**MINISTRY OF EDUCATION AND TRAINING**
**UNIVERSITY OF COMMUNICATIONS AND TRANSPORTATION**

---

**Nguyen Duc Thi Thu Đinh**

# RESEARCH ON APPLICATION TUNED LIQUID DAMPER FOR CONTROL VIBRATION OF STAYED CABLE BRIDGE IN VIET NAM

SUMMARY OF TECHNINCAL DOCTOR THESIS

***Supervisors:*** Prof. Dr Trung, Nguyen Viet

Dr. Toshihiro Wakahara

Hà NỘI - NĂM 2014

# GENARAL

Affect of dynamic action on the structure including wind, earquake and verhicle were considered in design of sensitive structures such as tall building, tower, stayed cable Bridge, and suspension Bridge ……

There are 2 ways can be applied to reduce vibration for stayed cable. Firstly, changing members of structure such as: changing the suitable girder form with aerodynamic characteristec for strusture, addition some components to member of structure. Secondary, addition a certain damper equipment to structure. Damper device is one of solutions for control vibration for structure now. There are 3 types of current damper including: active damper, passive damper and semi – active damper. Each type of damper have some advantages and disadvantage. However, passive damper is a kind of damper that can be activity without power for remain, specially, during natural disaster as storm, earthquake… And tuned liquid damper - a passive control device (TLD) – that active by using sloshing motion of liquid inside tank to supressing vibration for structure under dynamic action is main object for this research.

Research on application of tuned liquid damper for control vibration of stayed cable Bridge in Viet Nam is necessary.

All researched contents combine in 4 chapters as following:

Chapter 1: General about stayed cable Bridge and vibration control problem using tuned liquid damper (TLD)

Chapter 2: Basical theory for design tuned liquid damper and the structure – Tuned liquid damper interaction.

Chapter 3: analysis the effective in supressing vibration for the pylon of stayed cable Bridge using tuned liquid damper.

Chapter 4: Experiment with a structure model on the shaking table to evaluate the effective in supressing vibration of tuned liquid damper.

# CHAPTER 1:
# GENERAL ABOUT STAYED CABLE BRIDGE AND VIBRATION CONTROL PROBLEM USING TUNED LIQUID DAMPER (TLD).

Stayed cable Bridge are application widening all over the world and Viet Nam. Stayed cable Bridge is a complex structure system with the relationship between girder, cable and pylon and so sensitive under dinamic action such as wind, earthquake, and verhicle.

Pylon of stayed cable Bridge with large height and so slender, thus, under horizontal action, pylon will be occur vibration with large amplitude. Futhermore, the pylon have to bear the action from cable and girder.

Cables are one of the main parts of a cable-stayed bridge. They transfer the dead weight of the deck to the pylons. These cables are usually post-tensioned based on the weight of the deck. The cables post-tensioned forces are selected in a way to minimize both the vertical deflection of the deck and lateral deflection of the pylons.

Thesis focus on analysis effective of passive damper in supressing vibration, particular is tuned liquid damper what use liquid motion inside tank to make the effective for reducing vibration for structure.

When considering the pylon without cable and girder, the pylon will be consisdered as a cantilever column that the deflected shape is expressed in terms of translational displacements. And at each mode sharp, the translational displacements of structure folllowing certain direction that consisdering. Thus, when consisder vibration of structure following certain direction, the effective of action on other direction to translational displacements on consisdered direction is small and it can be ignored.

In particular of stayed cable Bridge, when consisdering the vibration of pylon on horizontal direction under wind action, the affective of vibration of pylon in cacse connect with cable and girder and in case not connect with cable and girder is small and it can be ignored. For this reason, pylon of stayed cable is consisdered in design control vibration in more extreme stage. That is a cantilever column with one fix and one free.

Moreover, when calculating some pylon of some stayed cable Bridge, the natural frequency of pylon in case with girder and stayed cable increase. It means that the stiffness of pylon increase uith thí connection.

**Main contents for research focus on**

Via analysis researches about TLD up to now, the scope research of topic with name "Research on application tuned liquid damper for control vibration_of cable stayed Bridge in Viet Nam" can be view as following:

- Research theoritically model of SDOF structure – MTLD interaction system.
- Estimating the transfer function for above system to survey the response of structure to frequency variable.
- Research to susggest some reasonable parameters for increase the effective in supressing vibration of MTLD for structure.
- Compare the effective supressing vibraion for structure – STLD system and structure – MTLD system.
- An experimental for real model structure to verify a part of theorical results. Conpare the experimental line and theorical line in the behavior of structure.
- Application re – design and analysis MTLD to compare with the current TLD at Bai Chay Bridge.

## CHAPTER 2

# BASICAL THEORY FOR ANALYSIS THE CHARACTERISTIC OF TUNED LIQUID DAMPER AND THE STRUCTURE – TUNED LIQUID DAMPER INTERACTION

Research on TLD up to now mainly focus following 3 ways: (1) subject and scope of TLD is for which kind of structure and compare the effective between this device and other control device (the general research of most research); (2) research on the dimension and sharp of TLD. This research usually focus determine the kind of tank and some parameters that affect the effective of TLD such as the depth of liquid in side tank, the ratio between liquid depth and length of tank…; (3) research on calculating the effective reduce vibration of TLD via determining the interaction between TLD and structure model. All 3 ways of research are presented on 2 systems that is STLD (system No1) and MTLD (system No2) with certain number TLD what installed suit for the characteristic of TLD and structure.

The system No 1 is mention in many research in which the structure is a degree of freedom and single TLD with the same liquid depth (the same natural frequency of liquid) is second degree of freedom (STLD). The system No 2 also concede the structure is a degree of freedom, however, the liquid depth inside difference tank in system is difference. It mean that the natural frequency of a single TLD is difference (MTLD). Thus, TLDs is not conceded a degree of freedom. That system become a multi degree of freedom with structure is a degree of freedom.

Research on system No 2 is not much and mainly focuses on experimental research and the detailed mathematical formulas is not shown. The transfer function (the function show the relationship between frequency ratio damper – structure and the amplitude of structure – TLD system). Therefore, main objective of research is find

out the transfer function equation and find out the damping ratio parameter to have the optimum value of transfer function of MTLD system. Addition, in order to have the data to improve the exactly of the transfer Function, one experimental case is necessary and is presented in this research.

Liquid pressure inside tank vesus external force act on the structure including static action and dynamic action. Effective in supressing vibration for structure is affected by some parameters of damper as: form and dimension of tank, type and height of liquid inside tank, number of tank, the ratio between height of liquid and length of tank.

Analysis TLD using TMD analogy with non-linear characteristic is mentioned in a lot of researches of authors including improve the equivalence. When the base excitation amplitude increase, the parameters of TLD such as effective mass (under motion) of water, effective damping ratio and effective natural frequency shall increase non-linearly, and thus the damping of liquid motion increase. When the base excitation amplitude is larger then at certain level, breaking wave occur and energy is dissipated due to wave breaking. The damping ratio becomes large. This indicates that the TLDs efficiency becomes relatively lower under large excitation amplitude since the damping of liquid sloshing exceeds the optimal value. But insensitiveness to the tuning condition of such an over-damped damper is increased (Sun 1995)". However, This is a complex problem and that is not main objective for my PhD research. These results is used for my research as a basic theory for analysis TLD.

TLD can be calculated by numerical simulation directly with using Shalow water wave theory. However, that model is so complex. Thus, TLD is ussually calculated by using equivalent TMD with nonlinear

stiffness and damping. Equivalent TMD can be used for calculating TLD by considering the problems as:

Alternative 1: By matching the force that is created by sloshing motion in TLD system and solid mass motion in TMD system.

Alternative 2: By matching energy equation in 2 system. However, this alternative is ussually considered with the association between theory and experiment.

This device include the tanks and liquid inside the tank with certain height in order to have a frequency that close the natural frequency of structure with the same amplitude and in phase.The length of tank is choosen in order to sloshing motion inside tank is shallow water wave motion. In particular, the ratio between height of liquid inside tank and length of tank should as:

*Determine type of wave inside tank*

| $h_0$ /L | 1/20 – 1/25 | | ½ |
|---|---|---|---|
| Wave type | Long wave (very shallow water wave) | shallow water wave | Deep water wave (surface wave) |
| Control parameters | h, H/L | H/h, H/L | H/L, L |

Nonlinearity characteristic of TLD is so complex and it can not be ignored in design TLD for supressing vibration for structure.

Analogy TMD of TLD is charactered by 3 parameters: effective mass (mass of analogy TMD), frequency and damping. However, unlike TMD, motion of liquid inside TLD posses strong nonlinear characteristic, and effective mass is a function with nonlinear characteristic and depend on wave motion in TLD, amplitude, frequency of excitation force and form of TLD tank.

The frequency of liquid sloshing inside rectangular tank increase with the increasing of excitation amplitude. When the excitation amplitude is small and so far from resonant frequency, amplitude wave is small and breaking wave is not occur, liquid inside tank is surface wave motion (shallow water wave), only a part of liquid in motion and the damping of liquid is small.

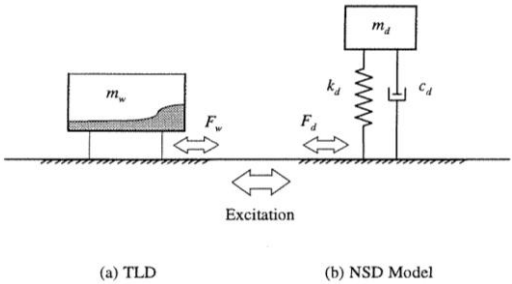



Fig 2.1 – analogy TMD of TLD

The damping of liquid motion will increase when the amlitude wave increase under excitation force with large amplitude. Nonlinear characteristic occur at the boundary and the surface of liquid and breaking wave (if occur). Breaking wave occur, the energy dissipation appear and the damping ratio become large and the effective if TLD decrease. The structure – analogy TMD interaction system will give approximated solution.

In this each system, every TLD is simulated as a equivalent TMD - tuned mass damper problem that have successful result in many research. The non – linear issue due to the liquid motion is presented in stiffness,k and damping that called non linear stiffness and damping of equivalent TMD.

## CHAPTER 3

# ANALYSIS THE EFFECTIVE IN SUPRESSING VIBRATION OF TUNED LIQUID DAMPER USING ESTIMATED TRNASFER FUNCTION.

The interaction between structure and damper is an important problem in establishing the equation of the transfer function. This transfer function show the response of structure variable follow the frequency ratio. That is a condition to evalute the efficient in suppressing vibration of TLD.

The transfer function of TLD – structure interaction system is establised for STLD and MTLD using energy conservation law and lagrange expression.

<u>In MTLD system :</u>

The ratio ws/w is a vector show the ratio between the frequency of structure and external force.

The ratio wi/w is a vector show the ratio between the frequency of single TLD of MTLD and external force. It depend on the number of single TLD in MTLD system the frequency of each single TLD is difference and:

That is: w1……. wi ……..wn, or

wmin……..…..wi……..wmax

- The center frequency of TLDs in the MTLD system is $w_0 = (w_{max} + w_{min})/2$
- Range width of frequency is $\Delta R = (w_{max} - w_{min})/w_0 = 0.2$
- And $\beta_i = w_{i+1} - w_i = const$
- The mass ratio between total single TLD and structure can be $\mu = \sum \mu_i = 1\%$
- $\xi_S \xi_i$ is the structure damping parameter and single TLD damping parameter number ith.

Tanks in MTLD take parallel on structure.

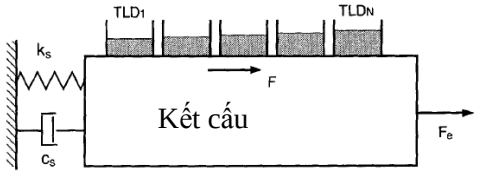



*Fig 3.1 – structure – MTLD interaction system Model*

*A difference level of piquid inside tank in each tank will make a difference frequency* $f_i$ and calculated by:

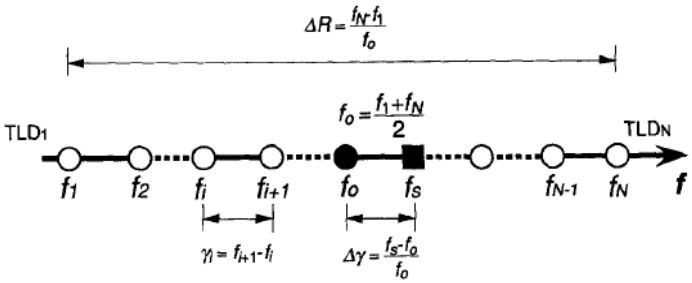
$$f_i = \frac{1}{2\pi}\sqrt{\frac{\pi g}{2a} tanh\left(\frac{\pi h_i}{2a}\right)} \text{ (Fujino)}$$

The center frequency of MTLD system is $f_0$, that is determined when take the average all frequency of all tanks in system [118]:

$$f_o = \frac{f_N + f_1}{2}$$

Frequency spacing is constant as,

$\beta i = f_{i+1} - f_i = (f_N - f_1)/(N-1) = \beta$.




Multi tuned liquid damper is modeled as multi degree of freedom in MTLD system.

Frequency band width is determined by

$$\Delta R = \frac{f_N - f_1}{f_0}$$

Frequency of MTLD (center frequency of MTLD system) or frequency of single tank is difference with the natural frequency of structure in some certain cases, it is necessary the off – tuning parameter to consisder this case. This off – tuning parameter is:

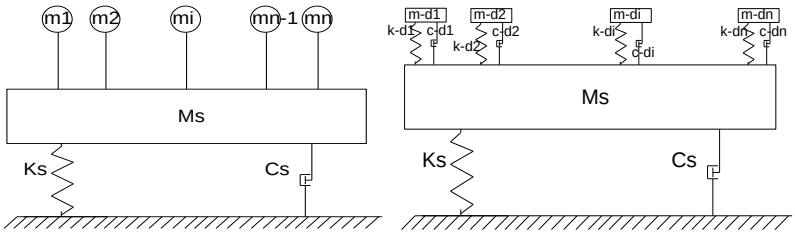
$$\Delta\gamma = \frac{f_s - f_o}{f_o}$$

Damping ratio of ith single TLD in system, $\xi_i$ is determined by equation:

$$\xi_{TLD} = \frac{1}{h}\frac{1}{2}\sqrt{\frac{\upsilon}{\pi f_{TLD}}}\left(1 + \frac{h}{b}\right)$$

where: $f_{TLD}$ = natural frequency of TLD; h and υ = liquid depth inside tank and vicous factor of liquid (Sun 1991).

The transfer function for strusture – MTLD interaction system is estimated from the dynamoc equation as:




*Proposed model for calculating structure – MTLD interaction system*

Using the Lagrange changing to build dynamical equations can have:

Multi-degree of freedom system with potential

$$T = \frac{1}{2}\ m_s\dot{x}_s^2 + \frac{1}{2}\sum_{i=1}^{N} m_i\dot{x}_i^2$$

the multi-degree of freedom system with dynamic

$$\pi = \frac{1}{2}\ k_s x_s^2 + \frac{1}{2}\ \sum_{i=1}^{N} k_i (x_i - x_s)^2$$

The multi-degree of freedom systems with dissipation is

$$\varphi = \frac{1}{2}\ c_s \dot{x}_s^2 + \frac{1}{2}\ \sum_{i=1}^{N} c_i (\dot{x}_i - \dot{x}_s)^2$$

The equation in matric form as:

$$\begin{bmatrix} m_s & & & & & \\ & m_1 & & & & \\ & & m_2 & & & \\ & & & \ddots & & \\ & & & & m_{n-1} & \\ & & & & & m_n \end{bmatrix} \begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_1 \\ \\ \ddot{x}_i \\ \\ \ddot{x}_n \end{Bmatrix}$$

$$+ \begin{bmatrix} c_s + \sum c_i & -c_1 & -c_2 & & & -c_n \\ -c_1 & c_1 & 0 & & & \\ -c_2 & 0 & c_2 & & & \\ & & & \ddots & & \\ & & & & c_{n-1} & \\ -c_n & & & & & c_n \end{bmatrix} \begin{Bmatrix} \dot{x}_s \\ \dot{x}_1 \\ \\ \dot{x}_i \\ \\ \dot{x}_n \end{Bmatrix}$$

$$+ \begin{bmatrix} k_s + \sum k_i & -k_1 & -k_2 & & & -k_n \\ -k_1 & k_1 & & & & \\ -k_2 & & k_2 & & & \\ & & & \ddots & & \\ & & & & k_{n-1} & \\ -k_n & & & & & k_n \end{bmatrix} \begin{Bmatrix} x_s \\ x_1 \\ \\ x_i \\ \\ x_n \end{Bmatrix} = \begin{Bmatrix} F_s \\ 0 \\ \\ \\ \\ 0 \end{Bmatrix}$$

From the matrix from can be rewritten equations as:

$$\begin{cases} m_s\ddot{x}_s + (C_s + \sum C_i)\dot{x}_s - c_1\dot{x}_1 - \ldots - c_i\dot{x}_i \ldots - c_n\dot{x}_n + (k_s + \sum k_i)\, x_s - k_1x_1 - \ldots \\ m_1\ddot{x}_1 - C_1\dot{x}_s + c_1\dot{x}_1 - k_1x_s + k_1x_1 = 0 \\ m_2\ddot{x}_2 - C_2\dot{x}_s + c_2\dot{x}_2 - k_2x_s + k_2x_2 = 0 \\ \\ m_n\ddot{x}_n - c_n\dot{x}_s + c_n\dot{x}_n - k_nx_s + k_nx_n = 0 \end{cases}$$

$$H(w) = \frac{F_0}{k_s\left[\left(-\frac{w^2}{w_s^2} + 2\xi_S i\frac{w}{w_s} + 1\right) - \sum_{i=1}^{N}\frac{w^2}{w_s^2}\mu_i\frac{\left(2\xi_i i\frac{w_i}{w} + \frac{w_i^2}{w^2}\right)}{\left(-1 + 2\xi_i i\frac{w_i}{w} + \frac{w_i^2}{w^2}\right)}\right]}$$

$$H(w) = \frac{F_0}{k_s}\frac{1}{\left[\left(1 - \frac{w^2}{w_s^2} + 2\xi_S i\frac{w}{w_s}\right) - \frac{w^2}{w_s^2}\sum_{i=1}^{N}\mu_i\frac{\left(2\xi_i i\frac{w}{w_i} + 1\right)}{\left(1 - \frac{w^2}{w_i^2} + 2\xi_i i\frac{w}{w_i}\right)}\right]}$$

**H(w) is non – dimension transfer function of MTLD system:**

Analysis, evaluating the effective of MTLD and compare with STLD system and structure without TLD is implemented following case: Using transfer function of STLD and MTLD to survey interaction structure – MTLD system in some cases. The results reflect the effectiveness of MTLD on supression vibration of structure, optimum some parameters of MTLD and comparision STLD and MTLD.

## 1.1 Initial data

**Case 1: changing the number single TLD N=3, 5, 7, 9** and the initial data is selected as:

- Consider the rectangular tank with the dimension is

| | | |
|---|---|---|
| L = | 65 | cm |
| b= | 40 | cm |

- The mass ratio between MTLD and structure is μ =1%
- The center frequency f0 is selected by fs (the natural frequency of structure) and in this example, fs = 0.38.
- The ratio between frequency of single TLD No ith and center frequency f0 in range: 0.9 < fi /f0 < 1.1
- The frequency band width ΔR = 0.2
- The damping parameter of structure in this survey is not optimum and the damping parameter of single TLD can be calculated by the equation that shown in the research of Fujino (1993):

$$\xi = \frac{1}{h}\frac{1}{2}\sqrt{\frac{\upsilon}{\pi f_{TLD}}}\left(1+\frac{h}{b}\right)$$

- Where: fTLD = natural frequency of TLD; h and υ = liquid depth and the kinematic viscosity (Sun 1991)

**Case 2:** changing the frequency band width ΔR = 0.1; 0.2; 0.3 for every case of N=3, 5,7, 9, and other innitial data is selected the same case 1.

Continue suvey some cases of the effective of MTLD as:

**Case 3:** How effective of MTLD when the ratio between center frequency of MTLD and structure is not equal 1. and other innitial data is selected the same case 1 (ΔR = 0.3)

**Case 4:** How effective of MTLD when the ratio between center frequency of MTLD and structure is not equal 1 (the ratio of this two frequency is, f0/f = 0.95, 1.05) and other innitial data is selected the same case 2 and ΔR = 0.3.

**Case 5:** Changing the ratio between damping ratio of tructure and damping ratio of MTLD (the average value of TLDs)

**Case 6:** Changing the mass ratio between MTLD and structure

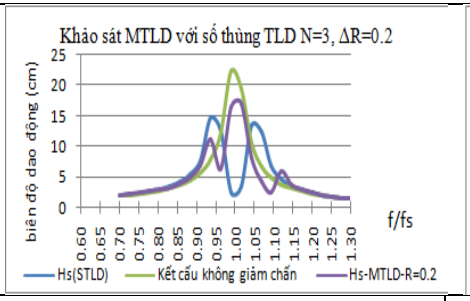
## 1.2 The results of case 1

For every case of number single TLD in survey, It can see that MTLD system is effective in reduce vibration comparing with structure no tuned liquid damper. When compare the STLD system and MTLD system, the effective of system depend on the number of single TLD in the MTLD system. The MTLD system have good effective at certain number single TLD, if number single TLD increase, the effective is not clear. The detail as following:

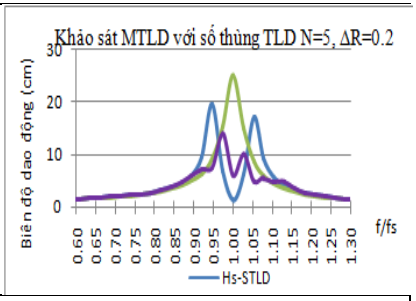
With the same frequency band width in survey ΔR= 0.2, the effectiveness is determined when changing the number of single TLD in the MTLD system as N =3, 5, 7, 9, 11, 15…21. The relationship between amplitude and frequency ratio (the ratio between excited frequency and natural frequency of structure) in each case present for 3 spline: one aligement chart for structure without TLD, other alignment chartcho structure with STLD and last spline for structure with certain number single TLD in MTLD system. The results show that: The MTLD system is more effective in supressing vibration for structure than STLD system and structure without TLD at the certain number single TLD in MTLD system. The survey results show that over the number of single TLD N = 21, the MTLD system have no even make opposite direction of effectiveness. The effectiveness of MTLD system is optimal at the flat alignment chart, peaks of that alignment chart is close at the same frequency band width. Detail as following:

For case of number single TLD of MTLD system N=3 and frequency band width ΔR = 0.2, the form of alignment chart for response of structure with STLD and MTLD is the same with 2 peak. However, the amplitude value in case of structure with MTLD is larger than the case

of structure with SLTD. It means that the effectiveness of MTLD is even smaller than STLD.



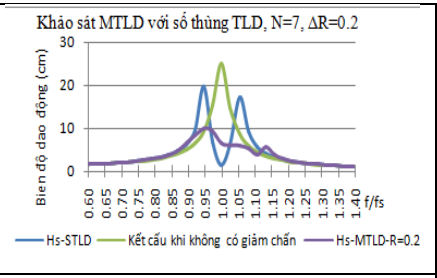

*The fingure survey the frequency response function of MTLD system with the number of single TLD N=3, ΔR = 0.2*



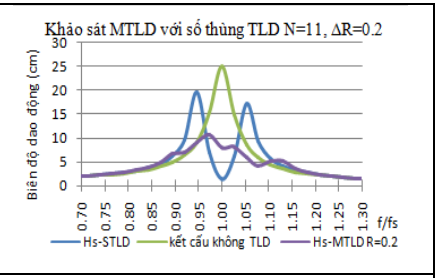

*The fingure survey the frequency response function of MTLD system with the number of single TLD N=5, ΔR = 0.2*

When increasing the number of single TLD N= 5, MTLD is more effective than STLD. The alignment chart have multi close peaks what show that MTLD is more effective than STLD.

The number of single TLD N=7, N=9 the alignment chart is so flat, it means that MTLD is more effective than STLD with the amplitude value reducing to 30% .



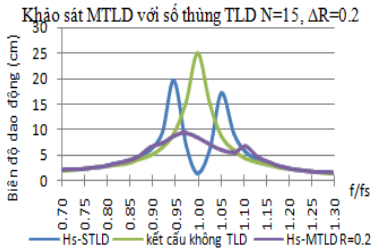
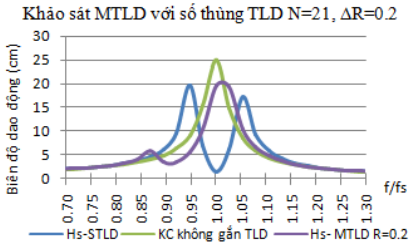

*The fingure survey the frequency response function of MTLD system with the number of single TLD N=7, ΔR = 0.2.*




*The fingure survey the frequency response function of MTLD system with the number of single TLD N=11, ΔR = 0.2*

Continue increasing the number of single TLD to survey the effective

in suppressing vibration of structure, the results show that the alignment chart at the number of single TLD, N =11, 15 changes a little comparing with the alignment chart at the number of single TLD, N=9.

| | |
|---|---|
|  |  |
| *The fingure survey the frequency response function of MTLD system with the number of single TLD N=15, ΔR = 0.2* | *The fingure survey the frequency response function of MTLD system with the number of single TLD N=21, ΔR = 0.2* |

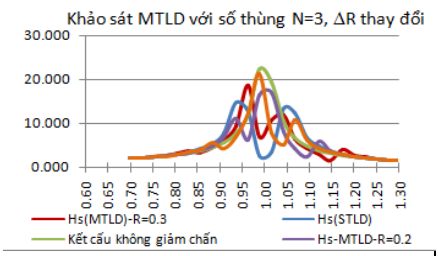
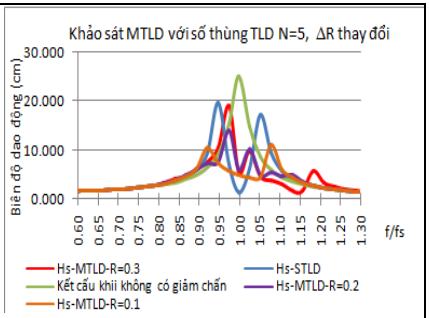
When continue survey the response of transtranfer function at the number of single TLD, N=21, the alignment chart changes complex, some peak of MTLD is larger than two peak of SLTD, it means that the effective in suppressing vibration for structure of MTLD is not good.

Conclusion, MTLD is only have effectiveness in suppressing vibration at the certain number single TLD, over this value the effectiveness of MTLD is not exist.

### 1.3 Results for survey case 2:

Changing the frequency band width of MTLD system ΔR = 0.1; 0.2; 0.3 at each number of single TLD in MTLD system N. It can be seen that when the frequency band width is small, as the number of single TLD is larger as the frequency of each single TLD is closer and the form of the alignment chart of MTLD system anf STLD system is similar with the number of single TLD changing from 5 to 15 tanks. With the number of single TLD is smaller or larger this band, the alignment chart change

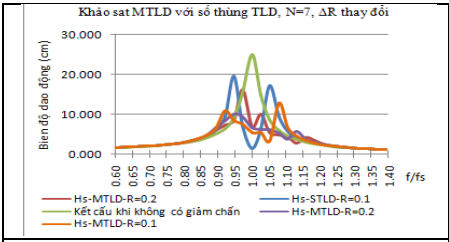
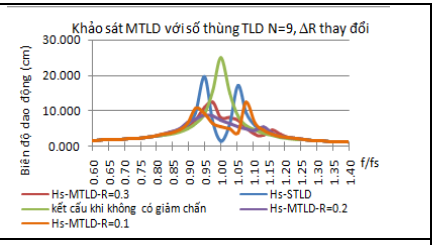
with the effectiveness of MTLD is not good and even no exist. It means that MTLD only have effectiveness with the difference frequency between each single tanks in MTLD system is enough in certain limited value. At this frequency band width, the number of single TLD N=5 show that MTLD is more effective than STLD, however the peak is not at fs/f =1.0, it is around the value 1 in range 0.9 – 1.1 of frequency ratio. Survey the effectivenes of MTLD system with the frequency band width 0.2, the results show that the alignment chart is so flat with multi close peaks in therange of munber single TLD 5-15 tanks. The number of single TLD is larger, the alignment chart at the frequency band width is nearly coincide at the frequency band width 0.2 và 0.3. One again, It means that MTLD is only have effectiveness in suppressing vibration at the certain number single TLD. The number of single TLD is smaller or larger, the frequency between each tanks of MTLD is far or close , the effective of MTLD will reduce. Detail as following:

| | |
|---|---|
|  |  |
| *The fingure survey the frequency response function of MTLD system with the number of single TLD N=3, ΔR changing* =0.1, 0.2, 0.3 | *The fingure survey the frequency response function of MTLD system with the number of single TLD N=5, ΔR changing* =0.1, 0.2, 0.3 |

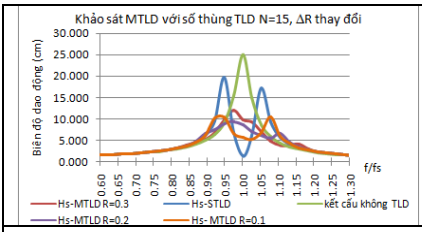
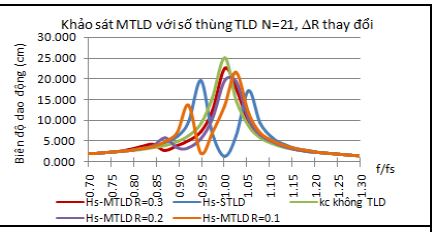
The frequency band width change with the number of TLD is small, the

effectiveness change not so much.

The alignment chart at the number of single TLD N =5 change clearly. The optimal effctiveness if MTLD is at frequency band width 0.2 and at 0.1 the alignment chart of MTLD system and SLTD system is similar, however the two peak of MTLD system is far from frequency ratio value 1 (the resonance value).

| | |
|---|---|
|  |  |
| *The fingure survey the frequency response function of MTLD system with the number of single TLD N=7, ΔR changing* =0.1, 0.2, 0.3 | *The fingure survey the frequency response function of MTLD system with the number of single TLD N=9, ΔR changing* =0.1, 0.2, 0.3 |

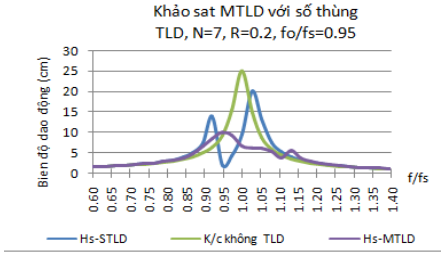
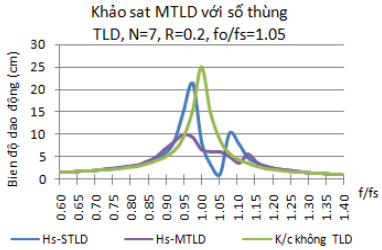
The case number single TLD N =7 is similar the case with number single TLD N =5. The number of single TLD increase continuously N=11, the alignment chart with the frequency band width *ΔR* = 0.2 and 0.3 nearly coincide.

| | |
|---|---|
|  |  |
| *The fingure survey the frequency response function of MTLD system with the number of single TLD N=15, ΔR changing* =0.1, 0.2, 0.3 | *The fingure survey the frequency response function of MTLD system with the number of single TLD N=21, ΔR changing* =0.1, 0.2, 0.3 |

Conclusion, the freqency band width is small, the number of single TLD is small, the effective ness of MTLD increase with the increase the number of TLD, N and exceed certain number TLD, the effective of MTLD is not increasingly and the alignment chart of MTLD and STLD is similar. With $\Delta R$= 0.2 và 0.3, N is smaller than 5, the difference between each tank in MTLD system is so far. N is larger the difference between each tank in MTLD system is close and reach to the same as the STLD system with multi simoilar tanks. The alignment chart with $\Delta R$ = 0.2, 0.3 is nearly coincide.

### 1.4 Results for survey case 3:

As usually, the center frequency of MTLD is controlled to the natural frequency of structure. However, in fact, there are some reasons for error of it such as: the nonlinear of structure, the changing natural frequency of structure, live load, etc… This case is implemented with the situation when the center frequency of MTLD system $f_0$ what installed is not equal the natural frequency of structure and error about ±5% (the ratio between center frequency and natural frequency of structure is not equal 1, that value is $f_0/f$ = 0.95, 1.05). Other condition in survey take the same the case 2 and ΔR = 0.3.

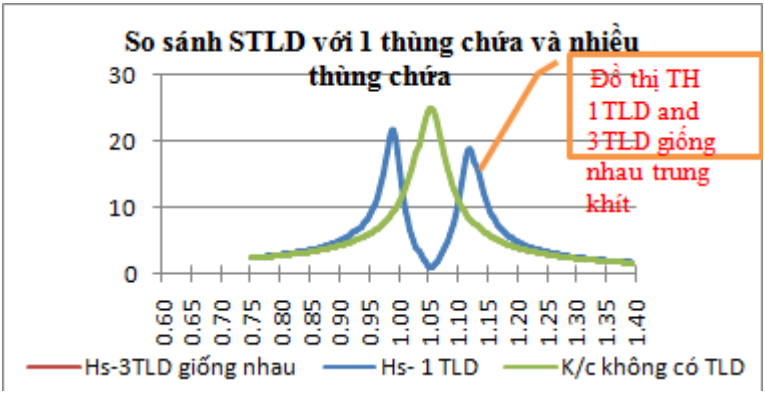
| | |
|---|---|
|  |  |
| *The fingure survey the frequency response function of MTLD system with the number of single TLD N=7, $\Delta R$=0.2, $f_0/f_s$ = 0.95* | *The fingure survey the frequency response function of MTLD system with the number of single TLD N=7, $\Delta R$=0.2, $f_0/f_s$ = 1.05* |

Turning frequency for MTLD or STLD reach to the natural frequency of structure is neccesary. This turning frequency is so sensitive to the SLTD system while MLTD system is so steady. The two peak of STLD alignment chart is changing around the value of frequency ratio 1. That two peak of STLD sustem is not remain opposite to the value of frequency ratio 1, there is one peak is larger. It means that MTLD respond to excited frequency well with certain frequency band width, and MTLD is more effective than STLD.

## 1.5 Results for survey case 4: Survey STLD using single tank and multiple tanks

With initial data as mentined in article 3.1 above, study is carried out to verify STLD using single tank and multiple tanks.

- Case 1: STLD consist of 1 tank only, mass of liquid is equal total liquid in tanks of case 2. Using transfer function of STLD;
- Case 2: STLD consists of 5 tanks with the same natural frequency and equal natural frequency of tank in case 1. Using transfer function of MTLD.

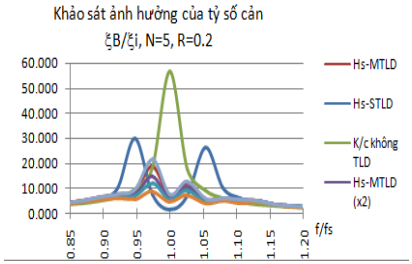
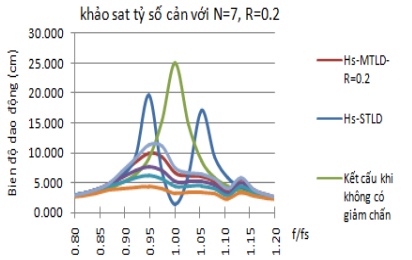



*The fingure survey the frequency response function of STLD system with the number of single TLD N=1 and N=3 (3 tanks is the same), ΔR=0.2*

## 1.6 Results for survey case 5: Survey the efectiveness of damping

**ratio parameter (the ratio between center damping ratio of MTLD system and damping ratio of structure)**

The case for survey is implemented with the number of single TLD in MTLD system N =5, 7 (the number making effective in supressing vabration well), the mass ratio μ =0.01, and frequency band width 0.2, the result as:

| | |
|---|---|
|   |   |
| *The fingure survey* the efectiveness of damping ratio parameter *of MTLD system with the number of single TLD N=5, ΔR*=0.2 | *The fingure survey* the efectiveness of damping ratio parameter *of MTLD system with the number of single TLD N=7, ΔR*=0.2 |

The difference between damping ratio of structure and MTLD is as larger as effective. The diagram is so flat with the ratio parameter is 5. It means that, using damper is one method to increase the damping for structure. However, the daming of damper is a part add to structure. The damping ratio parameter adding to structure about 0.2 – 1 is optimal effectiveness.

# CHAPTER 4
# EXPERIMENT WITH A STRUCTURE MODEL ON THE SHAKING TABLE TO EVALUATE THE EFFECTIVE IN SUPRESSING VIBRATION OF TUNED LIQUID DAMPER.

In order to determine the value of installed transfer function and the effective of MTLD system, experiment on a model to survey the behavior of structure following the frequency ratio in this chapter.

The content for research experimental including:

- Determine the model for experimental: structure, tuned liquid damper and shaking table;
- Calculating some characteristic parameters about mechanic and dynamic structure and tuned liquid damper.
- Consisdering on theory the response of structure with and without tuned liquid damper.

Using shaking table for the testing on the model structure when using MTLD. Measure the amplitude of vibration of structure with MTLD. Comparing the diagram of response of structure when analysisthe transfer function on theory and experiment. Changing solme parameters of MTLD system to survey response of structure with MTLD.

Analysis, evaluating the results from experiment and compare with the results from theory; and summary

*Experimental model: Using a model in H form, work as cantilever collumn. The natural frequency of structure in vibration analysis that take from structure analysis sofware Midas Civil 7.0.1 at first 6 mode sharp as:*

| No | Mode | Mass | Natural frequency (Hz) | Damping ratio |
|---|---|---|---|---|
| 1 | Mode 1 | 50.83 | 3.47 | 0.005 |
| 2 | Mode 2 | 50.83 | 3.94 | 0.005 |
| 3 | Mode 3 | 50.83 | 13.27 | 0.005 |
| 4 | Mode 4 | 50.83 | 28.46 | 0.005 |
| 5 | Mode 5 | 50.83 | 83.26 | 0.005 |
| 6 | Mode 6 | 50.83 | 103.03 | 0.005 |

Adjusting and determining real value of model such as: natural frequency, f = 2.85Hz; damping ratio, ξ =0.0018

Select the action force to shaking table and adjusting the shaking table.

The transfer action to shaking table is in form: $y = A\sin(wt)$ hoặc $y = A\sin(2\pi f\ t)$.

Selecting the dimension of tank of tuned liquid damper is:

L=80mm, b=60mm, và H=60mm.

I. THE PROGRESSING OF EXPERIMENT AS FOLLOWING:

1. Determine the resonance frequency of structure model: using the Sine Sweep Module (SineSweep) in the Dance sofware for control the shaking table. This program allows searching for resonance frequencies by varying the frequency (and amplitude) over a user defined range.
2. Establishing the sine function to make the initial data for the shaking table. The control function tranfer to the shaking table is in form:

$$y = A\sin(wt)$$

The frequency in above equation is selected following the natural frequency of structure model in calculation theory and such as to have the best results what used to draw the experiment circle. This experiment circle will be the basic data for compare with the theory circle. Thus, need to determine number of point in the theory circle to

make the number of sin function to transfer the shaking table with each chosen frequency. The frequency band width for shaking table is

$$0.8 \leq \frac{f}{f_s} \leq 1.2$$

The number value point of requency is larger , the experiment is more exactly. However, the woking for expperiment is big, thus suitable point is 9 with the value as:f/fs= 0.8; f/fs= 0.85; f/fs= 0.9; f/fs= 0.95; f/fs= 1; f/fs= 1.05; f/fs= 1.1; f/fs= 1.15;f/fs= 1.2. It mean that the frequen cy input the sofware to control the shaking table as: f = 2.603; 2.776; 2.95; 3.123; 3.29; 3.47; 3.64; 3.82; 4.0; 4.16 Hz. (fs is the real natural frequency that determined in section 1).

3. More cases to survey also implemented in the shaking table. However, the limited value of the intrusment (accelerometer and displacement), the excited amplitude A = 0.1. Defficult to survey the effect of excites amplitude in this condition. And this is the limit of experiment working.

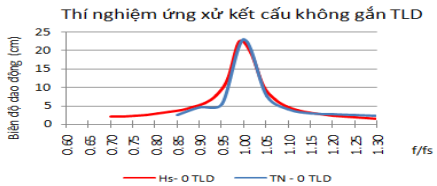
Detail cases for experiment as:

– Case 0: transfer to shaking table 9 the frequency in 9 sin function for the structure model without TLD.
– Case 1 to 7: The structure model with TLD (STLD and MTLD). Cases is in order to survey the effective of number TLDs, changing the frequency band width ΔR at the number of TLDs N =3, The ratio between the center frequency of MTLD and the natural frequency of structure at the number of TLDs N =7.

II. ANALYS THE DATA FROM THE EXPERIMENT AS FOLLOWING:

All cacse will be the comparation with 2 lines including: theorical line and experimental line.

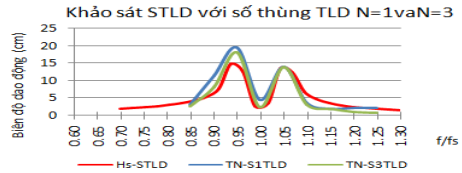
**Detail cases as following:**




**Case 0** – Determine the displacement of structure model for experimental without TLD.

In case of structure without TLD, theorical line and experimental line are the same form of diagram.The value of response of structure without TLD is close when comparation between theorical and experimental diagram.

### *4.6.1. The result for the case of structure with 1 TLD and multi similar TLD in system (single tuned liquid damper)*

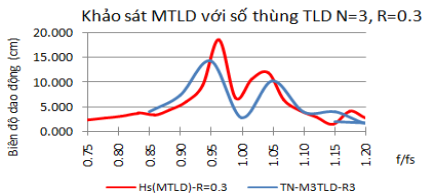



**Case 1a and 1b** – Determine the displacement of structure model for experimental with 1 TLD and 3 TLD (3 tank in TLD system with the same frequency.

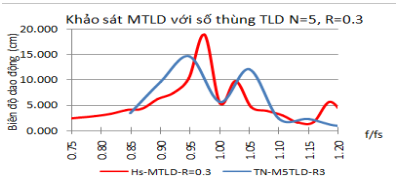
The result in 2 case show that: the form of 2 cases is similar, however the value is small difference. The reason for this is there is an error in fabrication stage of TLD tank, the liquid depth inside tank.

### *4.6.2. The result of suppressing vibration for structure when investigating the efficient of number tank in MTLD*

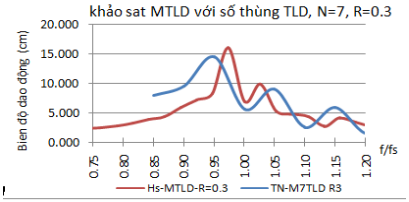
Case 2a – Determine the displacement of structure for 3 difference TLD tank with 3 frequencies value (3 tank have 3 liquid depth in MTLD). The frequency band width $\Delta R=0.3$.



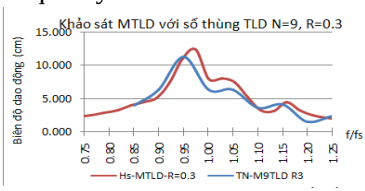
Case 2b - Determine the displacement of structure for 5 difference TLD tank with 5 frequencies value (5 tank have 5 liquid depth in MTLD). The frequency band width ΔR=0.3.



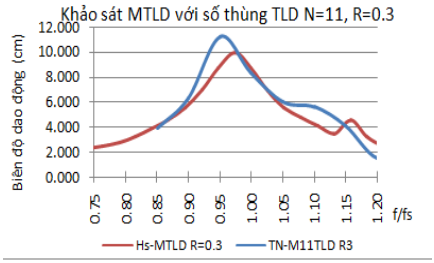

Case 2c - Determine the displacement of structure for 7 difference TLD tank with 7 frequencies value (7 tank have 7 liquid depth in MTLD). The frequency band width ΔR=0.3.



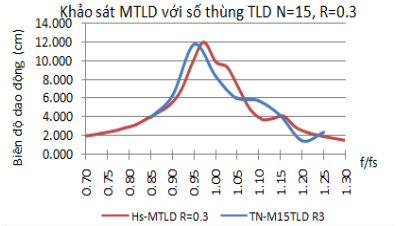

Case 2d - Determine the displacement of structure for 9 difference TLD tank with 9 frequencies value (9 tank have 9 liquid depth in MTLD). The frequency band width ΔR=0.3




Case 2e - Determine the displacement of structure for 11 difference TLD tank with 11 frequencies value (11 tank have 11 liquid depth in MTLD). The frequency band width ΔR=0.3



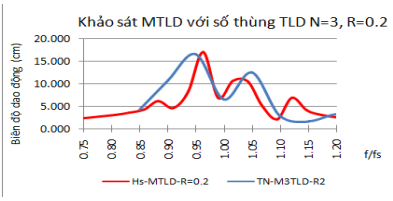
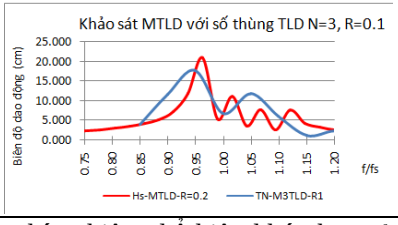

Case 2f - Determine the displacement of structure for 15 difference TLD tank with 15 frequencies value (15 tank have 15 liquid depth in MTLD). The frequency band width ΔR=0.3




The diagrams of all above cases investigated the affectiveness of number of tanks in MTLD system to the efficient in suppressing vibration for structure model are similar form with diagram in theorical analysis. The response of

structure at the position of frequency ratio 1 is so close. As far from this value the response of structure is so difference. This result show again that the suitable number of tank in MTLD that structure have the most efficient in suppressing vibration is N =5-11 tanks.

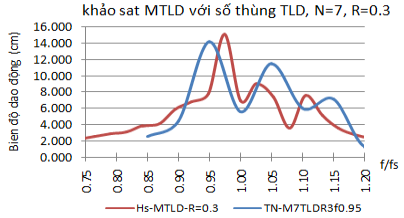
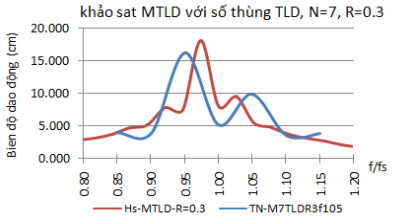
### *4.6.3. Kết quả khảo sát ảnh hưởng của bề rộng dải tần số của giảm chấn chất lỏng đa tần số MTLD đến hiệu quả giảm dao động*

| | |
|---|---|
| **Trường hợp 3a** - Trường hợp có 3 thùng giảm chấn chất lỏng TLD khác nhau (3 thùng được đổ lượng chất lỏng khác nhau), bề rộng dải tần số thay đổi so với trường hợp 2a, lấy là ΔR=0.2.   | **Trường hợp 3b** - Trường hợp có 3 thùng giảm chấn chất lỏng TLD khác nhau (3 thùng được đổ lượng chất lỏng khác nhau), bề rộng dải tần số thay đổi so với trường hợp 2a, lấy là ΔR=0.1.   |

Khi bề rộng dải tần số thay đổi dữ liệu thí nghiệm thể hiện khá nhạy cảm với sự thay đổi này. Đường thực nghiệm có dạng giống đường lý thuyết tuy nhiên với ít đỉnh giá trị hơn. Điều này có thể được giải thích do việc hạn chế khi thực hiện thí nghiệm với số điểm kích động chưa đủ nhiều nên chưa thể hiện được các biến đổi của đồ thị.

### *4.6.4. Khảo sát giảm chấn chất lỏng đa tần số MTLD với tỷ số giữa tấn số trung tâm của giảm chấn chất lỏng đa tần số MTLD và tần số dao động riêng của kết cấu không bằng 1 khi số lượng thùng chứa chất lỏng N= 7 TLD.*

Khi tỷ số tần số giữa tần số kích động với tấn số dao động riêng của kết cấu không bằng một, đường đồ thị thực nghiệm thể hiện khá nhạy cảm với sự thay đổi này. Dạng của đường đồ thị thí gnhiệm và lý thuyết là khá phù hợp.

| | |
|---|---|
| **Trường hợp 4a**: Trường hợp có 7 thùng TLD (khác nhau), bề rộng dải tần số ΔR=0.3 và tỷ số giữa tần số trung tâm của giảm chấn chất lỏng MTLD và tần số dao động riêng của kết cấu f/fs =0.95.   | Trường hợp 4b: Trường hợp có 7 thùng TLD (khác nhau), bề rộng dải tần số ΔR=0.3 và tỷ số giữa tần số trung tâm của giảm chấn chất lỏng đa tấn số MTLD và tần số dao động riêng của kết cấu f/fs =1.05.   |

Kết luận chương 4: Độ chính xác của hàm ứng xử tần số lý thuyết đã thiết lập, việc thí nghiệm mô hình cột trên bàn rung chịu tác động kích động của các tần số dao động khác nhau được thực hiện. Mô hình cột thép được thiết kế, mô hình hóa phân tích trên phần mềm và sau đó được chế tạo lắp đặt các đầu đo và đặt trên bàn rung. Kết quả thu được từ việc đo đạc được phân tích trên phần mềm Matlab và đường thực nghiệm được vẽ lại để đối chiếu với đường lý thuyết đã thiết lập.

**Conclusion:**

The efficient of the transfer function is estimeted. An experiment on structure model under range frequency of external force was implemented. The results data is analysed by Matlab sofware and the experimental diagram is re-drawn and compared with the theorical diagram.

The effective of number TLDs, changing the frequency band width ΔR and the ratio between the center frequency of MTLD and the natural frequency of structure surveyed for the structure model in H form. The effective suppresing the vibration for structure without TLD and with

SLTD, MTLD is determined via cases experimet in the shaking table. The experiment circle show that the effective suppresing the vibration for structure with TLD is more clear without TLD, and with MTLD is the better than wth SLTD. This results is suitable with the theorical analys, the error is about 11% that can be accepted. The circle response of MTLD is so flat with number of TLD is 7 and 9. This flat is so small phase diference between the motion of liquid inside each tanks of MTLD. The accuracy of the installed transfer function is evaluated via the experiment . The results in experiment is suitable for the theorical analysis results.

# CHAPTER 5
# APPLICATION TUNED LIQUID DAMPER FOR STAYED CABLE BAI CHAY BRIDGE – VIET NAM

Bai chay stayed cable Bridge is a single cable stayed with longest main span in the world 435m. The pylon of Birdge is in a column form with 143meters heigh, and slender. To reduce the wind action, a tuned liquid damper (TLD) system installed for the pylon of Bai Chay Bridge in 2006 before bridge open .

Detail some characteristics of current TLD as following:

- Firstly, determining the natural frequency of the pylon is the most important problem for design TLD. This frequency is determined by 2 ways: using structure analysis sofware and vibration test. The results show that the frequency that used for design this damper is f = 0.1886Hz (using the data from structure analysis sofware). The frequency that determined from the vibration test for Bai Chay Bridge by Shimizu institude is f = 0.2Hz. The main frequency, firstly used for design TLD is Tuned frequency of TLDs $f_L$ = 0.1886Hz. This means

that designing TLD need to modify following the real frequency mesured from the vibration test for the Bai Chays Bidge tower.

- In fact, There are 4 types of tanks in here. The dimension of each tanks is the same length and changed the width from 200-500mm:
    - ✓ TLD type 1 with L=1400, B= 500mm
    - ✓ TLD type 2 with L=1400, B= 400mm
    - ✓ TLD type 3 with L=1400, B= 300mm
    - ✓ TLD type 4 with L=1400, B= 200mm

For adjusting the mass ratio for TLD system and tower, each type of this dimension tank used a lot of layers to ensure the mass ratio in design TLD. The mass ratio used in design is $\mu_L = m_L/m_S = 0.0047$.

- However, changing the width of tank is not meaning for changing the dominant frequency of TLD system. There is only one frequency used for design TLD in Bai Chay Bridge. Thus, this TLD damper system is a single tuned liquid damper (STLD).
- Longitudunal height of the pylon, number of layers of TLD is installed for mode 1 in designing TLD system. Design TLD is implemented following each construction stage of Bridge. For each stage, number of layers of each type of TLD is installed corresponding segment of tower in construction stage.
- Detail some other parameters for design tuned liquid damper for Bai Chay Bridge tower as:
    - ✓ Liquid depth $h_0$= 2.85cm
    - ✓ Total liquid mass in TLD $m_L$ = 2.726T
    - ✓ Modal mass of tower $m_s$ = 585.2T
    - ✓ Structure damping of tower $\xi_s = 0.0031$
- 4 types of TLD installed in Bai chay Bridge were installed by

construction stage at difference position longitudunal of pylon.Detail as:

Stages 36-43: group 4 with 96 layers of TLD type 1;

Stages 30-35: group 1 with 70 layers of TLD type 2;

Stages 23-29: group 2 with 70 layers of TLD type 3;

Stages 16-22: group 3 with 86 layers of TLD type 4;

Stages 14-15: group 4 with 22 layers of TLD type 1.

Even total of 344 layers TLD is arranged along the height of pylon from the construction stage 14 to stage 42 which far from the top of pylon 1.875m. However, the natural frequency for all layers are the same, thus this is STLD system.

The number of layers in each position (each stage for installing the TLD) is calculated depend on the dimension inside pylon at that position. The largest number layers of TLD is installed in stage 42 with 36 layers of TLD type 1.

The current TLD design for Bai Chay Bridge is optimal solution to suppressing the vibtaion for the tower. However, for the research purpose, it is necessary to investigate more some case with changing the arranged position of TLD to have the efficient application of TLD. Especially, in case of investigating the ratio between each mass of single TLD in MTLD system and total liquid mass of TLD system and modal mass of structure. Finally, investigating the efficient in reducing vibraton with the natural frequency of structure from the vibration test for Bai Chay Bridge is used for design MTLD system.

Detail contents as following:

1- research on STLD system

- the tower without TLD;
- The tower with current TLD at Bai Chay Birdge;

- Investigate in reducing certain number of TLD along tower from the low level to top of tower or ignore some TLD in odd stage to extent the distant between TLD stage.

2- research on MTLD system

- Try to change the current STLD system to the MTLD system with N=5 tanks (5 difference frequency);
- Resrearch the efficient of tower with MTLD system and compare with the current STLD system at Bai Chay bridge;
- Research on the interaction about mass between center frequency TLD and other frequency TLD for determine the efficient of TLD in arrange the TLD system.

Both researches is implemented in 2 case; with natural frequency of tower from the structural analysis sofware (fs=0.1886 Hz) and with natural frequency of tower from the vibration test for the Bai Chay Bridge (fs=0.2 Hz).

**Consideration contents for investigating the efficient of TLD application for the Bai Chay Bridge.**

All consideration contents is presented with using the transfer function analysis and including 2 parts;

- ✓ part 1: research on efficient of TLD system for Bai Chay Bridge using calculated natural frequency of tower, the center frequency of designed MTLD $f_0$ = 0.1886Hz.
- ✓ Part 2 research on efficient of TLD for Bai Chay Bridge using natural frequency of tower determined from the vibration test, the center frequency of designed MTLD $f_0$ = 0.2Hz

***2.1 – Research on efficient of TLD system for Bai Chay Bridge using calculated natural frequency of tower , the center frequency of designed***

***MTLD $f_0$ = 0.1886Hz***

*2.1.1. Investigating with the STLD system*

Some cases will be investigated to have the behavior of pylon with and without some TLD in some stage. Detail as:

- Case 1: diagraph of the response of pylon without TLDs;
- Case 2:diagraph of the response of pylon without TLD at stages 14-15;
- Case 3: diagraph of the response of pylon without TLD at stages 14-22;
- Case 4: diagraph of the response of pylon without TLD at stages 14-29;
- Case 5: diagraph of the response of pylon without TLD at stages 14-35;
- Case 6: diagraph of the response of pylon without TLD at stages 14-42;
- Case 7: diagraph of the response of pylon without TLD odd stages (arrange spacing layout);

The efficiency of current TLDs at tower of Bai Chay Bridge estimated by using the transfer function for all case as fig 5.1.

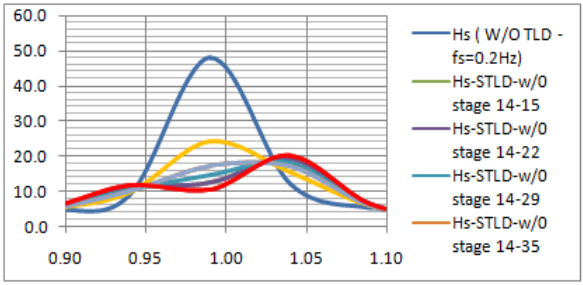



*Fig 5.1 – diagarm for cheching the efficient in suppressing vibration for tower of Bai Chay without some installed TLD at some position.*

It is very clearly that the TLD system have the most efficient when arrange such as the current STLD at Bai Chay Bridge. That is a optimal solution for suppressing vibration for tower of Bai Chay Bridge. If investigating with ignore some TLD at certain stages, the efficient in reducing vibration is lower. Especially, if ignore TLD at stages at the

top of tower (final stages construction), the efficient in supressing vibration for the tower is lowest with 1 peak line in diagram like the form of diagarm without TLD. It mean that this arrange alternative make low efficiency.

**Conclusion:**

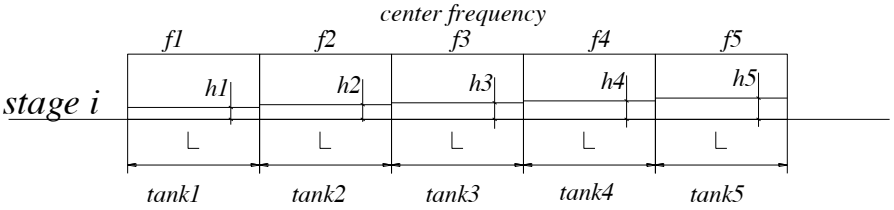
- The efficient of TLD is more clearly than original dynamic response of tower (without TLDs).
- Number of TLDs and the installed position affect so sensitive to behavior of structure.
- At mode 1 which used for design TLD, number of TLD as near top of tower as affect to efficient in sppressing vibration of tower.
- It is necessary to investigate more cases to consider the capacity modify TLD system to have the higher efficient in suppressing vibration for tower.

*2.1.2. Investigating with the MTLD system*

In this section, research on MTLD application for Bai Chay Bridge is implemented with investigating the number of Single TLD in MTLD system N=5. This result will compare with the efficient of current STLD at Bai Chay Bridge. Detail some information of MTLD system as:

- Number of single TLD in MTLD system N =5.
- The center frequency equal to the natural frequency of structure f=0.1886 Hz;
- Frequency band width $\Delta$R=0.2.
- Equal frequency spacing $\beta$=0.094 Hz;
- The dimension of 5 tanks are the same as 1400x500 mm.
- The difference frequency is installed by modify the liquid height inside each tank in each group of 5 tanks.

Group of 5 tanks in each installed position as following:




The dominant frequency used for design MTLD to ensure the center frequency of MTLD system $f_0=f_3$ and equal the natural frequency of Structure $f_s$. The frequency and the liquid height inside each tanks of group 5 tanks as:

| | group | frequency (Hz) | Liquid height (cm) | Damping ratio - ξ |
|---|---|---|---|---|
| 1 | Gr-TLD 1 | 0.16974 | 2.301 | 0.031 |
| 2 | Gr-TLD 2 | 0.17917 | 2.563 | 0.027 |
| 3 | Gr-TLD 3 | 0.18860 | 2.839 | 0.024 |
| 4 | Gr-TLD 4 | 0.19803 | 3.129 | 0.022 |
| 5 | Gr-TLD 5 | 0.20746 | 3.433 | 0.019 |

Investigating the response of structure by using the transfer function in cases as following:

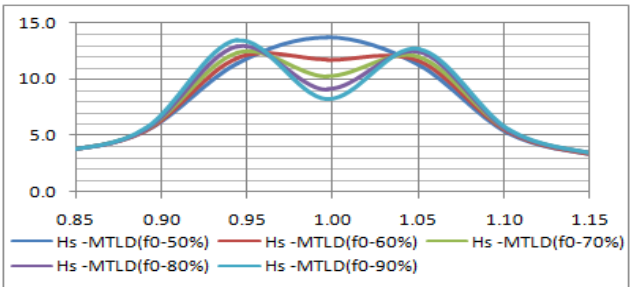
| No | group | Rate % of liquid weight on each group of tank | | | | |
|---|---|---|---|---|---|---|
| | | diagram 1 | diagram 2 | diagram 3 | diagram 4 | diagram 5 |
| 1 | Gr-TLD 1 | 2 | 5 | 5 | 10 | 10 |
| 2 | Gr-TLD 2 | 3 | 5 | 10 | 10 | 15 |
| 3 | Gr-TLD 3 | 90 | 80 | 70 | 60 | 50 |
| 4 | Gr-TLD 4 | 3 | 5 | 10 | 10 | 15 |
| 5 | Gr-TLD 5 | 2 | 5 | 5 | 10 | 10 |

In this system, total liquid mass $m_L = m_1+m_2+m_3+m_4+m_5$. Assume that each mass $m_i$ hold a certain scale in total liquid mass.***The question is How this each single TLD (each mass $m_i$) affect to the response of system if each mass hold difference scale in total mass***. Thus, it is necessary to investigate the affect the structure response when scale of

each liquid mass in a tank in MTLD system compare with the modal structure mass changing. Detail as:

- ✓ Case 1: liquid mass for the center frequency tank, m3 is selected 50% of total liquid mass in MTLD system. Other frequency tank is m1(10%), m2(15%), m4(15%), m5(10%).
- ✓ Case 2: liquid mass for the center frequency tank, m3 is selected 60% of total liquid mass in MTLD system. Other frequency tank is m1(10%), m2(10%), m4(10%), m5(10%).
- ✓ Case 3: liquid mass for the center frequency tank, m3 is selected 70% of total liquid mass in MTLD system. Other frequency tank is m1(5%), m2(10%), m4(10%), m5(5%).
- ✓ Case 4: liquid mass for the center frequency tank, m3 is selected 80% of total liquid mass in MTLD system. Other frequency tank is m1(5%), m2(5%), m4(5%), m5(5%).
- ✓ Case 5: liquid mass for the center frequency tank, m3 is selected 90% of total liquid mass in MTLD system. Other frequency tank is m1(2%), m2(3%), m4(3%), m5(2%).

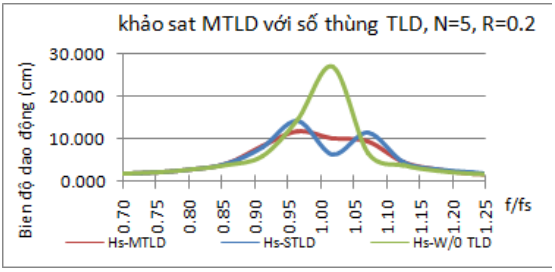
Investigated results as following:




In this figure, the efficient of MTLD at liquid mass scale have center frequency occupy 50% with 1 peak like the figure of system without TLD figure form. When this scale increase, this line become 2 peak more clearly and the response value at frequency ratio equal 1 is smaller.

The result from analys the response function of structure – MTLD

interaction system. Analys the response of tower for the designed case as following:




In this paragraph, It is easy to recognize that the efficient of MTLD is more clearly than STLD with the same initial data.

Mass scale in design is ensured by using layers for all tanks in MTLD system. The number of each tanks is difference in each group of 5 tanks and each position. Detail as:

| Tank | liquid mass in 1 tank | Liquid mass | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | stage 42 | mode 1 0.993 | stage 39 | 0.845 | stage 36 | 0.744 | stage 30 | 0.552 | stage 25 | 0.415 | total liquid mass (T) |
| m1 = | 0.016 | 1 | 0.016 | 1 | 0.014 | 1 | 0.012 | 1 | 0.009 | 1 | 0.007 | 0.057 |
| m2 = | 0.018 | 14 | 0.249 | 10 | 0.152 | 10 | 0.133 | 10 | 0.099 | 12 | 1.242 | 1.876 |
| m3 = | 0.020 | 18 | 0.355 | 12 | 0.201 | 12 | 0.177 | 10 | 0.110 | 18 | 2.654 | 3.498 |
| m4 = | 0.022 | 2 | 0.044 | 1 | 0.019 | 1 | 0.016 | 1 | 0.012 | 1 | 0.018 | 0.108 |
| m5 = | 0.024 | 1 | 0.024 | 1 | 0.020 | 1 | 0.018 | 1 | 0.013 | 1 | 0.010 | 0.085 |
| | **Total** | **36** | **0.688** | **25** | **0.405** | **25** | **0.357** | **23** | 0.243 | **33** | 3.931 | **5.624** |
| | | | | | | | | | | **total layers** | | **142** |

MTLD system will be installed in 5 positions; at stage 42, stage 39, stage 36, stage 30 and stage 25 following mode 1 in design. At each position,

there will be 1 group of MTLD with 5 single TLDs with 5 difference frequency in designed frequency band width. This mean that, at each position there will be 5 frequency of 5 tanks in MTLD system. The designed center frequency $f_0$ is 0.1886Hz similar with the current STLD at the Bai chay Bridge. At each stage, the number layers of each single TLD in 1 group is difference. The number layers of center frequency tank is largest. At stage 42, there will be 36 layers including 18 layers of the center frequency tanks $f_0$ = 0.1886Hz, 14 layers for the $m_2$ tank to modify the efficient of MTLD system (modify 2 peak of figure to have the same value). The same explaination for the group 2 to group 5.

With this way for arrange MTLD system along the height of tower, the efficient of system increase and the total number layers descrease compare with the current STLD at Bai Chay. It is so clearly to reduce the layers of single TLD for Bai Chay Bridge when using replaced MTLD system.

**Conclusion**

- The efficient of MTLD as good as the certain scale of liquid mass of center frequency tank. The most efficient of MTLD at the scale of mass of center frequency tank is about 60%.
- To make this scale for the center frequency, using certain number layers of tank that have the same center frequency to ensure the liquid mass ratio.
- When increase or descrease difference numer of layers (scale) of center frequency tank, 2 peak of curve is not equal. This mean that we can not reach to the optimal value in efficient supressing vibraion for structure.

***2.2 – Research on efficient of TLD system for Bai Chay Bridge using natural frequency of tower from the vibration test, the center frequency of designed MTLD f0 = 0.2Hz***

The vibration test in Bai Chay Bridge show that the dominant frequency of pylon is 0.2Hz.

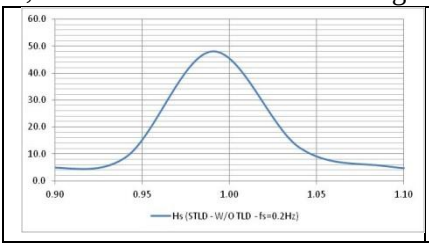
Detail frequency of first 6 mode in analysis by Midas Civil sofwere as :

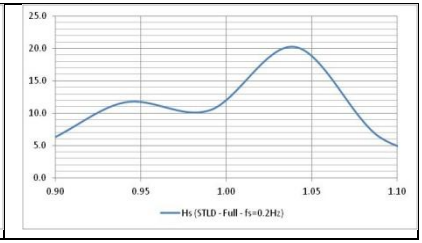
| STT | Mode | Frequency (Hz) |
|---|---|---|
| 1 | Mode 1 | 0.1935 |
| 2 | Mode 2 | 0.2054 |
| 3 | Mode 3 | 0.2499 |
| 4 | Mode 4 | 0.3177 |
| 5 | Mode 5 | 0.4547 |
| 6 | Mode 6 | 0.6562 |

The dominant frequency is selected for new design MTLD system is f= 0.2Hz (mode1).

*2.2.1. Investigating with the STLD system*

Calculating the response of tower in cases: Case 1: structure without TLD; Case 2: structure with full designed TLD;




**Conclusion:**

The figure show that when changing the frequency for design TLD from 0.1886 to 0.2Hz, the results affect so large to the response of displacement of tower compare the case with or without TLD.

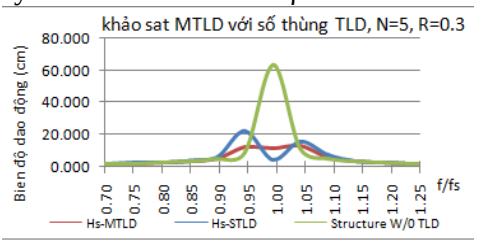
*2.2.2. Investigating with the MTLD system*

The dimension tank of TLD and the number of layers tanks with the same frequency in group of 5 tanks of MTLD system in each construction stage TLD is selected depend on the dimension of pylon at that stage.

TLD for Bai Chay Bridge is rectangular tuned liquid damper form. The dimension of tank is selected similar to the dimension of current TLD at Bai Chay bridge as: L = 1400mm, B=500mm, h=80mm. The dominant frequency for design MTLD (the center frequency) $f_0$= 0.2Hz.

**Detail some other parameters for design MTLD for the tower of Bai Chay Bridge:**

| | |
|---|---|
| Liquid mass in TLD | $m_L$ = 2.876T |
| Modal mass of tower | $m_s$ = 585.2T |
| Structure damping of tower | $\xi_s = 0.0031$ |
| Liquid mass ratio | $\mu_L = m_L/m_S = 0.005$ |
| The frequency band width | $\Delta R = 0.2$ |
| Spacing frequency | $\beta = 0.015$ |




The figure show that the efficient of MTLD in suppresing vibration for the tower is better than STLD clearly. Detail some parameters for design MTLD:

| No | group | frequency (Hz) | Liquid height (cm) | Damping ratio - ξ | Liquid mass in 1 tank |
|---|---|---|---|---|---|
| 1 | Gr- 1 | 0.180 | 2.586 | 0.027 | 0.018 |
| 2 | Gr- 2 | 0.190 | 2.881 | 0.024 | 0.020 |
| 3 | Gr- 3 | 0.200 | 3.191 | 0.021 | 0.022 |
| 4 | Gr- 4 | 0.210 | 3.517 | 0.019 | 0.025 |
| 5 | Gr - 5 | 0.220 | 3.858 | 0.017 | 0.027 |

There are 5 tanks in each of 5 groups in MTLD system. Each group of 5 tanks will arranged at some position following constructure stages similar

to designed current STLD at Bai Chay bridge. However, the first time in this report, investigating each group of MTLD applying for tower of Bai Chay for each position with using the ratio between liquid mass of each single TLD in MTLD system and modal mass of structure, especially.

Detail mass scale of each single TLD in MTLD system and number of stage for install MTLD for Bai chay Bridge as:

| group | stage 42 | | stage 40 | | stage 37 | | stage 33 | | stage 30 | | stage 25 | | stage 22 | | total liquid mass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mode 1 | 0.9933 | | 0.8799 | | 0.7768 | | 0.6434 | | 0.5517 | | 0.4146 | | 0.3417 | |
| Gr - 1 | 1 | 0.018 | 1 | 0.016 | 1 | 0.014 | 1 | 0.012 | 1 | 0.012 | 1 | 0.007 | 1 | 0.006 | 0.084 |
| Gr - 2 | 2 | 0.040 | 1 | 0.018 | 1 | 0.016 | 1 | 0.013 | 1 | 0.026 | 1 | 0.007 | 1 | 0.007 | 0.126 |
| Gr - 3 | 10 | 0.222 | 8 | 0.157 | 8 | 0.139 | 8 | 0.115 | 6 | 0.857 | 6 | 0.391 | 6 | 0.046 | 1.927 |
| Gr - 4 | 8 | 0.196 | 2 | 0.043 | 2 | 0.038 | 2 | 0.032 | 2 | 0.252 | 2 | 0.036 | 2 | 0.017 | 0.613 |
| Gr - 5 | 1 | 0.027 | 1 | 0.024 | 1 | 0.021 | 1 | 0.017 | 1 | 0.017 | 1 | 0.010 | 1 | 0.009 | 0.125 |
| **Total** | **22** | **0.502** | **13** | **0.258** | **13** | **0.228** | **13** | 0.18867 | **11** | 1.163 | **11** | 0.451 | **11** | **0.085** | **2.876** |

**Conclusion of chapter 5**:

- MTLD is so sensitive with changing frequency to response of structure system. With a small variable of dominant frequency for design TLD (this frequency is ussually used following the natural frequency of structure), the behavior of structure is variable clearly.
- At the designed frequency for MTLD 0.2Hz, parameters of MTLD is variable clearly compare with the case of frequency 0.1886Hz such as liquis height, freuqency and damping ratio of each tank of group 5 tanks in MTLD system.

The efficiency in suppressing vibration of MTLD increase while total number of layers of MTLD is 94 layers, reduce 250 layers from the current TLD 344 layers. This mean that it can be save material in design damper for the tower of Bridge and also ensure the efficiency suppressing

vibration of structure when using MTLD system.

## CONCLUSION

This thesis have completed with achieve results conforming with objectives as follows.

- Research theory, proposed multi-degree of freedom model of computing interaction between MTLD and structure.
- Establish the transfer function reflect behavior of structure versus frequency ratio between MTLD ($f_i$) and $f_s$ structure.
- Comparision effectiveness of STLD and MTLD in supression vibration of structure.
- Optimum some parameters of MTLD.
- Application of TLD in a stayed cable bridge in Viet Nam (Bai Chay bridge).
- The theorical results are compared with the experimental data what mesured on the structure model in H form.
- In all case, the form of alignment chart of theorical analysis and experimental data on structure model for experiment is similar.
- The error between the experimental data and calculated data is about 11% that can be accepted.
- The circle response of MTLD is so flat with number of TLD is 7 and 9 that can be explained by small phase diference between the motion of liquid inside each tanks of MTLD.
- The accuracy of the installed transfer function is evaluated via the experiment . The results in experiment is suitable for the theorical analysis.

**For the Bai Chay Bridge:**

- MTLD is so sensitive with changing frequency to response of

structure system. With a small variable of dominant frequency for design TLD (this frequency is ussually used following the natural frequency of structure), the behavior of structure is variable clearly.

- At the designed frequency for MTLD 0.2Hz, parameters of MTLD is variable clearly compare with the case of frequency 0.1886Hz such as liquis height, freuqency and damping ratio of each tank of group 5 tanks in MTLD system.
- The efficiency in suppressing vibration of MTLD increase while total number of layers of MTLD is 94 layers, reduce 250 layers from the current TLD 344 layers. This mean that it can be save material in design damper for the tower of Bridge and also ensure the efficiency suppressing vibration of structure when using MTLD system.