Earthquake Response of TFPS-isolated Elevated Steel water tank under Near-f ault ground motions

Ankita K Shah[1], Vijay R Panchal[2*]

[1]PG Student of M. Tech (Structural Engineering), CSPIT, CHARUSAT Changa, Gujarat, India
[2]Civil Engineering Dept, CSPIT, CHARUSAT, Changa, Gujarat, India

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Correspondence to:
*Vijay R Panchal:
vijaypanchal.cv@charusat.ac.in.

Abstract:

In this study, the elevated steel water tank isolated with Triple Friction Pendulum System (TFPS) under normal component of near-fault ground motions is evaluated. TFPS is placed at top and bottom level of tower structure. Mathematical model of storage tank is distinct with four degree of freedom model includes tower structure, sloshing mass, isolation system and impulsive mass. Comparison is made between tank isolated with TFPS at top of tower and tank isolated with TFPS at bottom of tower. From the comparison, it is observed that tower displacement, isolator displacement, base shear and impulsive displacement are less in tank isolated with TFPS at top of tower than tank isolated with TFPS at bottom of tower. On the other hand, convective displacement is increased in the tank isolated by TFPS at top of tower.

Keywords: Elevated steel water tank, base shear, TFPS, SAP 2000

INTRODUCTION

For industries and power plants, storage tanks of fluid are very curious structures due to their variable storage level. It is important to provide effective technique to prevent effect of a strong external disturbance. In the past many failure of water tank has been recorded due to earthquake. As Triple Friction Pendulum System (TFPS) is derivative of Friction Pendulum System (FPS), so it may be very adequate device for controlling earthquake effect on a structure during earthquake excitation.

Shenton and Hampton (1999) have studied the seismic response of elevated water tanks. In that they had discrete three degree of freedom model of isolated tank. And he compared elevated tank with fixed based tank and found that seismic isolation is effective in reducing the base shear, overturning moment and tank wall pressure. Shrimali and Jangid (2002) investigated performance of different isolation system for storage tank of fluid and found that sliding type isolation is more powerful then elastomeric bearing. Panchal and Jangid (2008) investigated advanced VFPS which controls isolator displacement base shear in desirable assortment for near fault ground motion. Seleemah and Sharkway (2011) examine accuracy in prediction for modeling of isolated tank using SAP 2000 and 3D BASIS ME. Authors found that SAP 2000 is successful in producing results as compared to 3D BASIS ME. Malu and Pranesh (2014) presented the behavior of Pure Friction (PF), Friction Pendulum System (FPS), Conical Friction Pendulum Isolator (CFPI), Variable Frequency Pendulum Isolator (VFPI), Polynomial Friction Pendulum Isolator (PFPI), Variable Friction Pendulum Isolator (VFPS), Variable Frequency and Variable Friction Pendulum Isolator (VFFPI) and Variable Friction Isolator (VFI) in Sliding Isolation Systems. Nerkar and Nayak (2016) examine the seismic performance of water tank using finite element method.

For that they have taken circular and rectangular water tank with different water level, and static and dynamic time history analysis was performed on it. It is found that as water level increases, base shear also increases. Base shear for circular tank is more than rectangular tank.

MATHEMETICAL MODELING OF ELEVATED WATER TANK

The model taken for study is shown in Figure 1, which shows elevated water tank isolated with TFPS (a) provided at top of tower structure (b) provided at bottom of tower structure. Liquid in tank is incompressible, non- viscous and ir-rotational flow. The supporting system of the tank, i.e., tower structure is considered as columnar type. Here constant liquid mass which is lumped as convective mass m_c, impulsive mass *mi* and rigid mass m_r. The sloshing and impulsive masses are connected to the tank wall by corresponding equivalent spring having stiffness k_c and k_i, respectively. c_c is known asdamping constants of convective and c_i is known as damping constants of impulsive mass. Tank mainly consist of three degree-of-freedom subjected to one directional excitation u_c, u_i and u_t, which denote the absolute displacements of sloshing mass, impulsive mass and tower drift respectively. Since the introduction of the isolation system, the tank has one additional degree of freedom which corresponds to the deformation in the isolation system and denoted by u_b. The self-weight of steel tower structure is assumed as 5% of the total mass. To

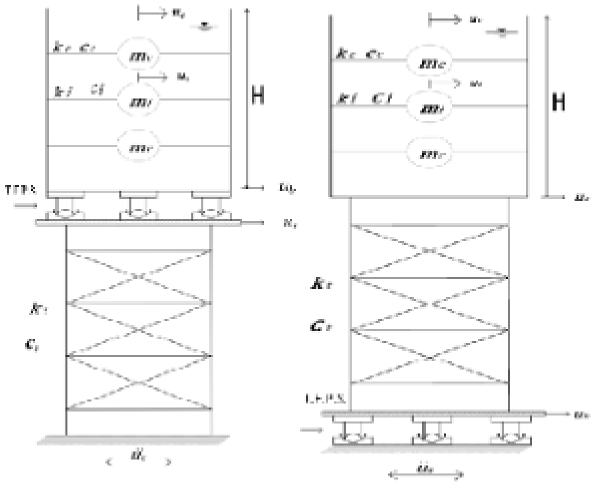

Figure 1 Mathematical model of elevated water tank isolated with TFPS (a) at top of tower (b) at bottom of tower

check performance of the isolated water tank six near fault ground motions are demonstrated. Assumptions for modelling of tank are as follows:

(1) Self weight of tank is neglected since it is very small.

(2) System excited by normal component and contribution of parallel component of near fault ground motion is neglected.

Table 1 Properties of elevated water tank

Elements	Description	
	M-1	M-2
Aspect ratio (H/R), H, (Where H Height, R Radius of tank)	1.85, 11.3m	1.85, 11.3m
Convective mass m_c(ton)	346.6	346.6
Impulsive mass m_i (ton)	917.35	917.35
Rigid mass m_r (ton)	1031.6	1031.6
Total mass (ton)	2295.5	2295.5
Assume 5% eight for tower structure	114.77	-

Table 2 Some charecteristics of Near-fault ground motion used for study

Near fault ground motion (Normal component)	Recording Station	Magnitude	PGA (g)
October15,1979 Imperial Valley, California	ELCentro Array #5	6.4	0.36
October15,1979 Imperial Valley, California	ELCentro Array #7	6.4	0.45
January17,1979 Imperial valley, California	Newhall	6.7	0.87
June28,1992, Landers California	Lucerne Valley	7.3	0.71
January17,1994 Northridge California	Rinaldi	6.7	0.70
January17,1994 Northridge California	Sylmar	6.7	0.72

Isolator provided at top of tower structure is referred as model 1(M-1) and isolator provided at bottom of tower structure is referred as model 2 (M-2). Calculations of mass, equivalent stiffness and damping of elevated water tank are based on methodology used in [3] for model 1 and 2. The calculated parameters are shown in Table 1 for model 1 and 2. For the present study six near fault ground motions are selected. The properties of selected near-fault ground motions are shown in Table 2.

GOVERNING EQUATION OF MOTION

The equation of motion for elevated liquid storage steel tank expressed in the matrix form as: $[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}+\{F\}=[M]\{r\}\ddot{u}_g$

Where, [M] is mass matrix, [C] is damping matrix and [K] is stiffness matrix of the system; {r} is the influence coefficient vector and $\ddot{u}_g$ is the earthquake

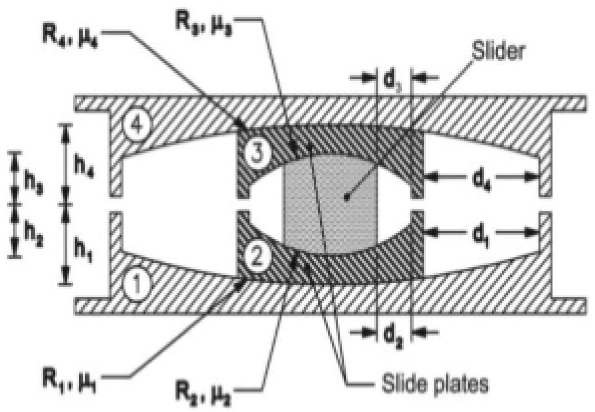

Figure 2 Cross section of TFPS

acceleration. The displacement vector $\{x\}= \{x_t\ x_c, x_i, x_b\}^T$ and frictional force vector $\{F\}= \{0, 0, 0, F_x\}^T$.

TRIPLE FRICTION PENDULUM ISOLATOR CALCULATION

To create the isolator model, a sample TFPS carrying vertical load of 2410.27 ton (2295.5+ 114.77) with the following properties. Figure 2 indicates the cross section of TFPS.

Geometric Properties

$R_1 = R_4 =$ 20521.77mm or 20.521m

$R_2 = R_3 =$ 3727.89mm or 3.727m

$h_1 = h_4 =$ 936.56mm or 0.936m

$h_2 = h_3 =$ 697.83mm or 0.697m

$d_1 =$ 3268mm $\quad d_2 =$ 468.28mm

$R_{1eff} = R_{4eff} = R_1 - h_1$

= 20521.77- 936.56 = 19585.21mm

$R_{2eff} = R_{3eff} = R_2 - h_2$

= 3727.89 – 697.83 = 3030.06mm

$d_1^* = d_4^* = d_1.\ R_{1eff}/R_1 =$ 3118.85 mm

$d_2^* = d_3^* = d_2.\ R_{2eff}/R_2 =$ 380.62 mm

Calculating Frictional Properties of the bearing

Bearing Pressure at surfaces 1 and 4

$P = Load / Area$ Here $V_k load =$ 2410.27 ton

Area $A = \pi r^2 \quad r = h_1 + h_4 = 936.56 + 936.56$

$P = 2.18E\text{-}04\ ton/mm^2$,

$P = 0.0002 \times 1450 = 0.317 ksi$,

$1 ksi = 1450\ ton/mm^2$

3-Cycle Friction, $\mu = 0.122 - 0.01P$ μ = 0.118

Adjust for high velocity = -0.033

= 0.110 – 0.033 = 0.085

(Lower bound friction)

I–cycle friction μ = 1.2 × 0.078 = 0.096

Lower bound $\mu_2 = \mu_3 =$ 0.08

Upper bound $\mu_2 = \mu_3 =$ 0.096

μ = force at zero displacement divided by the normal load

For Lower Bound,

$\mu = \mu_1 - (\mu_1 - \mu_2) \times (R_{2eff}/R_{1eff}),\ \mu = 0.083$

For Upper Bound,

$\mu = \mu_1 - (\mu_1 - \mu_2) \times (R_{2eff}/R_{1eff}),\ \mu = 0.100$

Table 3 Summery of Isolation Properties

Geometry Properties		Frictional Properties	
Property	Value	Property	Value
$R_{1eff} = R_{4eff}$ mm	19585.21	$\mu_1 = \mu_4$ Lower bound	0.085
$R_{2eff} = R_{3eff}$ mm	3030.06	$\mu_2 = \mu_3$ Lower bound	0.078
$d_1^* = d_4^*$ mm	3118.85	μ Lower bound	0.083
$d_1^* = d_4^*$ mm	380.62	$\mu_1 = \mu_4$ Upper bound	0.093
		$\mu_2 = \mu_3$ Upper bound	0.093
		μ Upper bound	0.100

Calculating *Dd* (Upper bound Analysis)

$S_d = 1.13 \qquad \mu = 0.100$

$\mu_1 = 0.093 \qquad D_y = 0.0424$

$F_d = 1.01 \qquad W = 2410.27$ ton

No. of bearing = 2

$\Sigma F_d = F_d \times W \times Total\ Bearing$

= 1.01×2410.27 × 2

ΣF_d =4868.74

$\Sigma W = Vk\ Load \times No.\ of\ bearing$

ΣW = 4820.54 ton

Let the displacement be D_d = 0.4306 m

Effective Stiffness, $Q_d = \mu \times \Sigma W$

= 0.100 × 4820.54

Q_d = 482.05 ton

$K_D = \Sigma F_d / D_d$ = 4868.74/ 0.4306

K_D = 11306.87 ton/m

$K_{eff} = K_D + Q_D / D_D$ = 11306.87 + 482.05 / 0.4306

K_{eff} = 12426.35 ton/m

Effective period, - refer Eq. 17.5-2, ASCE 7-10

$T_{eff} = 2\pi\sqrt{((\Sigma w)/(K_{eff} \times g))}$ T_{eff} = 2.5 sec.

Effective damping, - refer Eq. 17.8-7, ASCE 7-10

$ß_d = E/ (2\pi K_{eff} D_d^2$ $ß_{eff} = ß_d = 0.0525$

Damping Reduction Factor,

$ß = (ß_{eff}/0.05)^{0.3}$ $ß = 1.0147$

$D_{d1} = (S_d \times T^2 g)/ (4\pi^2 ß)$, D_{d1} = 0.4326m

Calculating Sap2000 links/support property data (Upper Bound)

Main Properties

Determination of Bearing (Rotational Inertia)

Diameter φ = 0.305 m with height h = 0.32 m (Total height of the bearing)

It had been considered that the isolator is a cylinder with $\varphi = 0.484$ m, $h = 0.5$ m.

Then C/s Area $A = (\pi\varphi^2)/4 = 0.1840\ m^2$

$K_{eff} = (W/R_{1eff}) + (\mu \times W/D_d)$ K_{eff} = 650.29 ton/m

$I = (K_{eff} \times h^3) / 12E$ = $(650.29 \times 0.5^3) / 12$

= 6.77E-07 m^4

E = 1.00E+07 N/mm².

Determine of bearing mass

$D_{m\text{-}max}$ = 0.4326 m.

$D_{TM} = 1.15 \times 0.4326$

refer (Eq. 17.5.3.5 – **ASCE 7-10**)

D_{TM} = 0.4974 m.

$D = 2\ D_{TM} = 2 \times 0.4974$, D = 0.16146 m.

$W = 0.241\ D^2 - 0.0564\ D$ W = 0.182393 ton.

$m = W/g$ = 0.182393/ 9.8 m

= 0.0185925 ton sec^2/m.

Directional Properties (U2 – U3)

Linear properties.

Effective stiffness K_{eff} = 650.29 ton/m

Effective damping β_{eff} = 0.0525 or 5.25%

Height for outer surface, = $h_1 = h_4$ = 936.56 mm.

Height for outer surface, = $h_2 = h_3$ = 697.83 mm

Non-linear properties

Stiffness = $\mu_1 W/D_y$, R_{2eff} = 3030 mm or 3.030 m

$D_y = (\mu_1 - \mu_2)\ R_{2eff}$ = (0.102 – 0.093) * 0.526

D_y = 0.02727m.

Stiffness of outer surface = $\mu_1 W/D_y$

= (0.102× 2295.5) / 0.02727 = 8586.02 ton/m

Stiffness of inner surface = $\mu_2 W/D_y$

= (0.093× 2295.5) / 0.02727 = 7828.43 ton/m

Friction slow = μ_1 for outer surface = 0.102

Friction slow = μ_1 for Inner surface = 0.093

Friction fast = 2 × μ_1 for outer surface = 0.204

Friction fast = 2 × μ_1 for outer surface = 0.186

Rate Parameter = Friction slow / Friction fast

= 0.102 / 0.204 = 0.5

* Radius of sliding surface

For outer = R_{1eff} = 19.585 m.

For inner = R_{2eff} = 3.030 m.

* Stop distance

For outer surface $u_1^* = 2\ D_y + 2\ d_1^*$ = 6.290 m.

For outer surface $u_2^* = 2\ D_y$ = 0.05454

NUMERICAL STUDY

The earthquake response of isolated tank is investigated for two tank models (i.e. model I and II) for six different near-fault ground motions. For elevated tank, the damping ratio of convective mass has been taken 0.5% and impulsive mass has been considered as 2%. The tank wall is prepared from steel having mass density ϱ_s = 7900 kg/m,^{3} and modulus of elasticity E =200 GPa. The response quantities of concentration are tower displacement x_t, base shear F_b (W), sloshing mass x_c, isolation system x_b, and impulsive mass, x_i. The Time variation of x_t, $F_b(W)$, x_c, x_b, and x_i for slender tank isolated with TFPS for both model is shown in Figure.3 and Figure 4. The value for the TFPS (T_b = 2.5 s and μ = 0.1) are taken for the seismic response. Figure 3 exhibits the seismic response of M-1 and M-2 under Imperial Valley (1979), California El Centro Array#5 seismic ground motion. Figure 4 exhibits the seismic response *of* M-1 and M-2 under Imperial Valley (1994), California Sylmar, seismic ground motion. Figure 3 and Figure 4 indicates that there is significant reduction in F_b *(W)*, x_i *and* x_b, but x_c increases for M-1 as compared to M-2. Figure 5 and Figure 6 shows the hysteresis behavior of tank isolated by TFPS for M-1 and M-2 and also indicates isolator displacement variation of base shear of tank isolated with TFPS. The peak response of elevated tank under six near- fault ground motions are shown in Table 4 for both model M-1 and M-2. From the Table 4 we can say that if we were applying isolation at top of tower it decreases F_b *(W)* 3 to 8 %, x_i 2 to 10 % and x_b 3 to 10 % decreases but x_c increases almost 12 to 20 %.

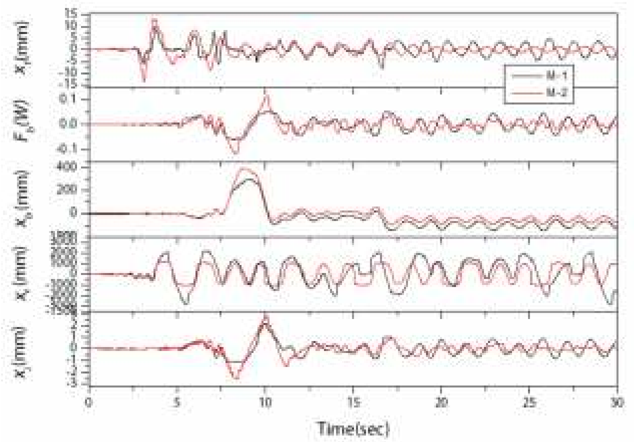

Figure 3 Time variation of x_t, $F_b(W)$ x_b, x_c, and x_i for tank isolated by TFPS (T_b = 2.5 sec and μ = 0.1) under normal component of Imperial Valley (1979), California [El Centro Array#5] seismic ground motion for M-1 and M-2

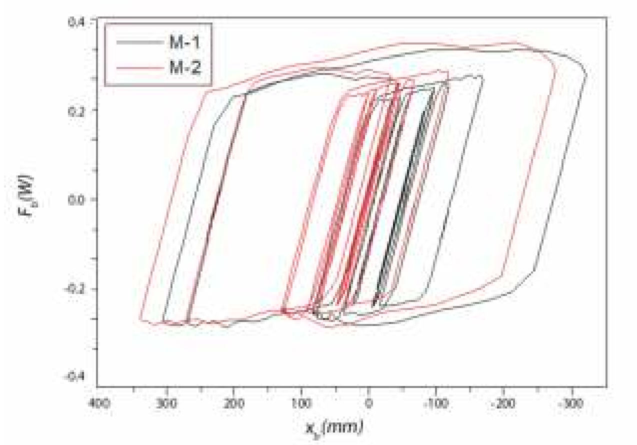

Figure 5 Hysteresis loop of tank isolated by TFPS under normal component of Imperial Valley (1979), California [El Centro Array#5] seismic ground for M-1 and M-2

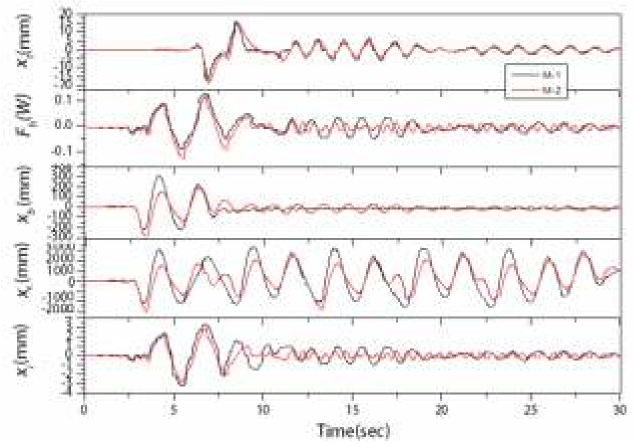

Figure 4 Time variation of x_t, $F_b(W)$ x_b, x_c, and x_i for tank isolated by TFPS (T_b = 2.5 sec and μ = 0.1) under normal component of Northridge (1994), California [Sylmar] seismic ground motion for M-1 and M-2.

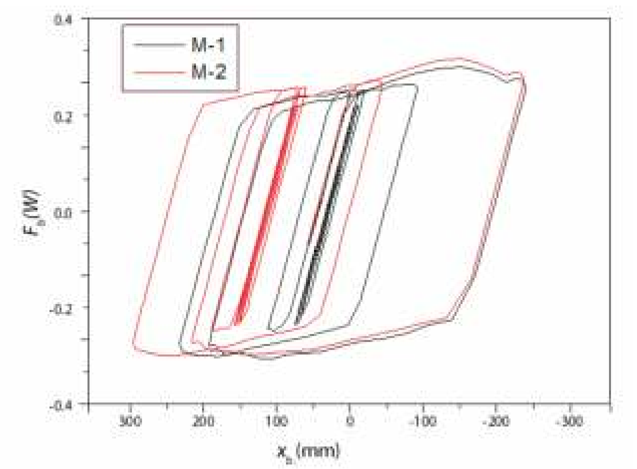

Figure 6 Hysteresis loop of tank isolated by TFPS under normal component of Nortridge (1994), California [Sylmar]seismic ground motion (a) for M-1 (b) for M-2.

Table 4 Peak responce of elevated water tank undr near-fault ground motion

Near fault ground motions	Tank conditionx	X_t(mm)	F_b(W)	x_c(mm)	x_b(mm)	x_i(mm)
Imperial valley,1979 (ELCentro) (Array#5)	Non Isolated	56.32	0.67	1978.4	-	4.72
	M-1	12.02	0.11	2416.08	365.98	2.28
	M-2	12.95	0.12	1992	372.62	2.80
Imperial valley,1979 (ELCentro) (Array#7)	Non Isolated	57.07	0.70	2062.4	-	6.08
	M-1	15.56	0.13	2468.52	392.62	2.65
	M-2	15.82	0.132	2143.70	354.23	2.78
Imperial Valley, California, 1979 (Newhall)	Non Isolated	57.95	0.76	2034.8	-	5.22
	M-1	18.63	0.14	2438.80	312.66	2.22
	M-2	18.78	0.148	2059.40	365.52	2.40

Near fault ground motions	Tank conditionx	X_t(mm)	F_b(W)	x_c(mm)	x_b(mm)	x_i(mm)
Landers, California, 1992(Lucerne valley)	Non Isolated	63.08	0.82	2246.2	-	8.28
	M-1	19.78	0.122	2982.12	262.18	2.42
	M-2	20.62	0.13	2494.28	292.12	2.76
Northridge, California,1994 (Rinaldi)	Non Isolated	57.67	0.89	2478.62	-	8.80
	M-1	21.68	0.13	2952.62	392.78	3.02
	M-2	22.43	0.136	2639.32	386.56	3.22
Northridge, California, 1994 (Sylmar)	Non Isolated	58.13	0.78	1984.2	-	5.26
	M-1	19.24	0.12	2529.92	326.22	2.20
	M-2	19.45	0.124	2012.90	306.28	2.28

CONCLUSIONS

Detailed study has been conducted to check the effectiveness of TFPS and its position in elevated liquid steel storage tank.

- Placing TFPS at top of tower was judged to be more effective than placing at bottom of tower because it reduces base shear, isolator displacement and impulsive displacement.
- Tank isolated with TFPS reduces almost 3 to 8% base shear, 2 to 6 % tower displacement, 2 to 10 % impulsive displacement, and 3 to 10% isolator displacement.
- Convective displacement is increased almost 12 to 20 %. due to application of TFPS at top of tower in comparison to TFPS at bottom of tower. Due to this reason, more free board is required.

NOMENCLATURES

F_b	[*W*]	Base shear in terms of weight
m_c	**[ton]**	**Convective mass**
m_i	**[ton]**	**Impulsive mass**
m_r	**[ton]**	**Rigid mass**
x_c	[mm]	Convective displacement
x_i	[mm]	Impulsive displacement
x_t	[mm]	Tower displacement
x_b	[mm]	Isolator displacement
S_d	[ms^{-1}]	Spectral Acceleration
F_d	[kN]	Design force
D_d	[mm]	Design Displacement
D_{m-max}	[mm]	Maximum Displacement
D_{TM}	[mm]	Total Maximum Design Displacement
K_{eff}	[kN m^{-1}]	Effective Stiffness of isolator unit
T_b	[sec]	Time period of isolation system

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