

# **Modern Techniques for Earthquake Resistant Design of Retaining Structures**

by

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**Why this Topic?**

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September, 1999 Ji Ji, Taiwan Earthquake

Devastating effect of earthquake on retaining wall

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### Preamble and Background

- Design of retaining walls under seismic condition is very important in earthquake prone areas to reduce the devastating effect of earthquake.
- Evaluation of earth pressure under seismic condition is important.
- Estimation of passive pressure under both static and seismic conditions are very important for the design of retaining walls, anchors, foundations etc.
- Research on static passive earth pressure is plenty whereas the same under seismic condition is still lacking.

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## Mononobe-Okabe

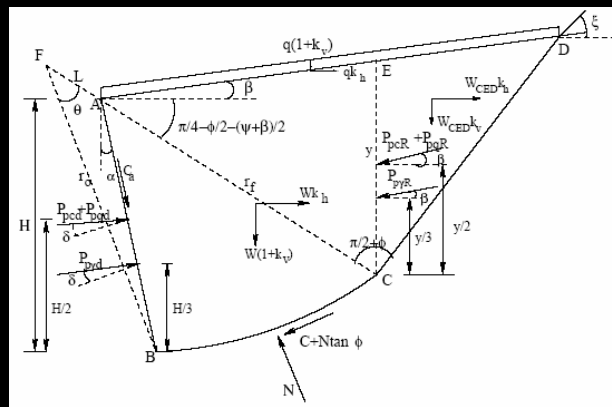
$$P_{ae,pe} = \frac{1}{2} \gamma H^2 (1-k_v) K_{ae,pe}$$

$$K_{ae,pe} = \frac{\cos^2 (\phi \mp \beta - \theta)}{\cos \theta \cos^2 \beta \cos (\delta \pm \beta + \theta) \left[ 1 - \left( \frac{\sin (\phi + \delta) \sin (\phi \mp i - \theta)}{\cos (\delta \pm \beta + \theta) \cos (i - \beta)} \right)^{0.5} \right]^2}$$

$$\theta = \tan^{-1} \left[ \frac{k_h}{1 - k_v} \right]$$

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## Seismic Passive Earth Resistance

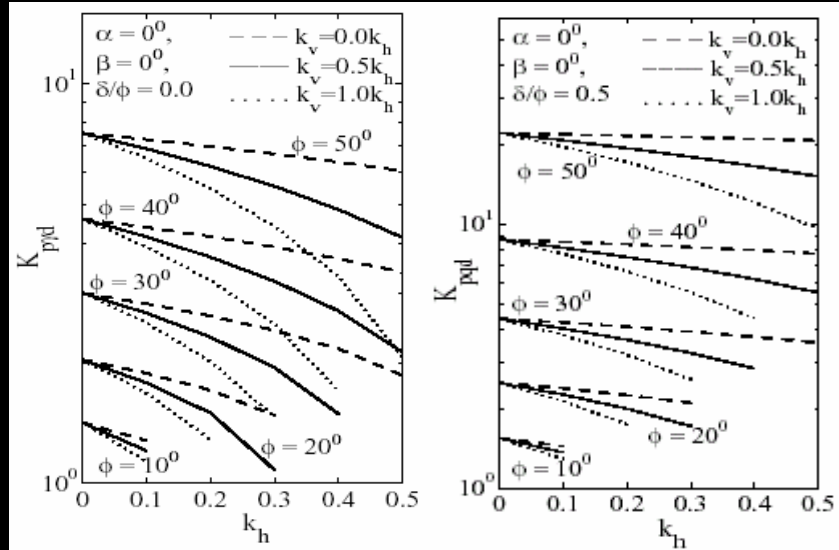


$$\xi = \frac{\pi}{4} - \frac{\phi}{2} + \frac{1}{2} \tan^{-1} \left( \frac{k_h}{1 - k_v} \right) + \frac{\beta}{2} - \frac{1}{2} \sin^{-1} \left[ \frac{\sin \left\{ \tan^{-1} \left( \frac{k_h}{1 - k_v} \right) - \beta \right\}}{\sin \phi} \right]$$

**Failure surface and forces by Subba Rao and Choudhury (2005)**

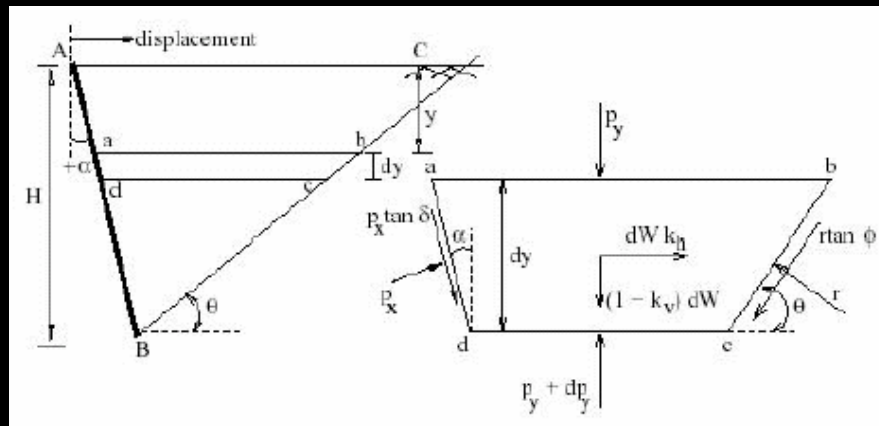
Subba Rao, K. S. and Choudhury, D. (2005), "Seismic passive earth pressures in soils",  
*Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, USA, 131(1): pp. 131-135.

## Typical Design Charts



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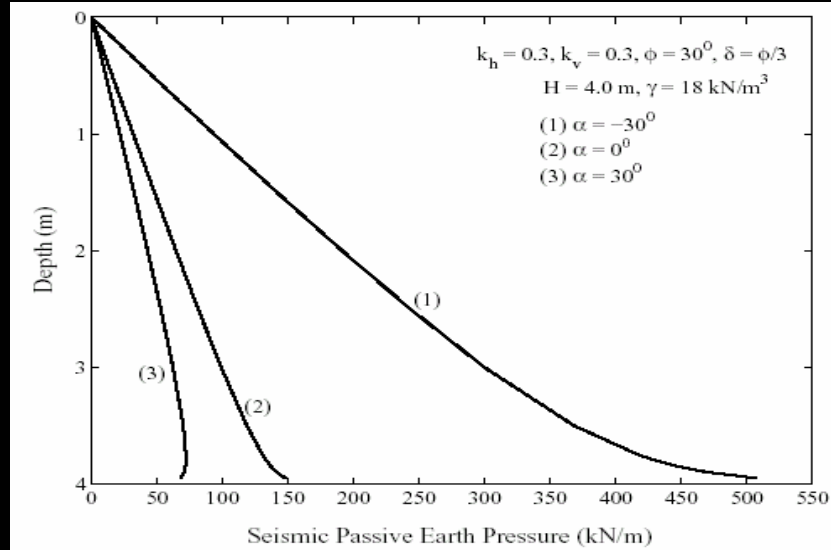
## Seismic Passive Earth Pressure Distribution



Analytical model proposed by Choudhury et al. (2002)

Choudhury, D., Subba Rao, K. S. and Ghosh, S. (2002), "Passive earth pressures distribution under seismic condition", 15th International Conference of Engineering Mechanics Division (EM2002), ASCE, Columbia University, NY, in CD.

## Typical Results



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## Design As Per Seismic Code

### IS 1893: 1984, Part 3 (Bridges and Retaining Walls)

- Using pseudo-static approach to evaluate stability of retaining walls.
- Compute seismic earth pressure using Mononobe-Okabe equations.
- Dynamic increment of earth pressure will act at mid height of the wall.
- Effect of dry, partially submerged and saturated backfill is considered.
- Range of permissible displacement is not specified.
- Soil amplification has not considered.

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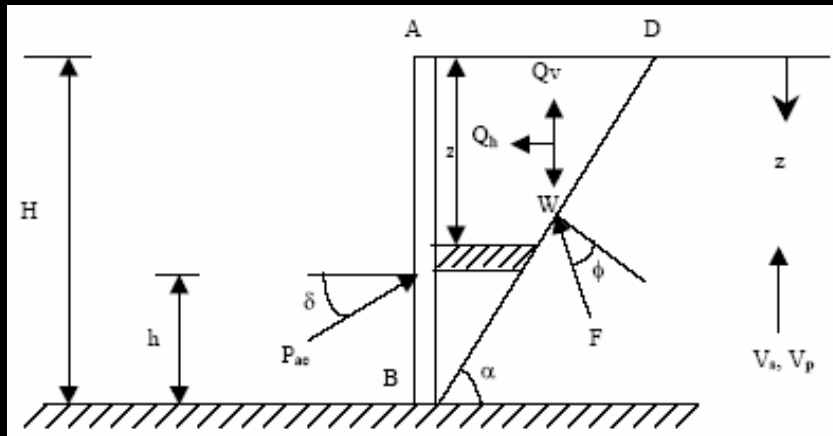
## Eurocode 8 – 1998

- Based on modified pseudo-static analysis.
- Compute seismic earth pressure using Richards and Elms (1979) model.
- Permissible displacement for sliding and rocking movement of the wall are considered.
- Included non-linear behaviour in base soil and backfill.
- The point of application of the dynamic earth pressure increment is at mid-height of the wall.
- Soil amplification is considered.

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## Seismic active earth pressure by pseudo-dynamic model



Choudhury and Nimbalkar (2006)

Choudhury, D. and Nimbalkar, S. (2006), "Pseudo-dynamic approach of seismic active earth pressure behind retaining wall", *Geotechnical and Geological Engineering*, Springer, The Netherlands, Vol. 24, No. 5, pp. 1103-1113.

$$a_h(z, t) = a_h \sin [\omega \{t - (H - z)/V_s\}] \quad a_v(z, t) = a_v \sin [\omega \{t - (H - z)/V_p\}]$$

where  $\omega =$  angular frequency;  $t =$  time elapsed;  $V_s =$  shear wave velocity;  
 $V_p =$  primary wave velocity

$$Q_h(t) = \int_0^H m(z) a_h(z, t) dz = \frac{\lambda \gamma a_h}{4\pi^2 g \tan \alpha} [2\pi H \cos \omega \zeta + \lambda (\sin \omega \zeta - \sin \omega t)]$$

where,  $\lambda = TV_s$  is the wavelength of the vertically propagating shear wave and  $\zeta = t - H/V_s$ .

$$Q_v(t) = \int_0^H m(z) a_v(z, t) dz = \frac{\eta \gamma a_v}{4\pi^2 g \tan \alpha} [2\pi H \cos \omega \psi + \lambda (\sin \omega \psi - \sin \omega t)]$$

where,  $\eta = TV_p$ , is the wavelength of the vertically propagating primary wave and  $\psi = t - H/V_p$ .

The total (static plus dynamic) active thrust is given by,

$$P_{ae}(t) = \frac{W \sin(\alpha - \phi) + Q_h(t) \cos(\alpha - \phi) - Q_v(t) \sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)}$$

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The seismic active earth pressure coefficient,  $K_{ae}$  is defined as

$$K_{ae} = \frac{1}{\tan \alpha \cos(\delta + \phi - \alpha)} + \frac{k_s}{2\pi^2 \tan \alpha} \left( \frac{TV_s}{H} \right) \times \frac{\cos(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \times m_1 + \frac{k_v}{2\pi^2 \tan \alpha} \left( \frac{TV_p}{H} \right) \times \frac{\sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \times m_2$$

where,

$$m_1 = \left[ 2\pi \cos 2\pi \left( \frac{t}{T} - \frac{H}{TV_s} \right) + \left( \frac{TV_s}{H} \right) \left( \sin 2\pi \left( \frac{t}{T} - \frac{H}{TV_s} \right) - \sin 2\pi \left( \frac{t}{T} \right) \right) \right]$$

$$m_2 = \left[ 2\pi \cos 2\pi \left( \frac{t}{T} - \frac{H}{TV_p} \right) + \left( \frac{TV_p}{H} \right) \left( \sin 2\pi \left( \frac{t}{T} - \frac{H}{TV_p} \right) - \sin 2\pi \left( \frac{t}{T} \right) \right) \right]$$

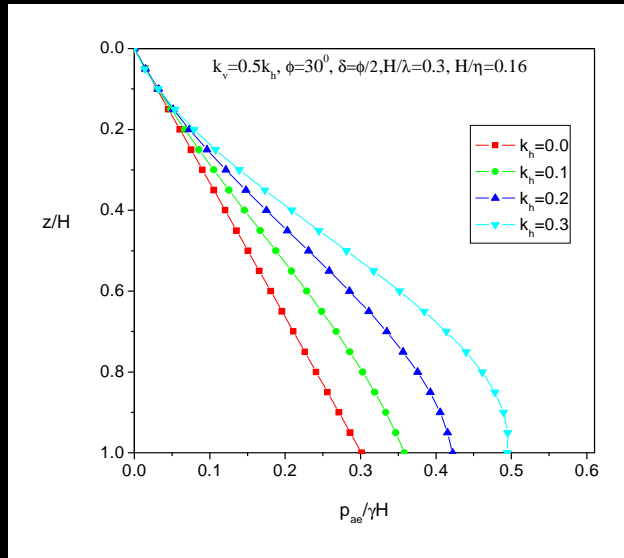
The seismic active earth pressure distribution is given by,

$$P_{ae}(t) = \frac{\partial P_{ae}(t)}{\partial z} = \frac{\gamma z}{\tan \alpha} \frac{\sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} + \frac{k_s \gamma z}{\tan \alpha} \frac{\cos(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \sin \left[ w \left( t - \frac{z}{V_s} \right) \right] + \frac{k_v \gamma z}{\tan \alpha} \frac{\sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \sin \left[ w \left( t - \frac{z}{V_p} \right) \right]$$

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Choudhury and Nimbalkar (2006)

### Typical non-linear variation of seismic active earth pressure

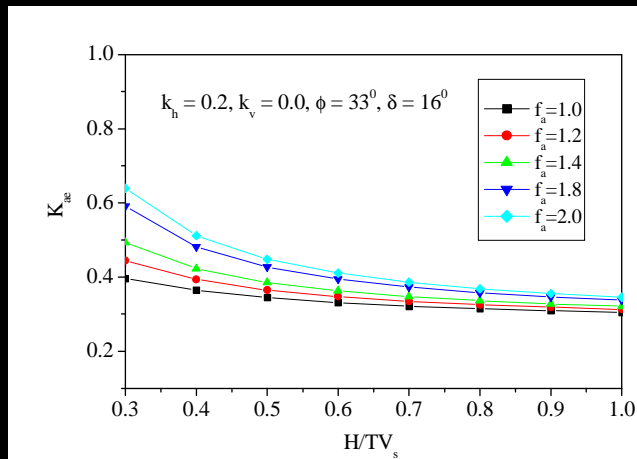


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Choudhury and Nimbalkar (2006)

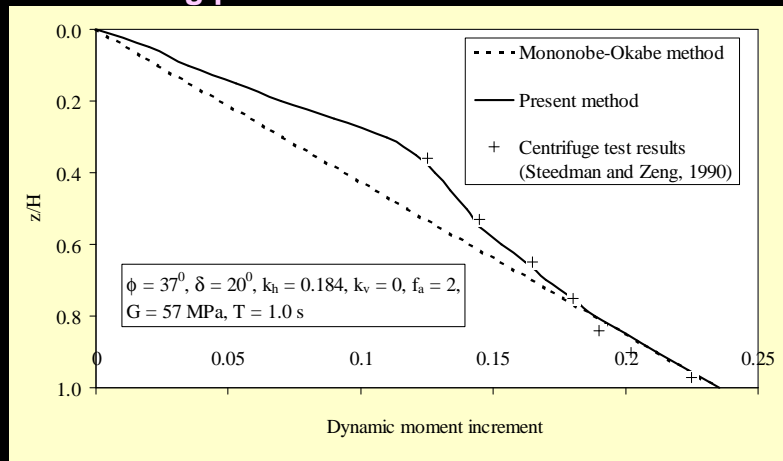
### Effect of amplification factor on seismic active earth pressure

$$a_h(z, t) = \{1 + (H - z) \cdot (f_a - 1)/H\} a_h \sin [\omega \{t - (H - z)/V_s\}]$$



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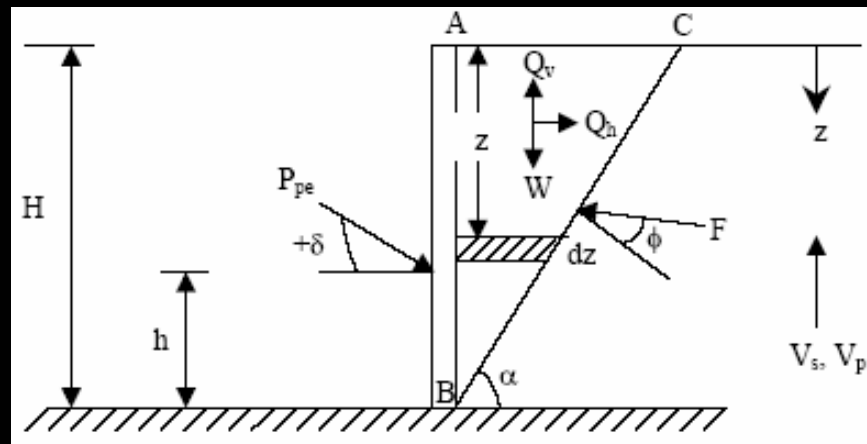
### Comparison of proposed pseudo-dynamic method with existing pseudo-static method – Active case



Dynamic moment increment,  $\sqrt[3]{\frac{M}{\gamma H^3}}$ , where  $M(Z, t) = \int_0^Z p_{ae}(z, t) \cos \delta (Z - z) dz$

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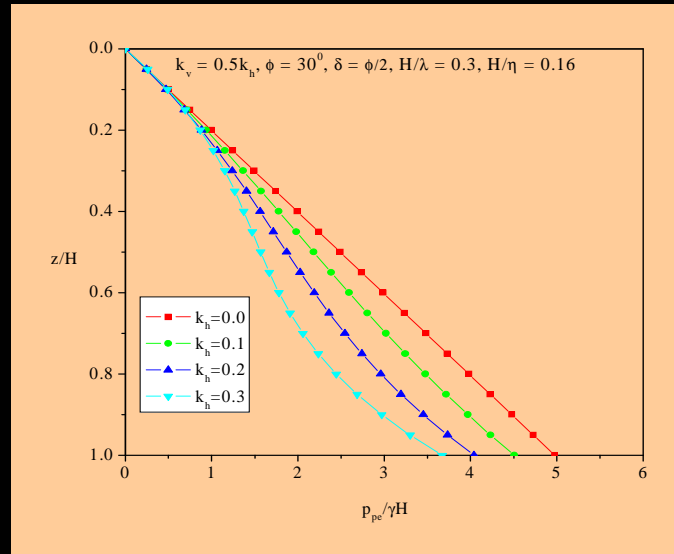
### Seismic passive earth pressure by pseudo-dynamic model



Choudhury and Nimbalkar (2005)

Choudhury, D. and Nimbalkar, S. (2005), "Seismic passive resistance by pseudo-dynamic method", *Geotechnique*, London, Vol. 55, No. 9, pp. 699-702

### Typical non-linear variation of seismic passive earth pressure

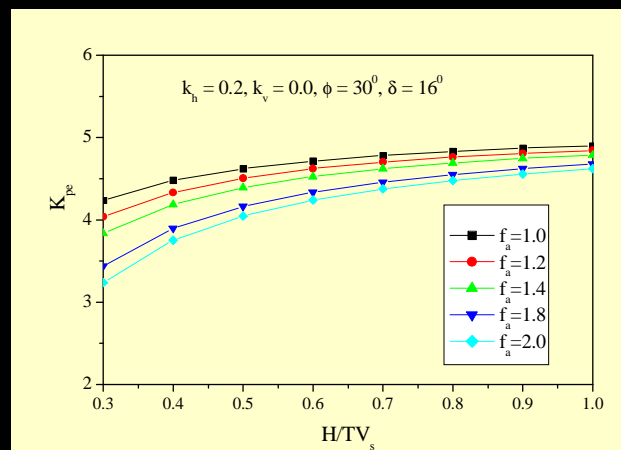


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Choudhury and Nimbalkar (2005)

### Effect of amplification factor on seismic passive earth pressure

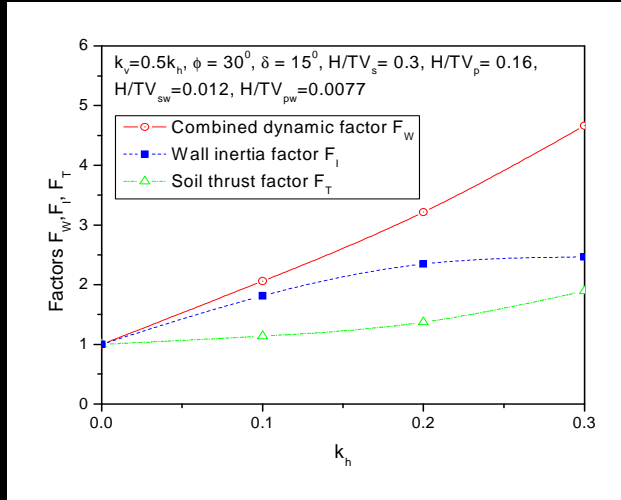
$$a_h(z, t) = \{1 + (H - z) \cdot (f_a - 1)/H\} a_h \sin [\omega \{t - (H - z)/V_s\}]$$



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## Typical Variation of Soil thrust factor $F_T$ , Wall inertia factor $F_I$ and Combined dynamic factor $F_W$

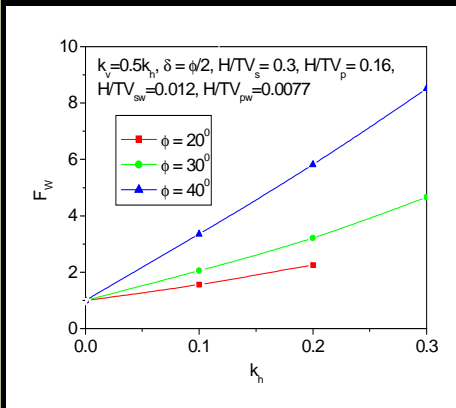


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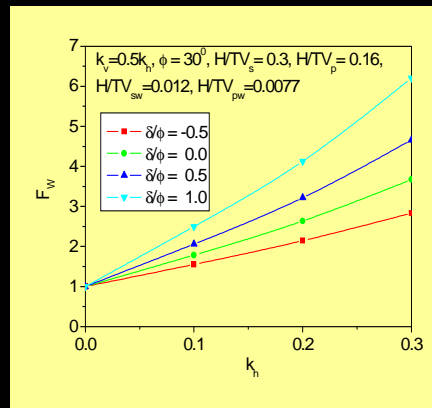
**Choudhury and Nimbalkar (2006)**

## Typical Results

### Effect of angle of internal friction ( $\phi$ )



### Effect of wall friction angle ( $\delta$ )



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**Choudhury and Nimbalkar (2006)**

**Comparison of Soil thrust factor  $F_T$ , Wall inertia factor  $F_I$   
and Combined Dynamic Factor  $F_w$**

$k_h$	$k_v$	Present study			Richards and Elms (1979)		
		$F_T$	$F_I$	$F_w$	$F_T$	$F_I$	$F_w$
0.0	0.00	1.0	1.0	1.0	1.0	1.0	1.0
0.1	0.00	1.231	1.517	1.868	1.221	1.209	1.476
	0.05	1.137	1.812	2.060	1.234	1.287	1.588
	0.10	1.043	2.160	2.253	1.248	1.376	1.718
0.2	0.00	1.527	1.834	2.800	1.500	1.530	2.295
	0.10	1.371	2.347	3.217	1.572	1.806	2.840
	0.20	1.256	2.928	3.676	1.669	2.205	3.681
0.3	0.00	1.922	1.994	3.832	1.866	2.082	3.885
	0.15	1.892	2.464	4.662	2.114	3.027	6.400
0.4	0.00	2.493	2.021	5.039	2.382	3.255	7.753
0.5	0.00	3.500	1.909	6.683	3.223	7.464	24.059

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**Choudhury and Nimbalkar (2006)**

**Concluding Remarks**

- \* **Using limit equilibrium method and adopting both pseudo-static and pseudo-dynamic approach for seismic forces, comprehensive results of active and passive earth pressures are obtained for static and seismic conditions with wide range of variation in design parameters.**

*active and passive earth pressure coefficients,  
point of application of resultant earth force,  
effects of shear and primary waves,  
wall-soil inertia are considered together,  
design factor  $F_w$  is proposed for wall design.*

- \* **Present solutions compare well with existing theories for static case and very rarely available seismic cases. In most of the cases, present study generates new solutions for the seismic cases.**

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## Concluding Remarks (contd.)

- \* Apart from the approximate pseudo-static approach, considering shear and primary waves through the soil-structure with variation of time can be used to get better solution by using pseudo-dynamic approach.
- \* Point of application of seismic earth pressure should be computed based on some logical analysis instead of some arbitrary selection.
- \* IS code must be revised for design of retaining wall under seismic conditions.

Hope to build 'STABLE Earthquake Resistant'  
Retaining Structures in Soil

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Thank You

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