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Passive Control in Baffled Liquid storage Tank under Bi-directional Earthquakes

S. Vern [1, *], M. K. Shrimali [2], S. D. Bharti [3], A.S. Vibhute [1]

[1] National Center for Disaster Mitigation and Management, Research Scholar, Malaviya National Institute of Technology, Jaipur, 302 017, India
[2] National Center for Disaster Mitigation and Management, Professor, Malaviya National Institute of Technology, Jaipur, 302 017, India
[3] National Center for Disaster Mitigation and Management, Professor, Malaviya National Institute of Technology, Jaipur, 302 017, India

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Abstract

A comprehensive study of a 3D baffled concrete liquid storage tank (LST) is conducted to find out the maximum reduction in responses of the LSTs under a set of important parametric variations. They include (i) the type of earthquake; (ii) the optimum position and number of coupled baffles (top-mounted and bottom supported); and (iii) the angle of incidence earthquakes. Further, the percentage reductions of different responses of interest for the optimum baffled LST are investigated. The numerical study is performed in ABAQUS software for a square LST of 6m X 6m X 4.8m having a water height of 3.6m. The response quantities include the maximum mean values of base shear, overturning moment, top board displacement, hydrodynamic pressure, and sloshing height. The results of the study show that (i) with the optimum arrangement of baffles, significant reduction of in the sloshing height can be achieved; (ii) the type of earthquake does not have significant effect response reductions; and (iii) both PGA and angle of incidence of the earthquake have a moderate effect on response reductions.

Keywords: liquid storage tank, baffles, bi-directional ground motion, ALE-FE, passive control

1. Introduction

During an earthquake event, the sloshing of the fluid inside the liquid storage tanks (LSTs) has a governing effect on its durability and operability. Failures in LSTs can cause the leakage or spillage of hazardous chemicals in the nearby surrounding that can have long-lasting ecological effects, especially when these LSTs are used in the chemical and nuclear industries. During an earthquake, many LSTs experienced sloshing heights of enormous scale, facilitating the unbalanced forces that can make LSTs structural strength susceptible to damage or even destruction. To limit the chances of the damage in the LSTs, they are typically given with enough freeboard that enables the fluid to freely move inside the LST, but it adds to the hazardous and economically unviable design of LSTs.

Housner [1,2] gave the most generally accepted empirical theory for the seismic analysis of the LST. Later, the huge seismic experimental setup supported not only the previous analytical studies but also dramatically improved numerical methods [3-8]. With the innovations in the finite element method (FEM), several analyzes were carried out using FEM to verify the response in LSTs under the seismic ground vibrations [9–14]. Further, FEM based software was systematically used to resolve the fluid-structure interaction problem in LSTs during earthquake excitations [15,16].

Several of the earlier works on the impact of baffles in LSTs were conducted by Evans and Mciver [17]. Many researchers have studied the effect of the baffle on the cylindrical three-dimensional LST. The solution was adapted for seismic excitations that prove that ring baffles were more efficacious in decreasing sloshing height [18–20]. The impact of the vertical baffle plates in a rectangular tank undergoing earthquake excitations and periodic base vibration was explored by Goudarzi and Danesh [21]. It was concluded that the actual sloshing height can be substantially decreased by applying the baffle plates. The effects of the suspended annular baffle (SAB) on a cylindrical LST was analyzed by Hosseini et al. [22] by using experimental and analytical studies. The results showed that an average reduction of 35% and 90% under cyclic loads and seismic excitation could be achieved for the sloshing height respectively. They examine the impact of baffles on the rectangular LSTs' resonance frequency. Cheng et al. [23] had already described the impact of a single perpendicular baffle blade on the dynamic hydrostatic forces of the rectangular LST in earthquake ground motions. The study was performed with the aid of the potential velocity function to be optimized the hydrodynamic pressure coefficient. It was suggested that a single baffle should be used to control hydrodynamic pressure and sloshing movements. The placement of the baffle blade must be at the center of the tank with a width less than that of the thickness of the LST wall for a safe and cost-effective design.

The present study investigates the effectiveness of the two arrangements of the top and bottom-mounted vertical baffles in the mitigation of the seismic responses. The behavior of the baffled 3D square concrete LST under the bi-directional earthquake excitation is investigated under the set

*Corresponding author. Tel: +919717759027; E-mail address: sourabh.vern@gmail.com

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of important parameters. They include variation in the type of earthquakes, PGA, optimum locations of the top and bottom baffles, and the angle of incidence of the earthquake. The response quantities of interest are shear force, overturning moment, sloshing height, and hydrodynamic pressure on the LST.

2. Theory

In the present study, the LST is designed for gravity and seismic loads, the bottom of the LST is assumed to be resting on the hardened concrete floor. The computation of seismic responses in the LST involves a complicated fluid-structure interaction (FSI), which gets further computationally costly when the baffles are introduced in it. To maintain the continuous flow in the simulation of the fluid under the seismic excitation of the solution involves the use of the adaptive meshing and arbitrary lagrangian and eulerian (ALE) technique. The operation of the ALE method involves the use of both Lagrangian and eulerian formulation. The basic operation of the ALE technique can be divided into two parts. In the initial phase, the mesh is treated as the lagrangian element in which the material remains confined inside the mesh boundaries and the mass is conserved. After the lagrangian phase, a split operator is used which shifts the behavior of the mesh to the eulerian elements, in which material is allowed to flow through the mesh after which an advection part calculate the transfer of mass, change in the internal energy, and momentum across the boundaries which helps in the development of the new mesh and finally shifts mesh to lagrangian elements. The governing equilibrium equation of the lagrangian phase is given by Eqs. (1-2)

$$\rho \frac{\partial v_i}{\partial x_i} = \sigma_{ij,j} + \rho b_i \tag{1}$$

$$\rho \frac{\partial E}{\partial x_i} = \sigma_{ij} v_{i,j} + \rho b_i v_i \tag{2}$$

2.1 Tank and fluid modeling

The behavior of the liquid under the earthquake excitation is modeled in the ABAQUS which uses the Navier-Stokes equation. In the present study, the use of the Mie-Gruneisen equation of the state is used which holds a linear behavior with the energy form of the liquid, as represented by Eq.4.

$$p - p_H = \rho\Gamma(E_m - E_H) \tag{3}$$

Here, p is the pressure stress, ρ is the density of the fluid, $p_{H,}$ and E_m are known as the Hugoniot pressure and the specific energy as the density function, whereas Γ and E_H are known as the Gruneisen ratio and Hugoniot energy. For solving the difficult Mie-Gruneisen EoS curve fitting values are used which are derived from the Hugoniot data which is shown as in Eq. 4

$$\mathrm{U}_s = c_0 - sU_p \tag{4}$$

In which c_0, s, $U_{s,}$ and U_p are the speed of sound on the medium, material constant, shock, and particle velocity respectively. By using Equation 3 and 4 the final form of the EoS comes out to be:

$$p_H = \frac{p_0 c_0^2 \eta}{(1-s\eta)^2}\left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m \tag{5}$$

For the present analysis, the LST and water are modeled by the help of the eight nodded linear brick element(C3D8R) with the reduced integration but with different hourglass, control is available in the explicit operator. Another advantage of using an explicit timer integration technique is that it uses the large deformation theory which can manage the large deformation and rotations of the elements in the LST.

3. Numerical Study

A 6m X 6m X 4.8m flexible concrete square LST is investigated in the present study. The LST is primarily used in the chemical industries.

The LST is attached to the rigid base. The wall and baffle thickness are taken as 0.3m and 0.15m. The various material properties of the LST and fluid are shown in Table 1. Different dimensions of the hybrid LST and its baffle arrangement are shown in Fig.1.

The LST is evaluated for various important parameters which include location and number of the baffles, PGA, and the angle of incidence of the earthquake. Two baffle arrangements are considered in the present study are shown in Fig. 2.

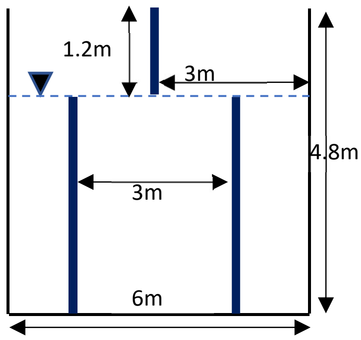
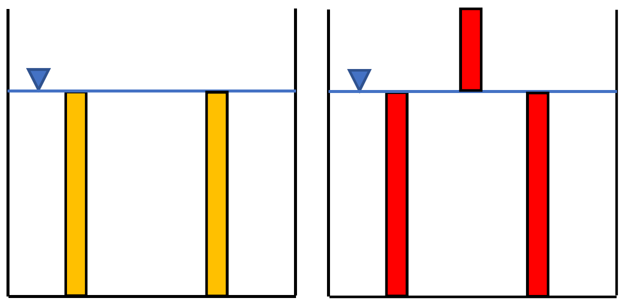


Fig.1 Details of hybrid baffle arrangement in LST

Table 1. Properties of the building frames.

Fluid(water)	Concrete (LST)
Density, ρ_w=*983.204Kg/m³*	ρ_c=*2450Kg/m³*
EoS: c_0= *1450, s =0,* γ_0=*0*	E_c = *24.96 GPa*
Dynamic Viscosity =*0.001 N-sec/m²*	Poisson's ratio, υ=*0.2*



(a) two bottom vertical baffles arrangement

(b) hybrid baffle arrangement

Fig.2 Various baffle arrangements considered for the comparison

In the first arrangement, two-bottom mounted baffles are studied whereas, in the second configuration a hybrid model in which both the bottom and one top-mounted baffle are employed simultaneously. The response quantities of interests investigated are shear force, overturning moment, sloshing height, and hydrodynamic pressure acting on the base of the LST. For the present study, four different earthquake records are used which are taken from the PEER strong motion database of Berkeley University. The acceleration time history plot and response spectra of various earthquakes are shown in Fig.3 and Fig.4 respectively. To investigate the effect of the PGA on the structure three PGA levels are taken namely, 0.2g, 0.4g, and 0.6g as per the three-level seismic design concept.

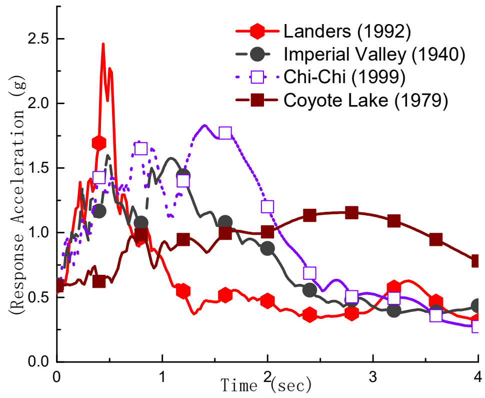


Fig.3 Acceleration response spectra of earthquake records (5% damping)

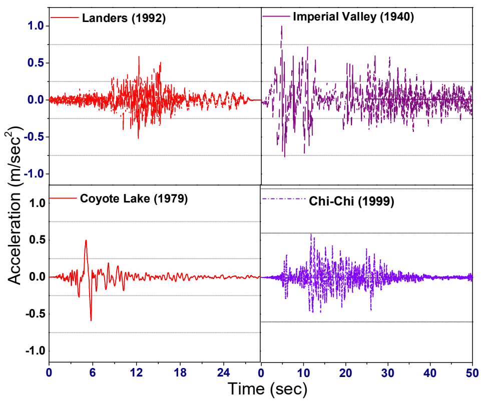


Fig. 4 Earthquake time histories used in the present study

For the bidirectional excitation, the ratio between the two horizontal components is taken as 1:2/3.

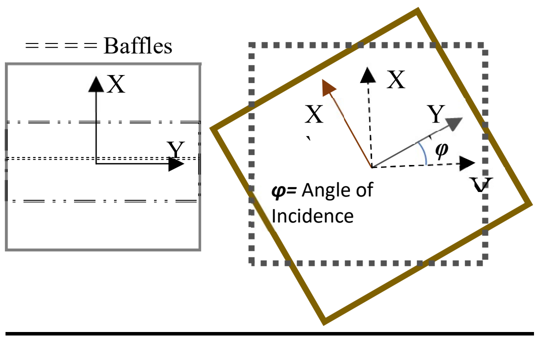


Fig. 5 Variation of the angle of incidence in LST

To further evaluate the behavior of the LST due to earthquakes in the present study the effect of angle of incidence of the earthquake is also considered for six different orientations which are, 0^0,15^0,30^0,45^0,60^0 and 75^0 as shown in Fig.5.

3.1 Validation of current ALE-FEM approach

The present ALE-FEM approach is verified against two different studies, first was an experimental study done by Akyildiz and Unal [24] whereas, the second study was the extension of the first experimental study but executed by the FEM approach Akyildiz by [25]. In all the three studies presented in this section, a 3D LST is subjected to the pitching harmonic motion with $\theta_R=8sin(2t)$ excitation. The dimension of the LST is 0.92mX0.46mX0.31m having a baffle height of 0.0465m. the fluid height is taken as 0.24m.

It can be seen from Fig. 6 that the present ALE-FEM approach can proficiently capture the results obtained by both the analytical and experimental results.

4. Discussion of Results

As discussed in the earlier section, the effectiveness of the baffle is investigated for various parameters which include the type of earthquake, PGA, and the angle of the incidence. Two different configurations of the baffles considered in the present study are shown in Fig.2. In the hybrid model of the baffle configuration, one top-mounted baffle is added in the two bottom-mounted baffle arrangement. The percentage change in the response quantities of interests is investigated. These response quantities of interest are shear force, overturning moment, sloshing height and, hydrodynamic pressure. For the present study, the effect of the angle of incidence of the earthquake is reported for the hybrid arrangement of baffles. As the percentage change for the lower PGA is not much significant therefore only the result of the 0.6g PGA is discussed.

4.1 Shear force

Table 2 shows the maximum percentage reduction in the shear force for the various earthquakes. It can be seen that the hybrid arrangement of baffles in the LST is more apt in the reduction of the shear force, particularly for the Imperial Valley earthquake with a reduction of 26% which is a near-field in nature. The effect of the PGA variation on the shear force is not very significant.

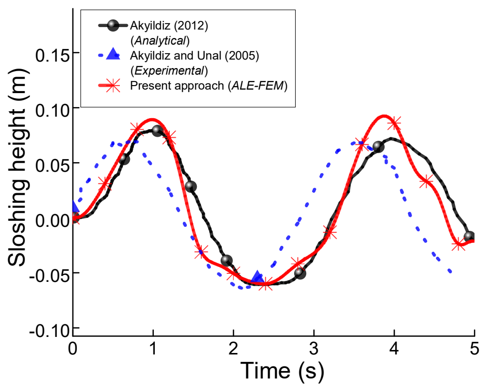


Fig.6 Validation of current ALE-FEM approach

Table 2. Maximum percentage reduction in shear force for different arrangements of the baffles for PGA= 0.6g

Type of Earthquake	Baffle configuration	
	Two bottom-mounted baffles	Hybrid arrangement
Landers Eq.	9%	15%
Coyote lake Eq.	6%	19%
Imperial Valley Eq.	7%	26%
Chi-Chi Eq.	6%	22%

It can be seen from Fig.7 that the effect of the angle of incidence of the earthquake is not that significant for the present case of the LST. By implementation of the vertical baffles inside the LST, the variation in the percentage change remains constant. However, for the case of the Imperial valley earthquake, there is little change in the percentage reduction towards the angle of incidence of 75^0. It can be seen from the figure that for an angle of incidence of 45^0 the reduction is maximum for all the cases of the earthquakes.

4.2 Overturning moment

Table 3 shows the maximum percentage reduction in the overturning moment. It can be seen from the results that baffles are not very effective in the reduction of the overturning moment. The effect of the PGA variation of the earthquake is found to be more profound for the case of the Chi-Chi earthquake than any other ground motion. The maximum reduction is found to be for the case of the Chi-Chi earthquake as compared to any other earthquake. For both the cases of the baffle arrangement the percentage reduction is higher at a higher value of the PGA.

Table 3. Maximum percentage reduction in the overturning moment for different arrangements of the baffles for PGA= 0.6g

Type of Earthquake	Baffle configuration	
	Two bottom-mounted baffles	Hybrid arrangement
Landers Eq.	5%	13%
Coyote lake Eq.	7%	12%
Imperial Valley Eq.	8%	13%
Chi-Chi Eq.	6%	15%

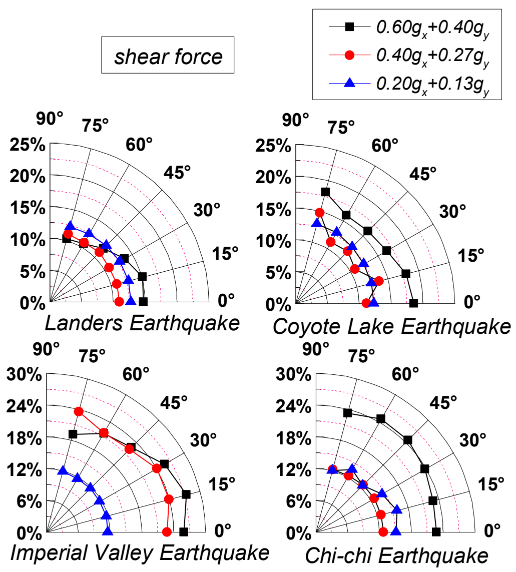


Fig. 7 Percentage change in the reduction of shear force with the angle of incidence

It can be seen from Fig.8 that as the case of shear force the effect of the angle of the incidence on the overturning moment is not very significant. The maximum reduction is found to be at the angle of incidence of 75^0 for the Chi-Chi earthquake.

4.3 Sloshing height

Table 4 shows the percentage reduction in the sloshing height for various earthquakes. It can be seen that baffles are an excellent option for the control of the sloshing height. The effect of the PGA variation on the sloshing height is not very substantial. The maximum reduction of 46% can be seen for the Imperial Valley earthquake. However, the maximum reduction for the two bottom-mounted baffles is achieved for the case of the Landers earthquake. The significant reduction in the sloshing height is due to the formation of the eddies at the sharp tips and vertices of the baffles, as the number of the baffles are increased the reduction in the sloshing height is also gets amplified.

Table 4. Maximum percentage reduction in sloshing height for different arrangements of the baffles for PGA= 0.6g

Type of Earthquake	Baffle configuration	
	Two bottom-mounted baffles	Hybrid arrangement
Landers Eq.	33%	44%
Coyote lake Eq.	26%	40%
Imperial Valley Eq.	30%	47%
Chi-Chi Eq.	20%	40%

Fig.9 shows the effect of the angle of incidence of the earthquake on the sloshing height for the various earthquake records. The maximum reduction in sloshing height is achieved at an angle of incidence of 45^0 for all earthquakes whereas, the minimum reduction is observed at 0^0 and 75^0 of the angle of incidence.

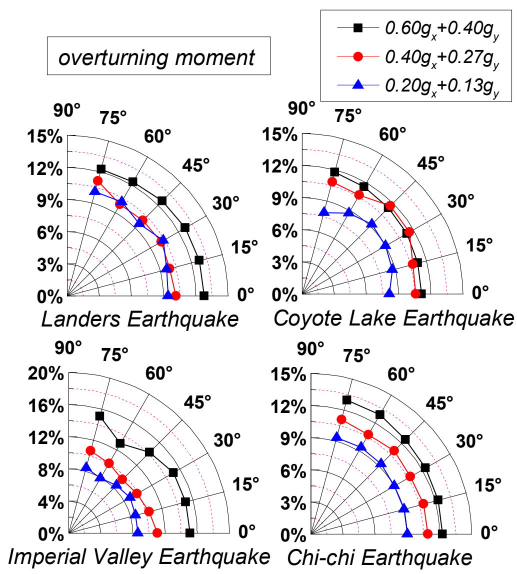


Fig. 8 Percentage change in the reduction of sloshing height with the angle of incidence

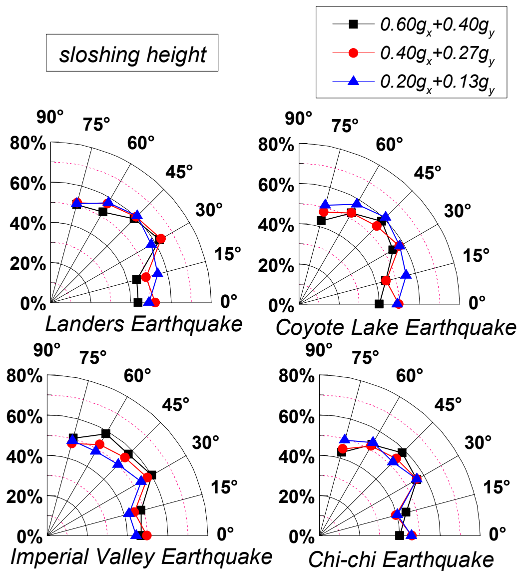


Fig. 9 Percentage change in the reduction of sloshing height with the angle of incidence

4.4 Hydrodynamic pressure

Table 5 shows the maximum percentage reduction in the hydrodynamic pressure for the various earthquakes. It can be seen from the results that by adding the baffles inside the LST moderate level of reduction can be achieved.

The effect of the PGA variation is also most pronounced than any other response quantities. The maximum reduction is for the case of the Imperial Valley earthquake whereas, the minimum reduction is for the Landers and Chi-Chi earthquake.

Table 5. Maximum percentage reduction in hydrodynamic pressure for different arrangements of the baffles for PGA= 0.6g

Type of Earthquake	Baffle configuration	
	Two bottom-mounted baffles	Hybrid arrangement
Landers Eq.	16%	22%
Coyote lake Eq.	21%	20%
Imperial Valley Eq.	14%	23%
Chi-Chi Eq.	21%	20%

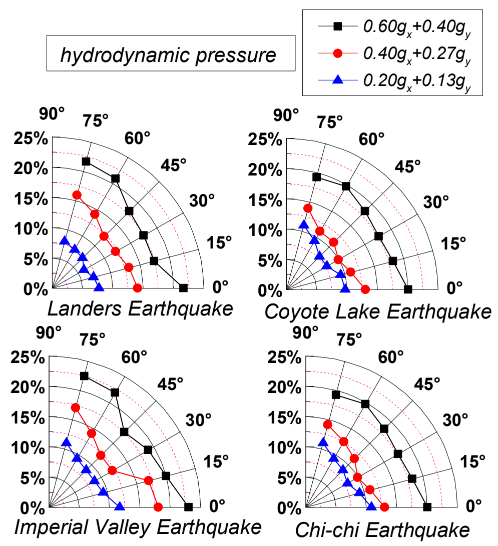


Fig. 10 Percentage change in the reduction of shear force with the angle of incidence

It is quite interesting to note that for the Coyote lake and Chi-Chi earthquake effect of the baffle arrangement is not very significant as both of them are providing almost the same reductions.

It can be seen from Fig. 10 that the effect of the angle of incidence of the earthquake is not very dominant for the hydrodynamic pressure. Unlike the sloshing height response, the maximum reduction is observed at an angle of incidence of 75^0 and 0^0 whereas, the minimum reduction in the response is observed at an angle of incidence of 45^0.

5. Conclusions

The performance of baffled square LST is investigated along with the effectiveness of the two arrangements of the top and bottom-mounted vertical baffles in the mitigation of the seismic responses. The behavior of baffled LST under the bi-directional earthquake excitation is investigated under the set of important parameters. They include variation in the type of earthquakes, PGA, optimum locations of the top and bottom baffles, and the angle of incidence of the earthquake. The response quantities of interest are shear force, overturning moment, sloshing height, and hydrodynamic pressure on the LST:

1. A higher reduction in sloshing height can be achieved by the application of the vertical baffles inside the LST. The order of reduction in the sloshing heigh for the present study is found to be of order 40%-60%.
2. The significant reduction in the sloshing height can be seen due to the formation of the eddies at the sharp tips and vertices of the baffles. As the number of the baffles is increased the reduction of sloshing height also gets amplified.
3. About 20%-25% reduction can be seen for the base shear, overturning moment, and hydrodynamic pressure.
4. The impact of the type of earthquake is found to be not a governing factor in the reductions.
5. The effect of the angle of incidence of the earthquake was found to be not that significant in the reduction of the base shear, overturning moment, and hydrodynamic pressure.
6. The reduction variation in sloshing height due to the angle of incidence was found to be of order 40%-70%.
7. The maximum reduction in sloshing height is achieved at an angle of incidence of 45^0 for all earthquakes whereas, the minimum reduction is observed at 0^0 and 75^0 of the angle of incidence.

Disclosures

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