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PRELIMINARY NUMERICAL MODELLING OF A TUNED LIQUID DAMPER WITH LIMITED FREEBOARD

McNamara, Kevin P.[1,4], Tait, Michael J.[2] and Love, J. Shayne[3]
[1] Graduate Student, Department of Civil Engineering, McMaster University, Canada
[2] Professor, Department of Civil Engineering, McMaster University, Canada
[3] Project Engineer, Rowan Williams Davies and Irwin Inc., Canada
[4] mcnamark@mcmaster.ca

Abstract: A tuned liquid damper (TLD) is often used to mitigate the wind-induced vibrations of tall slender structures. A TLD typically consists of a partially filled rigid water tank located near the top of a structure and is often equipped with screens or devices to increase energy dissipation. The required freeboard for the TLD tank is determined by calculating the maximum sloshing wave height and ensuring sufficient space such that the water does not impact the roof of the tank. A TLD tank designed such that the water can impact the roof would reduce the space required in the structure. To implement a TLD with limited freeboard for a structure, it is necessary to understand the effect that limiting the freeboard has on numerical modelling, TLD performance, and structural tank design. This paper discusses preliminary research on numerical modelling of a TLD with limited freeboard and sloshing water impact with the tank roof. A smoothed particle hydrodynamics (SPH) model is implemented to study a TLD equipped with slat screens for both unlimited and limited freeboard. A comparison between the results of each case is presented. The limited freeboard case is observed to potentially reduce the higher sloshing modes in the tank. Significant spikes in pressure on the tank boundaries are observed for the limited freeboard case. A comparison to existing numerical models shows differences in the magnitude of sloshing response. Refining the treatment of the slat screens in the SPH model may provide improved agreement with existing models.

1 INTRODUCTION

A tuned liquid damper (TLD) is a system used to control the wind-induced motion of tall flexible structures. A TLD typically consists of a partially filled water tank located near the top of a structure. When the building sways in one direction, the water sloshes out-of-phase with the sway motion, providing controlling forces that counteract the motion of the structure. TLDs often contain internal damping devices, such as baffles or screens, which increase the damping of the system above what the water viscosity alone provides. There are many different numerical models that have been applied to studying the response of a TLD containing internal damping devices. Tait et al. (2005) proposed both a linear model based on linear wave theory, and a nonlinear model based on shallow water wave theory, for application to a TLD with slat screens. Deng and Tait (2008) proposed equivalent mechanical models for TLDs with rectangular, cylindrical, and hyperboloid geometry. Deng and Tait (2009) further detailed models for a TLD with various bottom geometries using linear long wave theory. A nonlinear model for a TLD with damping screens based on a modal expansion technique used commonly in studying sloshing in the ocean engineering field was created by Love and Tait (2010). This model was further extended to consider TLDs of arbitrary tank geometry by combining the nonlinear model with a Finite Element Method model (Love and Tait, 2011). Molin and Remy (2013) studied the sloshing within a rectangular tank containing perforated screens. The numerical model developed was based on potential flow theory using linearized equations. A frequency domain approach was employed to solve the model equations which is particularly suited to harmonic excitation. Love and Haskett (2018) developed a fourth order nonlinear model and equivalent linear mechanical model for a TLD with cruciform shape paddles as the internal damping device.

To determine the response of the water in a TLD, these models require knowledge of the sloshing frequencies and mode shapes. In a TLD with limited freeboard, the models described may no longer be applicable once the water in the tank impacts the roof, as the free surface boundary condition is modified. The development of a numerical model that can capture the behavior of sloshing water in a TLD with limited freeboard is important for understanding the impact that the limited freeboard has on tuning frequency, TLD damping, and structural design parameters such as hydrodynamic pressure and force.

This paper presents the results of a preliminary study on implementing a Smoothed Particle Hydrodynamics (SPH) model to analyze the response of a TLD equipped with slat type damping screens. Both unlimited and limited freeboard cases are considered under sinusoidal base excitation. The results of these two cases are compared to each other and to existing numerical models.

2 SMOOTHED PARTICLE HYDRODYNAMICS

Smoothed Particle Hydrodynamics (SPH) is a meshless Lagrangian method originally developed for modelling fluids in the field of astrophysics (Lucy, 1977; Gingold & Monaghan, 1977). SPH is often used in hydrodynamics applications over mesh-based methods due to its ability to model complicated free surface problems. In SPH, a set of particles define the domain, including both the fluid and boundaries. The particles act as interpolating points in space to approximate the solution to the Navier-Stokes equations based on the calculation of properties such as density, velocity, and position. This interpolation is based on the use of an interpolating kernel function, where each particle quantity is interpolated from the values of the particles surrounding it using a weight function, shown in Equation 1 (Monaghan, 1992).

[1]. $$A_1(\boldsymbol{r}) = \int A(\boldsymbol{r}')W(\boldsymbol{r}-\boldsymbol{r}',h)\boldsymbol{dr}'$$

Where A is the quantity of interest, r' is the location of interest in the domain, and W is the kernel function.

For this paper, the Qunitic Wendland Kernel function was used, which is described by Equation 2 (Wendland, 1995).

[2]. $$W(\boldsymbol{r},\boldsymbol{h}) = \alpha_D\left(1-\frac{q}{2}\right)^4(2q+1),\ q=\frac{r}{h},\ 0\le q\le 2$$

Where α_D=7/4πh^2, r = the distance between particles, and h = the smoothing length.

The originally developed SPH method was created primarily to study compressible fluids. However, there are two major types of SPH simulations that are used to model incompressible fluids like water. Weakly Compressible SPH (WCSPH) relates the density to pressure using a very stiff equation of state, limiting the density fluctuations to a small amount (Monaghan, 1994). WCSPH can be very sensitive to the small fluctuations in density (and thus pressure), which is not ideal when pressure is a specific parameter of interest, as in the case of a TLD having limited freeboard with roof impact. Some methods have been proposed to reduce the impacts of these fluctuations (Cao et al., 2014), however they generally result in significant additional computational overhead.

Incompressible SPH (ISPH) deals with incompressibility directly by solving a Poisson equation to determine the pressure at each time step (Cummins and Rudman, 1999). For the implicit ISPH method, this process involves solving a very large system of implicit equations at each time step. However, an explicit SPH method has been presented in the literature, which allows the pressure to be explicitly calculated without solving an entire system of equations (Hosseini et al., 2007), though this requires a smaller time step.

Limited studies have focused on modelling a TLD using the SPH method. Marsh et al. (2009, 2010a, 2010b) and Bulian et al. (2009) both studied a shallow water TLD under angular excitation using the WCSPH method. This research aims to expand on this by considering TLDs with internal energy dissipation devices such as screens, deeper water depths, and different excitation cases.

3 SPH MODEL OF A TLD WITH SLAT SCREENS

There are a number of open source and commercially available software packages for SPH. For this study, DualSPHysics was selected due to its robust features and previously demonstrated performance in tank sloshing simulations (Crespo et al., 2015). DualSPHysics is currently based on weakly compressible SPH. A 2-dimensional TLD was modelled. Figure 1 shows the overall particle geometry of the system for unlimited freeboard. The TLD tank boundaries and slat screens are modelled as solid boundary particles such that the fluid particles are unable to penetrate them. A TLD length of 966 mm was specified, which is consistent with the model scale dimensions of a TLD used in previous research. The water depth in the TLD was set to 144 mm, which corresponds to 15% of the tank length. Based on these dimensions, using linear wave theory, the fundamental natural sloshing frequency of the tank was 0.594 Hz.

Slat type screens with a solidity ratio of 42% (solid area to open area), were placed at 40% and 60% of the tank length, which is consistent with previous research. These screens consisted of slats of 5 mm height, with 7 mm of spacing between them. The depth of the slats in the direction of flow was set as 1 mm. This slat configuration has been shown previously to provide an adequate level of damping for a TLD with this configuration (Hamelin, 2007). Previous models have included the effects of the slat screens as an equivalent head loss in the fluid at the slat location based on empirically determined loss coefficients (Tait et al., 2005), rather than directly modelling the geometry of the slats. For this investigation, the geometry of the slats was modelled directly to determine how accurately SPH could account for the damping added by the screens. In this SPH model the slats were represented as an array of rectangular boundary particles, as shown by the black points in Figure 2.

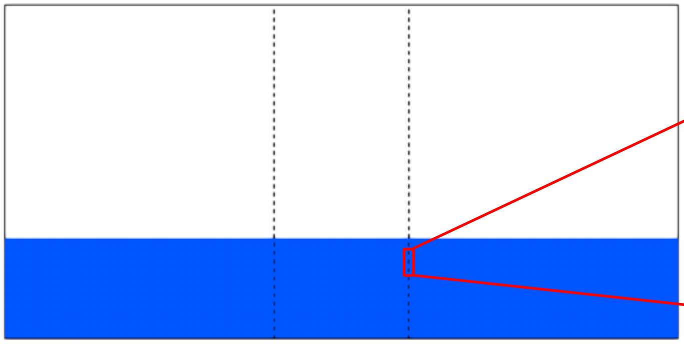

Figure 1: SPH Model Domain

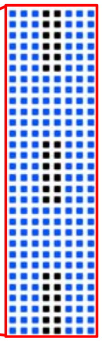

Figure 2: SPH Slat Screen Closeup View

4 NUMERICAL ANALYSIS OF A TLD WITH LIMITED AND UNLIMITED FREEBOARD

The TLD was modelled using DualSPHysics for two cases, unlimited and limited freeboard. The tank was excited at its fundamental resonant sloshing frequency of 0.594 Hz using a sinusoidal base displacement with an amplitude of 20 mm (2% of the tank length). This is a fairly substantial amplitude for a TLD to experience, however it was selected to obtain a significant free surface response of the fluid. Current TLD design practice is to set the tank height such that the sloshing wave does not impact the roof. For the unlimited freeboard case, the TLD height was set as 480 mm, which is well above the maximum sloshing wave experienced. For the limited freeboard case, the TLD height was reduced to only 160 mm, leaving 16 mm of freeboard between the still water depth and the roof of the tank. This amount of freeboard was selected to ensure that impact of the fluid on the roof would occur in the simulation to study the influence of limited freeboard on the response. The liquid was originally at rest, and the total simulation length considered was 20 seconds for both cases. Steady state fluid conditions were not reached within this time period as the computational resources available for this study restricted the duration of simulation employed.

4.1 Wave Height for Unlimited and Limited Freeboard SPH Models

The wave height in the SPH models was measured at a location x such that x/L=95%, where L is the length of the tank. These measurements were normalized by the quiescent water depth in the tank. The wave height response histories are shown in Figure 3 for the unlimited and limited freeboard models. The unlimited freeboard case is periodic, with normalized wave height peaks of 15% and troughs of -7.5%. This difference in magnitude results from higher order sloshing modes in the tank. As expected, the limited freeboard case is constrained to be less than the height of the tank roof. Despite repeated impact with the tank roof, the normalized wave height for the limited freeboard case remains periodic. The troughs of the normalized wave height are deeper for the limited freeboard case than they are for the unlimited freeboard case. A potential explanation of this behavior is that significant damping is added to the higher sloshing modes when the water impacts the top corner of the tank, which reduces the influence of these modes on the response. Further study is required to determine the exact cause of this behavior.

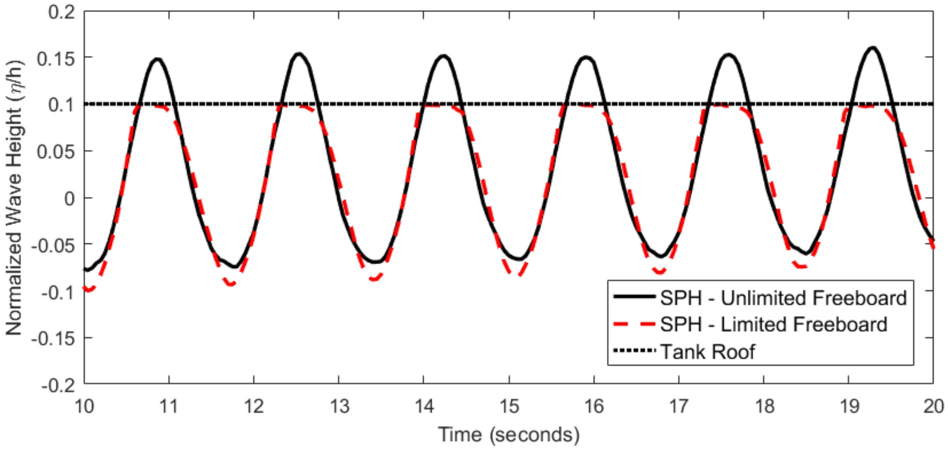

Figure 3: Normalized Wave Height for SPH Model with Unlimited and Limited Freeboard

4.2 Pressure on Tank for Unlimited and Limited Freeboard SPH Models

Values of pressure exerted by the fluid on the tank walls are of interest when determining the structural design of the TLD tank. Specifically of interest is the uplift pressure caused when the water impacts the roof of the tank, as in a limited freeboard case. A number of numerical pressure measurement points were placed at the boundaries of the SPH simulation. Figure 4 shows the locations of these measurement points.

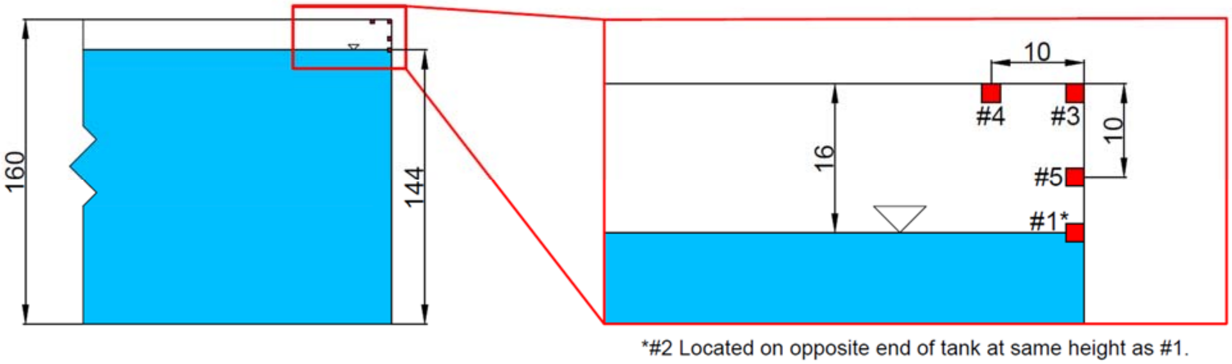

Figure 4: Pressure Measurement Locations (dimensions in mm)

The pressure was measured in the exact same locations for both the unlimited and limited freeboard cases. In the unlimited case locations 3 and 4 were not located on the roof of the tank, but rather floating. This was done so that the unlimited freeboard case could provide a pressure baseline to compare to the limited freeboard case, since in the unlimited freeboard case the water did not impact the tank roof. For all locations, the pressures were normalized by the maximum measured value at each location for the unlimited freeboard case. This allows for comparison between the unlimited and limited freeboard cases, as the increase in pressure can be observed directly. For example, a normalized pressure reading of 4 means that the pressure in the limited freeboard case was 4 times the maximum unlimited freeboard pressure at that location. Figure 5 shows the normalized pressure histories at the quiescent water depth for both ends of the tank. Generally, the limited freeboard case shows sharp spikes in pressure in comparison to the unlimited freeboard case. In some instances, such as at 8 seconds for location 2, the pressure for limited freeboard is less than that for unlimited. It is interesting to note the differences in the pressure histories between each end of the tank. While some phase delay would be expected in the pressure values as the water sloshes back and forth in the tank, the peak overall value for limited freeboard occurs at the initial impact on the negative end of the tank, but a similar peak is not observed at the positive end. This shows that when considering impact of the water with the roof of the tank in a limited freeboard case, there may be discrepancies between the values measured at each end of the tank.

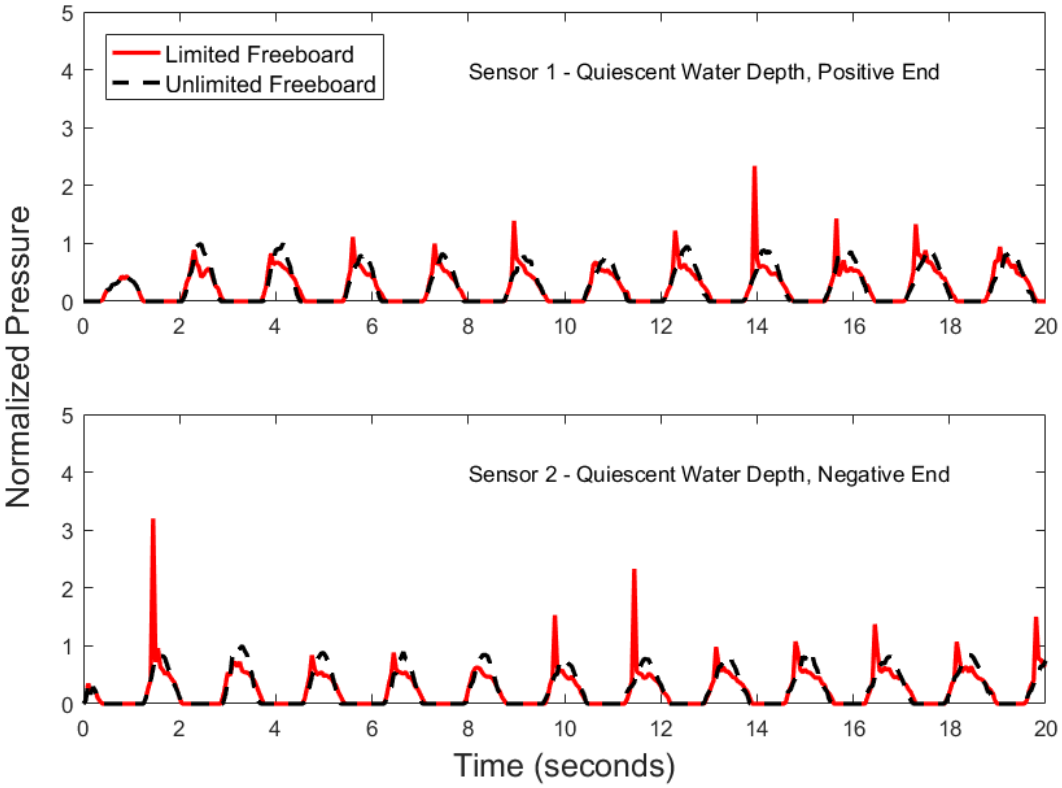

Figure 5: Normalized Pressure at Quiescent Water Depth

Pressure measurements at locations 3 through 5 represent the top corner of the tank. When the sloshing water impacts the roof of the tank, it is pushed into the corner and then back across the length of the tank. Figure 6 shows a portion of the normalized pressure histories for these three locations. A similar trend is observed for each measurement location, however the magnitude of the normalized pressures changes for each. The most significant spike in pressure is observed at a time of 14 seconds, when the normalized value is almost 5 for measurement locations 4 and 5. This is greater than the maximum normalized pressures observed at the quiescent water depth in Figure 5. It is interesting to note that the normalized pressure is higher on the wall and roof of the tank than it is at the top corner. Overall it can be seen that the increase in pressure between the unlimited and limited freeboard cases can be quite significant, up to a factor of approximately 5.

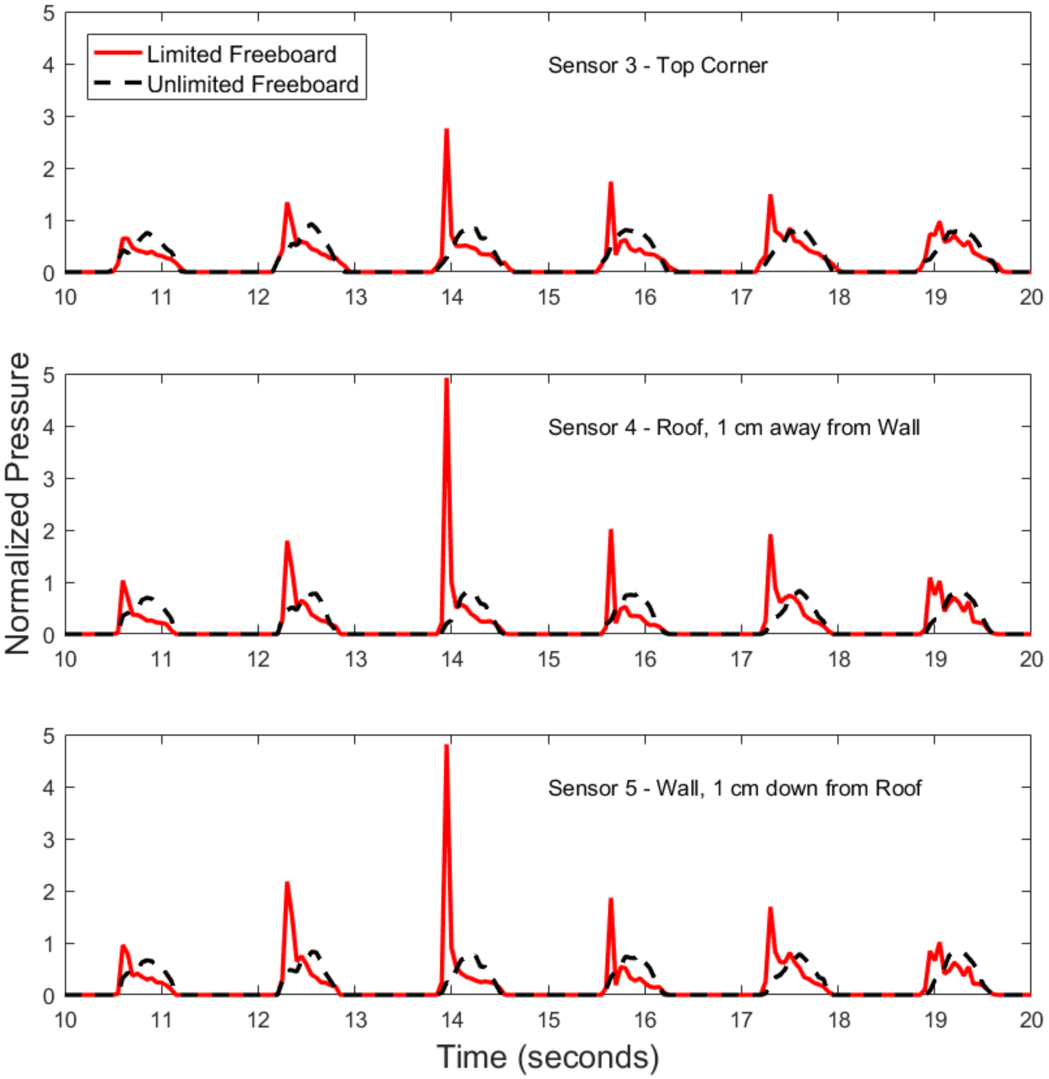

Figure 6: Normalized Pressure Near Tank Top Corner

4.3 Comparison to Existing Numerical Models for Unlimited Freeboard

The fluid response of the TLD determined from the unlimited freeboard SPH model was compared to a model based on linear wave theory (Tait, 2008) and a third order nonlinear multi-modal model (Love and Tait, 2010). The models do not consider the roof impact that occurs in the limited freeboard case, however they provide a baseline to determine if the SPH model is accurately capturing the behavior of the system when freeboard is unlimited. Initial comparisons showed significant discrepancies between the SPH model and the existing models. The predicted free surface response of the SPH model was significantly lower than the other models. Unlike in the other models, the slat screens are physically modelled in the SPH model as a set of boundary particles. This means that as the fluid sloshes it directly interacts with the solid slat screens. Figure 7 shows a closeup of the fluid particles surrounding the slat screens during the simulation. It can be observed that an empty void forms around the slats. This is likely a result of the boundary particle treatment used in DualSPHysics, where the boundary particles exert a repulsive force on the fluid particles around them to ensure that the fluid does not permeate the boundary (Crespo et al., 2007). As a result of the repulsive forces these voids form, less fluid is able to flow between the slats. This effectively increases their solidity and therefore increases the amount of damping added, which significantly reduces the fluid response.

To improve the comparison between the SPH model and existing models, the slat screen solidity was increased to be 66.5% for the linear and multi-modal models, from the initial value of 42%, based on the void formation shown in Figure 7. The normalized wave height response history in the tank for each of the models is shown in Figure 8. In general, the linear model does not accurately predict the peaks and troughs of the fluid response in comparison to the other two models. Reasonable agreement is shown between the SPH and multi-modal models. The peak values are similar between the two models. The multi-modal model predicts deeper troughs in the response than the SPH model. In this case, it is possible the multi-modal model is providing more damping to higher mode responses than the SPH models. For this preliminary study the agreement is reasonable, but further studies are necessary on how slat screen added damping is treated between the models.

For the SPH model to more accurately predict the response of the TLD with the actual target solidity of the slat screens, it will be necessary to change the way that the screens are treated. It is possible that a different type of boundary particle treatment could be implemented in the SPH model that does not use repulsive forces. Alternatively, the initial spacing between the particles may be decreased, as the repulsive force is proportional to this spacing. A reduction in the spacing would reduce the effect of the force. However, this option would likely result in a significant increase in computational requirements.

Figure 7: Example of Voids Surrounding Slat Screen Particles in SPH Simulation

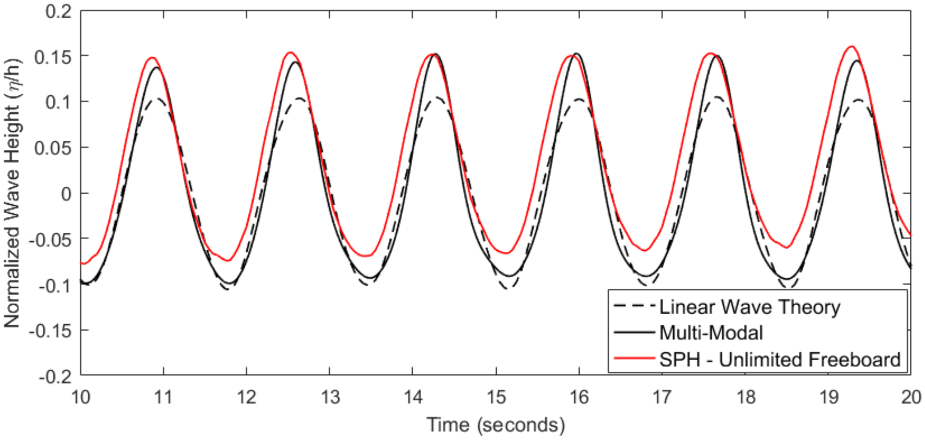

Figure 8: Comparison of Normalized Wave Height between SPH and Existing Models

5 CONCLUSIONS

This paper presents the results of a preliminary study on implementing a Smoothed Particle Hydrodynamics (SPH) model to analyze the response of a TLD equipped with slat type damping screens. Both unlimited and limited freeboard cases were considered under sinusoidal base excitation. The following conclusions can be obtained from this study:

1. The higher sloshing mode response of the TLD appears to be reduced when freeboard is limited, which could be a result of added damping when the water impacts the top corner of the tank.
2. Pressures acting on the boundaries of the TLD are different at each end of the tank when the freeboard is limited. This causes an asymmetrical response. As a result, for future numerical and experimental testing it may be necessary to instrument both sides of the tank.

3. Pressures acting on the boundaries of the TLD show significant increases for the limited freeboard case compared to the unlimited freeboard case. The most significant pressures are on the order of 5 times higher for the limited freeboard case.
4. In some instances, the pressures acting on the boundaries of the TLD are less for the limited freeboard case than the unlimited case. Further investigation is necessary on the cause of this.
5. Voids formed in the SPH model around the slat screens cause the fluid response to have higher damping than expected. To obtain agreement between the current SPH model and previous numerical models it is necessary to increase the solidity of the screens to account for this void. This is likely a result of repulsive forces generated by the boundary particle treatment in the SPH model. Refinement of the slat screen treatment is necessary to improve the agreement between the existing numerical models and the SPH model for the target screen solidity.

This paper outlines a preliminary study on the numerical modelling of a TLD with limited freeboard. Further experimental and numerical studies are necessary to obtain a more complete knowledge of the behavior of this system under a variety of scenarios.

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