) | ± 1.5 (x-axis, y-axis) | ± 1.5 (x-axis, y-axis) |
| Frequency of operation (Hz) | 0.1 ~ 50 | 0.1 ~ 50 |
| Overturning moment (kN m) | 2000 | 4000 |