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THE DAMPING PROPERTIES OF A STEEL STRUCTURAL MODEL WITH A BOX-SHAPED WATER RESERVOIR UPON TOP FLOOR

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ABSTRACT: A swimming pool or a reservoir on the roof of the high-rise building may contribute to the damping behavior of the building structure underneath due to the earthquake shake. The water waves in the swimming pool due to earthquake shake produce additional force to the building due to the change of momentum and vise versa. The structure's response supporting the reservoir in the form of lateral deformation and natural frequency is highly influenced by water depth, reservoir dimensions, stiffness of the structure, and the loading patterns. There is an interaction among water waves, box-shaped reservoir, and the structural elements underneath. A study was carried out with a numerical simulation using the DualSPHysics application using a box-shaped reservoir of 200 mm long, with widths of 50 mm, 75 mm, and 100 mm. The reservoir was shaken under lateral sinusoidal forces with various frequencies to produce the maximum force on the reservoir wall. Besides that, a three-story steel structural model having dimensions of 500x500 mm floor plan and 1200 mm high was tested under free vibrations with the box-shaped reservoir as mentioned above. The numerical simulation result indicates that at d/L ratios up to 0.144, the maximum resultant force is still increasing. On the other hand, at the free vibration test of the experimental model, the optimum of damping ratios (ξ) can be indicated by the decreasing lateral amplitudes of the structural model at d/L between 0.2 and 0.4 and at about the natural frequency of the structure i.e 2.2439 Hz.

Keywords: Water, Reservoir, Steel, Force, Damping

1. INTRODUCTION

A swimming pool is one of the many building facilities found in hotels, apartments, and other buildings. A swimming pool is often placed on the top floor of the building and such a water reservoir contributes to the dynamic behaviour of the building structure [9,12]. As a non-solid particle, water has a wave frequency as a function of water depth and wave length [5,14]. When the seismic excitation happen, water will move in the reservoir which produce pressing and pulling pressure at the water reservoir walls [2,3,8].

In the previous research, Tuned Liquid Damper (TLD) modeling has been done by simulating water waves and its reservoir which produce hydrodynamic pressure distribution at the walls of the water reservoir [4,10,11]. The interaction between water waves and its reservoir can be simulated using the DualSPHysics application with the SPH (Smoothed Particle Hydrodynamics) method by modeling the water as incompressible smooth particles [2]. Numerical simulation using the SPH method produce pressure distribution which is read at many point measurements so that it has a high degree of accuracy in identifying the pressure distribution of water particles at the walls of the water reservoir [21].

Generally, the use of TLD will reduce the structural displacement when the natural frequency of the water tank was set equal with the external force frequency [8]. In the previous numerical simulations, the continuous water mass was lumped as an equivalent impulsive mass and a convective mass to represent the hydrodynamic pressure of the water and the maximum TLD displacement was obtained at low frequency excitation with various tanks size [6]. The TLD system was tested experimentally at shallow depth tanks which exitated at different water depths and the ratio of length to width of the tank in the frequency excitation ranges. The test results of TLD system show that the maximum free-surface elevation happens in the low frequency range [7] and the TLD system was designed at low h/L value to get a high damping ratio [22].

Several previous studies have shown that the earthquake resistance for high-rise buildings that use water reservoirs is based on the interaction of water and reservoir walls [15,20]. The seismic activity can cause significant damage to high-rise structures with low damping systems [17,19]. At the beginning of the seismic excitation, the structure will vibrate freely and when the seismic excitation is removed the structure will experience a decrease in amplitude [13,16].

One of solution to obtain a structural system that has high damping is by designing the water reservoir which has the same natural frequency with the structure so that the phenomenon of resonance will be reached and give contribution to structure strength [1,8,20]. Beside that, the process of designing the water reservoir on the top of structure can be done by determining the natural frequency of structure and the ratio of water depth to length of reservoir (d/L) to obtain the optimum structure damping [7,9,18,22]. However there are not many the experimental studies have been investigating the effectiveness of TLD at the portal structures with various the ratio of water depth to length of reservoir (d/L).

This research aims to study numerically the effect of the ratio of water depth to length of reservoir (d/L) to the dynamic force on the wall of the reservoir. Instead of that, this study also investigate experimentally the effect of d/L on the damping ratio of a three story model of steel structure.

2. RESEARCH SIGNIFICANCE

It is widely known that Tuned Liquid Damper can be used to reduce dynamic lateral deformation due to earthquake excitation [9,12,15,20], but it is still not clear how to determine the parameters that affect the resonance which is of significance in reducing dynamic lateral deformation (increasing damping ratio). Parameters in terms of depth of the water inside the reservoir and the length of the reservoir instead water volume inside the reservoir are studied numerically and experimentally in this research. Therefore, the process of designing a water reservoir on the top of structure to increase damping properties of the structure underneath may be practically carried out.

3. LITERATURE REVIEW

3.1 Wave Characteristics

Some important parameters to describe wave characteristics are wave length (L_w), height (H), and water depth (d), see Fig.1.

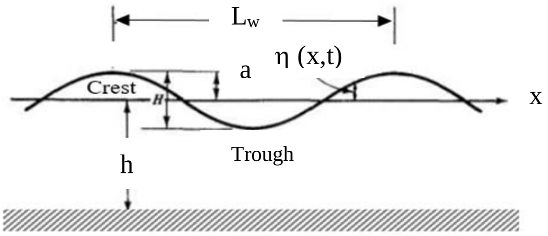


Fig.1 Two-dimensional schematic wave flow in the x (long) direction [5].

Where :

$\eta(x,t)$: profile of water level
H : wave height = 2a
a : highest displacement of the wave
h : distance between water level at rest and reservoir bottom
L_w : wave length
x : direction of movement of the waves

While the parameters of velocity and acceleration of water induced by waves can be determined theoretically from these parameters [5]

The Airy's wave theory states:

$$\mathbf{L_w} = \frac{gT^2}{2\pi}\,\mathbf{tanh}\left(\frac{2\pi h}{L_w}\right) \quad (1)$$

Waves do not always appear the same, nor do they always propagate in the same direction. A superposition of wave combines several sinusoidal waves moving in the same directions (see Fig.2).

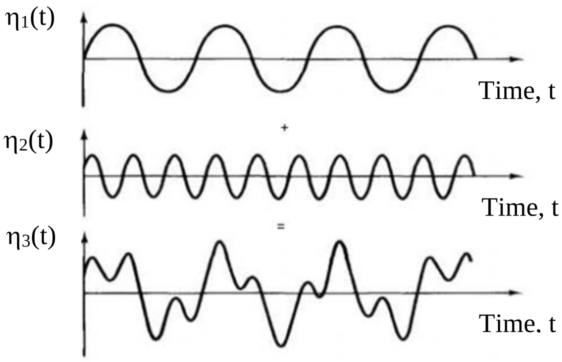


Fig.2 Complex wave (bottom) form as the summation of two sinusoids (above it) [5].

3.2 *Smoothed Particle Hydrodynamics* (SPH)

Based on previous studies was stated that the behavior of sloshing in a rectangular reservoir was analyzed by numerical simulations using the Smoothed Particle Hydrodynamics (SPH) method consisting of 2 (two) particle models namely water particles and boundary wall particles (see Fig.3). Pressure data at the reservoir wall may be obtained based on variations in angular frequency (ω) plotted at measurement points during SPH numerical simulation [2].

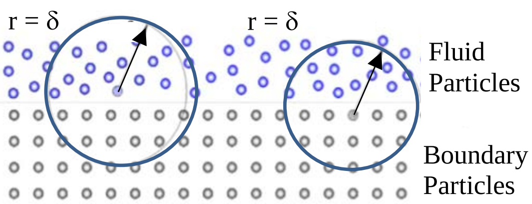


Fig.3 Distribution of boundary particles in the simulation of Smoothed Particle Hydrodynamics (SPH) [2].

A numerical simulation was carried out using the SPH software in a rectangular water reservoir. Visualization of water flow was done by using a digital camera. The water reservoir was driven by a sinusoidal motor provides a pattern of water flow which is captured by using a high-speed camera so it's similar with the numerical simulation of SPH at the same reservoir dimensions and water depth ratio [4]. The interaction between structures and tsunami-induced water at onshore buildings was presented with water modelling using the DualSPHysics application and onshore building modelling using the Abaqus application [14].

In previous studies it was stated the resultant force tends to decrease when the excitation frequency (ω_e/ω_1] was in the range 0.838–1.8. The maximum displacement of structures tends to decrease and the highest reduction of the force and displacement occurs at $\omega e/\omega 1 = 1.617$ [8], see Fig.4.

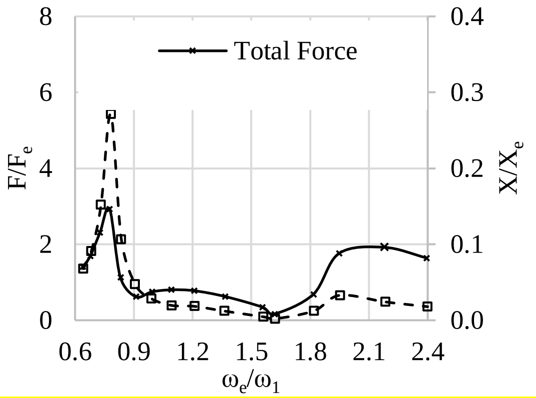


Fig.4 The maximum displacement of the structure system and the resultant force acting on the structure system under various excitation frequencies [8].

3.3 Tuned Liquid Damping System

The interactions between water and reservoir structures that experience periodic loads causes a hydrodynamic loading effect on the structure. The maximum hydrodynamic pressure varies between 20%-40% of the hydrostatic pressure [17].

The water reservoir functions as a damper which will reduce the energy generated by seismic excitation. The addition of baffles at a reservoir will reduce roof displacement due to the water sloshing effect in the water reservoir at the top of the structure [15].

Based on previous studies TLD has been optimized to investigate the effect of fluid characteristics on the damping performance of structures by optimizing the minimum displacement under seismic excitation. Liquid density and kinematic viscosity have no effect on single story structures. However, the other two types of structures (ten-story and forty-story structures) show that when the mass of the structure increases, the characteristics of viscosity and density become more prominent [12].

The finite difference method can be used to study the interaction between structure and the water reservoir. The characteristics of the water reservoir were described as the ratio between the water depth and the length of the reservoir as a Tuned Liquid Damper [3], see Fig.5.

Based on Fig. 5, it can be stated that the dynamic equation of motion is: [3]

$$m\ddot{\delta}(t) + c\dot{\delta}(t) + k\delta(t) = F(t) + F_{sloshing}(t) \quad (2)$$

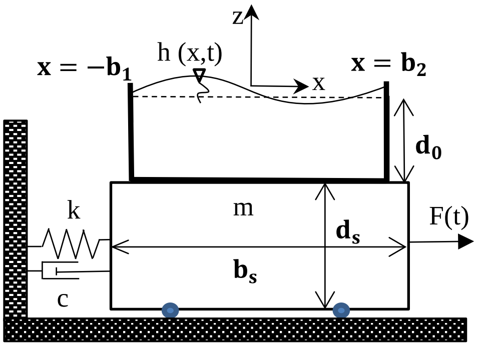
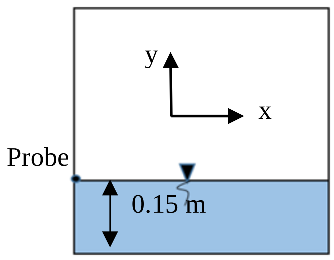
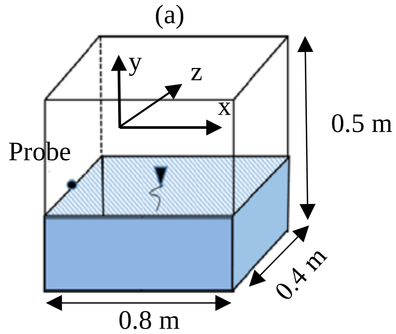


Fig.5 Sketch of the definition of the basic structural dynamic system of reservoir [3].

In previous studies it was stated that the influence of the natural frequency mode of the sloshing phenomenon in rectangular reservoirs was carried out by numerical simulations based on the level set method, see Fig.6.



(a)



(b)

Fig.6 Simulation scheme of (a) 2-D and (b) 3-D rectangular reservoir filled with water [10].

At the same length (L) but different depth (d) of the reservoir (variation of d/L) for 2-D and 3-D models, there was a similar pattern of forces for the variation of depth and frequency ratio (ω/p) [10],

A research was carried out about performance evaluation of the Tuned Liquid Damper by using shaking table and Ansys aplication software to get acceleration response from 7 kinds of TLD structural system models excited by the sinusoidal load. A TLD frequency was calculated based on a mathematic equation, while the frequency of the model was calculated by finite element software (Ansys) and experimental testing [18].

TLD as a linear equivalent mechanical was effective to reduce the structure response with seismic exitation at large amplitude and low ratios of depth water/tank length. TLD was more effective when the structure was excited with the resonant frequency. All parameters of equivalent mechanical model were represented in form of sloshing liquid mass by equivalent mass, liquid damping by damper, and sloshing frequency by spring system. When the container experiences a horizontal acceleration, the free liquid surface moves upwards on one side of the container and downwards on the other side forming a wave [1].

The water reservoir model on the top of structure has been designed as lumped mass single degree of freedom spring-mass system. Multiple Tuned Liquid Damper was placed on the top of the structure with various placement configurations of water reservoir. From three placement configurations model of water reservoir, the water depth (d) = 3/4 h gives the smallest roof displacement compared to water depth of 1/4 h and 1/2 h, where h is reservoir height [9].

3.4 Logarithmic Decrement

Logarithmic decrement is a method for determining the damping ratio from a free vibration experiment by obtaining a relationship between displacement and time [13], see Fig.7.

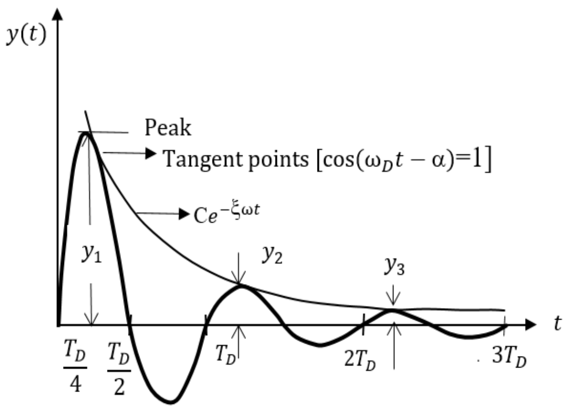


Fig.7 Logaritmic curve of peak displacements and displacements at the points of tangency [13].

Priyosulistyo [16] shows that the damping ratio can be analyzed by the following equations:

$$y(t) = Ce^{-\xi\omega t}\cos(\omega_D t - \alpha) \quad (3)$$

$$y_1 = Ce^{-\xi\omega t_1}. \quad (4)$$

$$y_2 = Ce^{-\xi\omega(t_1+NT_D)} \quad (5)$$

$$T_D = \frac{2\pi}{\omega\sqrt{1-\xi^2}}. \quad (6)$$

$$\delta = \ln\frac{y_1}{y_2} = N\xi\omega T_D = \frac{2\pi\xi N}{\sqrt{1-\xi^2}} \quad (7)$$

For small values of the damping ratio ξ, Eq. (7) can be approximated by:

$$\delta = \ln\frac{y_1}{y_2} = 2\pi\xi N \quad (8)$$

$$\xi = \frac{\ln(yi/y2)}{2\pi N} \quad (9)$$

Where: ξ : **damping ratio**
N : number of periode

4. RESEARCH METHODS

4.1 Numerical Simulation with The DualSPHysics Application Software [21]

Numerical simulation using the Smoothed Particle Hydrodynamics (SPH) method in the DualSPHysics application will use the water reservoir in the size of 200x50x150 mm with the amount of water added have d/L ratio 0.072, 0.096, and 0.144. While the generator wave frequency varies from 0.5 Hz to 5.0 Hz.

Numerical simulations are done with variations of reservoir width at the same water mass as a function of water level. This numerical simulation is aimed to obtain the pressure area and the water force resultant at the different generator wave frequency and water volume. The water reservoirs will be used in the size of length x width x height are 200x50x150 mm, 200x75x150 mm, and 200x100x150 mm.

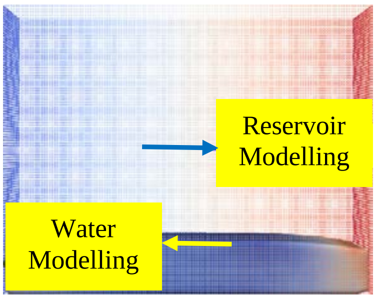


Fig.8 Display of model of water in a reservoir using the DualSPHysics application [21].

4.2 Free Vibration Testing on a 3-Storey Steel Structure (Experimental Model)

The scale factor of structure model in the laboratory is based on the response of the structure when it's receives dynamic loads with a scale factor is 1:10 to the prototype [19].

Tests of the Tuned Liquid Damping system on a 3-story steel structural model with added mass is done by adding water as a load into the water reservoir sized 400x200x300 mm, 400x100x300 mm, and 400x50x300 mm.

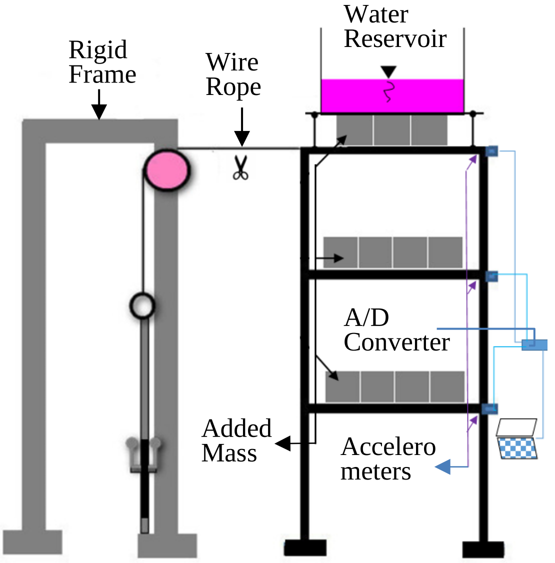


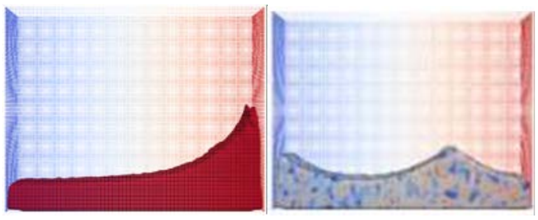
Fig.9 Free vibration model of the steel structure.

Process of the tests are done by adding water gradually based on the specified d/L ratio. Accelerometers are placed on each structure floor to record structural response data. The structure is pulled horizontally on the top floor with a string at a certain distance. At the time of breaking of the string wire, the free vibration is recorded (see Fig.9).

5. RESULTS AND DISCUSSION

5.1 Numerical mulation with the DualSPHysics Application [21]

The following are visualization of numeric simulation results by using DualSPHysics application for two pattern of water flow with different d/L ratio.

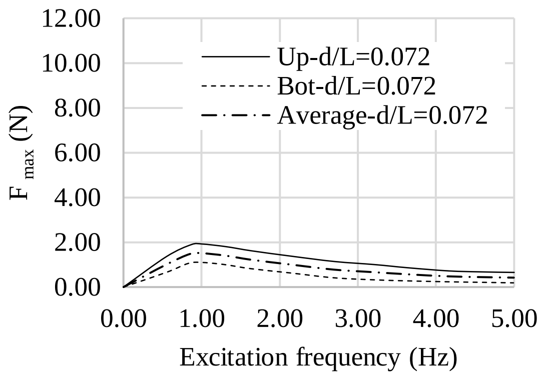


(a) (b)

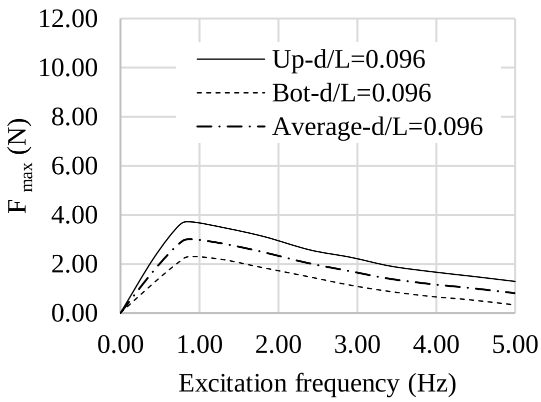
Fig.10 Specimens of DualSPHysics model at d/L ratio = 0.144 (a) frequency = 1.50 Hz (b) frequency = 3.00 Hz [21].

The DualSPHysics application uses the Smoothed Particle Hydrodynamic (SPH) method. Water is modelled as small particles that are capable of moving following the speed of load which work in it. In this case, water particle size (dp) = 1.5 mm (see Fig.10).

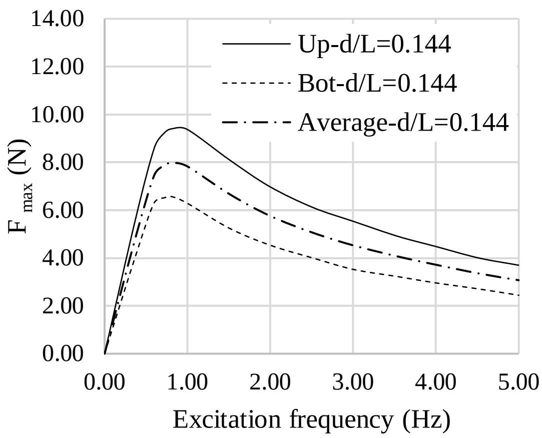
Based on the results of the numerical simulation it can be explained as follows:



(a) d/L ratio = 0.072, b/L = 0.25



(b) d/L ratio = 0.096, b/L = 0.25



(c) d/L ratio = 0.144, b/L = 0.25

Fig.11 Relationship between F_{max} and excitation frequency at the variation of d/L ratio with the same of b/L ratio.

Fig.11 shows the results of the resultant force (F_{max}) analysis at d/L ratios of 0.072, 0.096, and 0.144 with the excitation frequency between 0.50 to 5.00 Hz. The average resultant force is the sum of the pressing and pulling forces at the left and right sides of the water reservoir. The higher the excitation frequency causes the average resultant force of pressing and pulling at the reservoir walls tends to increase and reach its optimum at a certain the excitation frequency.

The maximum resultant force at d/L ratio = 0.072 and the excitation frequency of 1.00 Hz is 1.399 N, at d/L ratio = 0.096 and the excitation frequency of 0.90 Hz is 2.892 N, and at d/L ratio = 0.144 and the excitation frequency of 0.80 Hz is 7.958 N.

The results of numerical analysis at the same water mass with the variations of water heights (d) and the water reservoir widths (b) can be seen at Table 1 and Fig.12. It can be stated that at the same water mass (different b/L), the higher the d/L ratio, the maximum resultant force at the reservoir walls is still increasing from d/L = 0.072 to d/L = 0.144.

Table 1 Variation of the water reservoir widths and frequency at the same water mass

f (Hz)	L (cm)	b (cm)	d (cm)	d/L	b/L	ΣF (N)
0.80	20	5	2.88	0.144	0.250	7.96
0.80	20	7.5	1.92	0.096	0.375	2.89
0.80	20	10	1.44	0.072	0.500	1.40
1.80	20	5	2.88	0.144	0.250	6.13
1.80	20	7.5	1.92	0.096	0.375	2.49
1.80	20	10	1.44	0.072	0.500	1.15
3.00	20	5	2.88	0.144	0.250	4.53
3.00	20	7.5	1.92	0.096	0.375	1.65
3.00	20	10	1.44	0.072	0.250	0.71

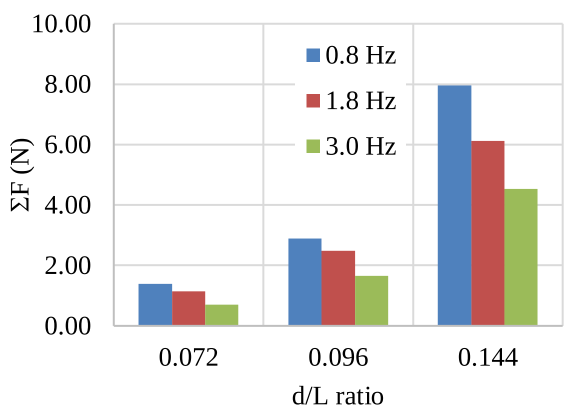


Fig.12 Relationship between the maximum resultant force and d/L ratio at the variation of the excitation frequency.

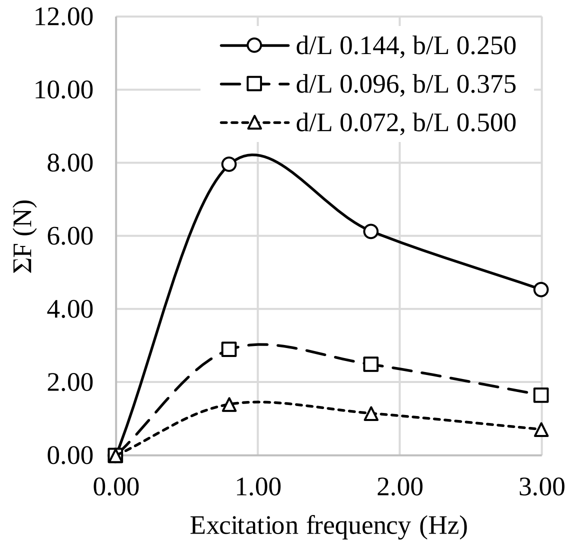


Fig.13 Relationship between the maximum resultant force and excitation frequency with the excitation frequency = 0 is assumed.

Based on Fig.13, it can be stated that the optimum value of the maximum resultant force is achieved at the excitaition frequency 0.8 to 1.0 Hz. When the excitaition frequency above 1.0 Hz the water wave breakes so the maximum resultant force decreases.

5.2. Free Vibration Testing on a 3-Storey Steel Structure with Added Mass

Based on equation (1) the relationships between wave length (L_w) and wave frequency (f) is obtained, as follows:

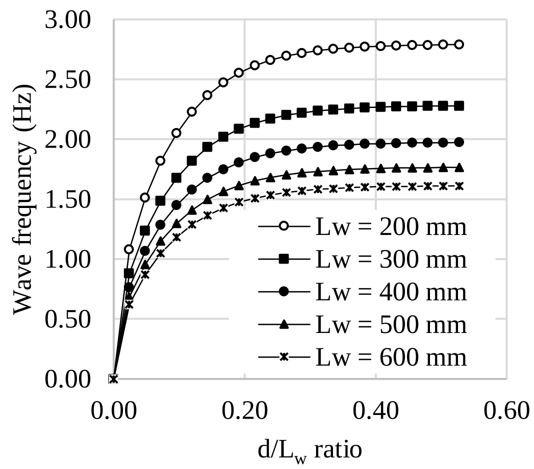


Fig.14 Relationship between d/L_w ratio (water depth/wave length) and wave frequency.

Based on Fig.14, it can be stated that the greater the wave length causes the wave frequency to be smaller. The increase of the d/L_w ratio causes the wave frequency tend to be constant for each certain wave length (L_w).

Based on the results of structural analysis using SAP 2000 application, the natural frequency of the steel structure model is obtained = 2.24 Hz. The length of the water reservoir is determined = 400 mm according to the wave frequency = 2.00 Hz (Fig.14). The closeness between the structure natural frequency and the wave frequency will cause the steel structural model reaches the highest damping. The steel structural model moves opposite to the water in the reservoir movement when the load applies.

Fig.15 The laboratory structural model with the additional mass on each floor.

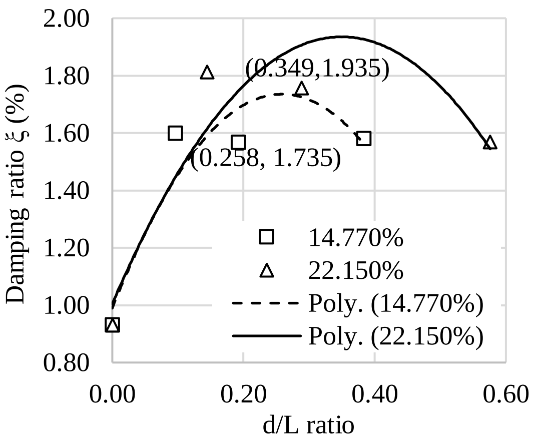


Fig.16 Relationship between d/L ratio and the damping ratio (ξ) at the addition of different water mass.

Based on Fig.16, it can be explained that the increasing of d/L ratio will increase the damping ratios (ξ). The damping ratio tends to increase and reach its optimum at d/L 0.2 to 0.4 on each addition of water mass.

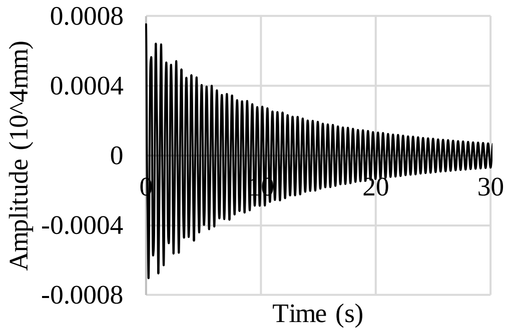


Fig.17 Relationship between the displacement amplitude and time function with d/L = 0.024 for L = 200 mm.

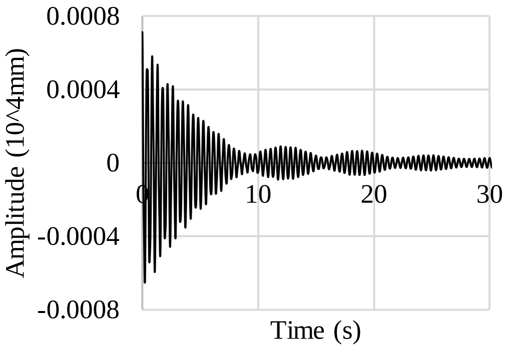


Fig.18 Relationship between the displacement amplitude and time function with d/L = 0.264 for L = 200 mm.

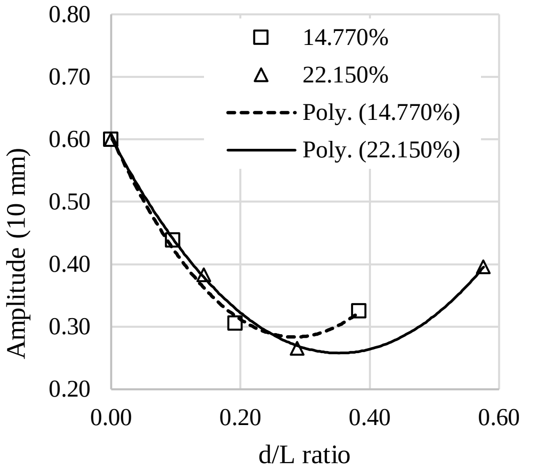


Fig.19 Relationship between d/L ratio and the amplitude at the addition of different water mass.

Based on Fig.19, it can be more explained that the smaller the widths of the water reservoir, the higher the d/L ratio. The displacement amplitude tends to decrease and reach its optimum at d/L 0.2 to 0.4 on each addition of water mass.

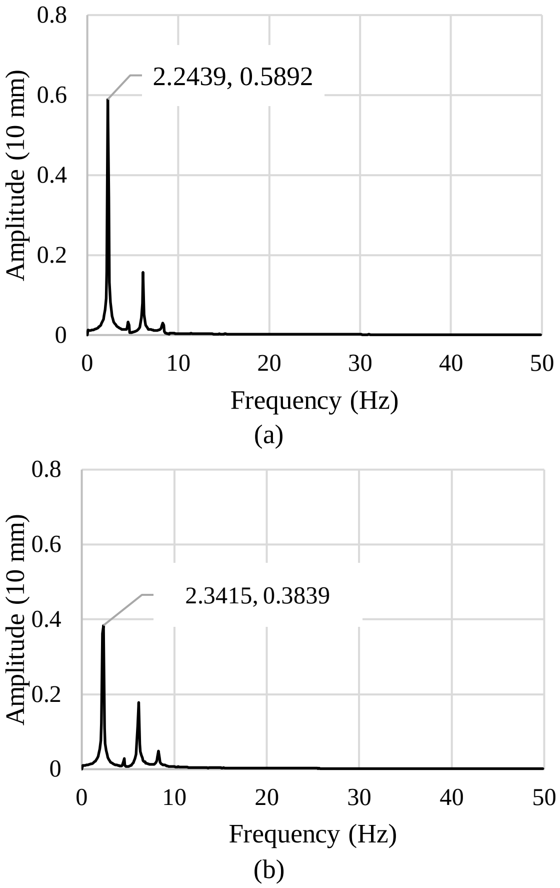


Fig.20 Average displacement amplitude of the structural model with added mass on every floors (a) no water weight; f = 2.2439 Hz (b) water weight for d/L ratio = 0.144; f = 2.3415 Hz [16].

6. CONCLUSION

Based on the results of numerical simulation using the DualSPHysics application it can be concluded that the maximum resultant force at the water reservoir walls is still increasing above d/L = 0.144. The maximum resultant force occurs always at the excitation frequency between 0.8 and 1.0 Hz.

Based on the free vibration test experiment it can be explained that the displacement amplitude and damping ratio (ξ) reach its optimum at d/L ratio between 0.2 and 0.4. The decreasing of the displacement amplitude of the structure is closely related to- the increasing of the damping ratio (ξ) of the structure. The displacement amplitude and damping ratio (ξ) is strongly influenced by the percentage of water mass added to the structure at the optimum d/L ratio.

7. ACKNOWLEDGMENTS

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