Methods for Evaluation and Mitigation of Earthquake-Induced Landslides

by

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Why this Topic?

September, 1999 Ji Ji, Taiwan Earthquake

Devastating effect of earthquake on slope

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Preamble and Background

- Design of slopes under seismic conditions are very important in earthquake prone areas to reduce the devastating effect of earthquake.
- Evaluation of factor of safety of slope under seismic condition is important.
- Estimation of pseudo-static factor of safety of slopes are available in literature since decades, however, the dynamic nature of earthquake forces in terms of PGA, period of shaking, shear and primary wave velocities, duration of shaking, amplification etc. are not addressed.
- Mitigation techniques like use of properly designed reinforced soil slope under earthquake condition is scarce**.**

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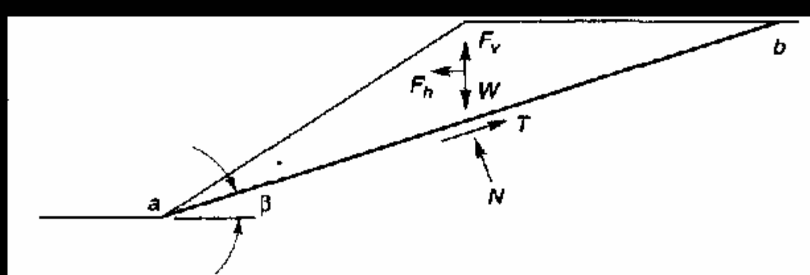
CLASSICAL THEORIES

- Terzaghi's method (1950)
- Newmark's sliding block analysis (1965)
- Seed's improved procedure for pseudo-static analysis (1966)
- Modified Swedish Circle method (1968)
- Modified Taylor's method (1969)

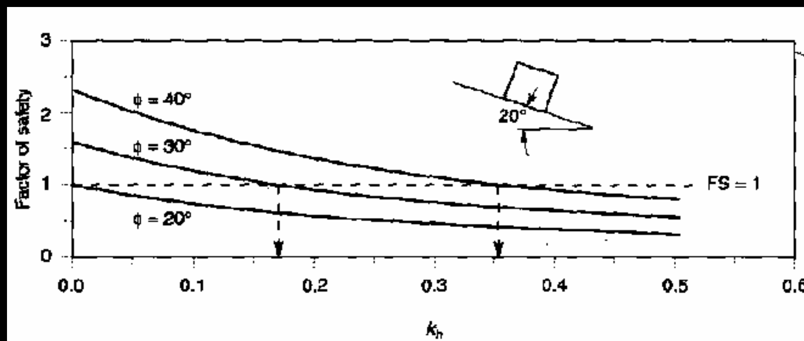
Terzaghi's Method (1950)



Forces acting on triangular wedge of soil above planar failure surfaces in pseudo-static analysis

$$FS = \frac{resisting-force}{driving-force} = \frac{cl_{ab} + [(W - F_v)\cos\beta - F_h \sin\beta]\tan\phi}{(W - F_v)\sin\beta + F_h \cos\beta}$$

Newmark's sliding block analysis (1965)



Variation of pseudo-static factor of safety with horizontal pseudo-static coefficient for block on plane inclined at 20^0. For $\phi = 20^0$, block is at the point of failure (FS = 1) under static conditions, so the yield coefficient is zero. For $\phi = 30^0$, and $\phi = 40^0$, yield coefficients are 0.17 and 0.36 respectively

Newmark's Method (1965)

$$FS = \frac{[\cos\beta - k_h(t)\sin\beta]\tan\phi}{\sin\beta + k_h(t)cso\beta}$$

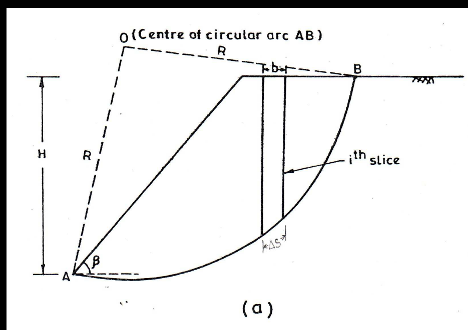
$$k_y = \tan(\phi-\beta)$$

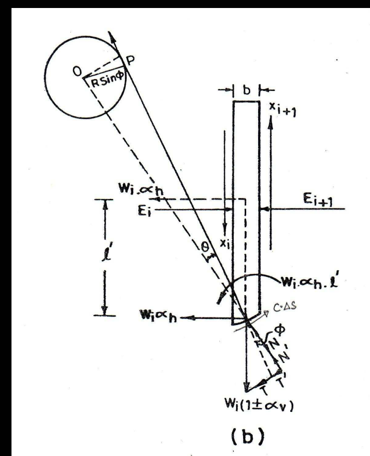
$$a_{rel}(t) = a_b(t) - a_y = A - a_y \qquad t_o \le t \le t_o + \Delta t$$

$$v_{rel}(t) = \int_{t_o}^{t} a_{rel}(t)dt = [A - a_y](t - t_o)$$

$$d_{rel}(t) = \int_{t_o}^{t} v_{rel}(t)dt = \frac{1}{2}[A - a_y](t - t_o)^2$$

Modified Swedish Circle Method





$$F = \frac{\sum\left[c.\Delta S.R + (N - N')\tan\phi.R\right]}{\sum\left[(T+T')R\right]}$$

$$F = \frac{cS + \sum\left[(N - N')\tan\phi\right]}{\sum\left[(T+T')\right]}$$

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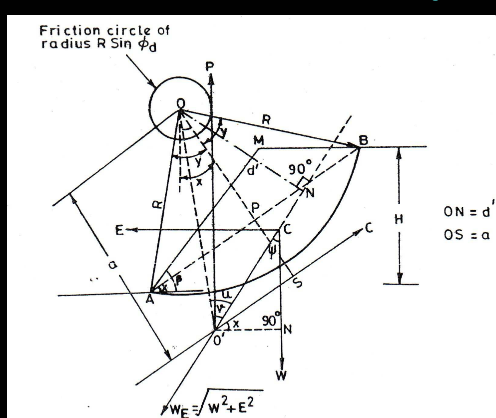
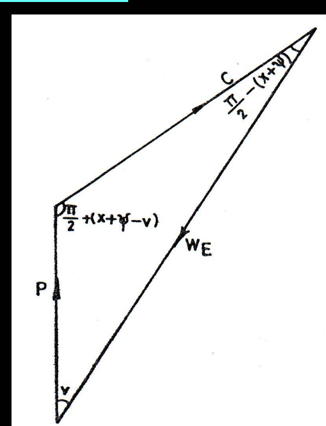
Modified Taylor's Method





$$F_c = \frac{c}{\gamma H}\left[\frac{2\cos(x+\psi)\cot y + 2\sin(x+\psi)}{\sqrt{1+\alpha_h^2}\,\sin x\left[\frac{1}{2}\text{cosec}^2 x\,(y\,\text{cosec}^2 y - \cot y) + \cot x - \cot\beta\right]}\right]$$

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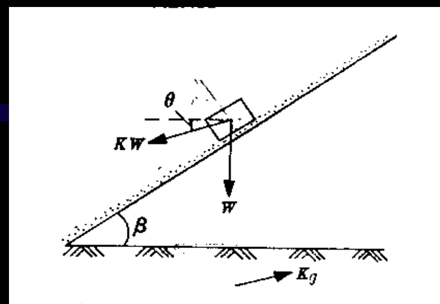
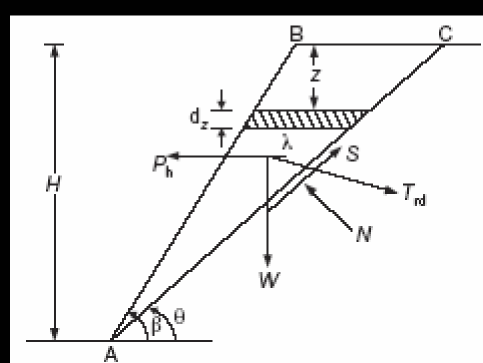
Sarma (1975)



Model of rigid block on a sloping surface

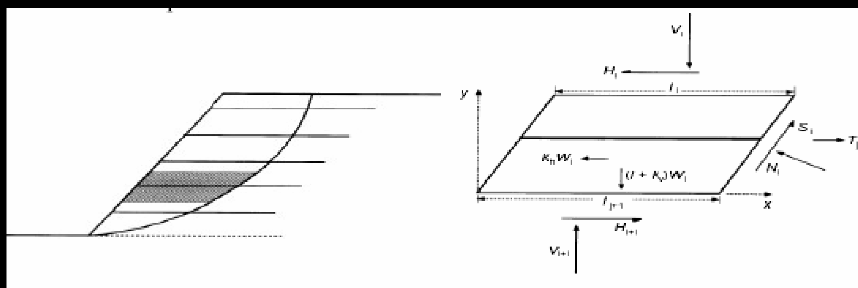
•Factor of safety and displacement along a failure surface depend on geometry, strength of material, pore-pressure parameters and magnitude of the inertia force.
•Total displacement is proportional to the square of the duration.
•Both the factor of safety and the displacement are unaffected by the inclination of the inertia force.

Sabhahit, Basudhar and Madhav (1996)



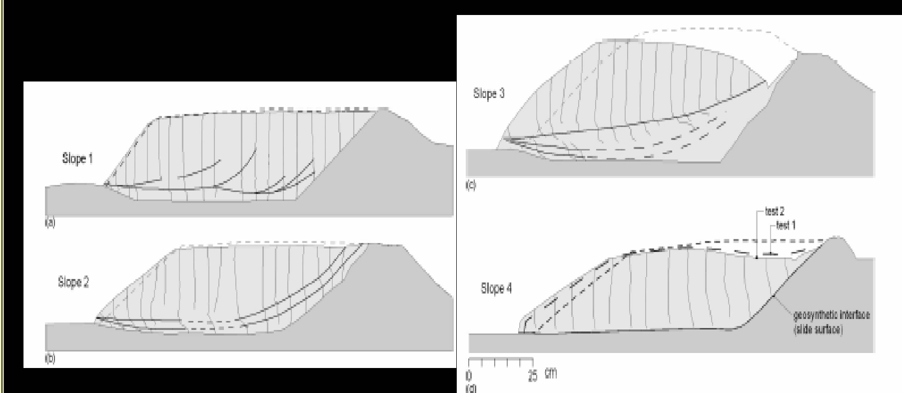
Model slope with planar failure surface and horizontal slices

SHAHGHOLI, FAKHER AND JONES (2001)



Model reinforced soil slope with circular failure surface and horizontal slices and forces acting on i th slice

WARTMAN, SEED AND BRAY (2005)



Pre and post shaking profiles of slopes 1–4 showing deformed spaghetti strands (near vertical lines shown in soft zone [upper portion] of model). Pretest geometry is shown with dashed line and localized shear displacement surfaces shown with dark solid line (dashed where inferred)

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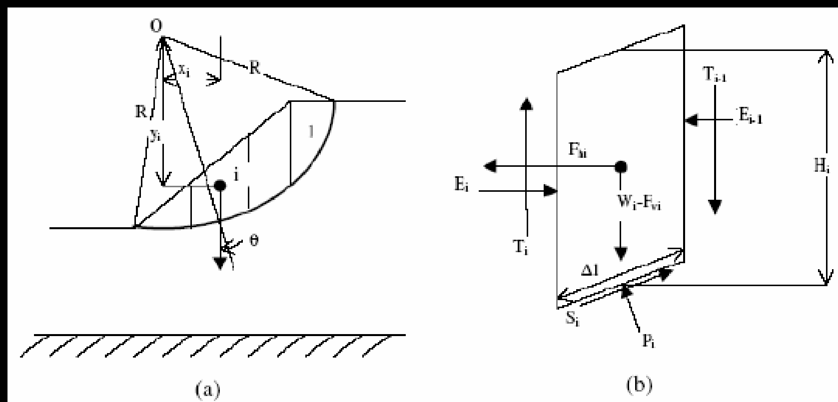
Choudhury, Basu and Bray (2007)



Model slope with circular failure surface and vertical slices and forces acting on i th slice

$$FOS = \frac{(P_i \tan\phi + cL)R + \{-\Delta E(R\cos\theta - H_i/3) + E_{i-1}L\sin\theta\}}{(W + Fv_i)R\sin\theta + Fh_i(R\cos\theta - H_i/2)}$$

D. Choudhury, S. Basu and J. D. Bray (2007); "Behaviour of slopes under static and seismic conditions by limit equilibrium method", ***Geo-Denver 2007***, February 18-21, 2007, Denver, CO, USA (accepted, in press as ***ASCE Special Publication***).

Typical Model Slope Study

The following parameters have been considered:

Unit weight of soil, γ = 20 kN/m^3,

Cohesion of soil, c = 5 kN/m^2,

Height of the slope, H = 10 m,

Soil friction angle, ϕ = 35^0, 40^0, 45^0.

Angle of slope, β = 20^0, 25^0, 30^0.

Horizontal seismic acceleration coefficient, k_h = 0.1, 0.2, 0.3.

Vertical seismic acceleration coefficient, k_v = 0, 0.5k_h, k_h.

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Typical Results

β (deg.)	φ (deg.)	k_h = 0	0.1			0.2			0.3		
		k_v	k_v			k_v			k_v		
		0.00	0.00	0.05	0.10	0.00	0.10	0.20	0.00	0.15	0.30
20	35	1.371	1.223	1.234	1.253	1.116	1.137	1.153	-	-	-
	40	1.534	1.185	1.189	1.193	1.084	1.097	1.108	1.017	1.037	-
	45	1.682	1.415	1.423	1.431	1.256	1.278	1.297	1.150	1.184	1.213
25	35	1.538	1.265	1.302	1.309	-	-	-	-	-	-
	40	1.552	1.311	1.319	1.353	1.165	1.185	1.203	-	-	-
	45	1.946	1.593	1.604	1.615	1.378	1.408	1.435	1.234	1.282	-
30	35	1.543	-	-	-	-	-	-	-	-	-
	40	1.590	1.325	1.334	1.341	-	-	-	-	-	-
	45	1.984	1.603	1.615	1.627	1.376	1.408	1.437	-	-	-

(Note: In the above table '-' refers that the results are not valid.)

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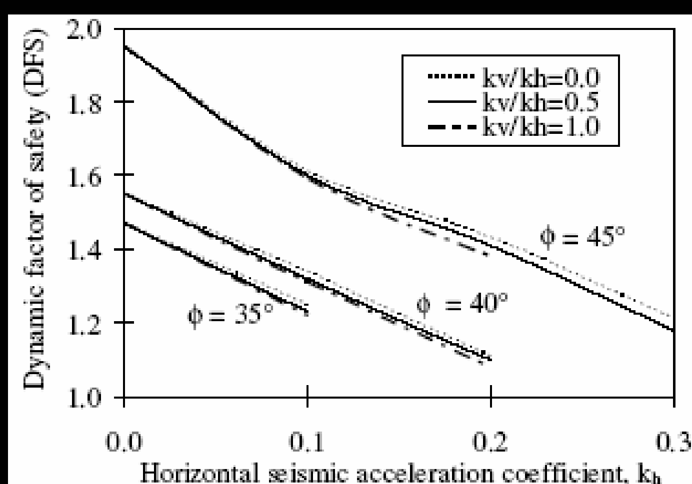
Typical Results



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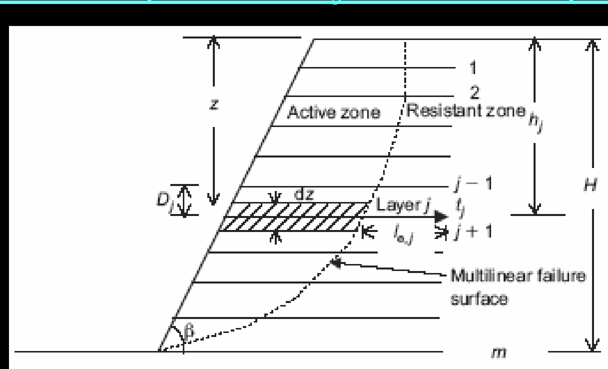
Nimbalkar, Choudhury and Mandal (2006)



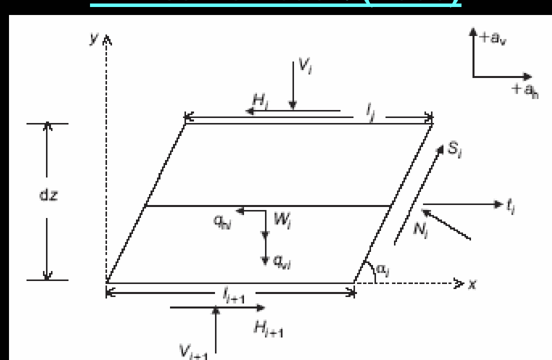
$$a_h(z,\ t) = a_h \sin\omega\left(t - \frac{H-z}{V_s}\right)$$

$$a_v(z,\ t) = a_v \sin\omega\left(t - \frac{H-z}{V_P}\right)$$

Pseudo-dynamic approach using Horizontal slices

S. Nimbalkar, D. Choudhury and J. N. Mandal (2006); "Seismic stability of reinforced soil-wall by pseudo-dynamic method", ***Geosynthetics International***, London, U.K., Vol. 13, No. 3: pp. 111-119.

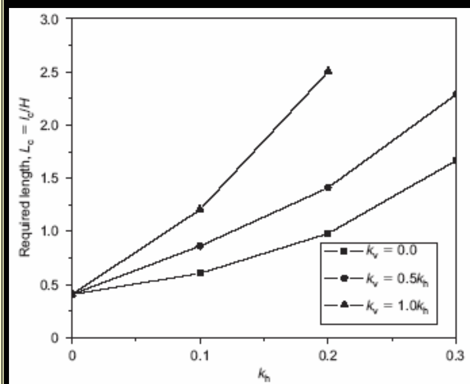
Nimbalkar et al. (2006)

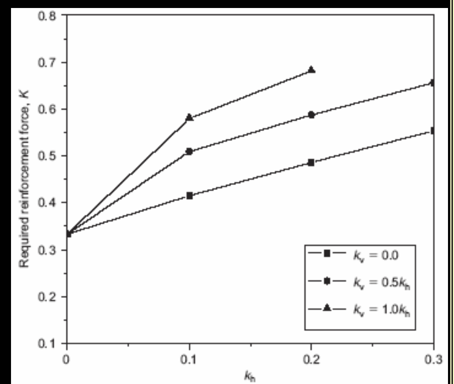


$$Q_h = \int_0^H q_{hi}\,dz = \int_0^H m_i(z)\cdot a_h(z,\ t)\,dz = \frac{\lambda\gamma k_h}{4\pi^2 \tan\alpha_i}[2\pi H\cos\omega\zeta + \lambda(\sin\omega\zeta - \sin\omega t)]$$

$$Q_v = \int_0^H q_{vi}\,dz = \int_0^H m_i(z)\cdot a_v(z,\ t)\,dz = \frac{\eta\gamma k_v}{4\pi^2 \tan\alpha_i}[2\pi H\cos\omega\psi + \eta(\sin\omega\psi - \sin\omega t)]$$

Typical Results





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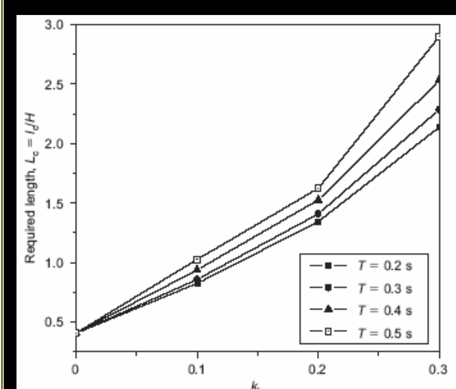
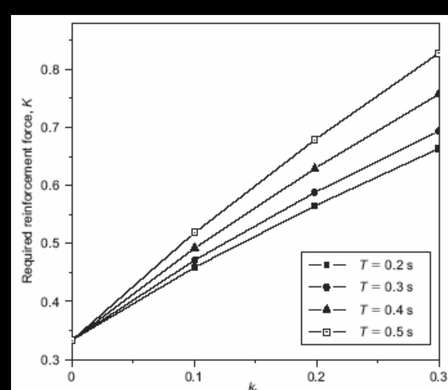
Typical Results





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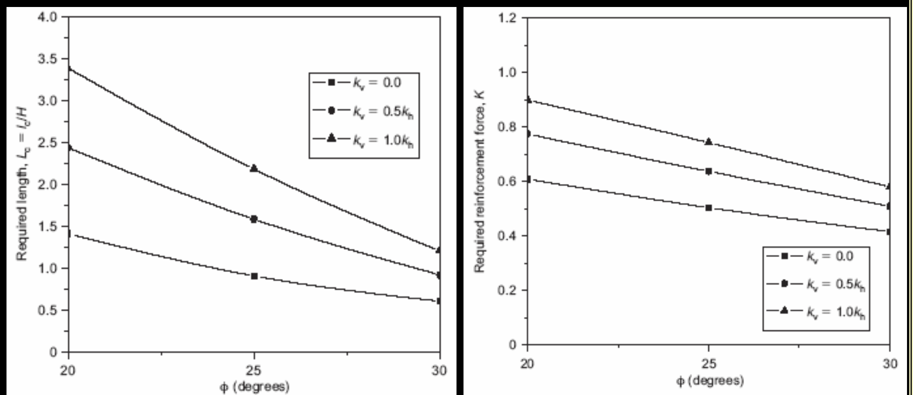
Typical Results



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Concluding Remarks

* For design of slope under earthquake condition, recently developed pseudo-dynamic method proves to provide more logical results compared to conventional pseudo-static methods.

* Reinforced soil slope provides more stability to the existing slope under earthquake conditions compared to the un-reinforced slope, provided the property and length of reinforcement is properly designed.

* Use of horizontal slice method is found to be more versatile than the vertical slice method, in terms of Reinforced and un-reinforced soil slopes are concerned and to take into account the changes in soil layer.

* Any analytical design of slope under earthquake conditions must be validated by preferably dynamic Centrifuge test and/or shake-table test.

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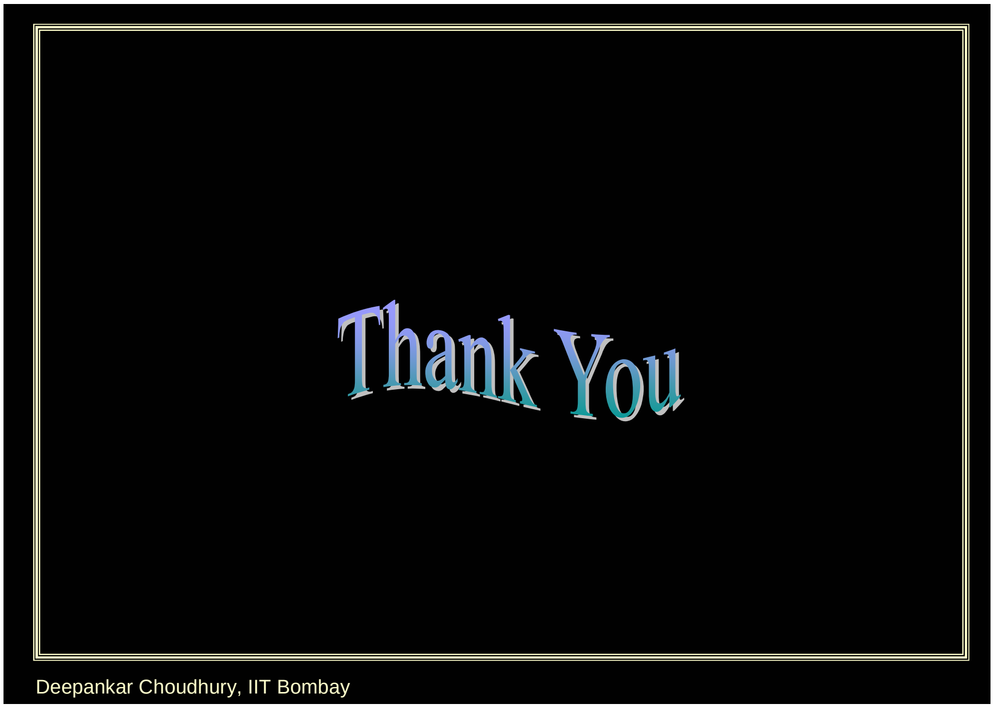
Thank You
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