**Research on Variable Curvature Rolling Isolation of Horizontal Storage Tanks**

**DOI 10.37153/2686-7974-2019-16-1124-1131**

Yuan Lü[[1]](#footnote-1), Jiangang Sun[[2]](#footnote-2), Zongguang Sun[[3]](#footnote-3), Lifu Cui[[4]](#footnote-4), ZhenWang[[5]](#footnote-5), Dongyu Luo[[6]](#footnote-6)

**ABSTRACT**

In order to reduce the seismic response of horizontal tank equipment in the petrochemical industry, according to the structural characteristics of horizontal storage tank, it can be considered to install variable stiffness rolling isolation devices at the base of storage tank. The isolation layer stiffness increases with the increase of isolation layer displacement, which can effectively reduce the seismic response and displacement of structure. Based on potential fluid theory, this paper deduced the simplified mechanical model of horizontal storage tank variable stiffness rolling isolation considering liquid sloshing effect. The numerical analysis method was used to study the horizontal tank seismic response. The results showed that variable stiffness rolling isolation can effectively reduce the seismic response of horizontal storage tank, especially the base shear force, overturning moments, and also have a certain control over the sloshing wave height of liquid storage. The variable stiffness rolling isolation device can effectively reduce hydrodynamic pressure, especially the rigid hydrodynamic pressure. It is recommended that the seismic design of horizontal storage tanks can adopt variable stiffness rolling isolation.

*Keywords: Horizontal storage tanks; Rolling isolation; Simplified mechanical model; Ground motion response*

**1. INTRODUCTION**

Horizontal storage tanks are commonly used in the petrochemical industry to store low temperature, high pressure chemical raw materials, process materials and finished products. Because the liquid storage in horizontal storage tanks is usually characterized by high toxicity, flammability, and explosiveness, once a strong earthquake is damaged, it may cause serious secondary disasters such as explosions and fires. Therefore, how to reduce the seismic response of horizontal storage tanks is a hot issue. The dynamic response of horizontal storage tanks during ground motion is complex, with structural vibrations and storage sloshing. At present, the research on the sloshing problem of horizontal storage tanks has been greatly developed (Lazaros, 2006, 2007; Seyyed M, 2011, 2011, 2012; Hasheminejad, 2011; Omar, 2012; Amir, 2015). However, there are still few studies on how to reduce the effect of reservoir sloshing and the overall seismic response of horizontal tanks. In fact, for horizontal storage tanks, base isolation is a suitable damping measure because of its small aspect ratio.

Base isolation is a very effective damping measure. The damping mechanism is: by installing a flexible isolation device at the bottom of the building, thereby prolonging the natural vibration period of the building to achieve the purpose of damping. In previous studies, base isolation was more applied to vertical storage tanks and elevated tanks (Harry W, 1999; M.K. Shrimali, 2003; Yuan Lü, 2016). Sun Jiangang et al.( Ying Sun, 2011; Jiangang Sun, 2009, 2010, 2015; Lifu Cui, 2016, 2013) systematically studied the damping mechanism of vertical storage tank base isolation from theoretical analysis, finite element numerical simulation and shaking table test, and proposed a variety of basic isolation forms, which can effectively reduce the basic isolation. The results show that the base isolation can effectively reduce the base shear, overturning moment and hydrodynamic force of vertical storage tanks, but the damping effect on the sloshing wave height of the liquid storage is not obvious. In view of this, this paper applies the base isolation to the horizontal storage tank, and deduces the simplified mechanical model of the variable stiffness rolling isolation of the horizontal storage tank, and uses numerical analysis method to study the damping performance of the variable stiffness rolling isolation.

**2. VARIABLE STIFFNESS ROLLING ISOLATION**

The variable stiffness rolling isolation system consists of two orthogonal rolling scroll systems, which can be independently rolled in two orthogonal directions. Any horizontal ground motion can be decomposed into two orthogonal directions of motion to achieve isolation of the horizontal plane in any direction. The rolling groove can be designed as an arc of equal curvature, or other curve that changes curvature (such as an elliptical arc, etc.). In this paper we use elliptical curved grooves. The characteristics of the groove are as the isolation layer displacement increases, the recovery stiffness increases, which can effectively limit isolation layer displacement and avoid the damage of isolation device.

|  |  |
| --- | --- |
|  |  |
| (a) Physical and schematic | (b) Force analysis diagram |
|  |  |
| Figure 1. Rolling isolation device | |

According to the balance principle of force, the equilibrium equation on the contact surface between the roller and the upper plate can be obtained:

|  |  |
| --- | --- |
|  | (1) |
|  |  |
|  | (2) |

Where W is the positive pressure, F is the restoring force, N is the normal reaction force, T is the rolling friction force, and is the rotation angle. According to the literature [18], the expression of rolling friction is:

|  |  |
| --- | --- |
|  | (3) |

Where  is the rolling friction coefficient and *r* is the roller radius. Assume that the elliptic equation of the bottom plate rolling section is:

|  |  |
| --- | --- |
|  | (4) |
|  |  |
|  | (5) |

According to Equation (1) to (5), the resilience expression of the rolling isolation device can be derived by equivalent transformation:

|  |  |
| --- | --- |
|  | (6) |

,are equivalent stiffness and rolling friction force, respectively.

**3. SIMPLIFIED MECHANICAL MODEL FOR ROLLING ISOLATED OF HORIZONTAL STORAGE TANK**

|  |
| --- |
|  |
|  |
| Figure 2. Horizontal tank schematic |

According to the potential fluid theory, it is assumed that the reservoir is an ideal fluid, and the velocity potential of a section of the reservoir in the polar coordinate system is . The velocity potential equation satisfies the Laplace equation and the following boundary conditions:

|  |  |
| --- | --- |
|  | (7) |
|  |  |
|  | (8) |
|  |  |
|  | (9) |
|  |  |
| at Liquid level S2 | (10) |
|  |  |
|  | (11) |

Where *R* is the tank radius,  is the ground motion speed,  is the tank movement speed, and  is the isolation layer movement speed. According to the separation variable method and the mode superposition method for solving the boundary value problem of Laplace equation, the expression of the total velocity potential equation of a certain section of the reservoir can be derived:

|  |  |
| --- | --- |
|  | (12) |

The vibrational form of the free liquid surface under the gravity field and the hydrodynamic pressure of the liquid storage on the tank wall:

|  |  |
| --- | --- |
|  | (13) |
|  |  |
|  | (14) |

Further, the base shear force and the overturning moment can be obtained as follows:

|  |  |
| --- | --- |
|  | (15) |
|  |  |
|  | (16) |

*S*1 is the liquid-solid coupling surface. Solving Equation (15), (16)：

|  |  |
| --- | --- |
|  | (17) |
|  |  |
|  | (18) |
|  |  |
|  | (19) |
|  |  |
|  | (20) |
|  |  |
|  | (21) |
|  |  |
|  | (22) |
|  |  |
|  | (23) |
|  |  |
|  | (24) |
|  |  |
|  | (25) |

Where  is sloshing component of liquid,  is rigid component of liquid,  is mass of tank,  is mass of isolation layer;  is total mass of liquid;  is equivalent height of sloshing component, and  is equivalent height of rigid component,  is equivalent height of tank body, and is height of isolation device. According to Equation (15)-(25), the simplified mechanical model of variable stiffness rolling isolation of horizontal storage tanks can be derived:

|  |
| --- |
|  |
|  |
| Figure 3. Initial simplified mechanical model |

 are the stiffness and damping coefficient of support structure respectively;  are the stiffness and damping coefficient of isolation layer;

|  |  |
| --- | --- |
|  | (26) |

According to Equation (17) and (19), the mass of tank and the rigid component can be simplified into a concentrated mass:

|  |  |
| --- | --- |
|  | (27) |

Equivalent height:

|  |  |
| --- | --- |
|  | (28) |

Normally, the horizontal storage tank support stiffness is much larger than the isolation layer stiffness  To simplify the calculation, the isolation layer and the tank body can be combined into one concentrated mass. Then. Therefore, the simplified mechanical model in Figure 3 can be further simplified.

|  |
| --- |
|  |
|  |
| Figure 4 Quadratic simplified mechanical model |

From the Hamilton principle, the equation of motion of Figure 4 can be derived.

|  |  |
| --- | --- |
|  | (29) |

**4. CASE ANALYSIS**

A LNG horizontal storage tank project is selected as an example to study the seismic response. Horizontal tank parameters are shown in Tables 1. The EL-Centro wave are selected as the ground motion input, PGA=0.2g. The initial isolation period of the base isolation design is T=3s, a=0.255m，b=0.054m，r=0.075m. The groove is made of Q345 steel, the roller is made of 20# steel (mild steel), and the rolling friction coefficient is 0.05cm.

Table 1 Horizontal tank geometry parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Parts** | **Structural parameters** | **Size/mm** | **Material** |
| Head | Head depth | 1200 | Q345R |
| Head wall thickness | 26 | Q345R |
| Tank body | Length | 14000 | Q345R |
| Inside diameter of | 5000 | Q345R |
| Wall thickness | 24 | Q345R |
| Saddle | Distance from the center of the saddle to the tangent of the head | 1200 | 16MnR |
| Width | 800 | 16MnR |
| Saddle wrap angle | 120º | 16MnR |

|  |  |  |
| --- | --- | --- |
|  |  |  |
| 1. Base shear | (b) Overturning moment | (c) Sloshing wave |
|  |  |  |
| (d) Hydrodynamic pressure | (e) Sloshing hydrodynamic pressure | (f) Rigid hydrodynamic pressure |
|  | | |
| Figure 5. Seismic response under EL-Centro wave | | |

Table 2. Seismic response peak under EL-Centro wave

|  |  |  |  |
| --- | --- | --- | --- |
| **Isolation/Non-isolation** | **Base Shear/kN** | **Overturning moment/kN∙m** | **Sloshing wave height/m** |
| Non-isolation | 283.9 | 962.0 | 0.246 |
| Isolation | 65.7 | 226.3 | 0.143 |
| Damping rate | 76.86% | 76.64% | 41.87% |

Note: Damping rate = (Non-isolation- Isolation) / Non-isolation;

From the data in Figures 5(a)~(c) and Table 5, we can see that the base isolation can greatly reduce base shear force and overturning bending moment, and the damping rate reaches 76%. At the same time, the base isolation can effectively reduce the sloshing response of the reservoir, and the damping rate of sloshing wave height is 41.87%. Figures 5 (d) ~ (f) shows the hydrodynamic pressure of reservoir under earthquake action. The figures shows that the variable stiffness rolling isolation device can effectively reduce the hydrodynamic pressure, especially the rigid hydrodynamic pressure. Generally speaking, variable stiffness rolling isolation can effectively reduce the seismic response of horizontal storage tanks. It is recommended that the seismic design of horizontal storage tanks can adopt variable stiffness rolling isolation.

**5. Conclusions**

(1) Based on potential fluid theory, this paper deduced the simplified mechanical model of variable stiffness rolling isolation horizontal storage tank considering liquid sloshing effect.

(2) The numerical analysis method was used to study the horizontal tank seismic response. The results showed that variable stiffness rolling isolation can effectively reduce the seismic response of horizontal storage tank, especially the base shear force, overturning moments, and also have a certain control over the sloshing wave height of liquid storage.

(3) The variable stiffness rolling isolation device can effectively reduce hydrodynamic pressure, especially the rigid hydrodynamic pressure.

(4) It is recommended that the seismic design of horizontal storage tanks can adopt variable stiffness rolling isolation.

**6. Acknowledgments**

Financial support was provided by the National Natural Science Foundation of China (Nos. 51878124 and 51478090). In addition, Liaoning Provincial Natural Science Fund Guidance Plan (20180550073，2015020620) through its funding of scientific research projects is gratefully acknowledged.

**7. References**

Lazaros A. Patkas, Manolis A. Platyrrachos. (2006) Sloshing Effects on the Seismic Design of Horizontal-Cylindrical and Spherical. *Industrial Vessels Journal of Pressure Vessel Technology*, 128: 328-340.

Lazaros A. Patkas, Manolis A. Platyrrachos. (2007) Variational Solutions for Externally Induced Sloshing in Horizontal-Cylindrical and Spherical Vessels. *Journal of Engineering Mechanics*, 133(6): 641-655.

Seyyed M. Hasheminejad, M.M. Mohammadi. (2011) Effect of anti-slosh baffles on free liquid oscillations in partially filled horizontal circular tanks. *Ocean Engineering* , 38: 49-62.

Seyyed M.Hasheminejad, MostafaAghabeigi. (2011) Transient sloshing in half-full horizontal elliptical tanks under lateral excitation. *Journal of Sound and Vibration* , 330: 3507–3525.

Seyyed M. Hasheminejad, Mostafa Aghabeigi. (2012) Sloshing characteristics in half-full horizontal elliptical tanks with vertical baffles. *Applied Mathematical Modelling* , 36: 57–71.

Hasheminejad, S.M., Mohammadi, M.M. (2011) Effect of anti-slosh baffles on free liquid oscillations in partially filled horizontal circular tanks. *Journal of Ocean Engineering*, 38: 49–62.

Omar Badran, Mohamed S. Gaith, Ali Al-Solihat. (2012) The Vibration of Partially Filled Cylindrical Tank Subjected to Variable Acceleration, *Engineering*, 4: 540-547.

Amir Kolaei , Subhash Rakheja , Marc J. Richard. (2015) Three-dimensional dynamic liquid slosh in partially-filled horizontal tanks subject to simultaneous longitudinal and lateral excitations. *European Journal of Mechanics B/Fluids*, 53: 251–263.

Harry W. Shenton III, Francis P. Hampton. (1999) Seismic Response of Isolated Elevated Water Tanks. *Journal of Structural Engineering*, 125(9): 965-976.

M.K. Shrimali, R.S. Jangid. (2003) Earthquake response of isolated elevated liquid storage steel tanks. *Journal of Constructional Steel Research*, 59: 1267-1288.

Yuan Lü, Jiangang Sun, Jinfeng Hao, Lifu Cui. (2016) The finite element numerical simulation analysis of base isolation elevated vertical cylinder storage tanks. *Earthquake Engineering and Engineering Vibration*,36(05):126-131.

Ying SUN, Jiangang SUN, Lifu CUI. (2011) Numerical research on large base isolation vertical storage tanks with floating roof. *World Earthquake Engineering*, 27(3):120-125.

Jiangang Sun, Feng Jiang, Ronghua Zhang. (2009) Earthquake response spectrum analysis of storage tanks with seismic isolation. *World Earthquake Engineering*, 25(2):130-139.

Jiangang Sun, Xian-nan Wang，Changjun Zhao. (2010) Theoretical study on seismic isolation of storage tanks. *Journal of Harbin institute of Technology*, 42(4):639-643.

Lifu Cui, Jiangang Sun, et al. (2016) Simulation shaking table test of vertical storage tank with reinforcement ring beam base isolation. *Earthquake Engineering and Engineering Vibration*, 36(4):130-138.

Jiangang Sun, Cui Lifu, et al. (2015) Simulated earthquake shaking table test of vertical floating roof tank with parallel base isolation. *Earthquake Engineering and Engineering Vibration*, 35(5):125-131.

Lifu Cui, Jiangang Sun et al. (2013) Base isolation mechanical model comparative analysis of vertical storage tank. *Journal of Harbin institute of Technology*, 45(6):102-106.

Department of Theoretical Mechanics, Harbin Institute of Technology. (2002) Theoretical mechanics. Beijing: Higher Education Press.

1. College of Transportation Engineering, Dalian Maritime University, Dalian, China, isodamper@163.com [↑](#footnote-ref-1)
2. College of Civil Engineering, Dalian Minzu University, Dalian, China, sjg728@163.com [↑](#footnote-ref-2)
3. College of Transportation Engineering, Dalian Maritime University, Dalian, China, sun@dlmu.edu.cn [↑](#footnote-ref-3)
4. College of Civil Engineering, Dalian Minzu University, Dalian, China, cuilifu1982@126.com [↑](#footnote-ref-4)
5. College of Civil Engineering, Dalian Minzu University, Dalian, China, Wangzhen0459@163.com [↑](#footnote-ref-5)
6. Institute of Earthquake Engineering, Dalian University of Technology, Dalian, China, ldy\_090821@163.com [↑](#footnote-ref-6)