

附錄A

在自由液面上，由於流體滿足不會發生剝離的現象且液壓為零等條件，因此必須滿足邊界條件 $\left. \frac{\partial \phi}{\partial z} \right|_{z=H} = \frac{\partial d}{\partial t}$ ，即(2.1-4d)式，另外，在流體不穩定 (unsteady) 及非旋性 (irrotational) 的情況下，流體必須滿足此 Bernoulli Equation:

$$\frac{\partial \phi}{\partial t} + \frac{p}{\rho_l} + \frac{1}{2} \nabla \phi \cdot \nabla \phi + g(z-H) = 0 \quad (\text{A.1})$$

其中 p 表示流體的液壓， ρ_l 表流體密度。

考慮流體為一微小質點，因此該質點之動能 $\frac{1}{2} \nabla \phi \cdot \nabla \phi$ 可以忽略。

將(A.1)式同乘以 ρ_l 並改寫如下：

$$\rho_l \frac{\partial \phi}{\partial t} + p + \rho_l g(z-H) = 0 \quad (\text{A.2})$$

$$\text{或 } p = -\rho_l \frac{\partial \phi}{\partial t} - \rho_l g(z-H) = 0 \quad (\text{A.3})$$

因為自由液面壓力 $p=0$ ，因此(A.3)或可改寫為 $\rho_l \frac{\partial \phi}{\partial t} + \rho_l g(z-H) = 0$ ，即邊界條件式(2.1-4c)。



附錄B

由(2.1-8)式

$$\frac{r^2}{\hat{R}} \frac{\partial^2 \hat{R}}{\partial r^2} + \frac{r}{\hat{R}} \frac{\partial \hat{R}}{\partial r} + \frac{r^2}{\hat{Z}} \frac{\partial^2 \hat{Z}}{\partial z^2} = -\frac{1}{\hat{\theta}} \frac{\partial^2 \hat{\theta}}{\partial \theta^2} \quad (\text{B.1})$$

成立等號必須兩邊均為常數，此常數記作 μ (特徵值)

則可將式(2.1-8)改寫成下列二式：

$$\frac{r^2}{\hat{R}} \frac{\partial^2 \hat{R}}{\partial r^2} + \frac{r}{\hat{R}} \frac{\partial \hat{R}}{\partial r} + \frac{r^2}{\hat{Z}} \frac{\partial^2 \hat{Z}}{\partial z^2} = \mu \quad (\text{B.2})$$

$$\frac{\partial^2 \hat{\theta}}{\partial \theta^2} + \mu \hat{\theta} = 0$$

因為極座標具有週期性，也就是恆有 $\phi(r, z, \theta, t) = \phi(r, z, \theta + 2\pi, t)$ ，因此 $\hat{\theta}(\theta)$ 必須是以 2π 為週期的週期函數，也是 $\hat{\theta}(\theta) = \hat{\theta}(\theta + 2n\pi)$ ，為滿足此條件，因此特徵值必須為某個整數的平方，也就是 $\mu = n^2$ 。



附錄C

由式(2.1-45a) $\left. \frac{\partial \phi_1}{\partial t} \right|_{z=H} = \sum_{n=1}^{\infty} \hat{T}_{1n}(t) \cos(n\theta) J_n(kr) \cosh(kH) = 0$

若上式恆成立，則 $\cosh(kH)$ 必須等於零。

$\cosh(x)$ 可表示如下：

$$\cosh(x) = \frac{e^x + e^{-x}}{2}, \text{ 因此 } \cosh(kH) = \frac{e^{kH} + e^{-kH}}{2} = \frac{e^{2kH} + 1}{2} > 0$$

由此可知該恆等式不成立，所以第二種情況不滿足。

同樣地，第三種情況亦不滿足。

附錄D

由式(2.1-53b)

$$\left. \frac{\partial \phi_2}{\partial t} \right|_{r=R} = \hat{T}_2(t) \cos \theta \frac{1}{R} = 0 \quad (\text{D.1})$$

若上式恆成立，則 $\cos \theta$ 必須為零，則 $\theta = \frac{\pi}{2}$

這表示流體在槽壁上的速度只在 $\theta = \frac{\pi}{2}$ 滿足此邊界條件，此與真實情況不

符，因此第二種情況不成立。

另外由(2.1-54c)

$$\left. \frac{\partial \phi_3}{\partial r} \right|_{r=R} = \sum_{i=1}^{\infty} \hat{T}_{3i}(t) \cos \theta \left(\frac{\lambda_i}{H} \right) I_1' \left(\frac{\lambda_i}{H} R \right) \cos \left(\frac{\lambda_i}{H} z \right) = 0 \quad (\text{D.2})$$

若上式成立，則 $I_1' \left(\frac{\lambda_i}{H} R \right)$ 必須為零。

$$I_n(x) = \sum_{m=0}^{\infty} \frac{1}{m! \Gamma(m+2)} \left(\frac{x}{2} \right)^{2m+n} \quad (\text{D.3})$$

因此 $I_1(x) = \sum_{m=0}^{\infty} \frac{1}{m! \Gamma(m+2)} \left(\frac{x}{2} \right)^{2m+1}$ ，則 $I_1'(x) = \sum_{m=0}^{\infty} \frac{1}{2} \frac{2m+1}{m!(m+1)\Gamma(m+1)} \left(\frac{x}{2} \right)^{2m}$

$$I_0(x) = \sum_{m=0}^{\infty} \frac{1}{m! \Gamma(m+1)} \left(\frac{x}{2} \right)^{2m} \quad (\text{D.4})$$

由 I_0 之圖形可得知， $I_0 > 0$

其中 $\Gamma(x+1) = \int_0^{\infty} t^{x-1} e^{-t} dt$

且 $\Gamma(x+1) = \int_0^{\infty} t^x e^{-t} dt = -e^{-t} t^x \Big|_0^{\infty} + x \int_0^{\infty} t^{x-1} e^{-t} dt = x\Gamma(x)$

因此 $\Gamma(2) = \Gamma(1+1) = 1\Gamma(1) = 1$

$$\Gamma(m+1) = m\Gamma(m) = m!$$

由此一關係可得知 $I_1'(x) = \frac{2m+1}{2(m+1)} I_0 > 0$

所以第三種情況不成立。

表 4.1 希臘 Revithoussa LNG 儲存槽圓形儲存槽結構參數

儲存槽高度(m)	32.5
儲存槽半徑(m)	34.5
儲存槽殼密度(kg/m ³)	7850
液體密度(kg/m ³)	135
儲存槽厚度(m)	0.05
槽殼阻尼比	2%



表 4.2 摩擦單擺支承參數

曲率半徑(m)	1
摩擦係數	0.05

表 4.3 希臘 Revithoussa LNG 儲存槽自然振動頻率(H=5cm)

h=5cm	隔震前		以 FPS 隔震後	
模態	頻率(Hz)	阻尼比(%)	頻率(Hz)	阻尼比(%)
1	0.1095	0	0.1095	0
2	0.1959	0	0.1959	0
3	0.2480	0	0.2480	0
4	0.2904	0	0.2904	0
5	0.3272	0	0.3272	0
6	0.3602	0	0.3602	0
7	0.3904	0	0.3904	0
8	0.4185	0	0.4185	0
9	0.4447	0	0.4447	0
10	0.4695	0	0.4695	0
11	5.5702	2	0.6346	0
12			8.6556	1.43

表 4.4 希臘 Revithoussa LNG 儲存槽隔震前自然振動頻率(unit = Hz)

			shell	liquid				
		H/R	1st	1st	2nd	3rd	4th	5th
Rigid tank		0.81	-	0.1095	0.1959	0.248	0.2904	0.3272
		0.5	-	0.0981	0.195	0.2479	0.2904	0.3272
		0.1	-	0.0491	0.1369	0.2064	0.2637	0.3109
Non-rigid tank	h=5cm	0.81	5.5702	0.1095	0.1959	0.248	0.2904	0.3272
		0.5	18.4767	0.0981	0.195	0.2479	0.2904	0.3272
		0.1	19.6611	0.0491	0.1369	0.2064	0.2637	0.3109
	h=4cm	0.81	3.2042	0.1095	0.1959	0.248	0.2904	0.3272
		0.5	18.1899	0.0981	0.195	0.2479	0.2904	0.3272
		0.1	19.6611	0.0491	0.1369	0.2064	0.2637	0.3109
	h=3cm	0.81	0.1458	0.1095	0.1959	0.248	0.2904	0.3272
		0.5	17.7198	0.0981	0.195	0.2479	0.2904	0.3272
		0.1	19.6611	0.0491	0.1369	0.2064	0.2637	0.3109

表 4.5 希臘 Revithoussa LNG 儲存槽隔震後自然振動頻率(unit = Hz)

			shell	liquid							
		H/R	1st	1st	2nd	3rd	4th	5th	isolated mode		
Rigid tank			0.81	-	0.1095	0.1959	0.248	0.2904	0.3272	0.6448	
			0.5	-	0.0978	0.1949	0.2478	0.2903	0.3272	0.5934	
			0.1	-	0.0491	0.1368	0.2064	0.2636	0.3108	0.5189	
Non-rigid tank		h=5cm		0.81	8.6556	0.1095	0.1959	0.248	0.2904	0.3272	0.6346
				0.5	21.467	0.0981	0.195	0.2479	0.2904	0.3272	0.5861
				0.1	22.265	0.0491	0.1369	0.2064	0.2637	0.3109	0.5172
		h=4cm		0.81	5.7053	0.1095	0.1959	0.248	0.2904	0.3272	0.6377
				0.5	20.686	0.0981	0.195	0.2479	0.2904	0.3272	0.5881
				0.1	21.774	0.0491	0.1369	0.2064	0.2637	0.3109	0.5177
		h=3cm		0.81	1.7364	0.1095	0.1959	0.248	0.2904	0.3272	0.6408
				0.5	19.704	0.0978	0.1949	0.2478	0.2903	0.3272	0.5902
				0.1	21.270	0.0491	0.1369	0.2064	0.2637	0.3109	0.5181

表 4.6 非剛性儲存槽在 El Centro 0.34g 地震槽存槽隔震效能(h=5 cm)

El Centro	PGA=0.34g		
	隔震前	隔震後	折減率%
最大波動位移 (cm)	76.21	76.30	-0.12
最大動水壓 (kN/m ²)	9.23	3.90	57.70
最大基底剪力 (kN)	13238	5543.9	58.12
最大傾覆力矩 (kN-m)	106250	49003	53.88

表 4.7 非剛性儲存槽在 Kobe 0.83g 地震槽存槽隔震效能(h=5 cm)

Kobe	PGA=0.83g		
	隔震前	隔震後	折減率%
最大波動位移 (cm)	57.66	108.37	-87.94
最大動水壓 (kN/m ²)	27.17	16.26	40.14
最大基底剪力 (kN)	30575	20318	33.55
最大傾覆力矩 (kN-m)	230760	143410	37.85

表 4.8 非剛性儲存槽在 Northridge 0.84g 地震槽存槽隔震效能(h=5 cm)

Northridge	PGA=0.84g		
	隔震前	隔震後	折減率%
最大波動位移 (cm)	122.82	201.48	-64.05
最大動水壓 (kN/m ²)	29.77	20.11	32.43
最大基底剪力 (kN)	30237	24556	18.79
最大傾覆力矩 (kN-m)	214890	168470	21.60

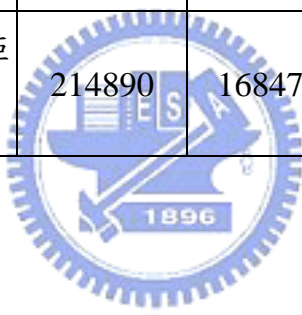




圖 1.1 槽殼挫屈 1971 San Fernando Earthquake, USA

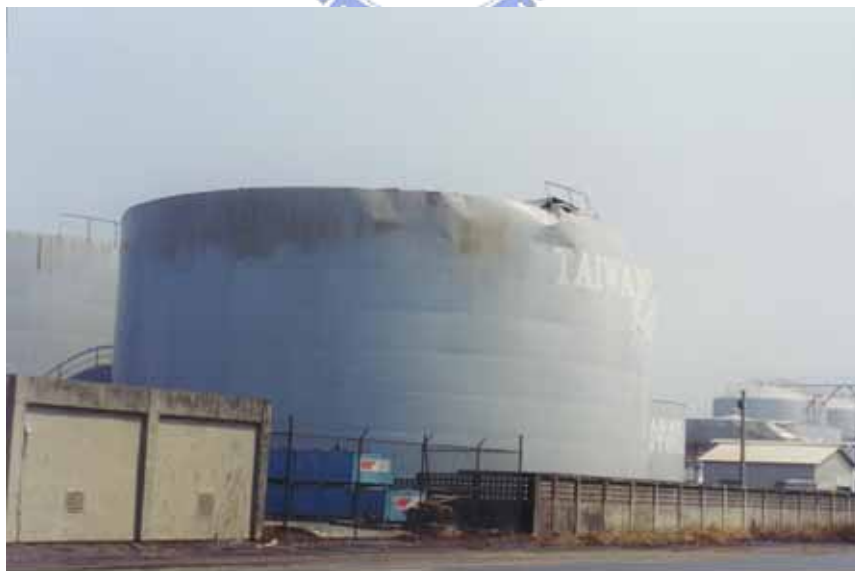


圖 1.2 槽頂破壞 1999 台灣集集地震(台中港)

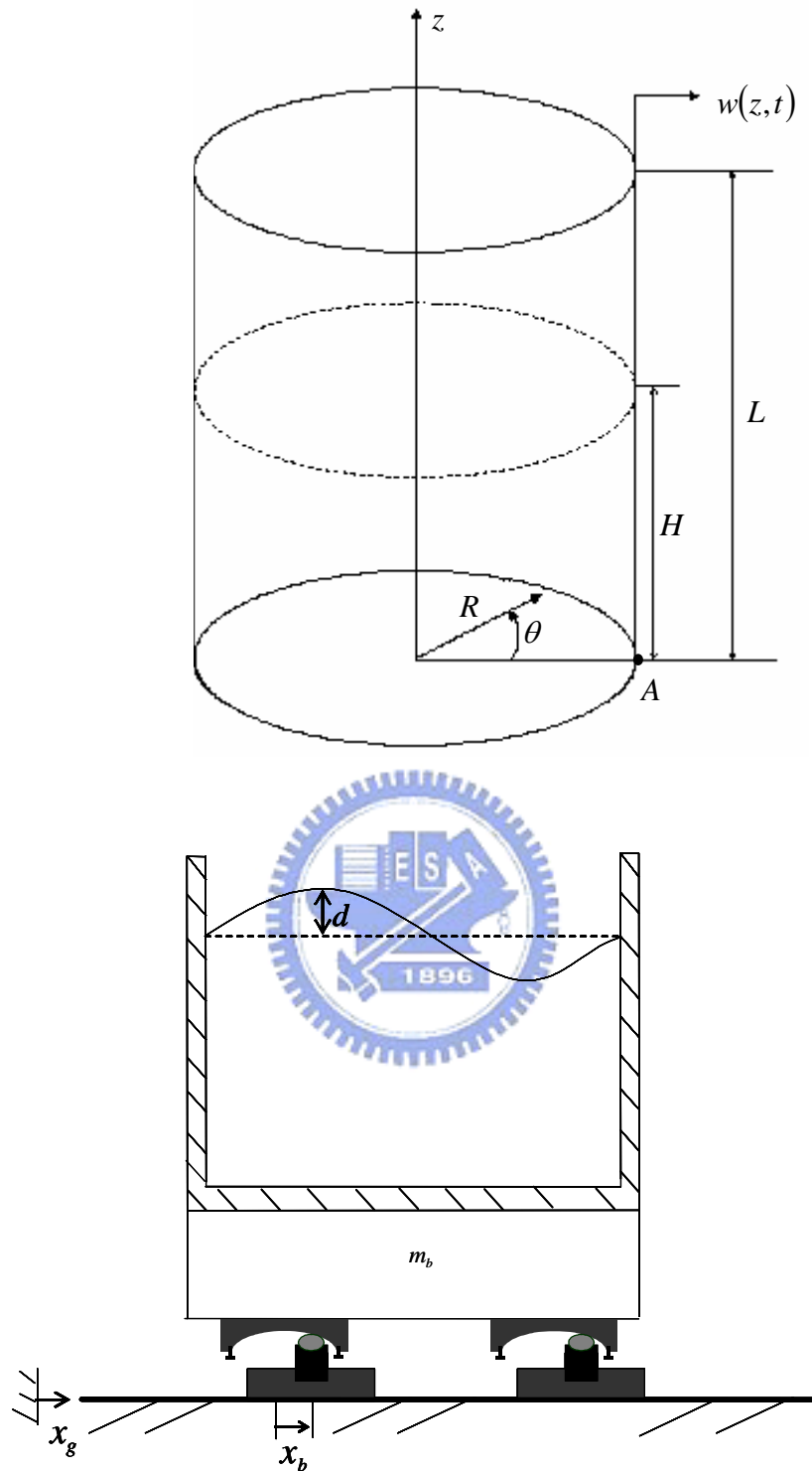


圖 2.1 儲存槽模型示意圖

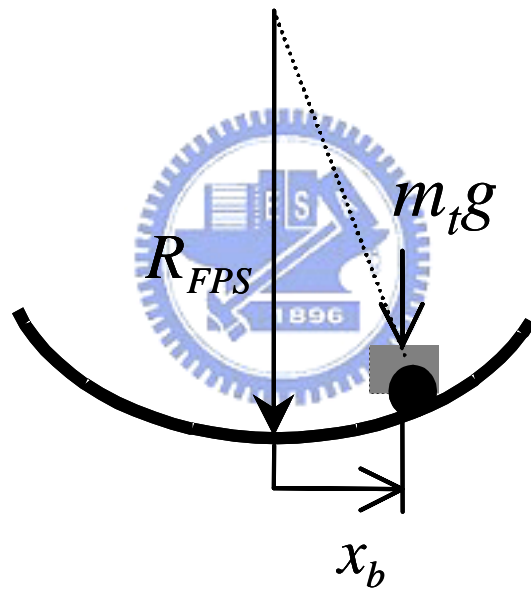
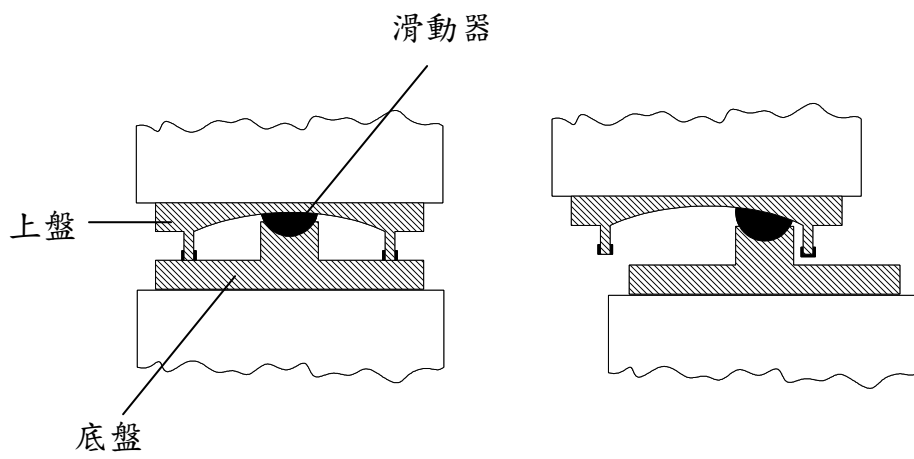


圖 3.1 摩擦單擺支承力學行為與構造

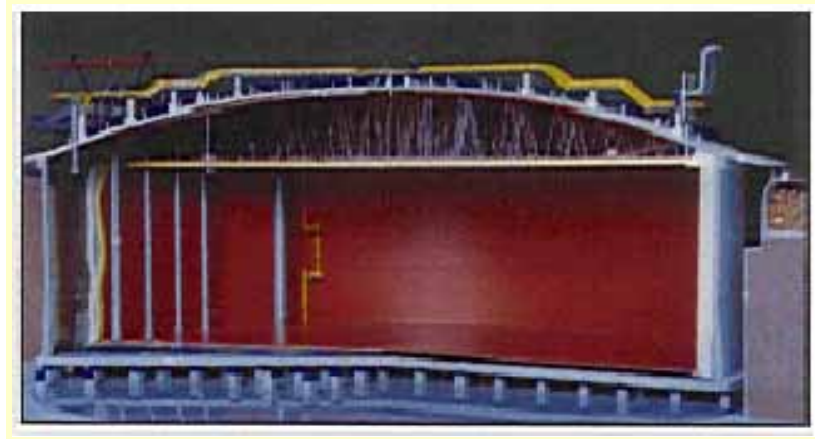


圖 4.1 希臘 Revithoussa LNG 儲存槽

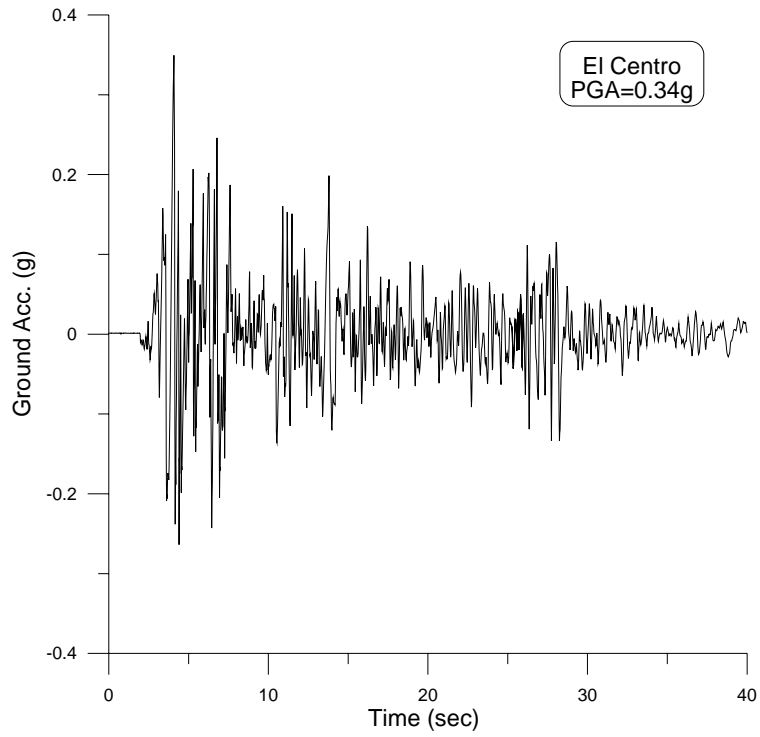


圖 4.2 El Centro 地震加速度歷時記錄(PGA=0.34g)

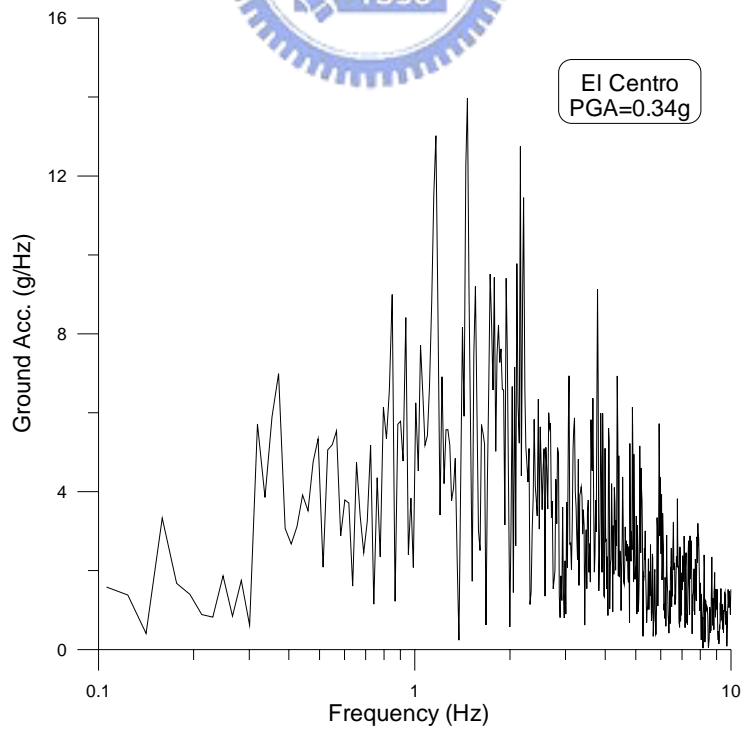


圖 4.3 El Centro 地震加速度富氏頻譜(PGA=0.34g)

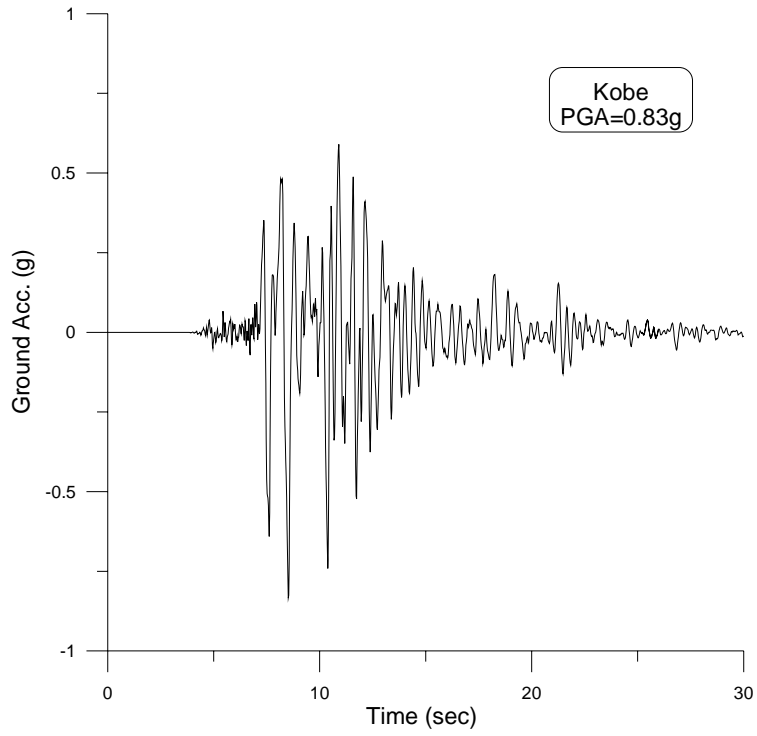


圖 4.4 Kobe 地震加速度歷時記錄(PGA=0.83g)

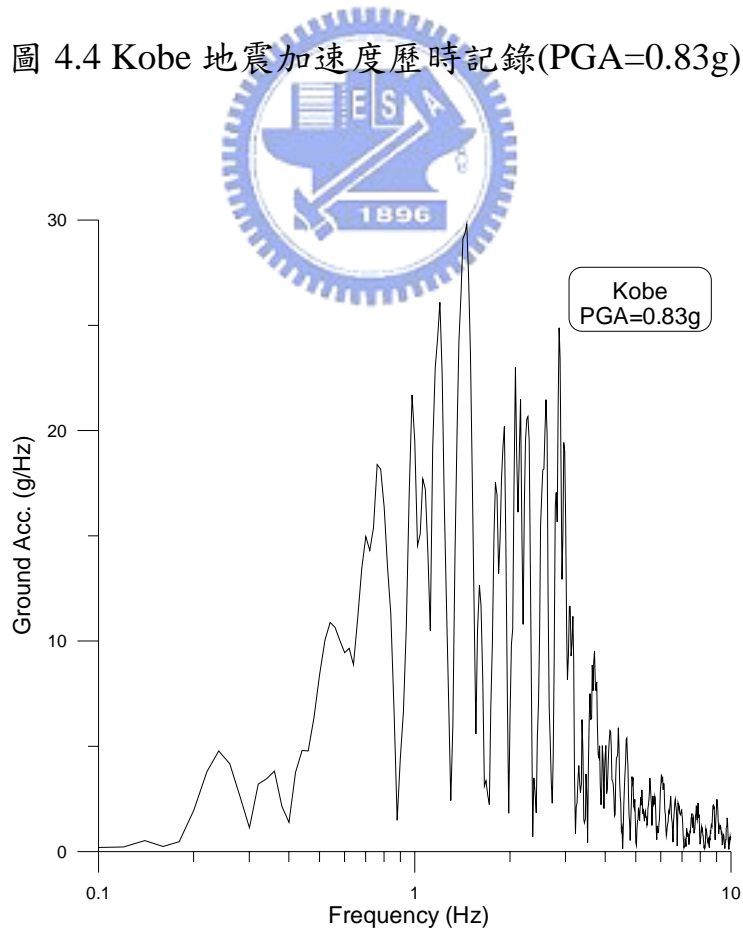


圖 4.5 Kobe 地震加速度富氏頻譜(PGA=0.83g)

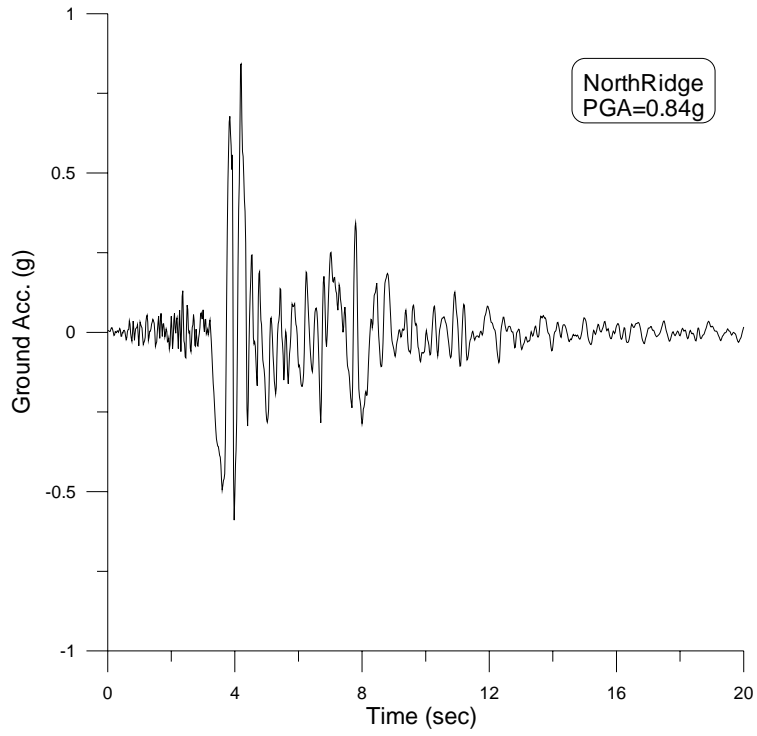


圖 4.6 Northridge 地震加速度歷時記錄(PGA=0.84g)

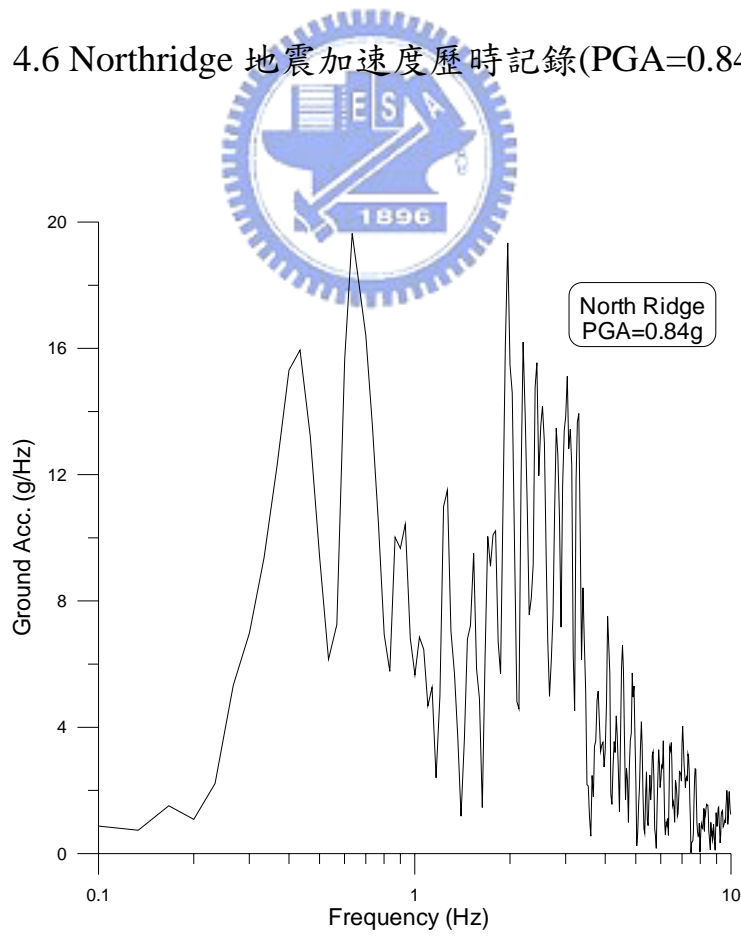


圖 4.7 Northridge 地震加速度富氏頻譜(PGA=0.84g)

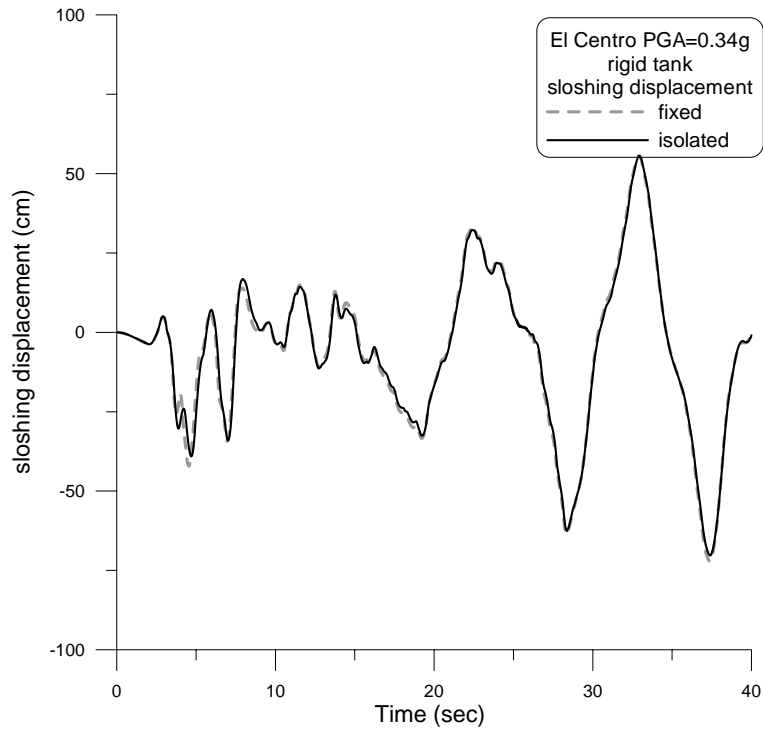


圖 4.8 剛性儲存槽液面波動位移歷時(El Centro PGA=0.34g)

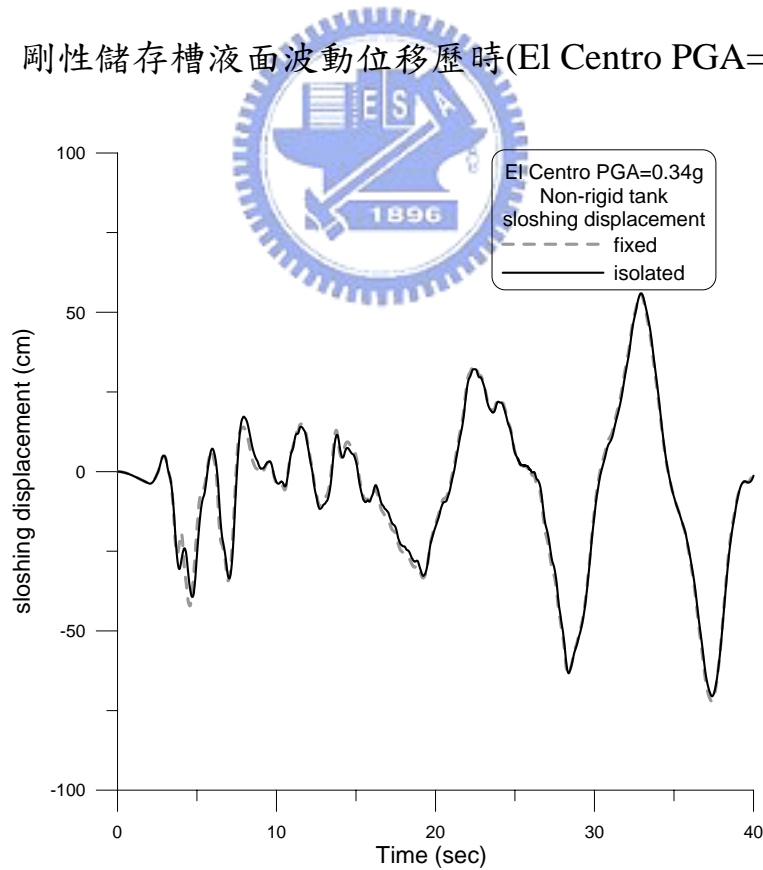


圖 4.9 非剛性儲存槽液面波動位移歷時(El Centro PGA=0.34g)

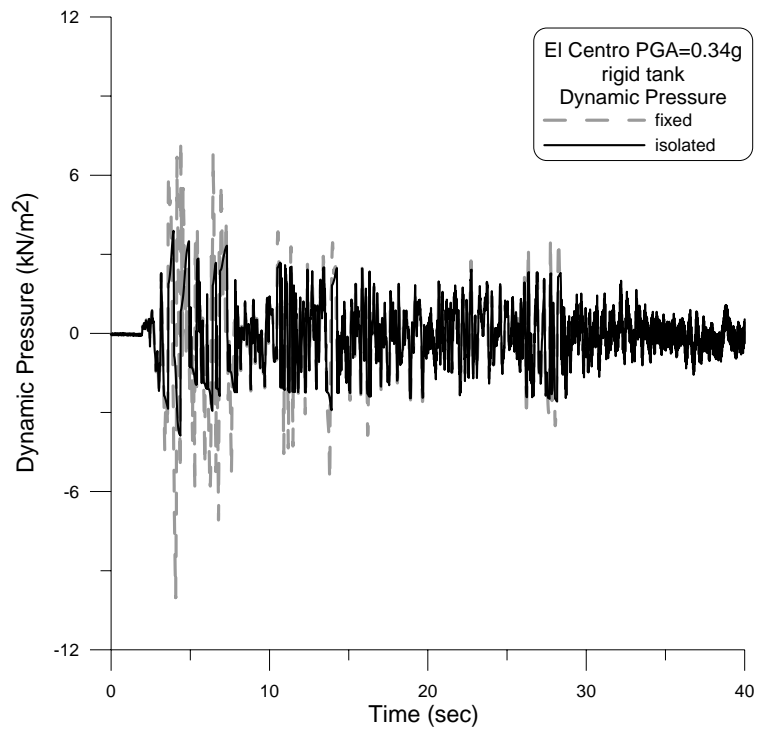


圖 4.10 剛性槽儲存槽底動水壓力歷時(El Centro PGA=0.34g)

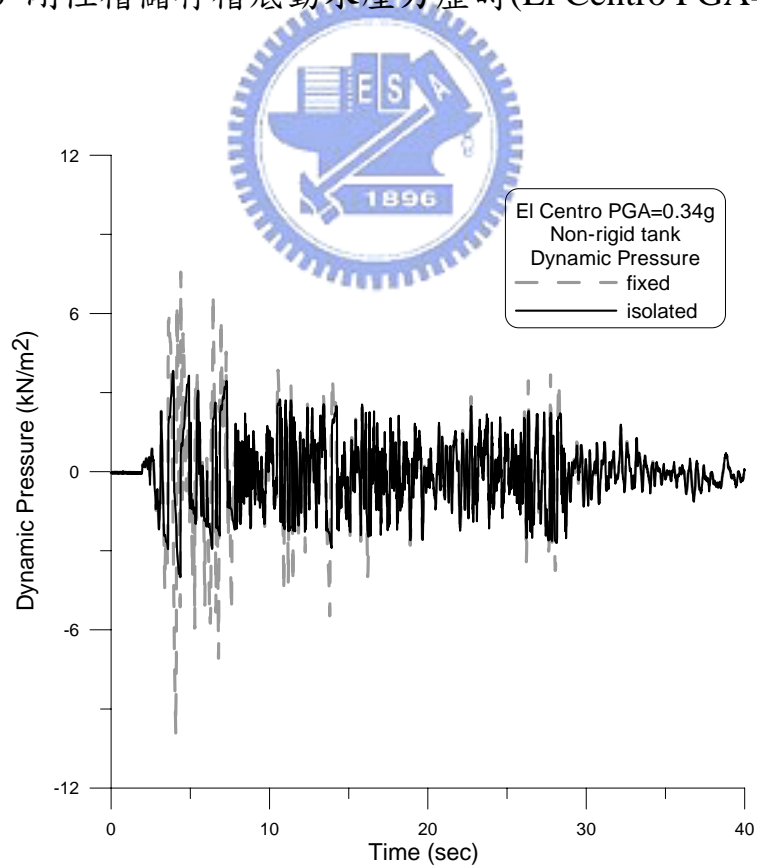


圖 4.11 非剛性儲存槽槽底動水壓力歷時(El Centro PGA=0.34g)

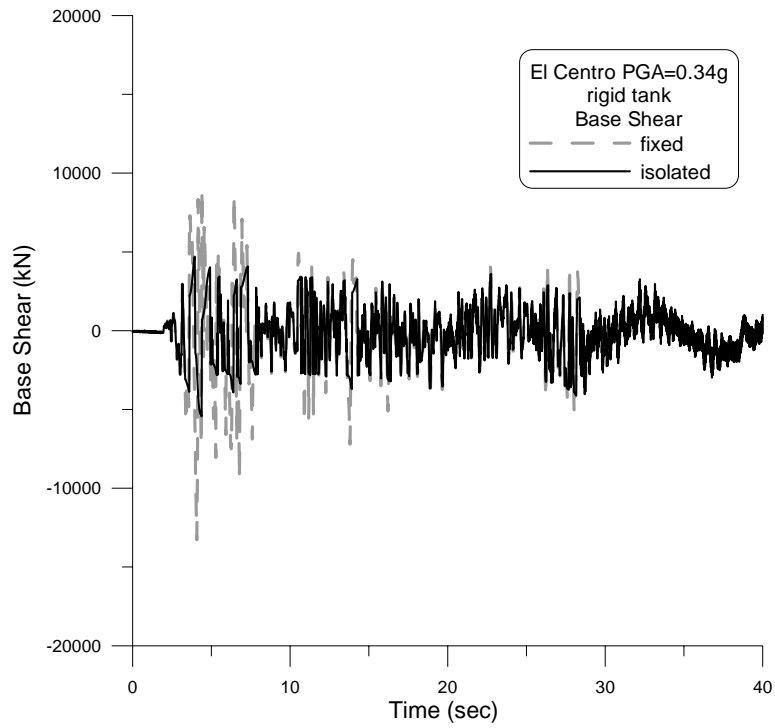


圖 4.12 刚性儲存槽基底剪力歷時(El Centro PGA=0.34g)

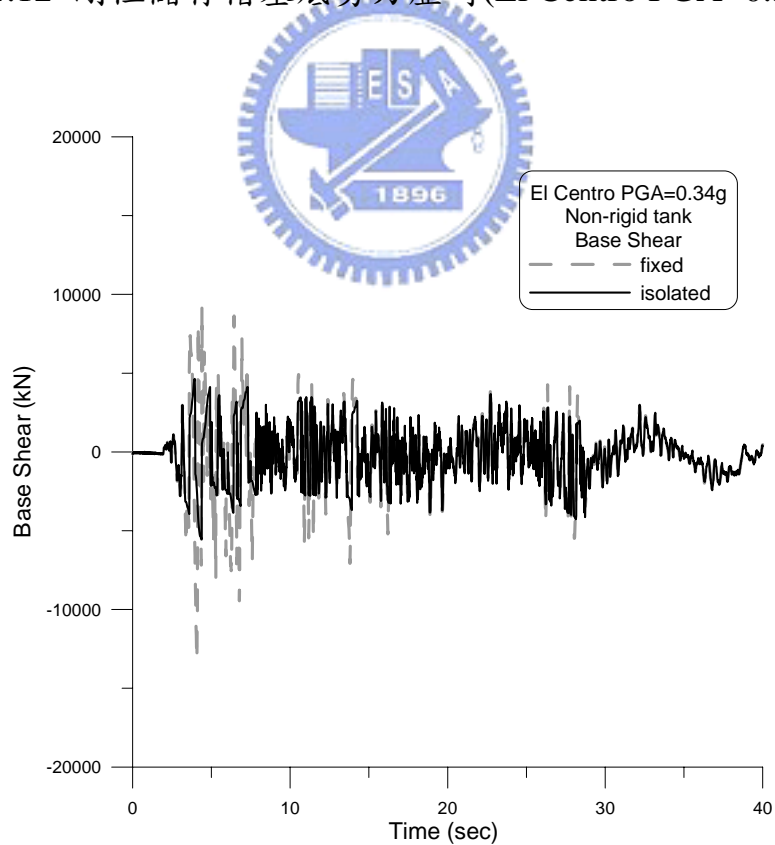


圖 4.13 非刚性儲存槽基底剪力歷時(El Centro PGA=0.34g)

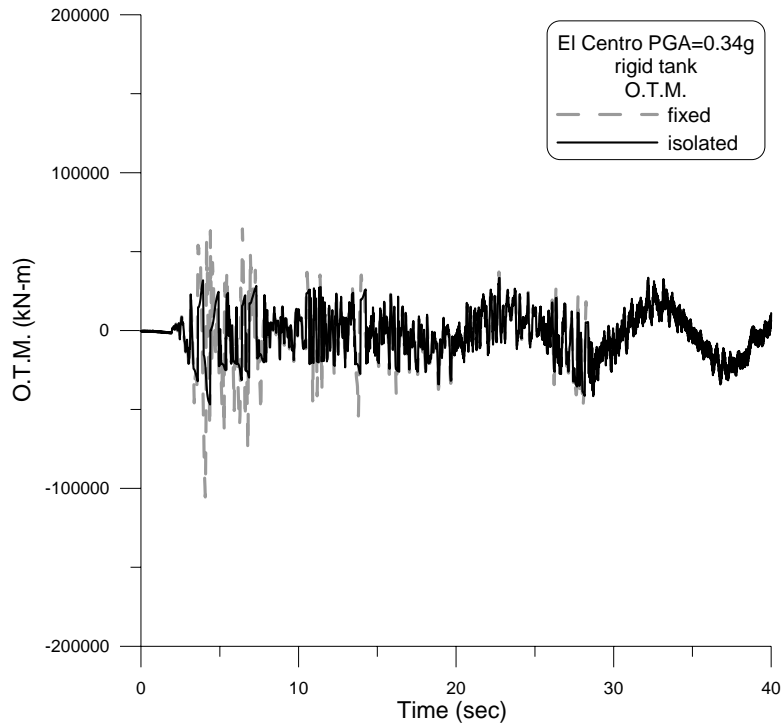


圖 4.14 剛性儲存槽傾覆力矩歷時(El Centro PGA=0.34g)

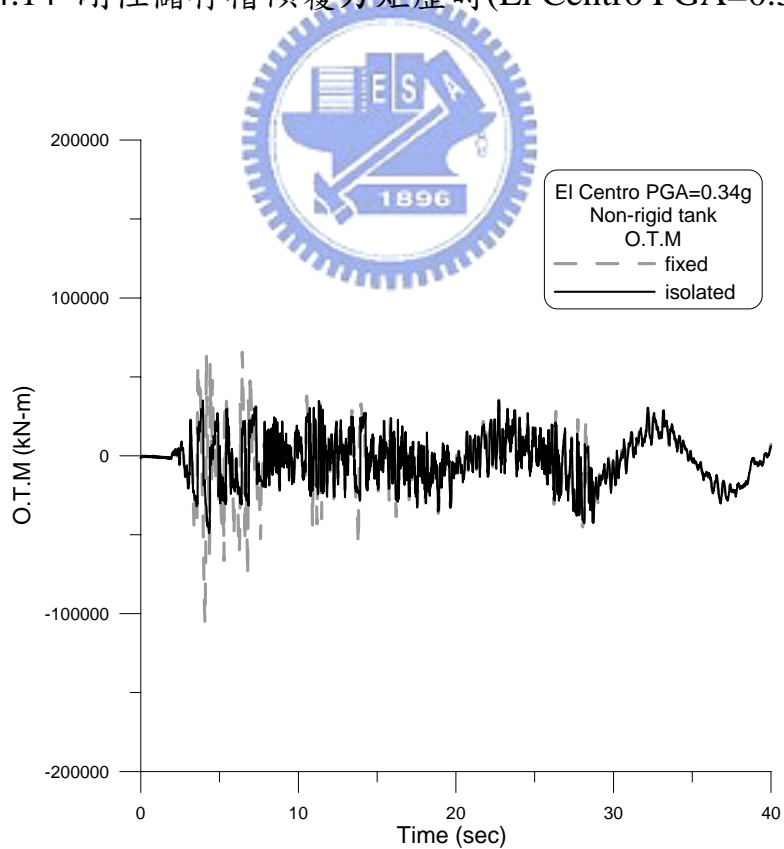


圖 4.15 非剛性儲存槽傾覆力矩歷時(El Centro PGA=0.34g)

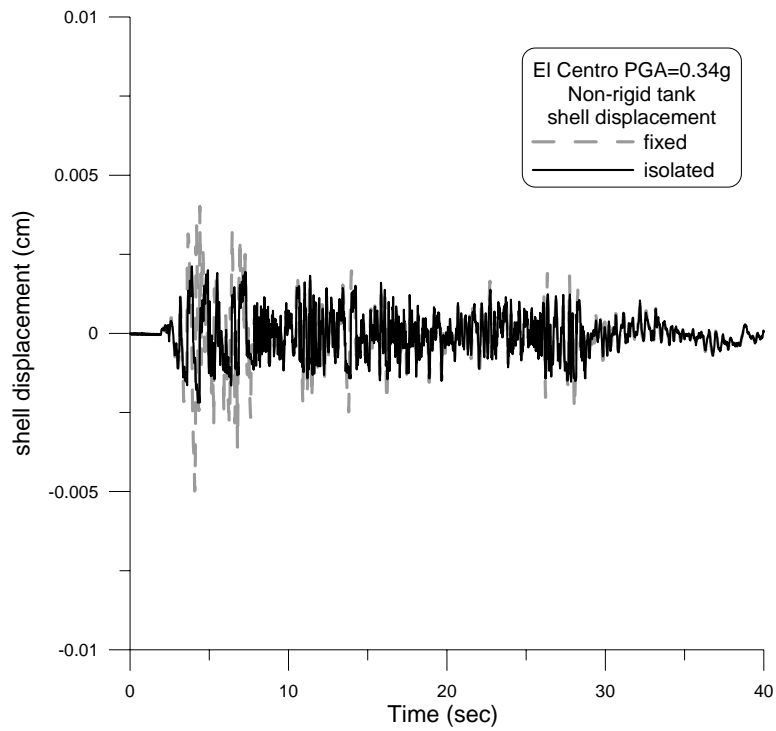


圖 4.16 非剛性儲存槽槽殼頂部位移歷時(El Centro PGA=0.34g)

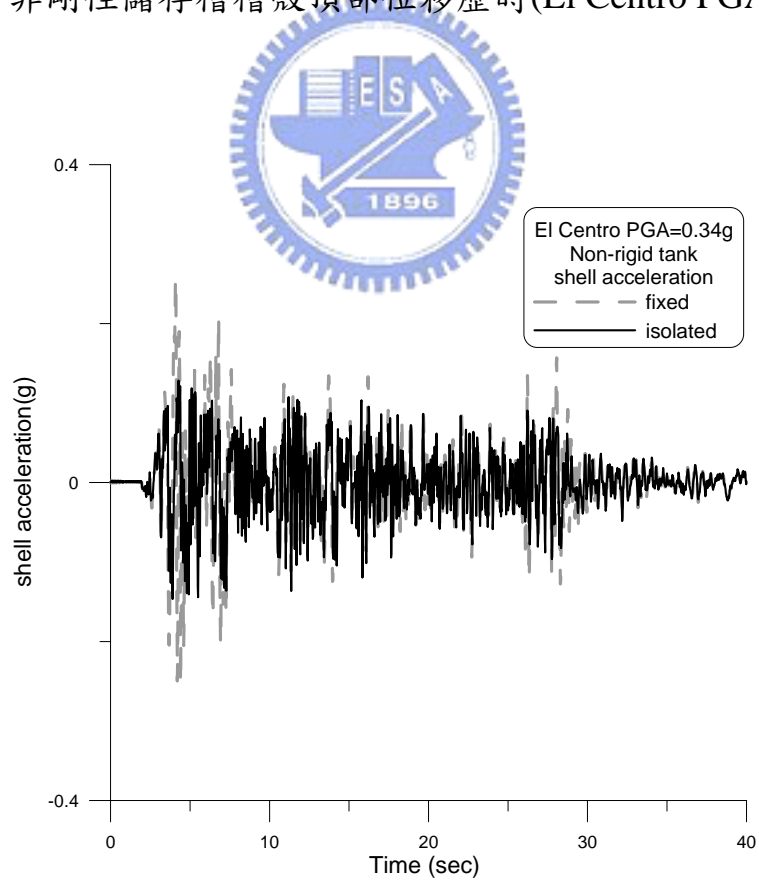


圖 4.17 非剛性儲存槽槽殼頂部加速度歷時(El Centro PGA=0.34g)

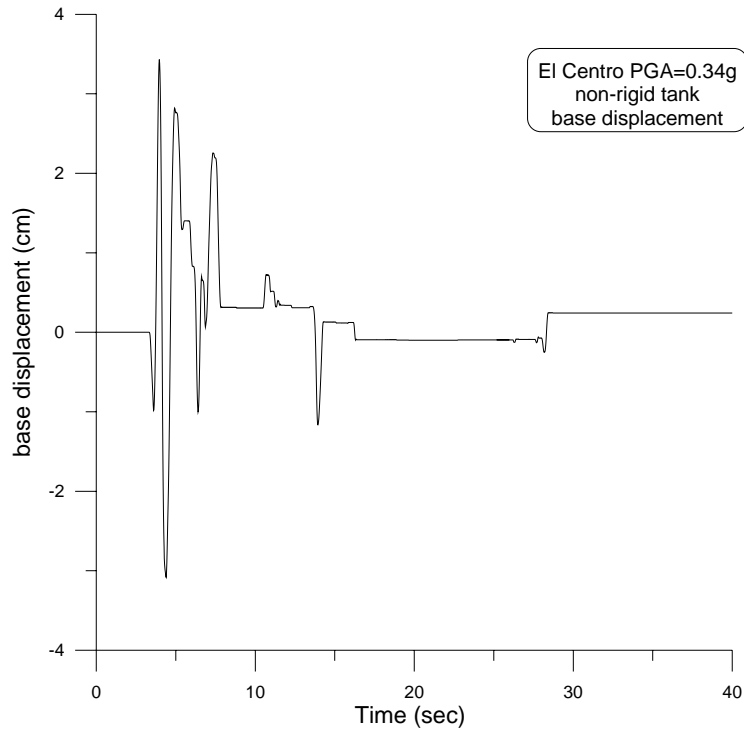


圖 4.18 非剛性儲存槽基座位移歷時(El Centro PGA=0.34g)

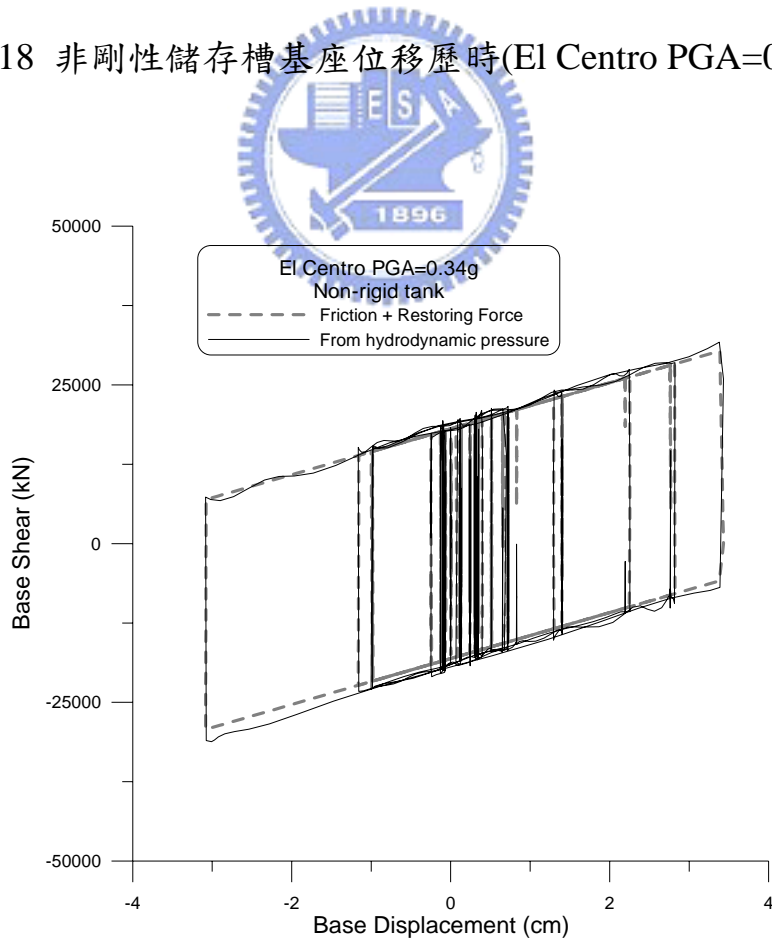


圖 4.19 非剛性儲存槽基底剪力—位移遲滯迴圈(El Centro PGA=0.34g)

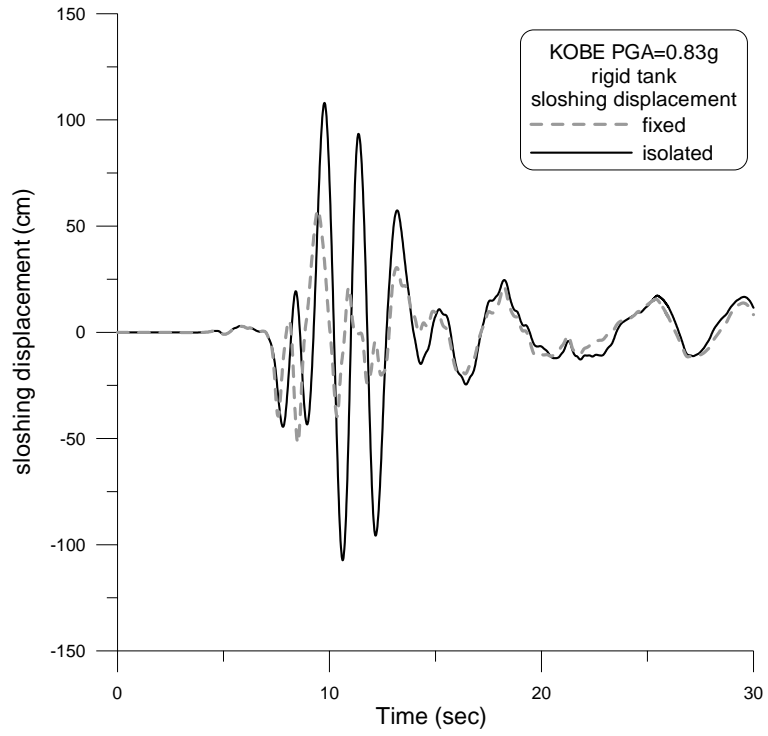


圖 4.20 剛性儲存槽液面波動位移歷時(Kobe PGA=0.83g)

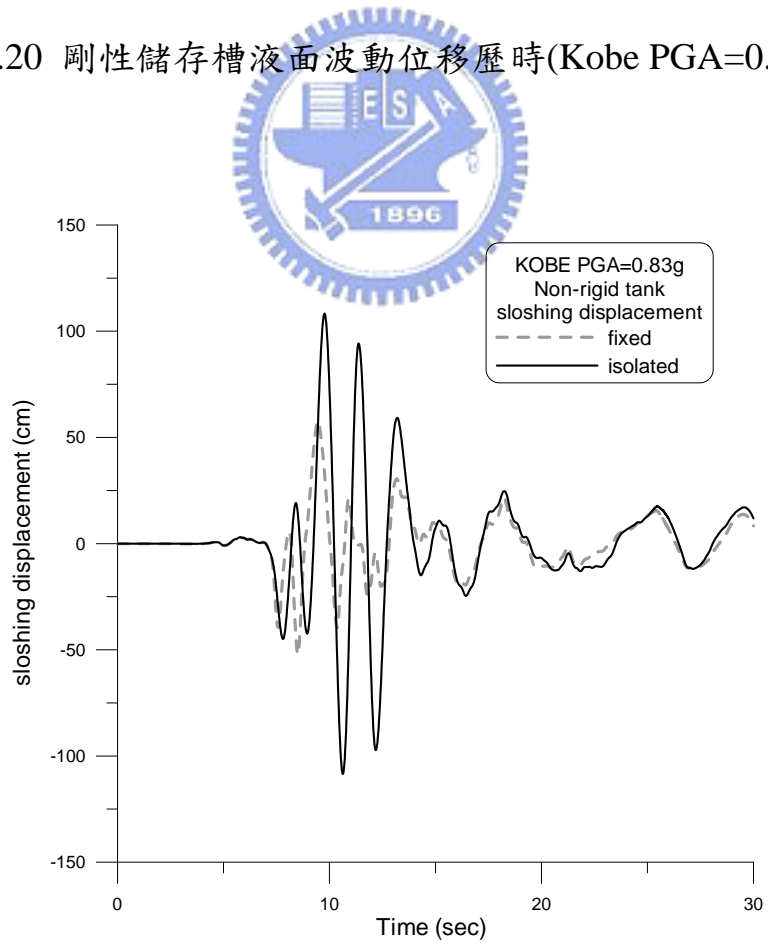


圖 4.21 非剛性儲存槽液面波動位移歷時(Kobe PGA=0.83g)

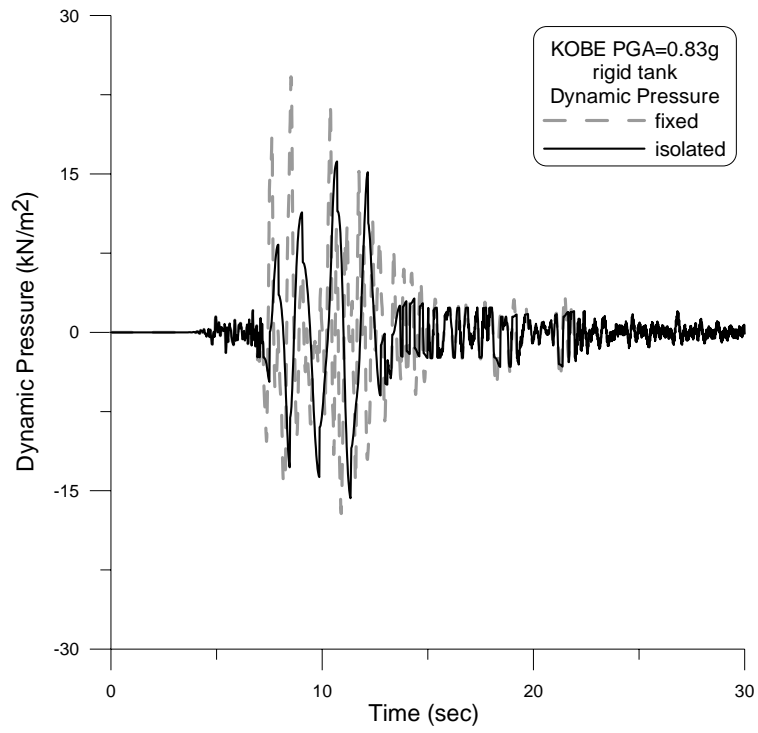


圖 4.22 剛性儲存槽槽底動水壓力歷時(Kobe PGA=0.83g)

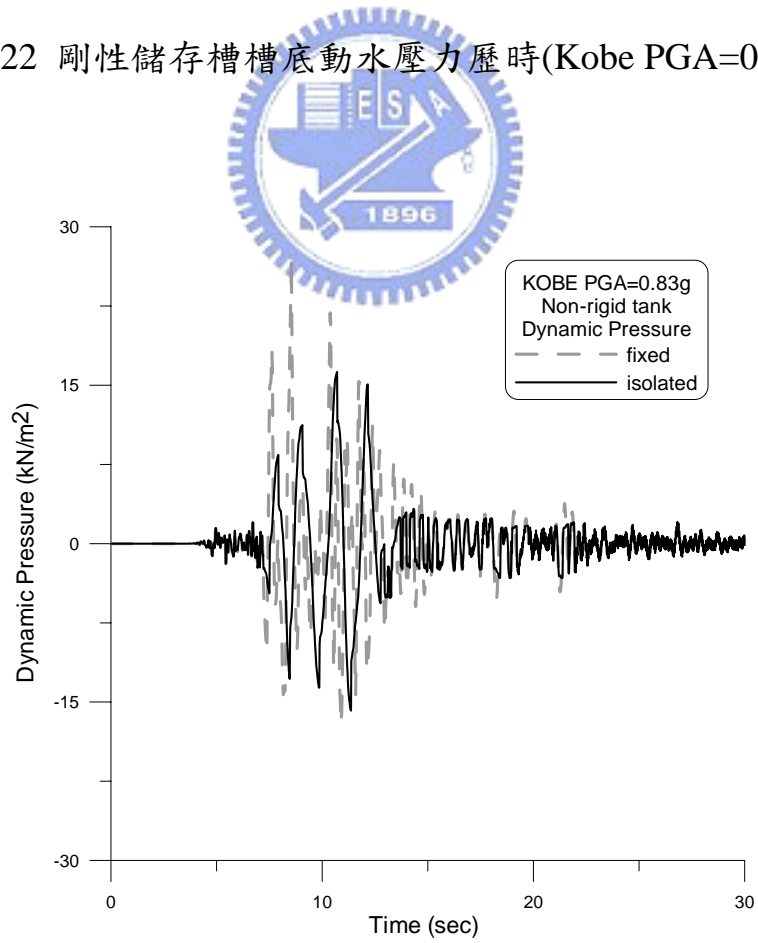


圖 4.23 非剛性儲存槽槽底動水壓力歷時(Kobe PGA=0.83g)

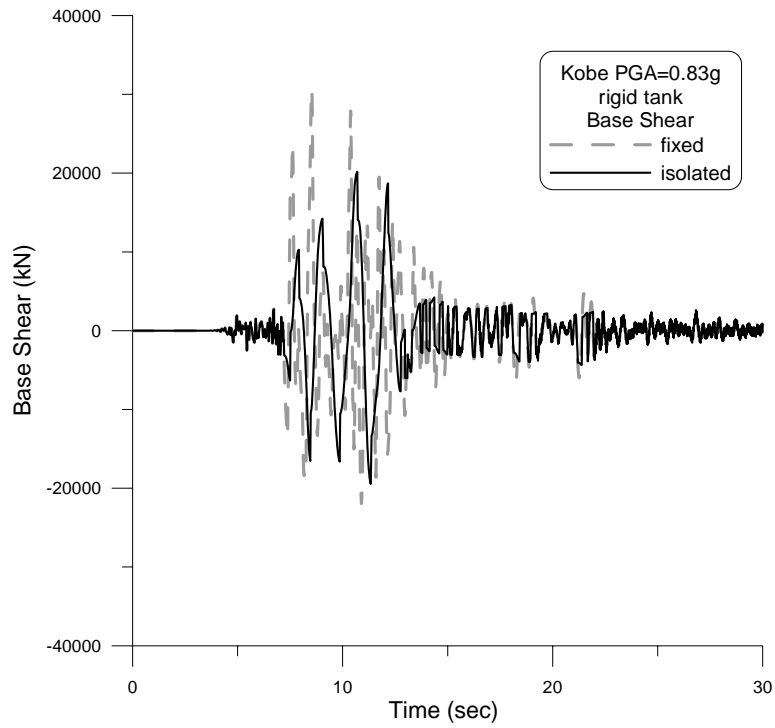


圖 4.24 剛性儲存槽基底剪力歷時(Kobe PGA=0.83g)

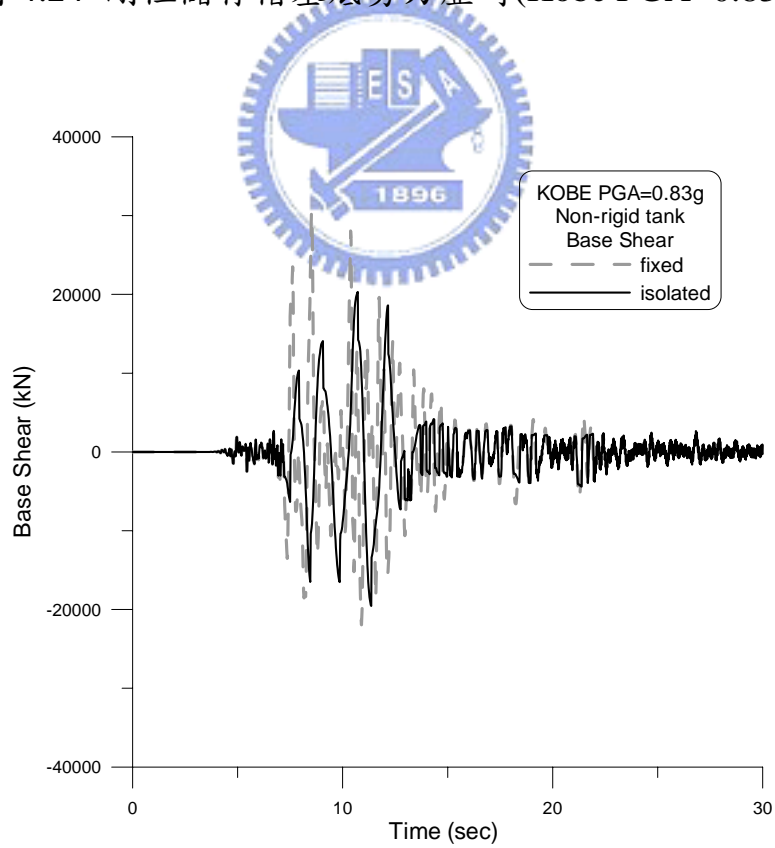


圖 4.25 非剛性儲存槽基底剪力歷時(Kobe PGA=0.83g)

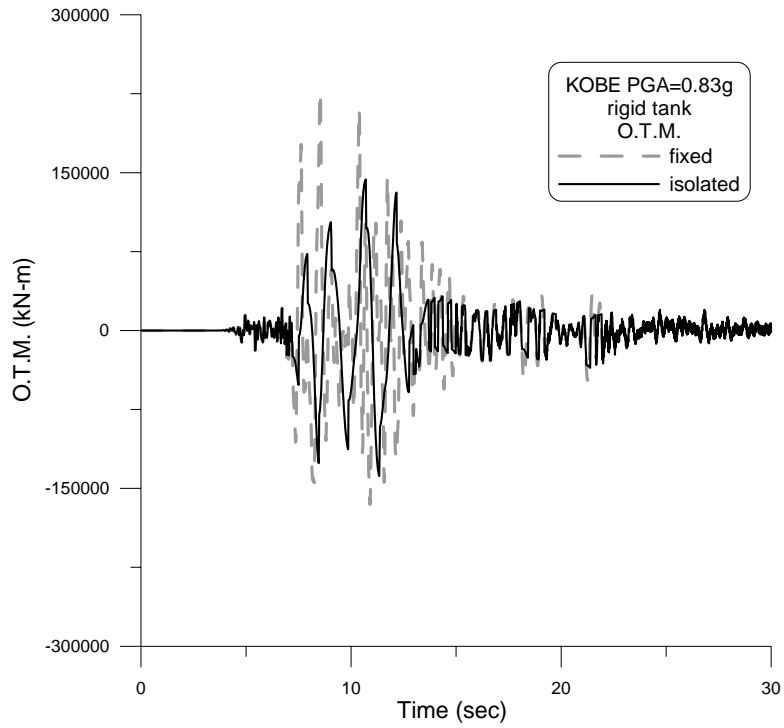


圖 4.26 剛性儲存槽傾覆力矩歷時(Kobe PGA=0.83g)

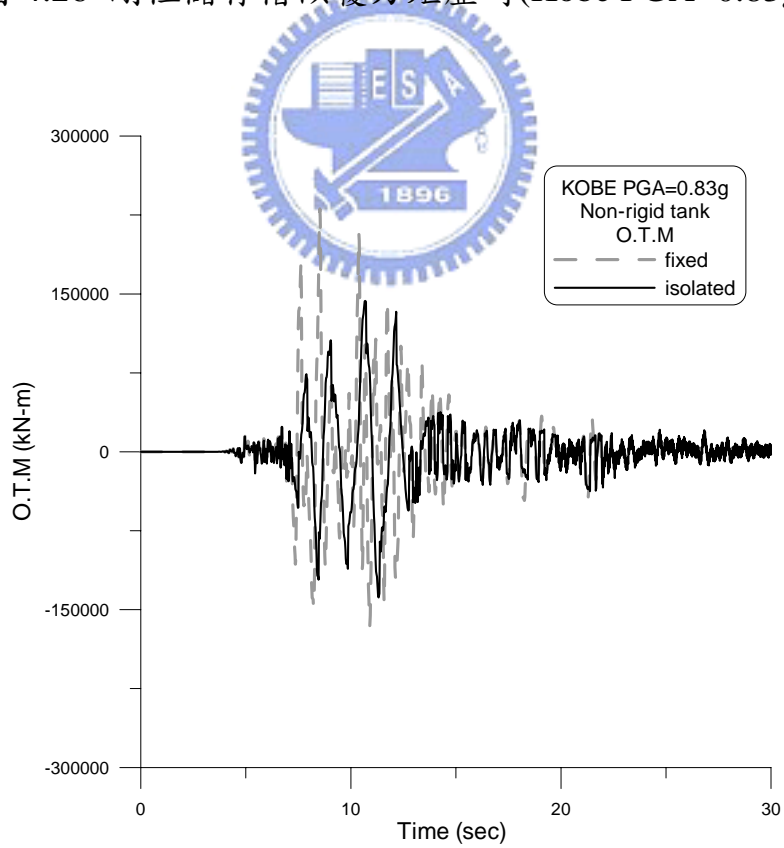


圖 4.27 非剛性儲存槽傾覆力矩歷時(Kobe PGA=0.83g)

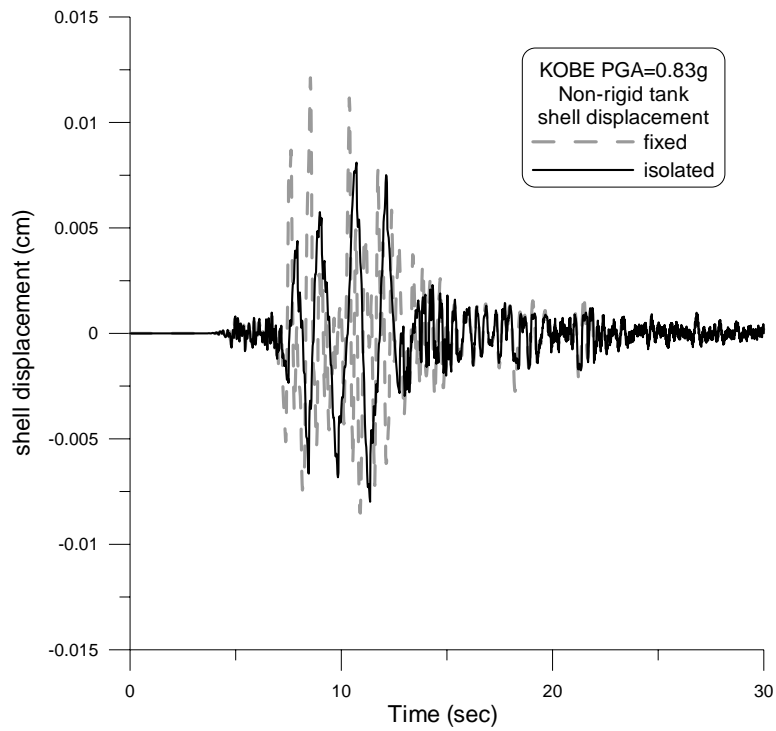


圖 4.28 非剛性儲存槽槽殼頂部位移歷時(Kobe PGA=0.83g)

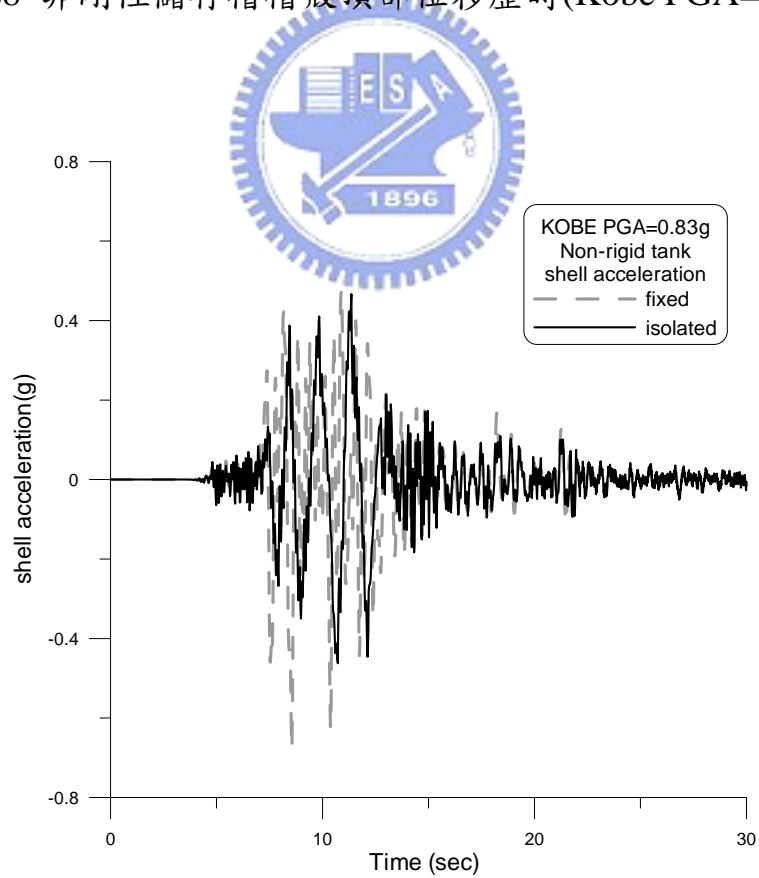


圖 4.29 非剛性儲存槽槽殼頂部加速度歷時(Kobe PGA=0.83g)

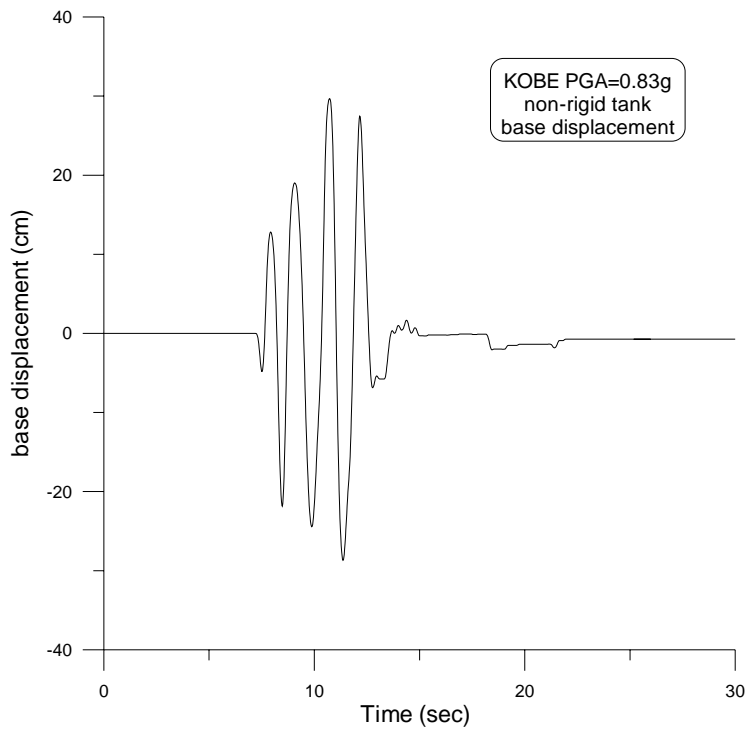


圖 4.30 非剛性儲存槽基座位移歷時(Kobe PGA=0.83g)

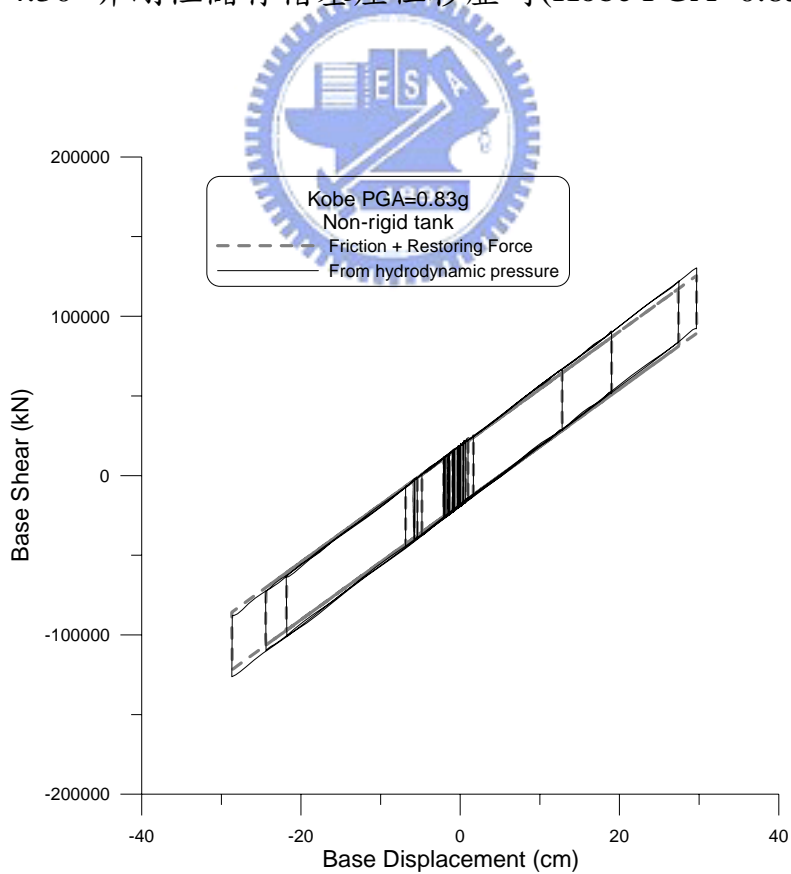


圖 4.31 非剛性儲存槽基底剪力—位移遲滯迴圈(Kobe PGA=0.83g)

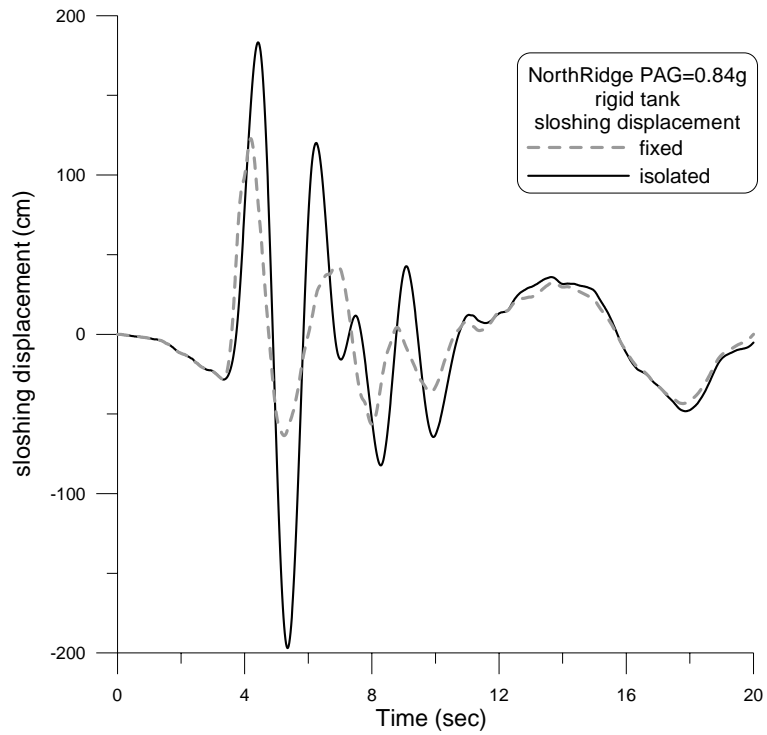


圖 4.32 剛性儲存槽液面波動位移歷時(Northridge 0.84g)

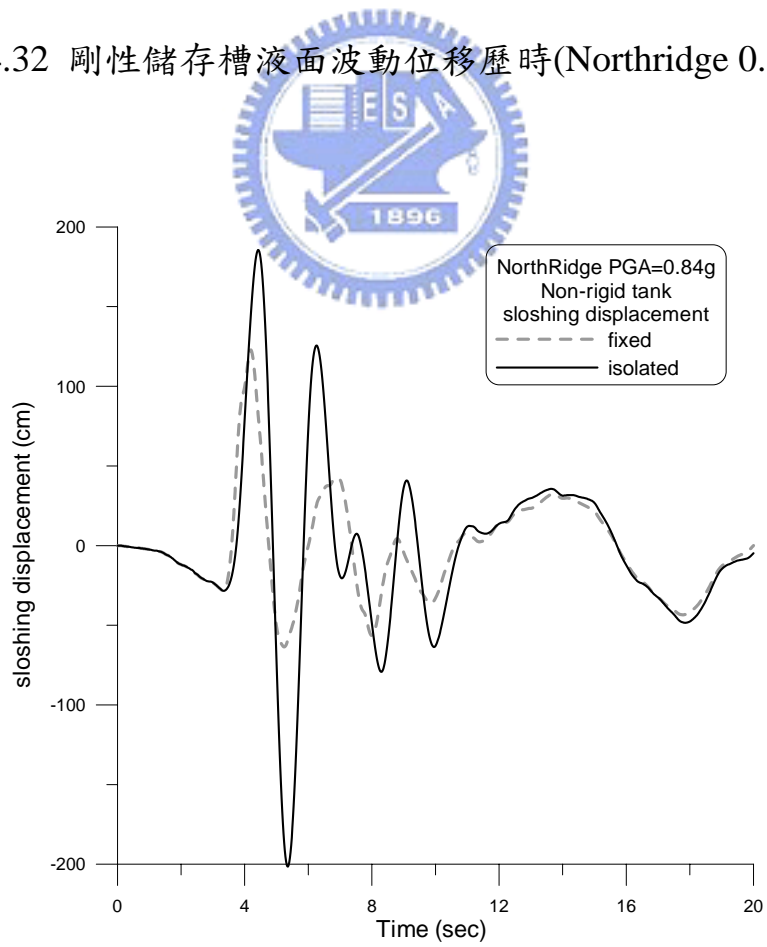


圖 4.33 非剛性儲存槽液面波動位移歷時(Northridge 0.84g)

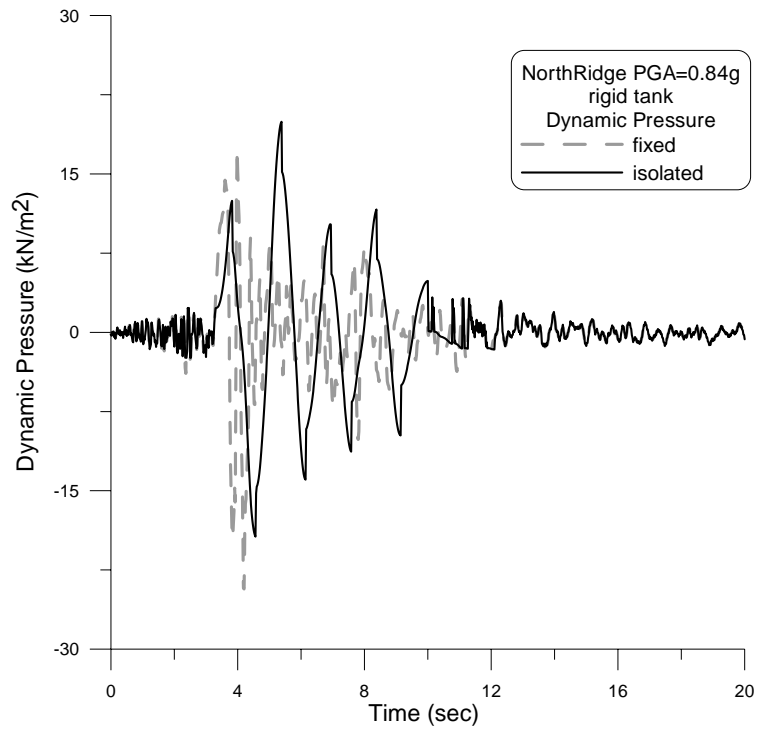


圖 4.34 刚性槽儲存槽底動水壓力歷時(Northridge 0.84g)

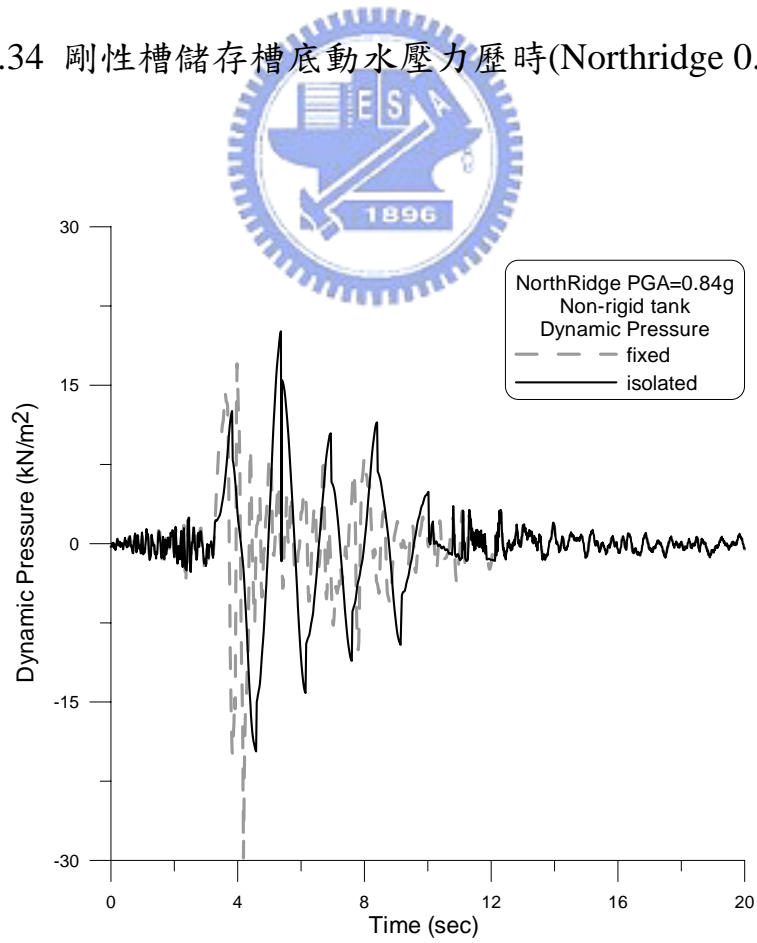


圖 4.35 非刚性儲存槽槽底動水壓力歷時(Northridge 0.84g)

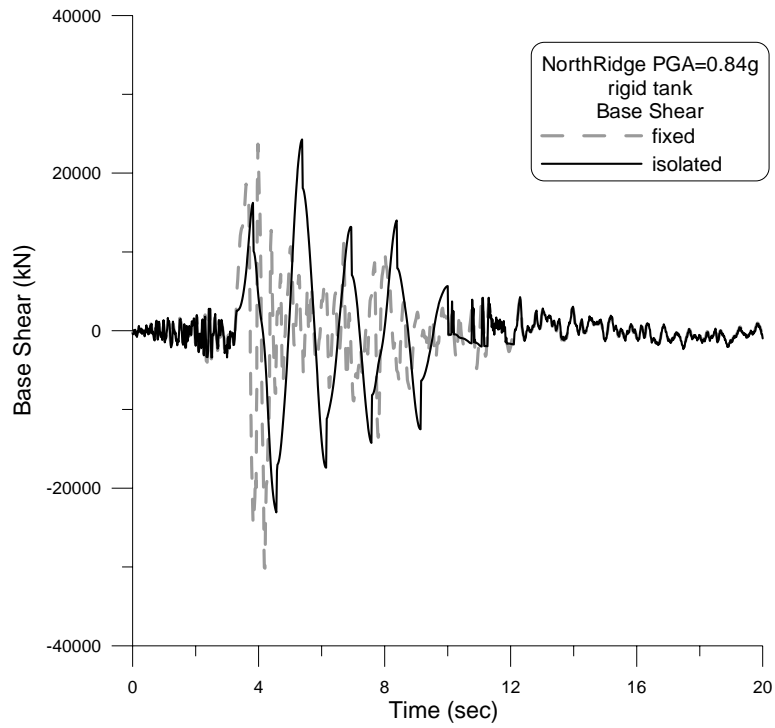


圖 4.36 剛性儲存槽基底剪力歷時(Northridge 0.84g)

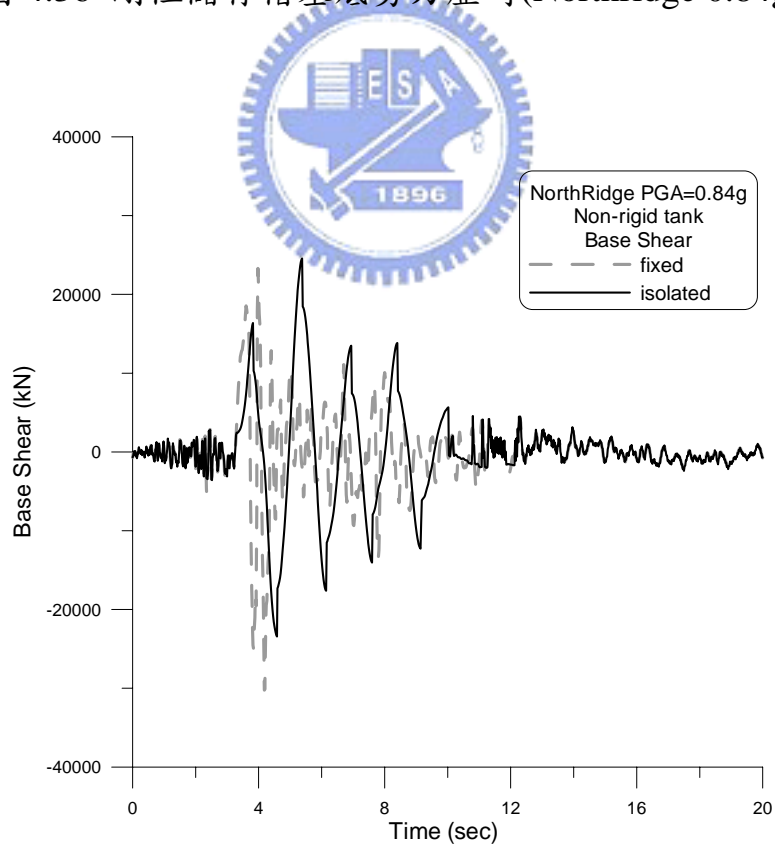


圖 4.37 非剛性儲存槽基底剪力歷時(Northridge 0.84g)

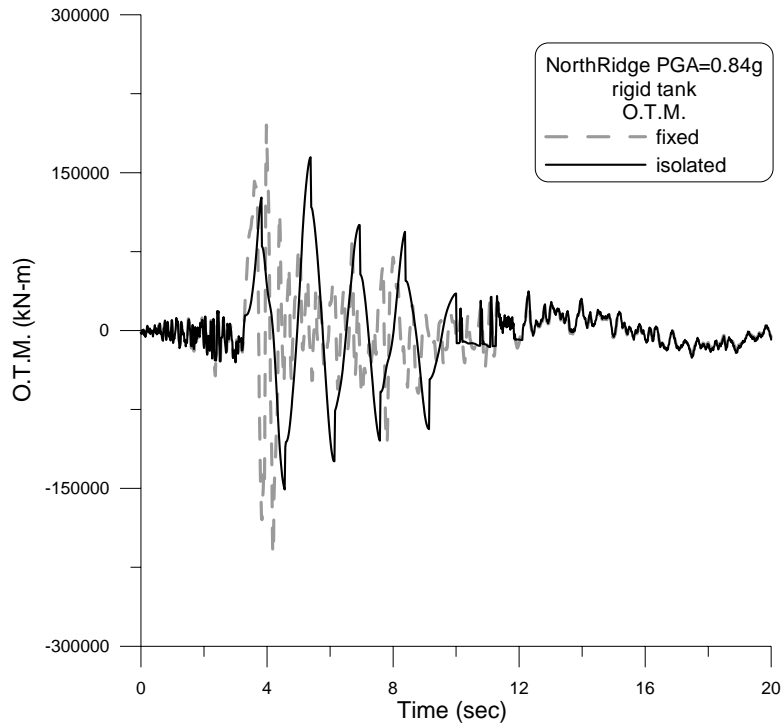


圖 4.38 剛性儲存槽傾覆力矩歷時(Northridge 0.84g)

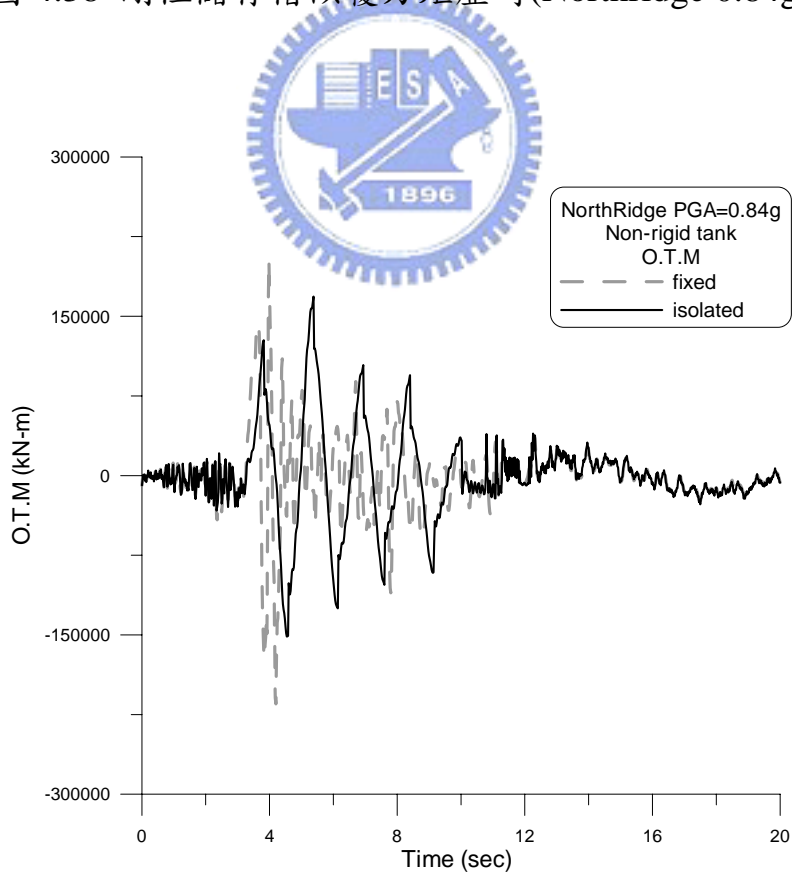


圖 4.39 非剛性儲存槽傾覆力矩歷時(Northridge 0.84g)

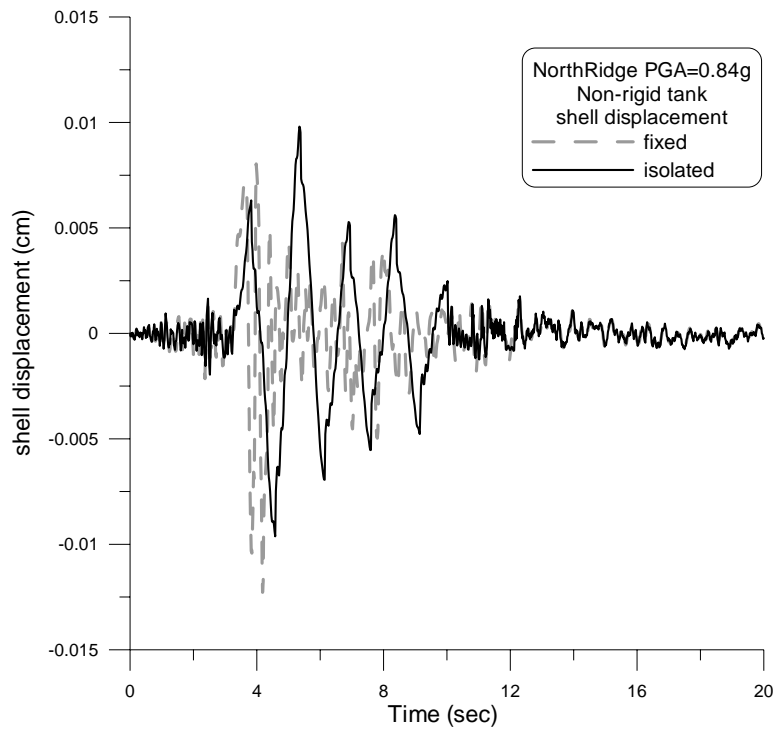


圖 4.40 非剛性儲存槽槽殼頂部位移歷時(Northridge 0.84g)

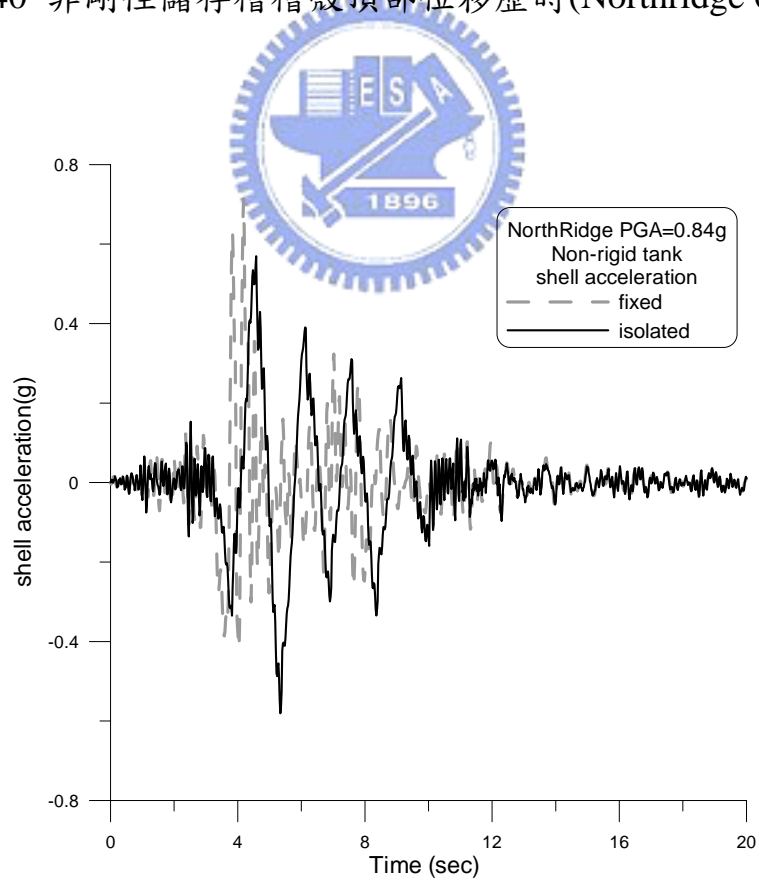


圖 4.41 非剛性儲存槽槽殼頂部加速度歷時(Northridge 0.84g)

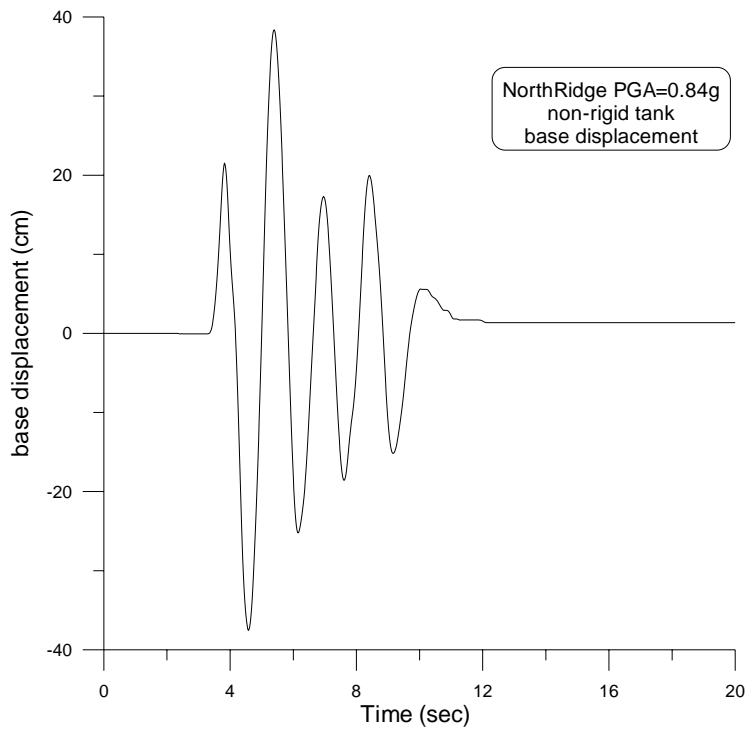


圖 4.42 非剛性儲存槽基座位移歷時(Northridge 0.84g)

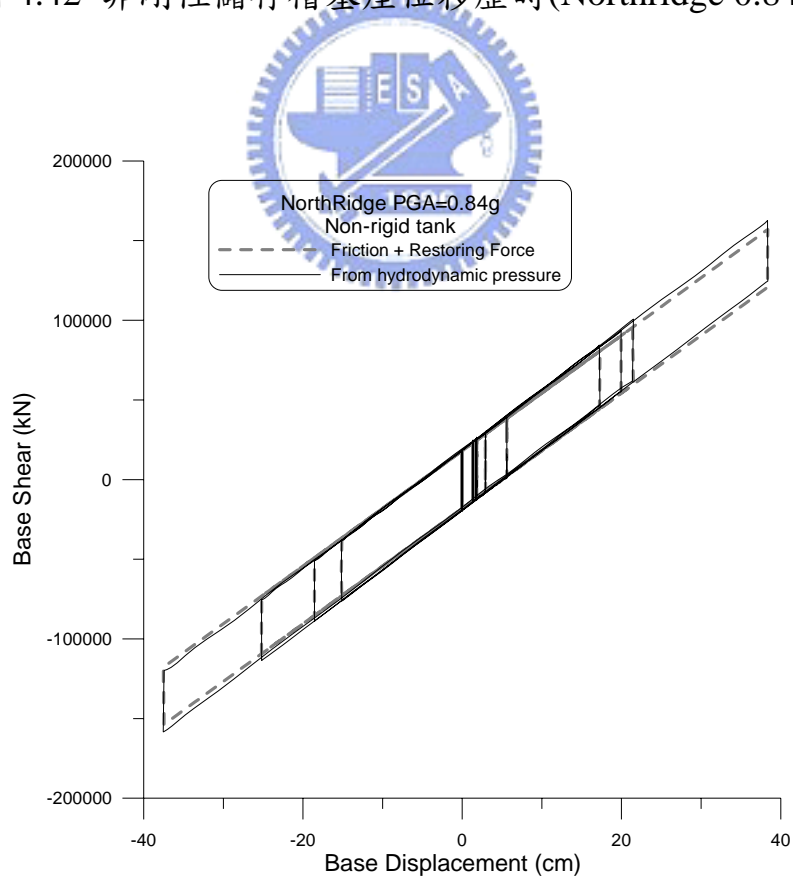


圖 4.43 非剛性儲存槽基底剪力—位移遲滯迴圈(Northridge 0.84g)

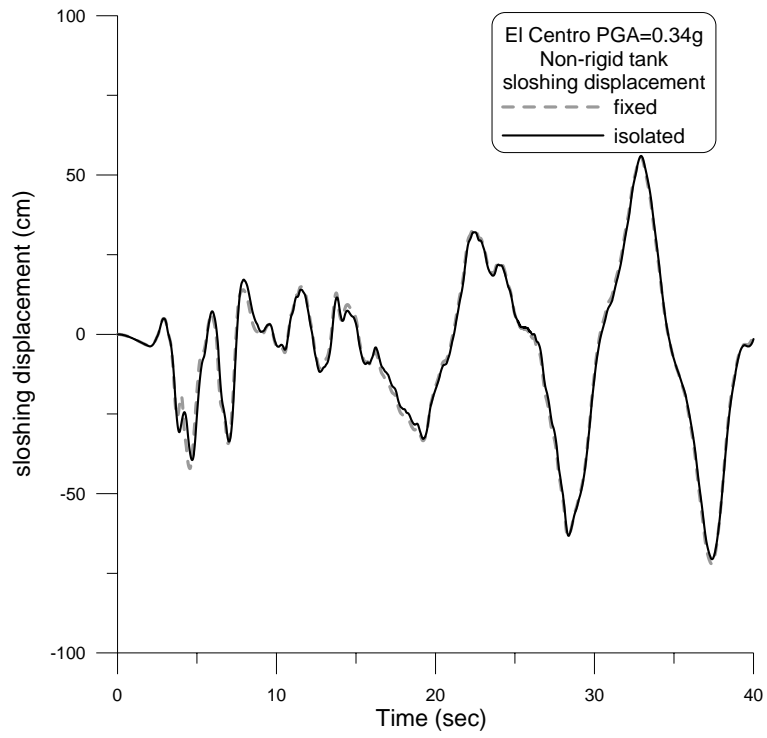


圖 4.44 非剛性儲存槽液面波動位移(h=3cm)

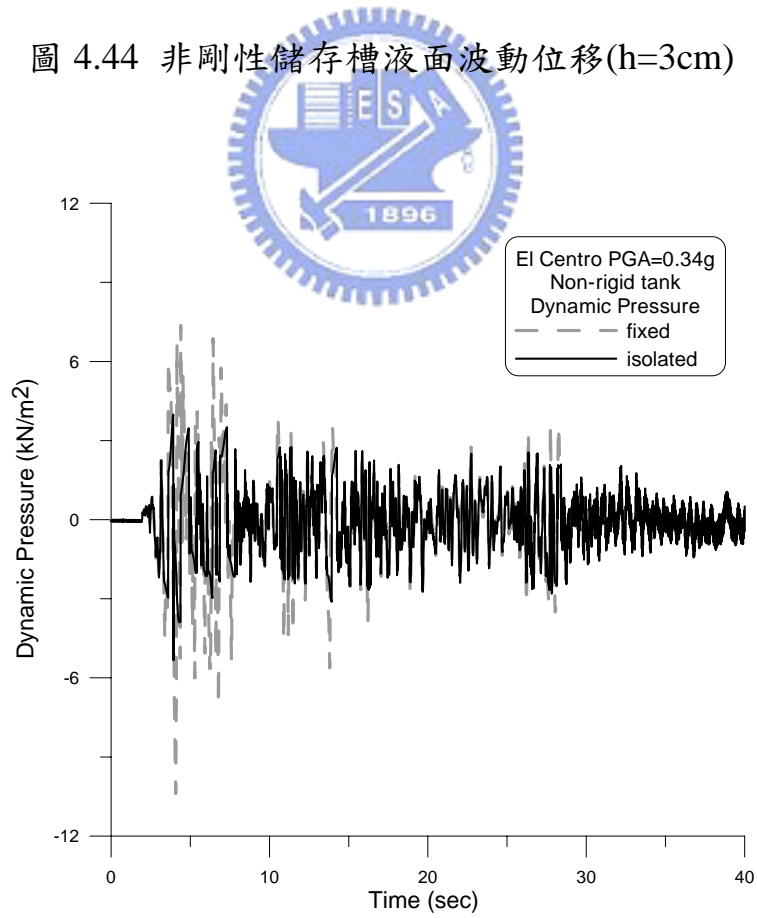


圖 4.45 非剛性儲存槽槽底動水壓力(h=3cm)

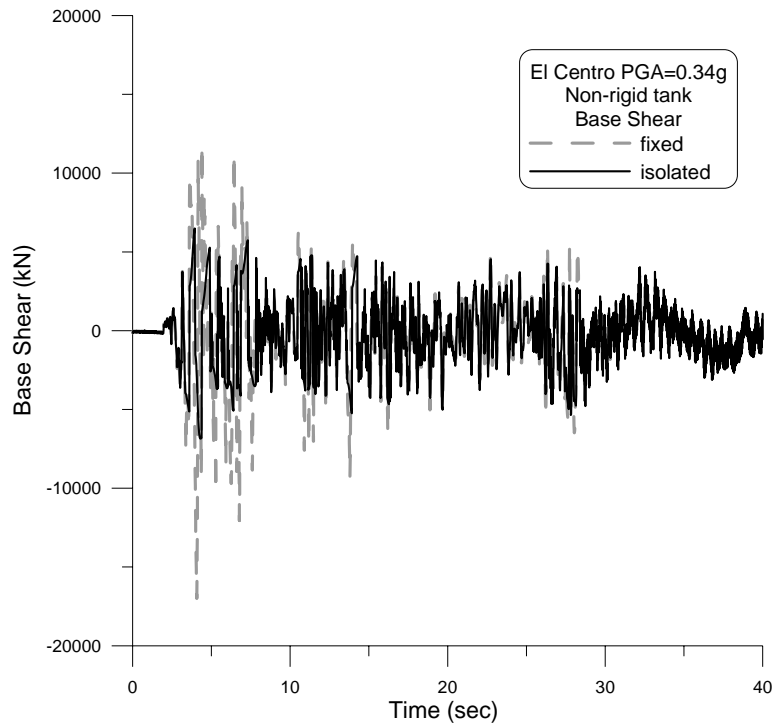


圖 4.46 非剛性儲存槽基底剪力(h=3cm)

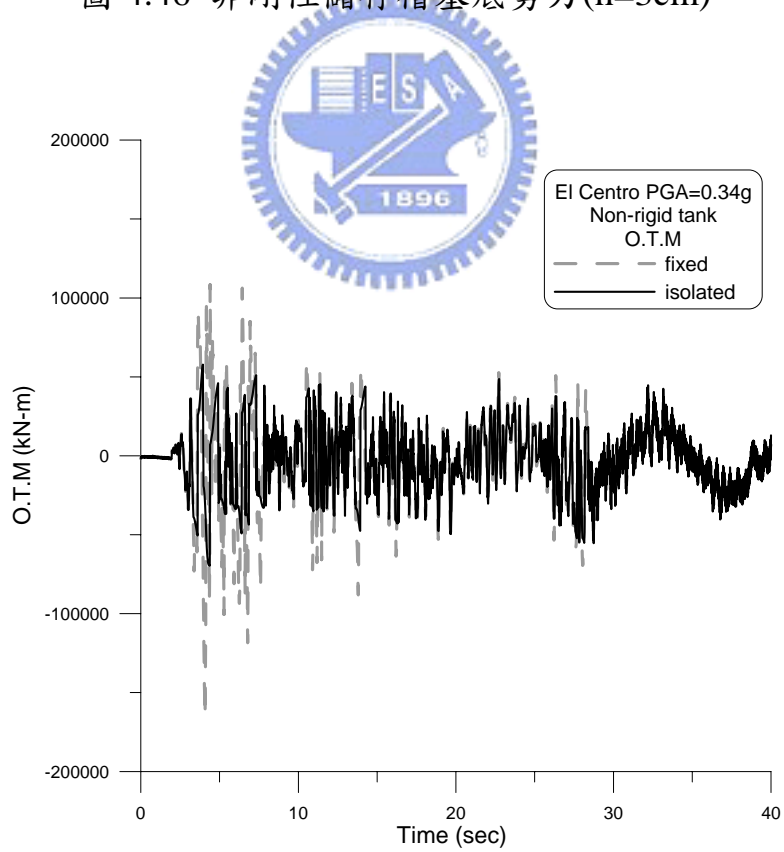


圖 4.47 非剛性儲存槽翻覆力矩(h=3cm)

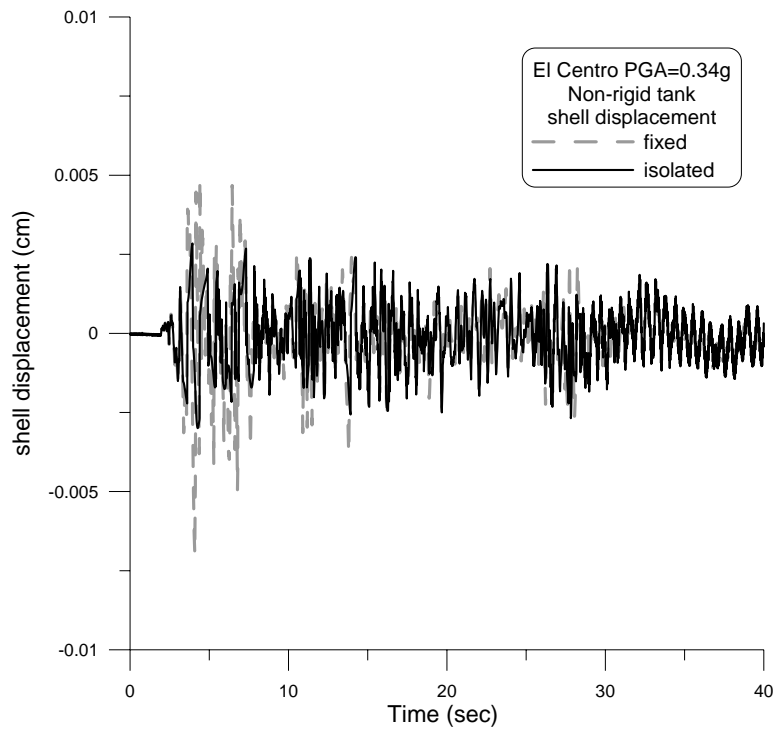


圖 4.48 非剛性儲存槽槽殼頂部位移(h=3cm)

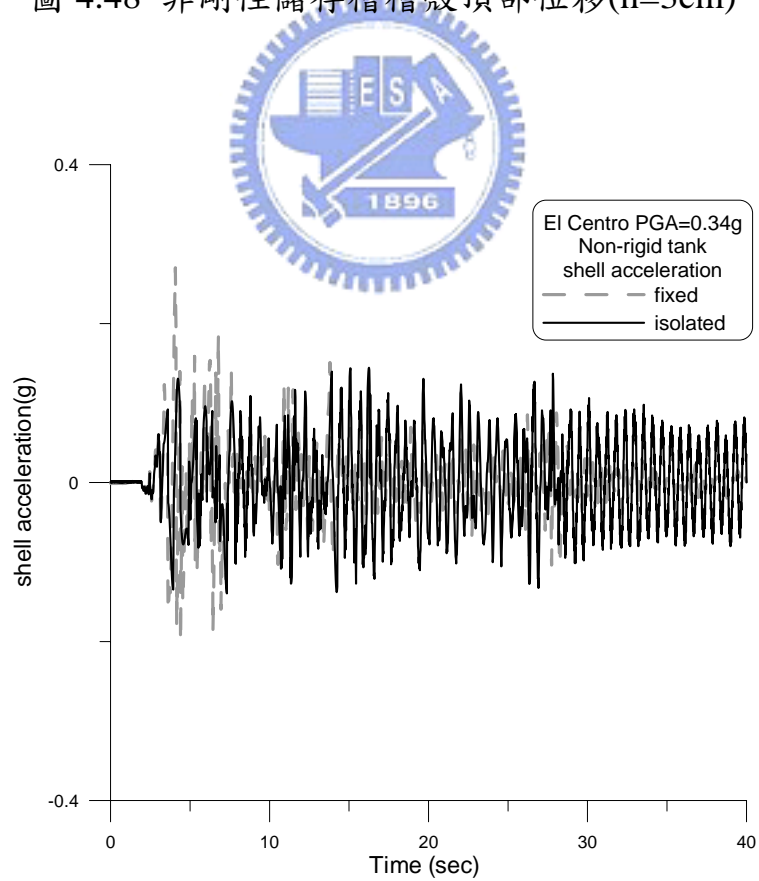


圖 4.49 非剛性儲存槽槽殼頂部加速度(h=3cm)

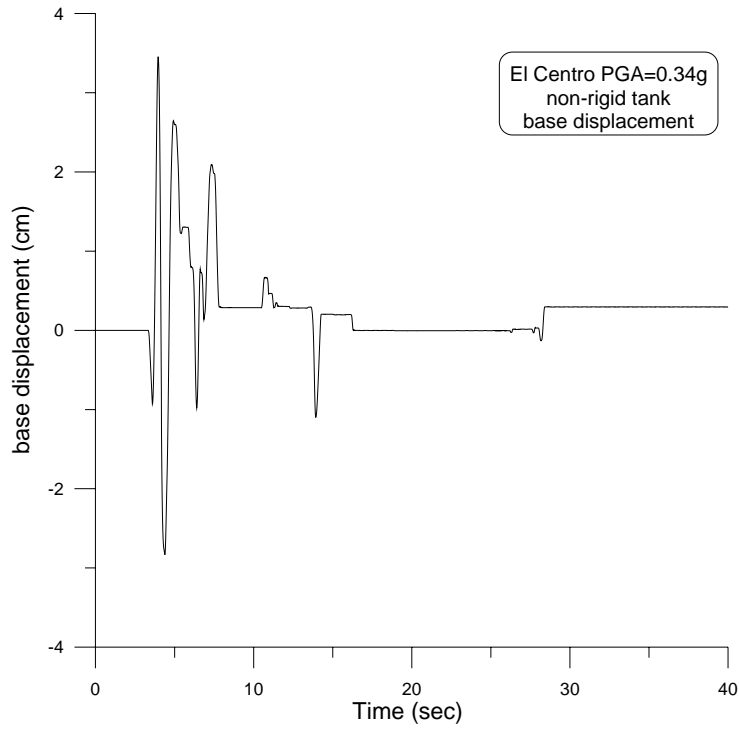


圖 4.50 非剛性儲存槽基座位移歷時(h=3cm)

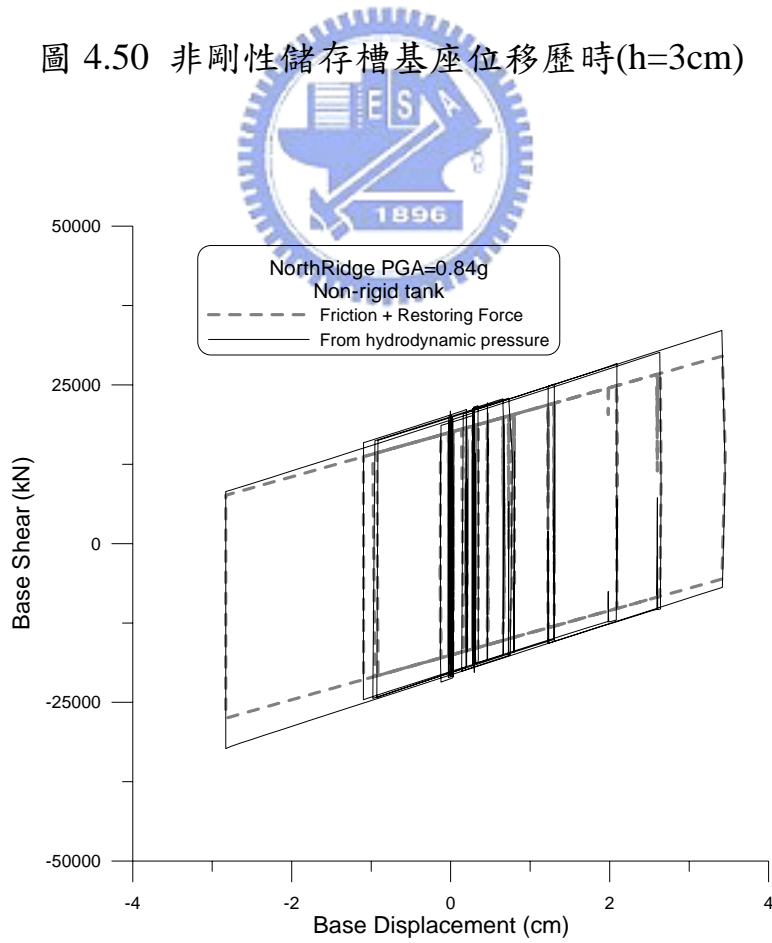


圖 4.51 非剛性儲存槽基底剪力—位移遲滯迴圈(h=3cm)

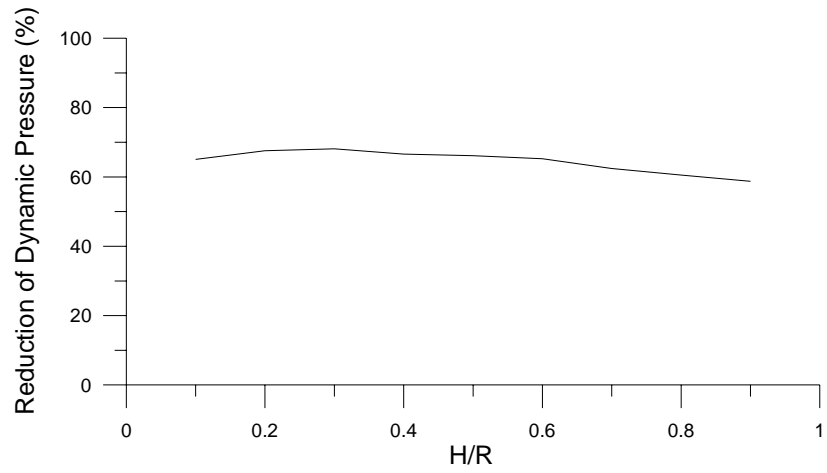


圖 4.52 液面高度與半徑比對於槽底動水壓力峰值折減之影響

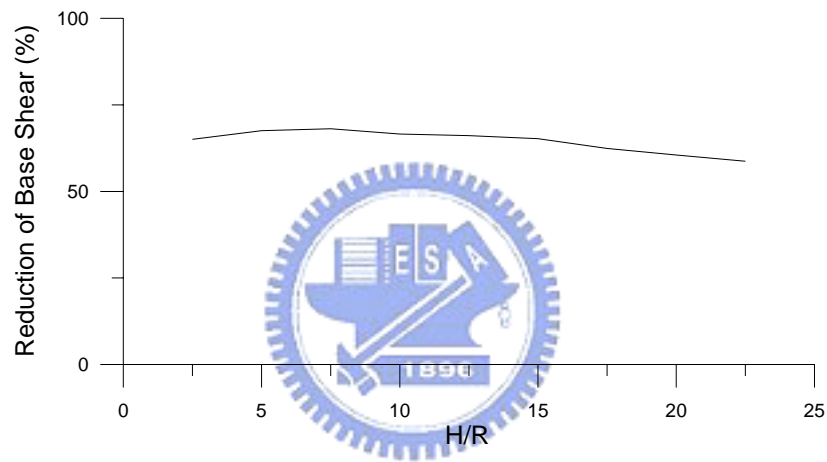


圖 4.53 液面高度與半徑比對於基底剪力峰值折減之影響

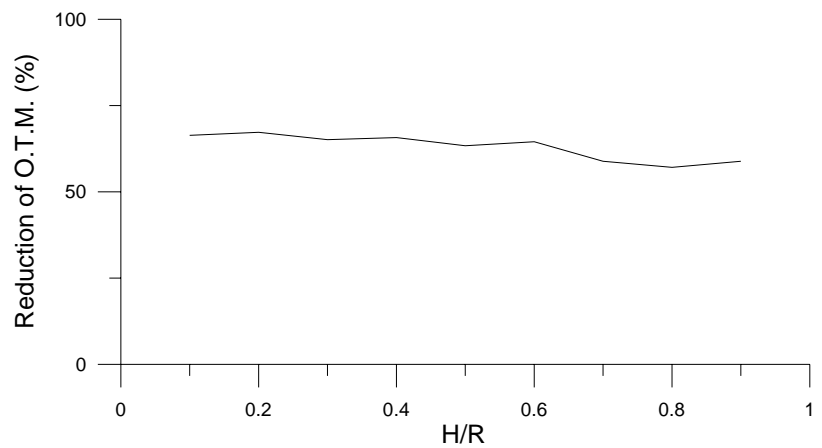


圖 4.54 液面高度與半徑比對於傾覆力矩峰值折減之影響

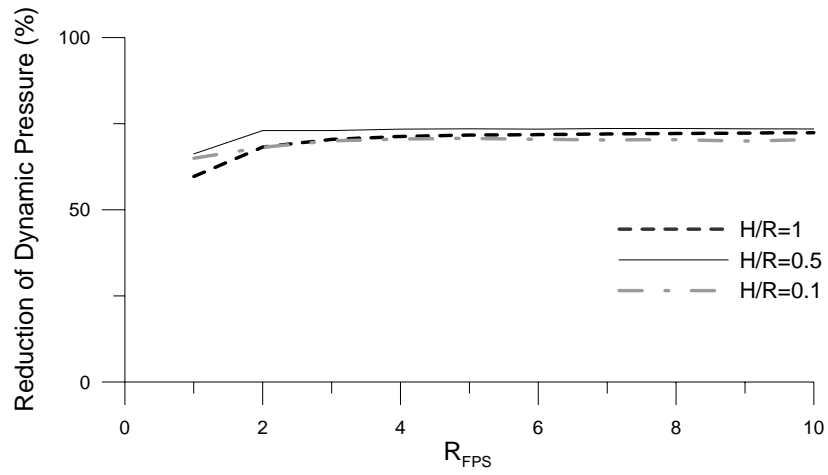


圖 4.55 隔震器曲率半徑對於槽底動水壓力峰值折減之影響

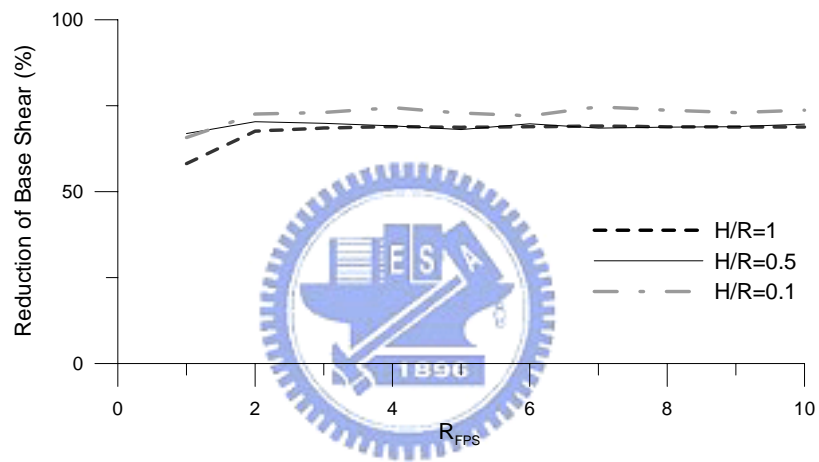


圖 4.56 隔震器曲率半徑對於基底剪力峰值折減之影響

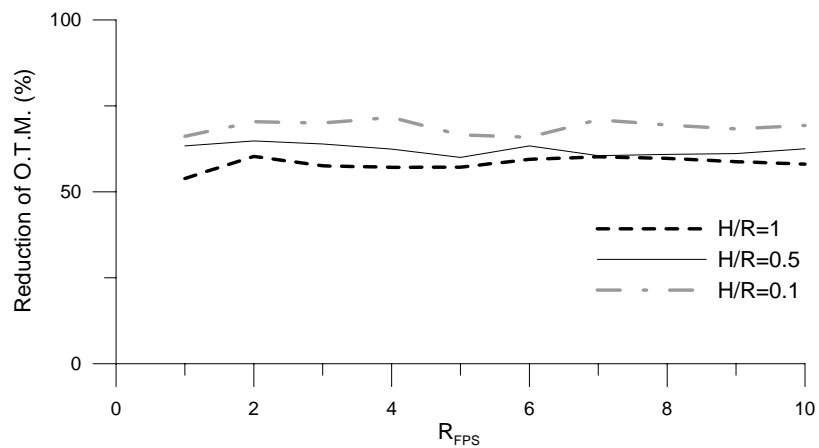


圖 4.57 隔震器曲率半徑對於傾覆力矩峰值折減之影響

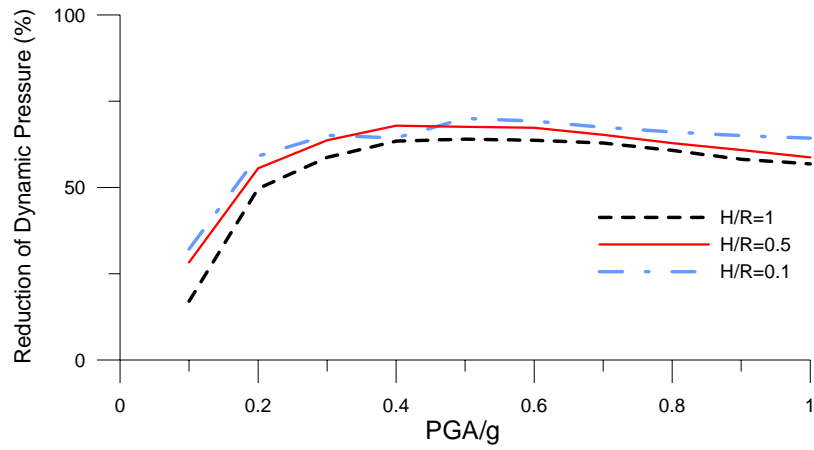


圖 4.58 地震強度對於槽底動水壓力峰值折減之影響

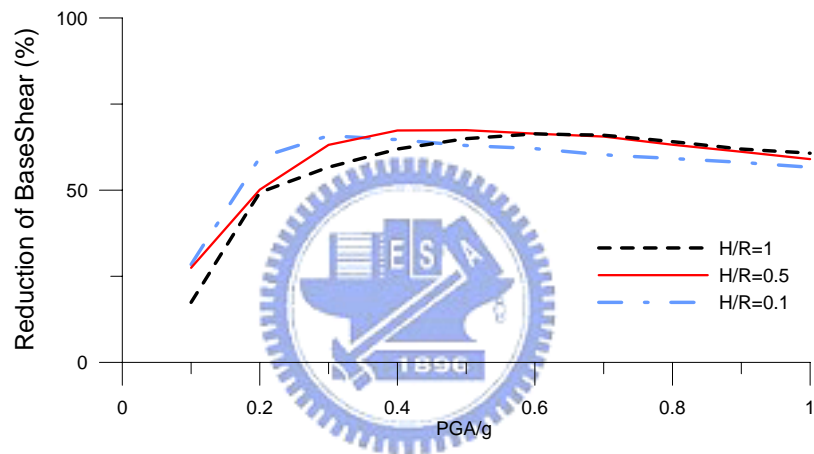


圖 4.59 地震強度對於基底剪力峰值折減之影響

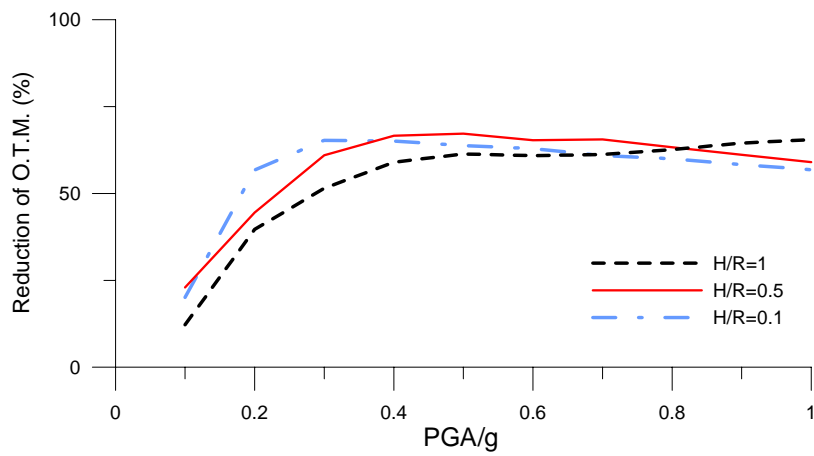


圖 4.60 地震強度對於傾覆力矩峰值折減之影響

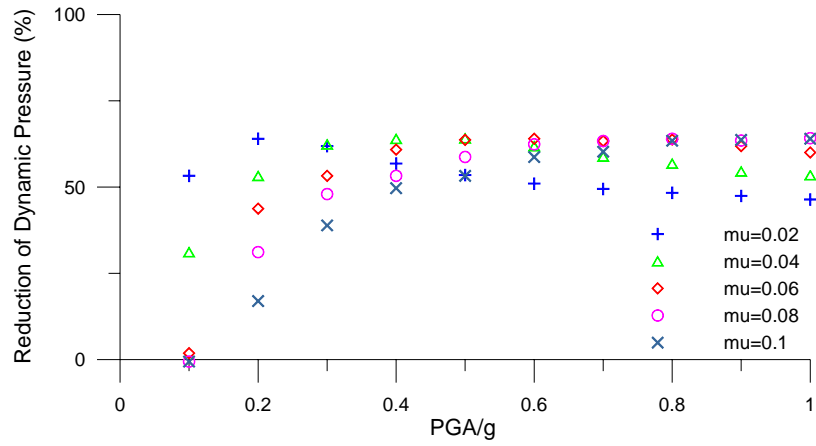


圖 4.61 地震強度對於槽底動水壓力峰值折減之影響

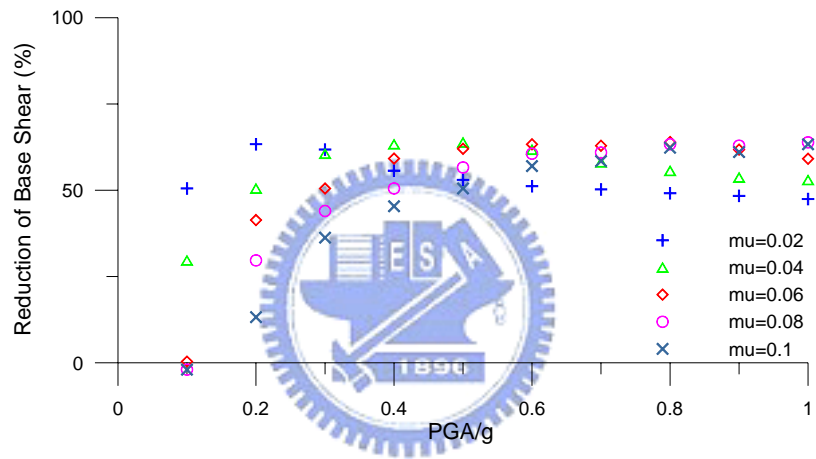


圖 4.62 地震強度對於基底剪力峰值折減之影響

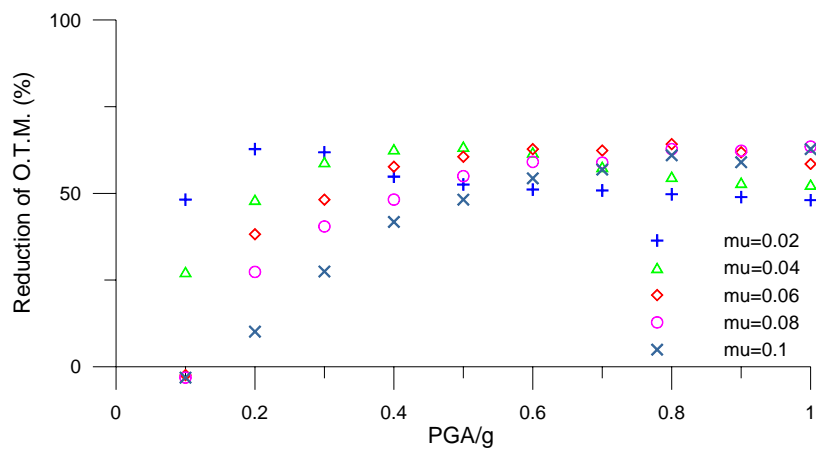


圖 4.63 地震強度對於傾覆力矩峰值折減之影響

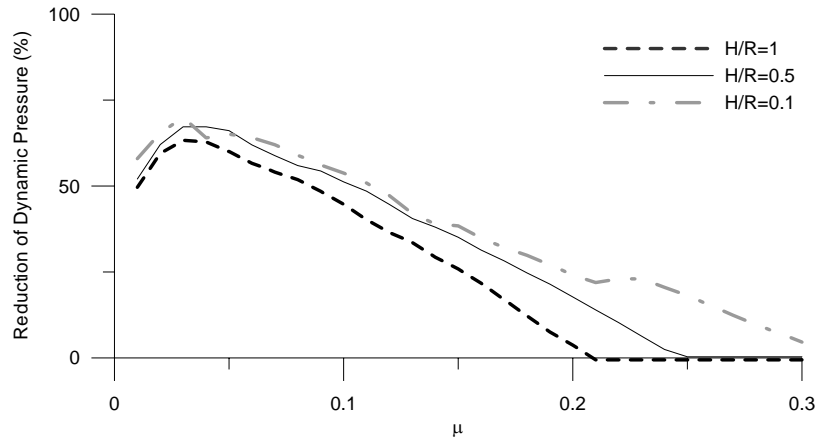


圖 4.64 隔震器摩擦係數對於槽底動水壓力峰值折減之影響

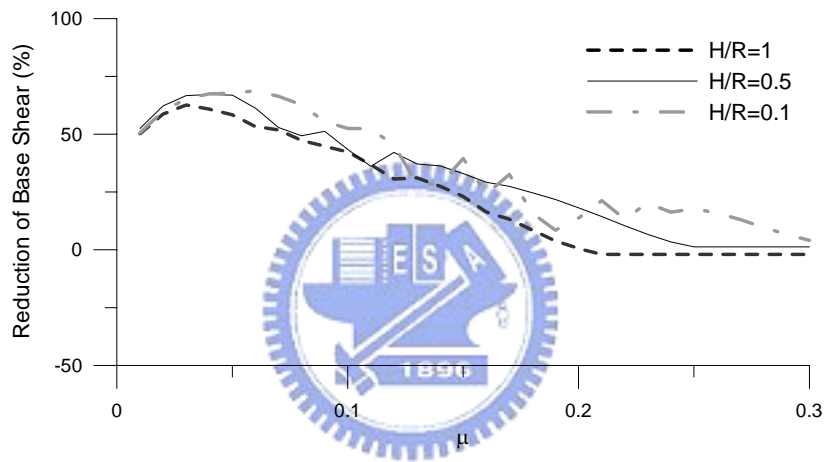


圖 4.65 隔震器摩擦係數對於基底剪力峰值折減之影響

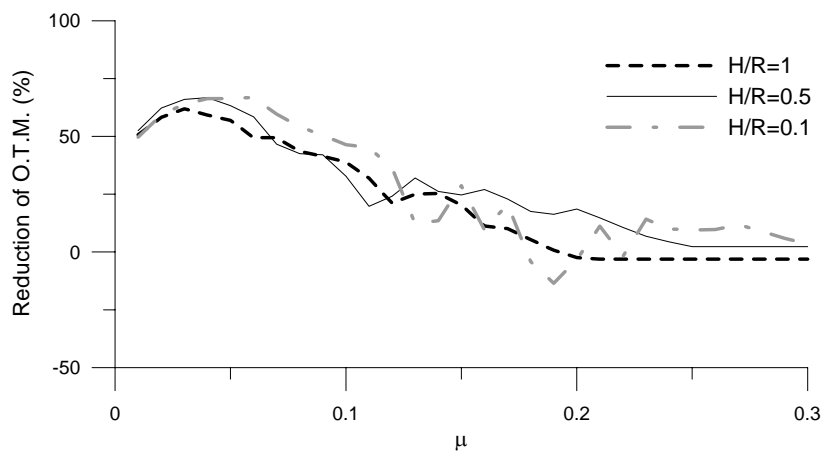


圖 4.66 隔震器摩擦係數對於傾覆力矩峰值折減之影響