EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMICS
Earthquake Engng Struct. Dyn. 2002; **31**:1037–1039 (DOI: 10.1002/eqe.129)

DISCUSSION OF PAPER

Tuned liquid dampers for controlling earthquake response of structures by P. Banerji *et al., Earthquake Engng Struct. Dyn.* 2000; **29**(5):587–602

Swaroop K. Yalla [1] and Ahsan Kareem [2,*,†]

[1] *NatHaz Modeling Laboratory, Department of Civil Engineering and Geological Sciences, University of Notre Dame, IN 46556, U.S.A.*
[2] *Department of Civil Engineering and Geological Sciences, University of Notre Dame, IN 46556, U.S.A.*

The purpose of this discussion is to clarify the underlying mechanism in sloshing at high amplitudes which has been modelled in a simplistic manner by most researchers studying tuned liquid dampers (TLDs). Unfortunately, while this simplified approach works adequately at low amplitudes of motion, it fails to capture the key features of prevailing sloshing/slamming actions at higher amplitudes of motion.

This discussion has been prompted by one of the latest papers dealing with TLDs by Banerji *et al.* [1]. The main thesis of the subject paper is that a TLD can be utilized for the reduction of motion induced by large amplitude excitations, e.g., earthquakes. The authors followed the formulation given by Sun *et al.* [2] for obtaining the equations of motion of the sloshing wave surface profile, which was not intended for a wide range of amplitudes of motion. By solving the equations of motion given in Reference [2], they obtain the wave heights at both ends of the tank, η_n and η_0. However, for calculating the shear force developed at the base of the TLD due to sloshing, the following equation was used in the paper:

$$F = \frac{\rho g b}{2}\left[(\eta_n + h)^2 - (\eta_0 + h)^2\right] \tag{1}$$

where ρ is the mass density of the water, b is the tank width and h is the liquid height of the still water. This equation is based on taking the difference between the integrated *hydrostatic* pressure over the two opposite walls of the container perpendicular to the direction of liquid oscillations, i.e.,

$$F = \rho g b \int_0^{(\eta_n+h)} x\,\mathrm{d}x - \rho g b \int_0^{(\eta_0+h)} x\,\mathrm{d}x \tag{2}$$

* Correspondence to: Ahsan Kareem, Department of Civil Engineering and Geological Sciences, University of Notre Dame, IN 46556-0767, U.S.A.
† E-mail: kareem@nd.edu

Received 23 June 2001
Accepted 2 July 2001

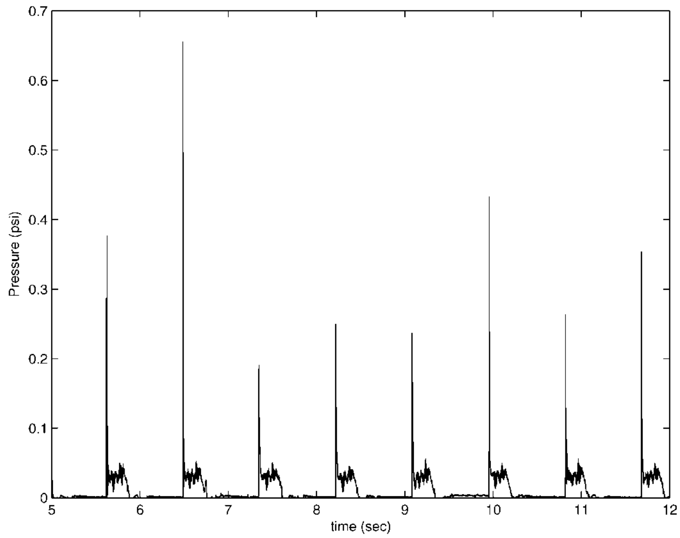

Figure 1. Time history of the resonant pressures at the mean liquid height.

It is the intent of this discussion to emphasize that this type of formulation for determining the sloshing force is not very accurate for all amplitudes of motion. It has been well understood that at large amplitudes of motion, the linear wave theory no longer holds due to wave breaking. The authors following Sun *et al.* [2] accounted for wave breaking in their equations of motion through a phenomenological approach based on experimental observations. This involves an introduction of empirical constants which account for the non-linearities in frequency and damping. However, the breaking waves problem is of a complex dynamic nature and cannot be simply reduced to an equivalent static problem. A large contribution of the sloshing force, which has been neglected by previous researchers, is due to the impact of the sloshing liquid on the container walls. This is characterized by a short duration pulse which introduces hydrodynamic force due to change in the momentum of the liquid mass at the container walls.

In fact, experimental studies conducted by Armenio and La Rocca [3] and Yalla [4] indicate that when large travelling waves or hydraulic jumps are formed at resonant conditions, the dynamic pressure time history reveals presence of impulsive peaks. Both studies concluded by noting that '... *when these circumstances* (travelling waves or hydraulic jumps) *occur, the pressure distribution at the vertical walls is far from being hydrostatic...'*

Yalla and Kareem [5, 6] have introduced a sloshing–slamming (S^2) model of the TLD which attempts to incorporate this impact component into the dynamics of the overall model. At low amplitudes, the S^2 damper model serves as a conventional linear sloshing damper. At higher amplitudes, the model also accounts for the convection of periodically slamming lumped mass on the container wall, thus characterizing both the hardening feature and the observed increase in damping. The amount of mass transfer between the two subsystems, namely the linear sloshing system and the impact slamming system, can be related to the amplitude of motion. In fact, experimental studies conducted in coastal engineering area [7];

for impact loads on vertical structures show that for a well-developed breaking wave, the mean peak pressure can be 10–15 times higher than the hydrostatic pressure. Based on the experimental studies involving TLDs, Yalla [4] has estimated the mean peak pressures caused by impulsive slamming to be 5–10 times higher than the regular sloshing pressures. Figure 1 shows a sample history of pressure pulses obtained by Yalla [4].

The above discussion clearly indicates that Equation (1) would underestimate the shear force developed at the base of the TLD, which is responsible for counteracting the structural motion. Infact, this equation is valid primarily at small amplitudes of motion when the wave slamming/impact action is not mobilized [6]. It is essential that the model in Equation (1) be validated experimentally when used for high amplitude excitations, experienced during earthquakes, to avoid reliance on misleading performance level of TLDs.

Furthermore, as a side note, we would also like to point out that the constant C_{fr} set equal to 1.05, regardless of the amplitude of motion, by Sun *et al.* [2] may not truly reflect the actual frequency shifts that take place under large amplitudes of motion. It has been demonstrated by Reed *et al*. [9] and Yalla [4] through experiments at large amplitudes of motion that the frequency shift is indeed dependent on the amplitude of motion.

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