Multi Hazard Dynamic Testing for Bridge Piers

by

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ABSTRACT

The goal of this research is to test various combinations of hazards such as wind, flood, scour and dynamic loadings (e.g., earthquakes and vessel impacts) for impacts to bridge pier structural stability. Most equations and design criteria currently in use treat these hazards separately, although they can occur concurrently. A study that combines all hazards and dynamic loadings would be very complicated. Therefore the initial research is designed and fabricated to study only flow (flood), soil (sediment particle size and river bed geometry) and dynamic loading (harmonic, random and impulsive loads). A rigid mass, single degree of freedom (SDOF) oscillator represents the simplified bridge pier. A specially designed flume, which is 3000 mm long and 400 mm wide, allows for the investigation of different soil conditions and various flow velocities. The oscillating pier is mounted elastically on a structure over the test section of the flume. Two synchronous linear drive motors apply the dynamic loads. The oscillating bridge pier, neglecting flow and soil conditions, represents a perfect linear spring-damper system. In combination with flow and soil the system is highly nonlinear. The goal of this initial research is to replace the soil and flow effects with an equivalent spring-damper system. Additional goals are to detect the nonlinear spring and damping characteristics and to determine an equation of motion.

KEYWORDS: fluid soil structure interaction, multi hazard impacts on bridge piers.

1.0 INTRODUCTION

This study is concerned with the safety of bridges subjected to different natural hazard events. The events of interest are earthquakes, scour, hurricanes and vessel impact. Several bridge foundations are under water, so the structural response during an earthquake under these combined conditions is very complicated. Research at the Federal Highway Administration (FHWA) Turner Fairbanks Highway Research Center (TFHRC) Seismic Hazard Mitigation has focused on developing an experimental set-up to investigate a simple model where flow, scour (soil) and earthquakes (dynamic forces) interact with a bridge pier structure.

The experimental set-up is designed to study the fluid-soil interaction of a rigid single degree of freedom (SDOF) oscillator using a forced oscillation experiment. The linear SDOF oscillator acts as a reference system to investigate the nonlinear behavior of the system when it interacts with fluid and soil. The identification procedure to determine the additional fluid and soil forces based on a forced oscillation test are similar used to identify fluid dynamic damping and stiffness. Staubli (1983) and Deniz (1997) used forced oscillation tests in a tow-tank to determine force coefficients and phase angle to describe the fluid dynamic system. Scruton (1963) and Bardowicks (1976) proposed a description of flow-induced load in the form of components in phase with body displacement and velocity. They use controlled vibration experiments in a wind tunnel.

2.0 EXPERIMENTAL SET-UP

The experimental set-up consists of two major subsystems: a flume to simulate various flow and

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riverbed conditions and the shaking device to apply different dynamic loadings.

2.1 Flume

The flume consists of a 1300 mm long inlet and a 2000 mm straight channel (Figure 1). The upstream flow conditioning is achieved using filter mats, a honeycomb flow straightener, and a carefully designed trumpet-shaped inlet. The flume is designed to have a uniform flow distribution over the width and to have fully developed turbulent flow (following Prandtl's velocity distribution) at the test section. The recess at the test section is 400 mm x 300 mm (length x width) and 80 mm deep, and can be filled with sand particles of various sizes. The roughness of the fixed bed upstream of the recess can be varied according to the sand particles used in the recess. A 25 l/s pump provides the flume with water, which is stored under the flume in a water tank. A flow meter measures the discharge and an ultra sonic flow depth meter determines the flow depth. A laser distance meter, which is mounted on a portal robot, can scan scour holes during test runs. The flow velocity is measured with an electro magnetic velocity probe.

2.2 Shaking device

The shaking device is mounted above the flume on a rigid frame at the test section. The rigid frame with shaker can be turned 90 degrees and is portable. Two synchronous linear drive motors apply dynamic forces up to 12 Hz. Band limited random noise can be used to simulate earthquake-loading. A ridged model bridge pier is fixed to a platform with linear bearings, which is attached to a linear guide system and mounted elastically to the drive platform. The natural frequency can be varied by using different coil springs for the elastical support. The mechanical (structural) subsystem represents a linear SDOF system, which is lightly damped to study a significant peak resonant response. The damping ratio is determined by the Half-Power (Band-Width) method. The other end of the vertical rigid model pier is mounted in soil to interact with the soil subsystem. The body response displacement is measured with a laser distance meter and the response acceleration with accelerometers. The response velocity is determined by integrating the response acceleration. Two load cells measure the applied dynamic loading.

3.0 MATHEMATICAL BACKGROUND

The objective of this research is to replace flow and soil with an equivalent spring damper system and to determine the non-linear behavior of the additional spring and damping coefficients (Figure 3).

3.1 Identification Procedure

The identification procedure is based on the idea of a forced oscillation experiments used to determine fluid dynamic stiffness and damping. Additional damping and stiffness coefficients can model the fluid dynamic and the soil subsystem (equation 1), which are functions of several parameters (e.g., amplitude and frequency)

$$\begin{aligned} &m\,\ddot{v}(t) + c\,\dot{v}(t) + k\,v(t) + \\ &+ c_e(a,\overline{\omega})\,\dot{v}(t) + k_e(a,\overline{\omega})\,v(t) \\ &= p_o \exp(\mathrm{i}\,\overline{\omega}t) \end{aligned} \tag{1}$$

For the tests described here only the exciting frequency $\overline{\omega}$ and the amplitude ρ will be varied by keeping scour depth s, pier depth d, flow depth h and flow velocity V_{FLUID} constant.

The identification concept is based on the balance of forces acting on the linear mass oscillator (Figure 4) under steady state harmonic condition whereby the total response is:

$$v(t) = \rho \exp[\mathrm{i}(\overline{\omega}t - \theta)]\,. \tag{2}$$

Force equilibrium requires that the sum of the inertial $f_I(t)$, damping $f_D(t)$ and spring forces $f_S(t)$ equal the applied load.

$$p(t) = p_o \exp(\mathrm{i}\overline{\omega}t)\,. \tag{3}$$

These forces are:

$$f_I(t) = m\ddot{v}(t) = m\,\overline{\omega}\,\rho\exp[i(\overline{\varpi}t - \theta)] \tag{4}$$

$$f_D(t) = c\dot{v}(t) = i\,c\,\overline{\omega}\,\rho\exp[i(\overline{\varpi}t - \theta)] \tag{5}$$

$$f_S(t) = k\,v(t) = k\,\rho\exp[i(\overline{\varpi}t - \theta)] \tag{6}$$

These forces, along with the applied loading, are shown as vectors in the complex plane (Figure 5) also shown is the closed polygon of forces required for equilibrium in accordance with equation (7)

$$f_I + f_D + f_S = p(t)\,. \tag{7}$$

Inertial, damping, and spring forces as given in equation (4) are in phase with the acceleration, velocity, and displacement motions, respectively. If the linear mass oscillator interacts with flow and soil additional damping and stiffness forces are required for equilibrium (Figure 6). These forces are frequency and amplitude dependent as shown in equations (8) and (9).

$$f_{S-FSI}(t) = k_e(\rho,\overline{\omega})\,v(t) = k_e(\rho,\overline{\omega})\;\rho \tag{8}$$

$$f_{D-FSI} = c(\rho,\overline{\omega})\,\dot{v}(t) = i\,c(\rho,\overline{\omega})\,\overline{\omega}\rho = i\,c(\rho,\overline{\omega}) \tag{9}$$

To determine these additional forces cross power spectrum is used to compute the phase angle θ between body response displacement amplitude ρ and applied dynamic force amplitude p_o. The forces can be expressed by equilibrating the dynamic force components

$$f_{S-FSI} = p(t)\cos\theta - f_S + f_I \tag{10}$$

$$f_{D-FSI} = p(t)\sin\theta - f_D \tag{11}$$

Substituting equations (4) to (6) and equations (8) and (9) into equation (10) and (11), one obtains the fluid-soil coefficient functions

$$k_e(\rho,\overline{\omega}) = \frac{p_o\cos\theta - k\,\rho + m\ddot{\rho}}{\rho} \tag{12}$$

$$c_e(\rho,\overline{\omega}) = \frac{p_o\sin\theta - c\,\dot{\rho}}{\dot{\rho}} \tag{13}$$

Where $\dot{\rho}$ and $\ddot{\rho}$ represent the response velocity and response acceleration amplitude, respectively.

4.0 REFERENCES

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Figure 1. Test flume and trumpet shaped inlet

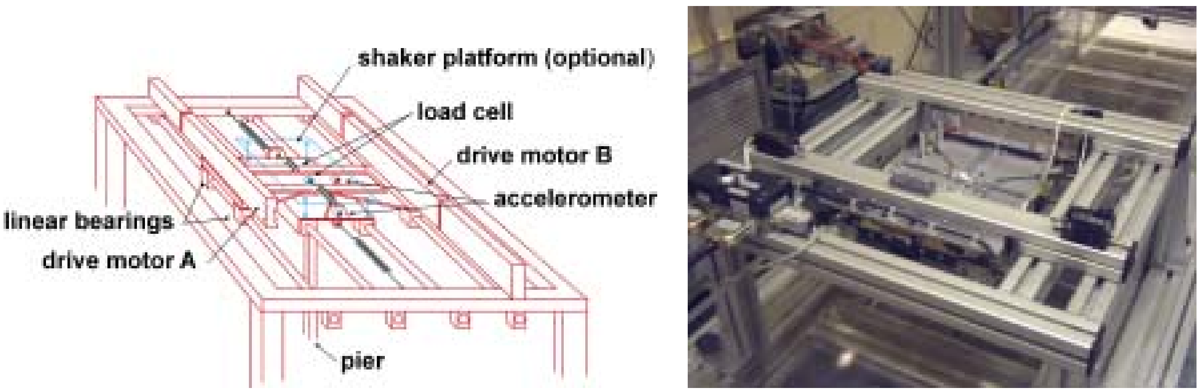

Figure 2: Shaking device

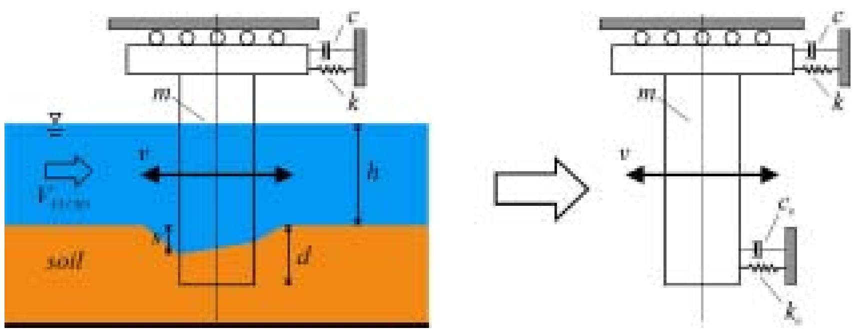

Figure 3: Equivalent fluid-soil spring-damper system

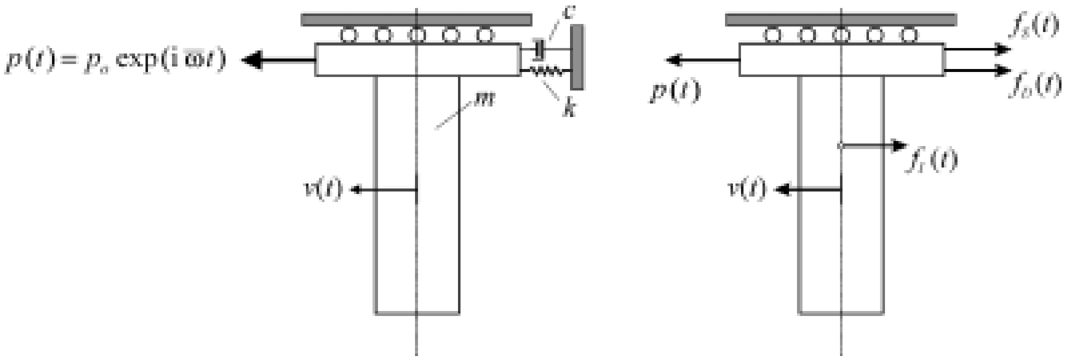

Figure 4: Linear SDOF system with basic components and forces in equilibrium

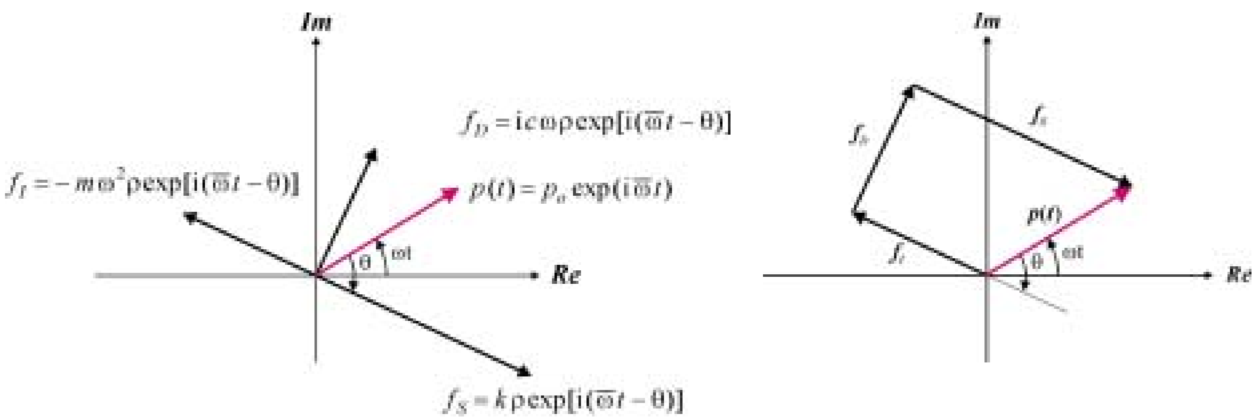

Figure 5: Steady state harmonic forces using viscous damping in a complex plane representation and closed force polygon representation

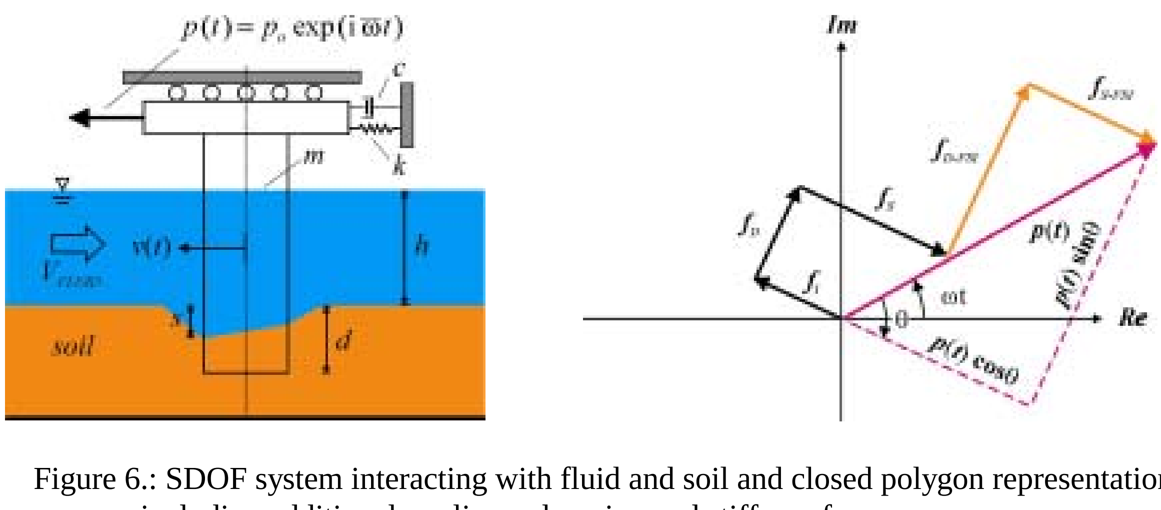

Figure 6.: SDOF system interacting with fluid and soil and closed polygon representation including additional nonlinear damping and stiffness forces