# Estimating Permanent Deformations of Earthquake-Induced Landslides

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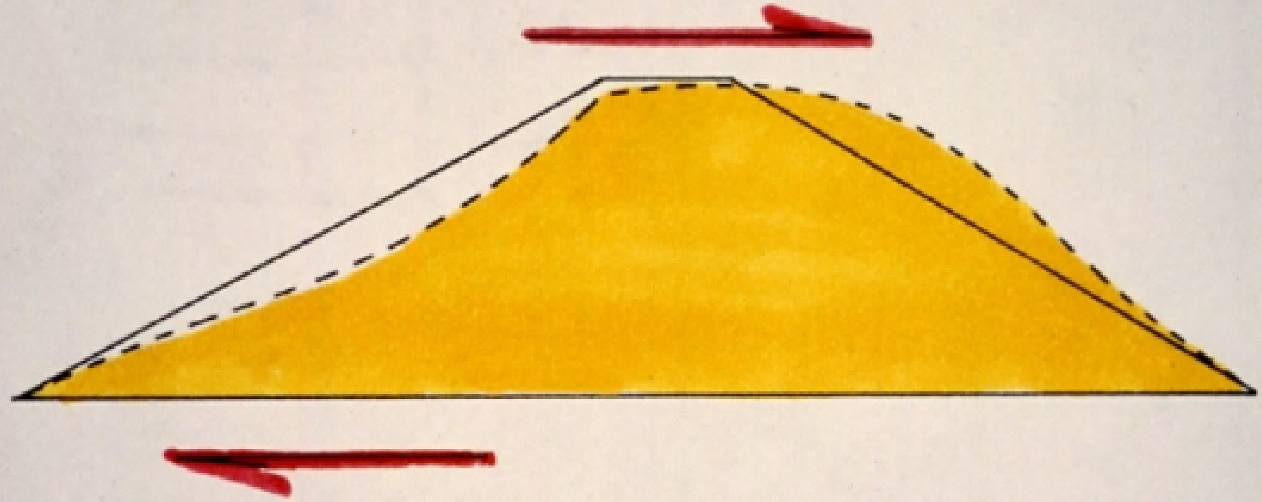
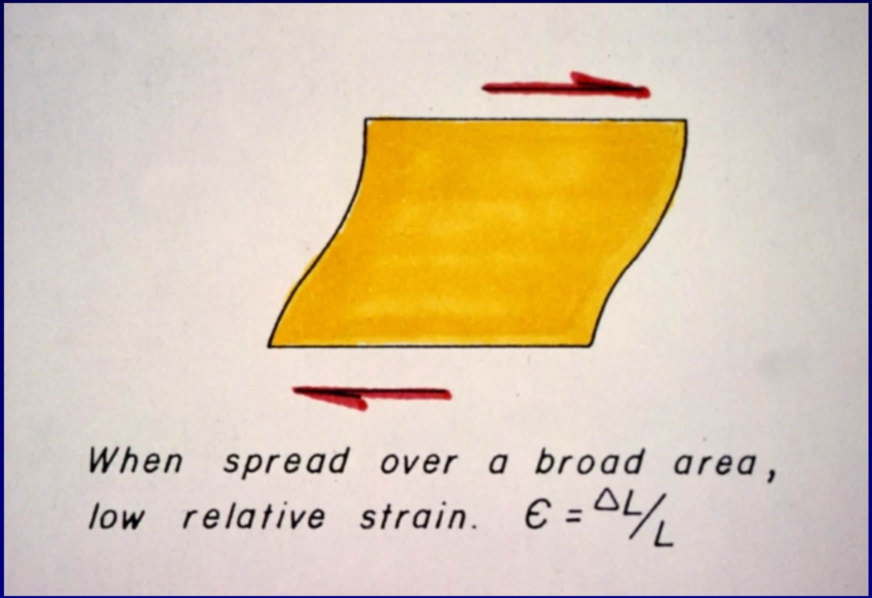
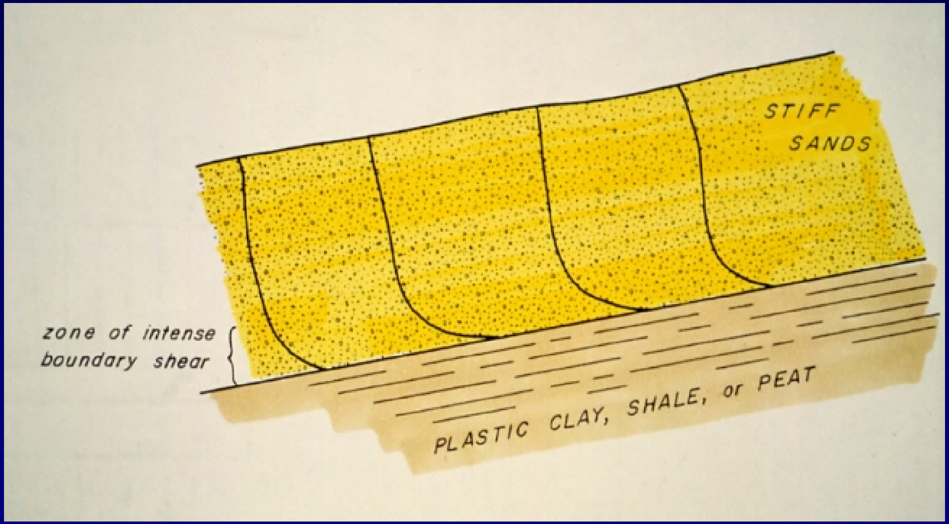
# DISTRIBUTION OF ENERGY DELIVERED BY A SEISMIC WAVE TRAIN



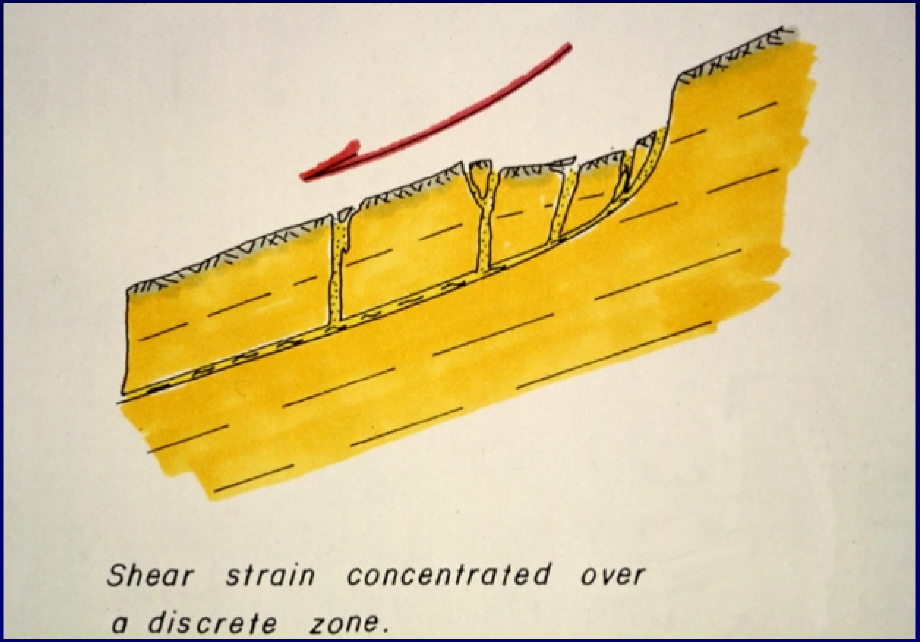
Semi-homogeneous clay embankment flexes with motion, thereby dispersing shear strain.

# SHEAR STRAIN





- If the shear stress induced by EQ motion is distributed vided over a wide area, the resulting shear strain will be lower than if it is confined to a discrete zone or horizon.



- Earthquakes tend to trigger shallow block failures on steep-sided bedrock ridges.
- These can be modeled easily using Newmark’s Method, which is a rigid block analysis that uses either PGA or time histories to simulate the EQ, then back-calculates a yield acceleration, $k_y$.

Rock detached by earthquake of June 17, 1929, at Murchison, New Zealand.

- In some earthquakes the duration of strong shaking can be of sufficient duration to trigger movement of very large blocks.

# Pseudostaic Slope Stability Analysis

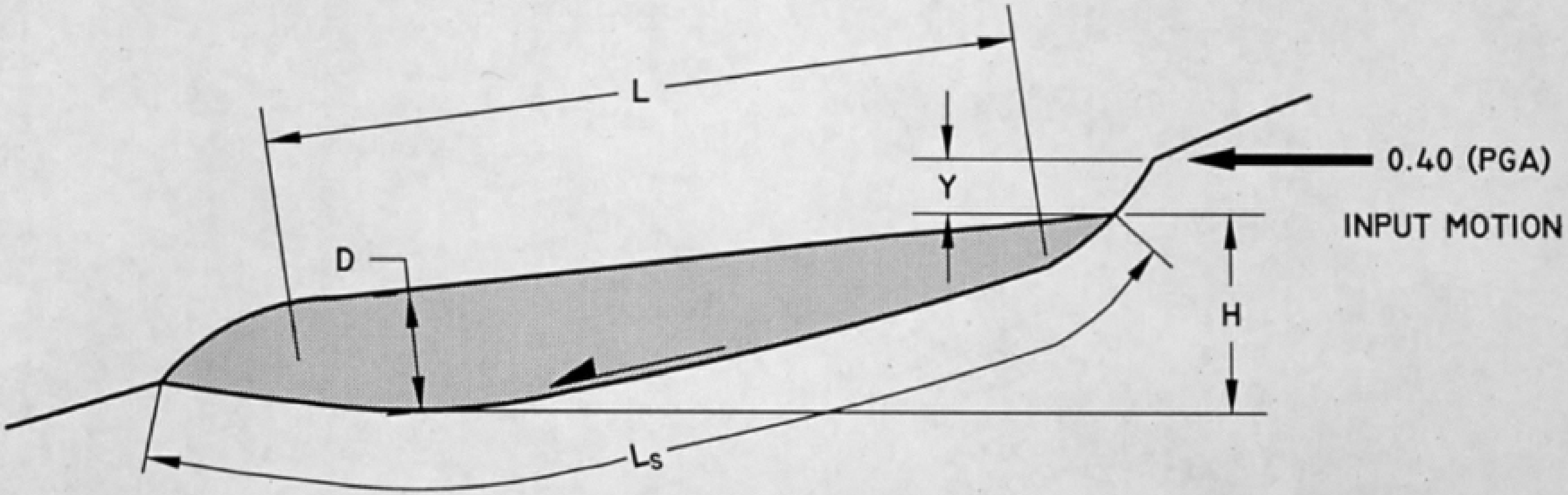
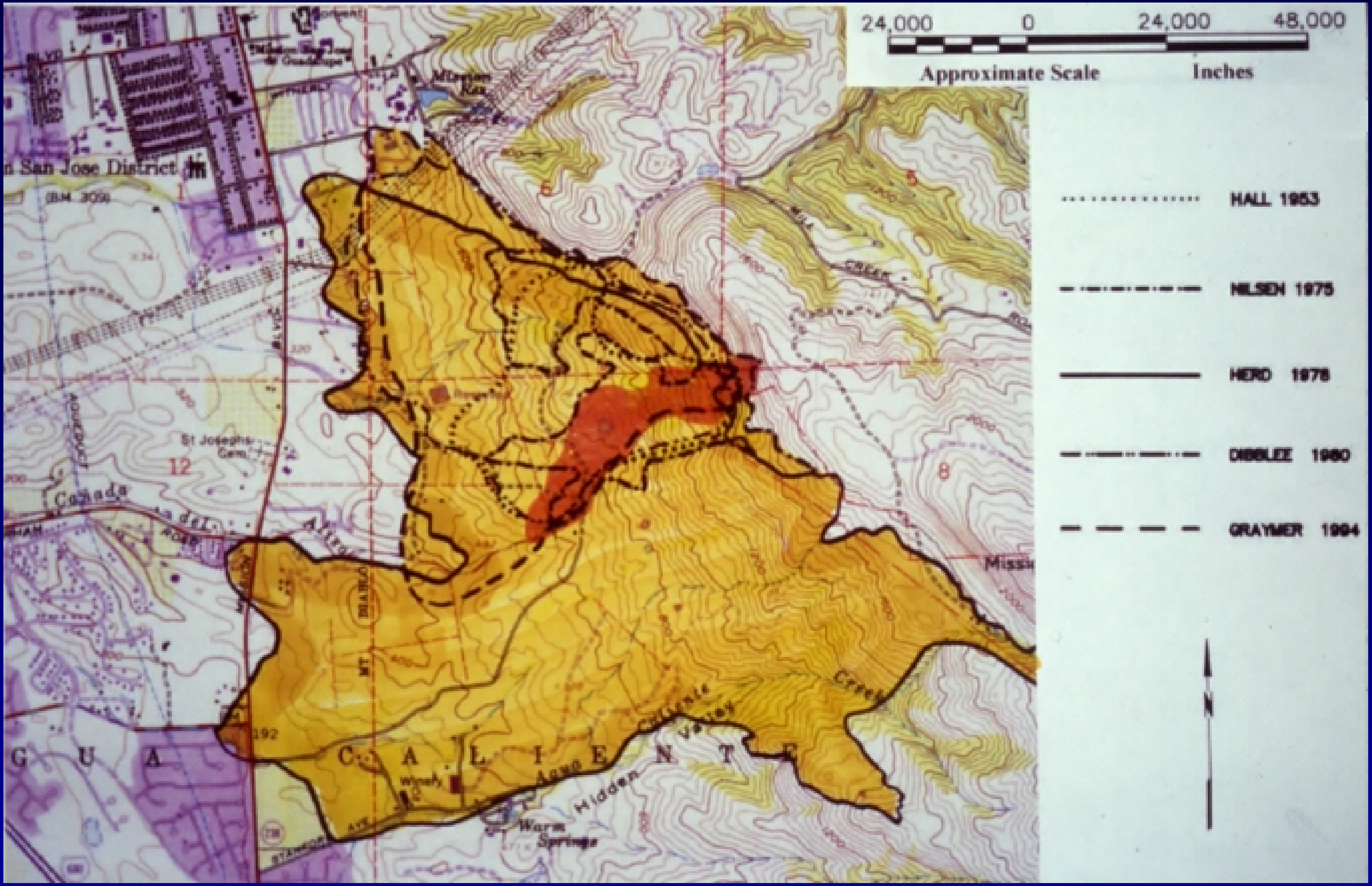


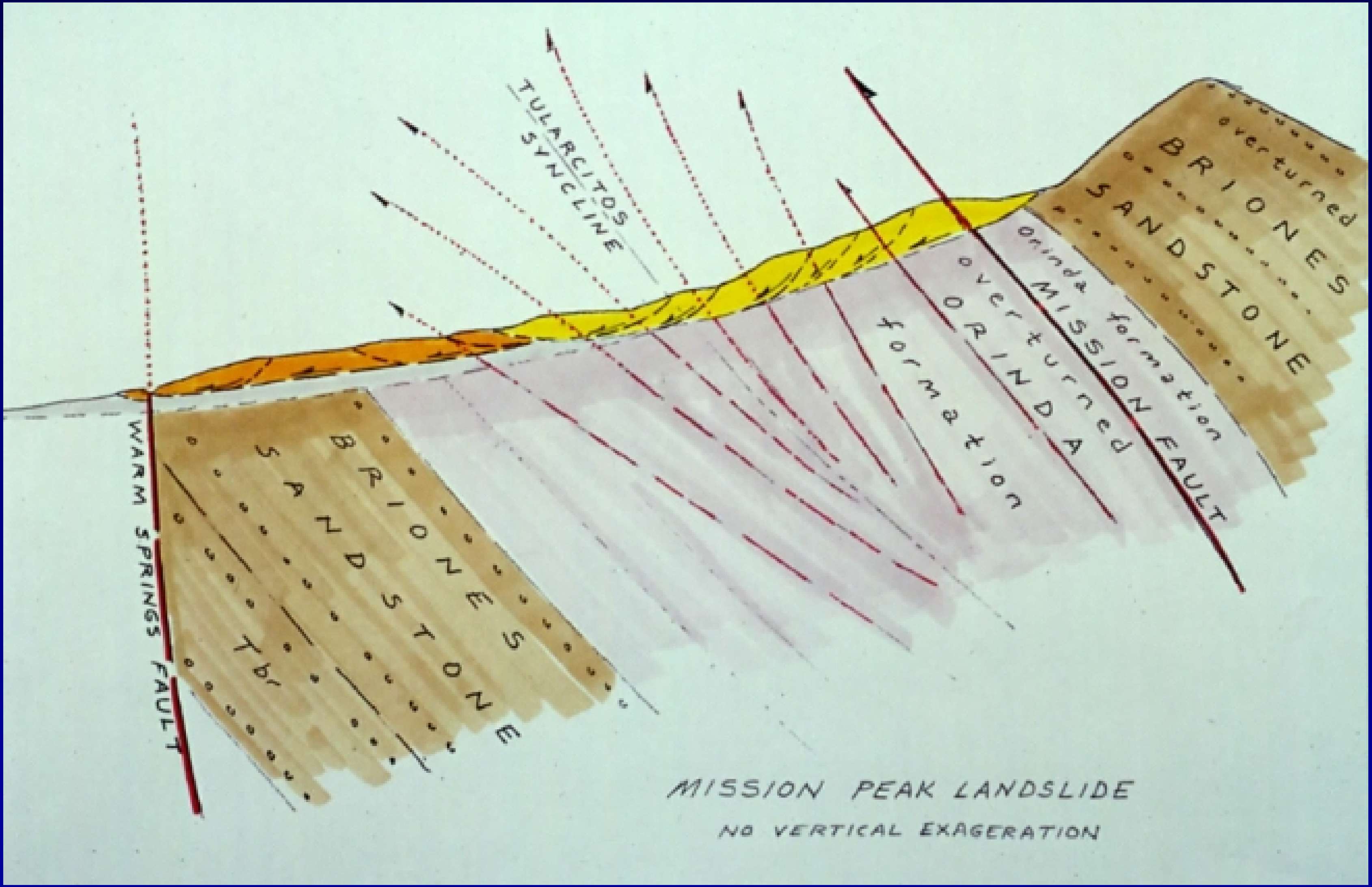
FIG 2 - GEOMETRY OF A DORMENT LANDSLIDE SUBJECT TO SEISMIC LOADING. L = LENGTH OF SLOPE-PARALLEL PORTION OF SLIDE; $L_S$ = THE LENGTH OF THE LANDSLIDE SLIP SURFACE; D = THE MAXIMUM DEPTH OF SLIDING; H = THE OVERALL HEIGHT OF THE SLIDING MASS; Y = THE SEISMICALLY - INDUCED DISPLACEMENT. THE EQUIVALENT ACCELERATION DESIRED FOR INPUT MOTION IS THAT PERCENTAGE OF THE PGA THAT PREDICTS THE CORRECT DYNAMIC SHEAR STRESS ON THE FAILURE PLANE. A MAXIMUM VALUE OF 40% PGA IS COMMONLY APPLIED TO LARGE DEEP-SEATED LANDSLIDES.

- Mission Peak Landslide in Fremont, CA on Mission fault
- Partially reactivated in March 1998
- 5,450 feet long, dropping 1,310 feet
- 17,000,000 $yds^3$
- 85.5 acres
- Threatening homes
- How much movement could occur in an earthquake



- The slide was recognized in five different geologic studies between 1958 and 1994. Orange area is March 1998 Mission Peak Landslide.

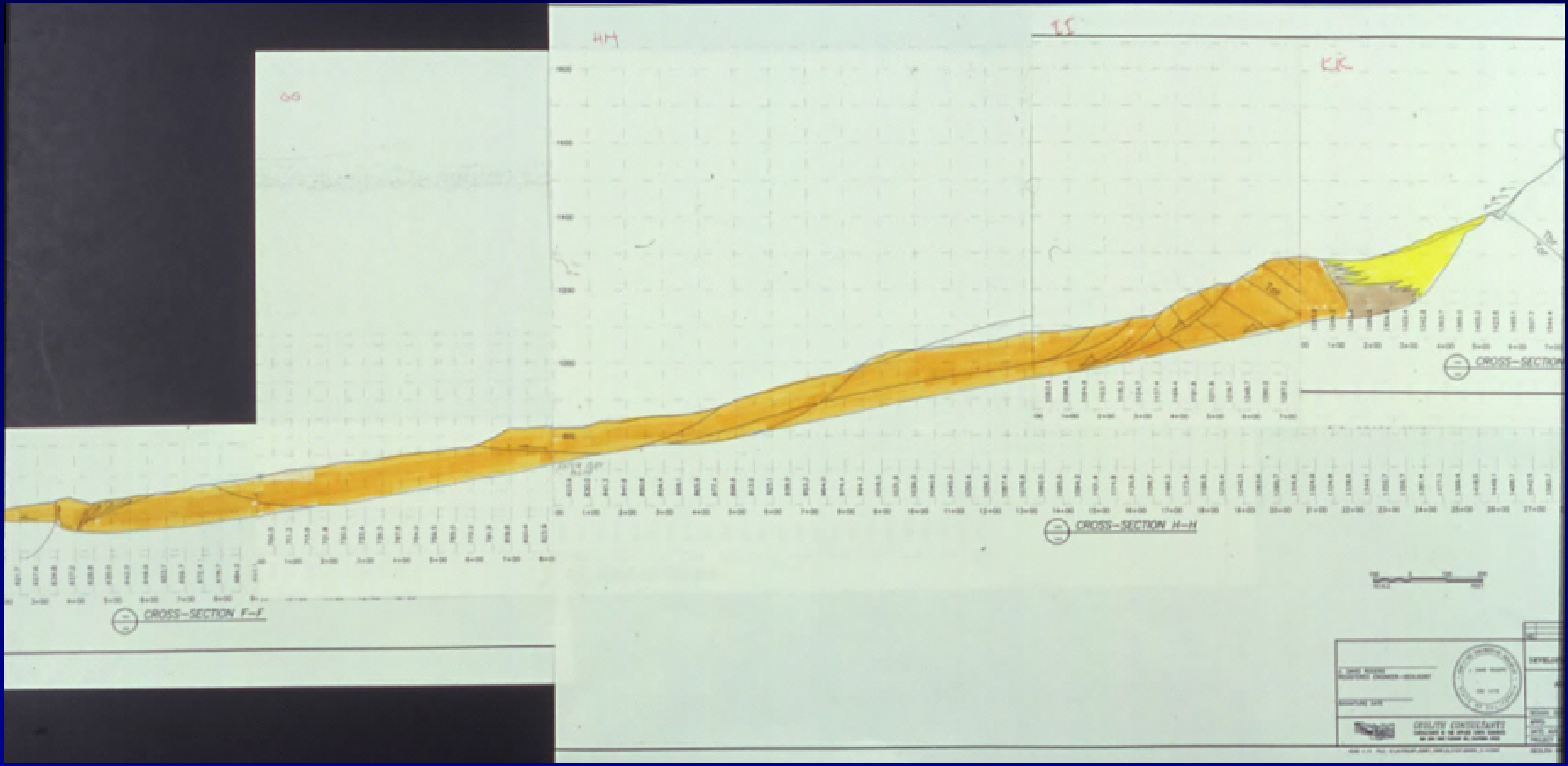
# GEOLOGIC CROSS SECTION



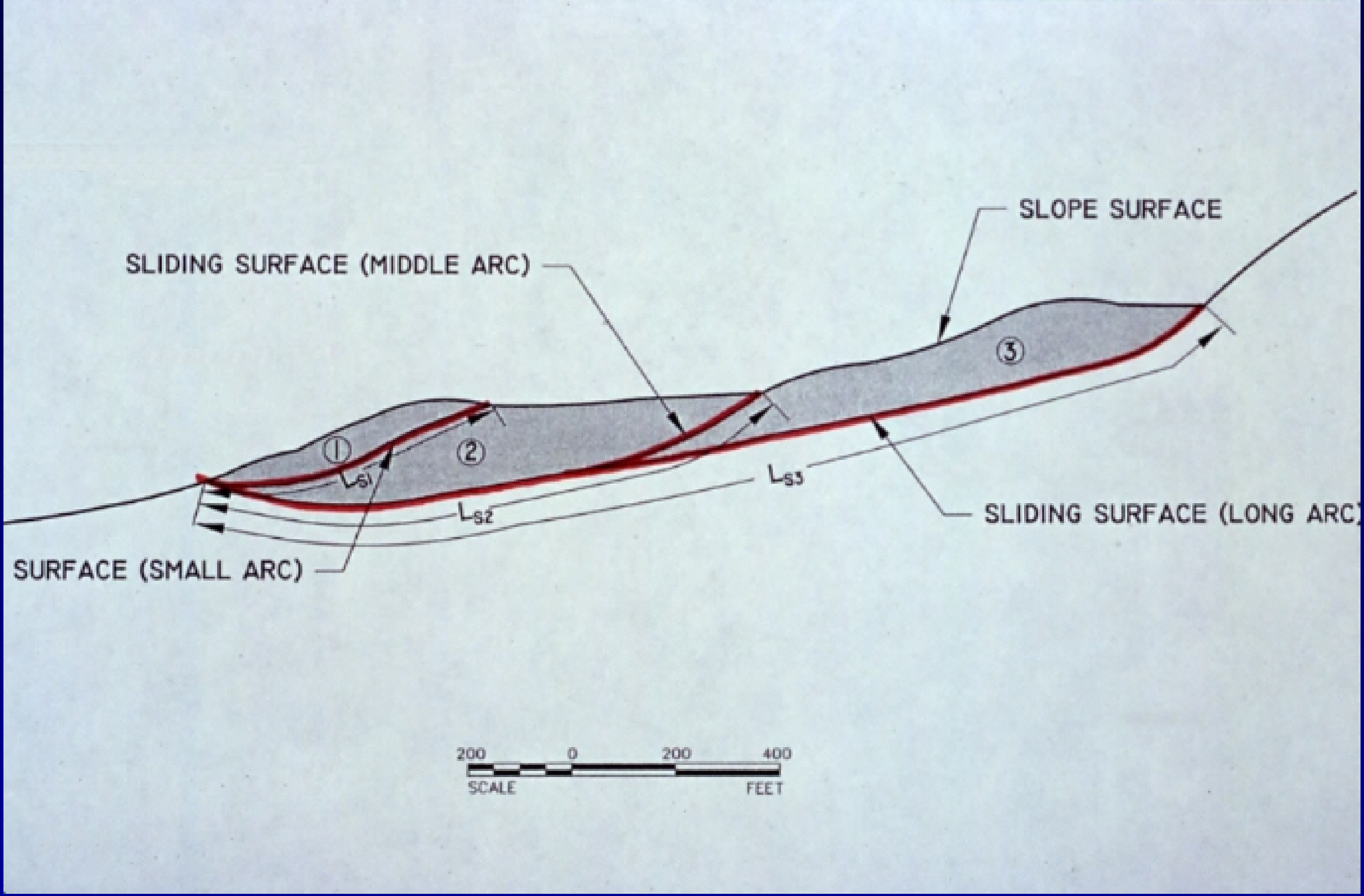
# COALESCING EARTHFLOWS

- The Mission Peak Landslide is a series of intercalating earthflows.  Individual flow lobes are up to 900 feet long and up to 180 feet deep.
- Very clayey source materials, mostly from the Pliocene-age Orinda formation

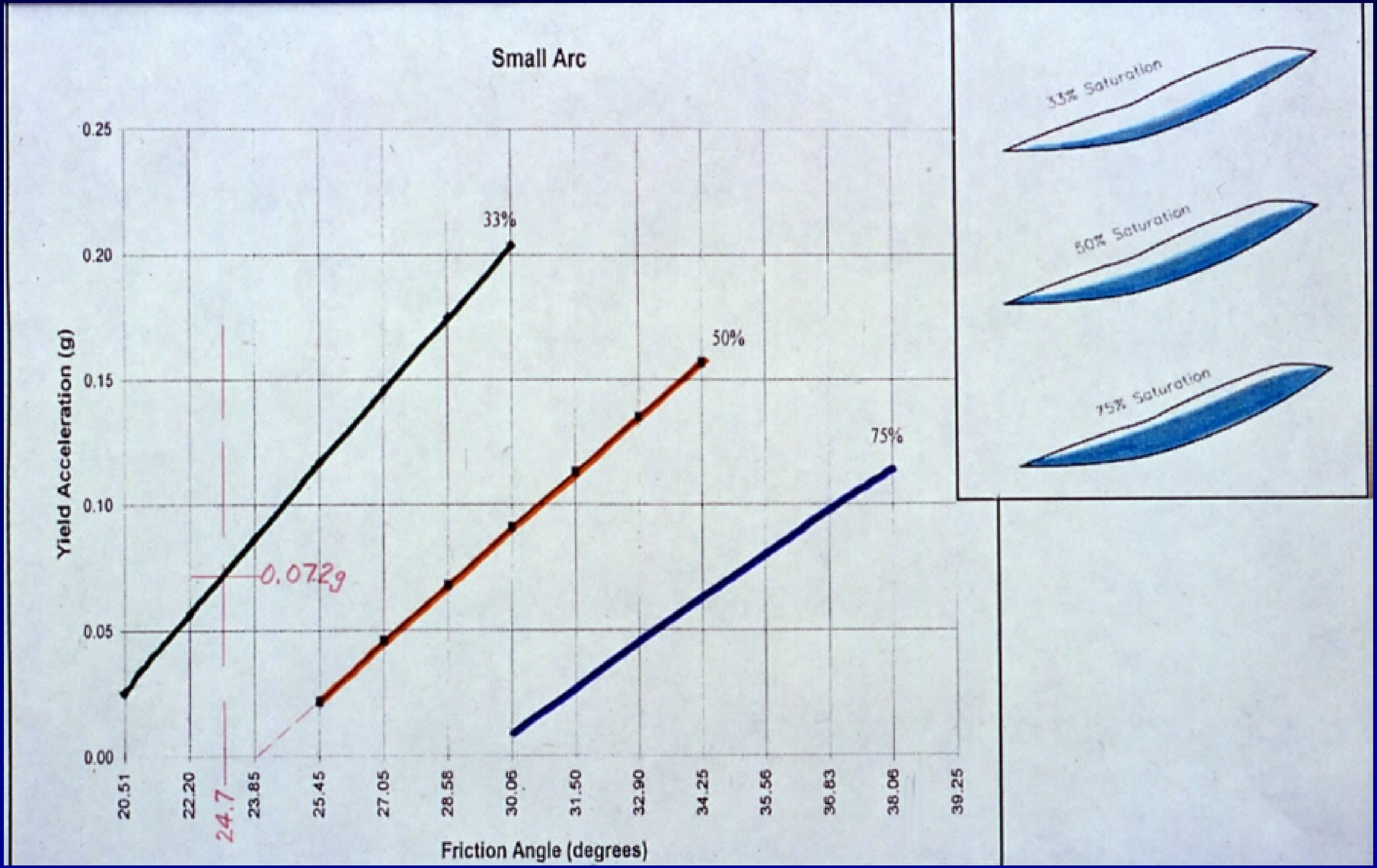
# MAXIMUM CROSS SECTION



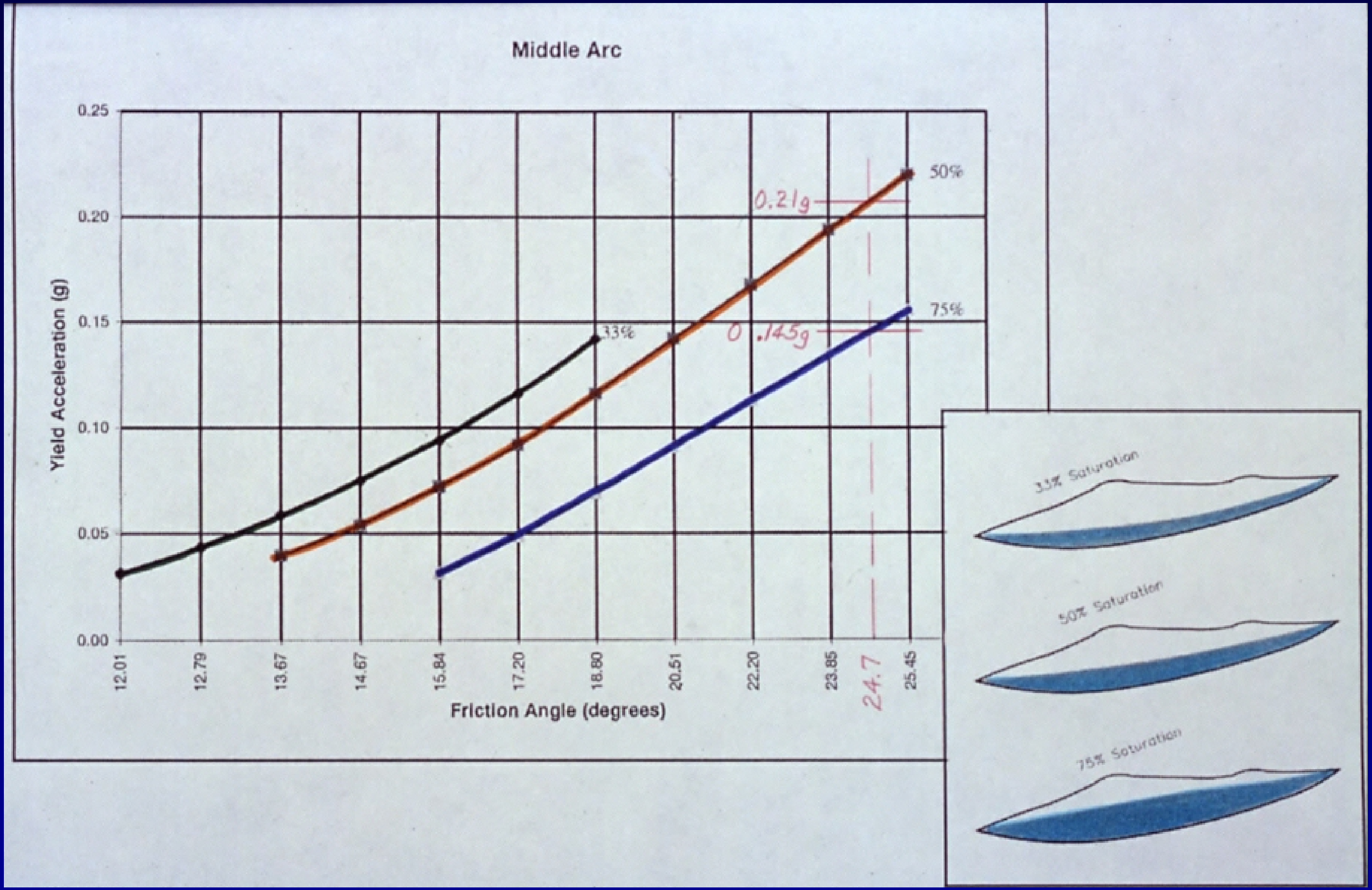
- Cross section through the Mission Peak Landslide, taken from headscarp to distal toe.  Portion that moved most (300 ft) was in the middle slope.



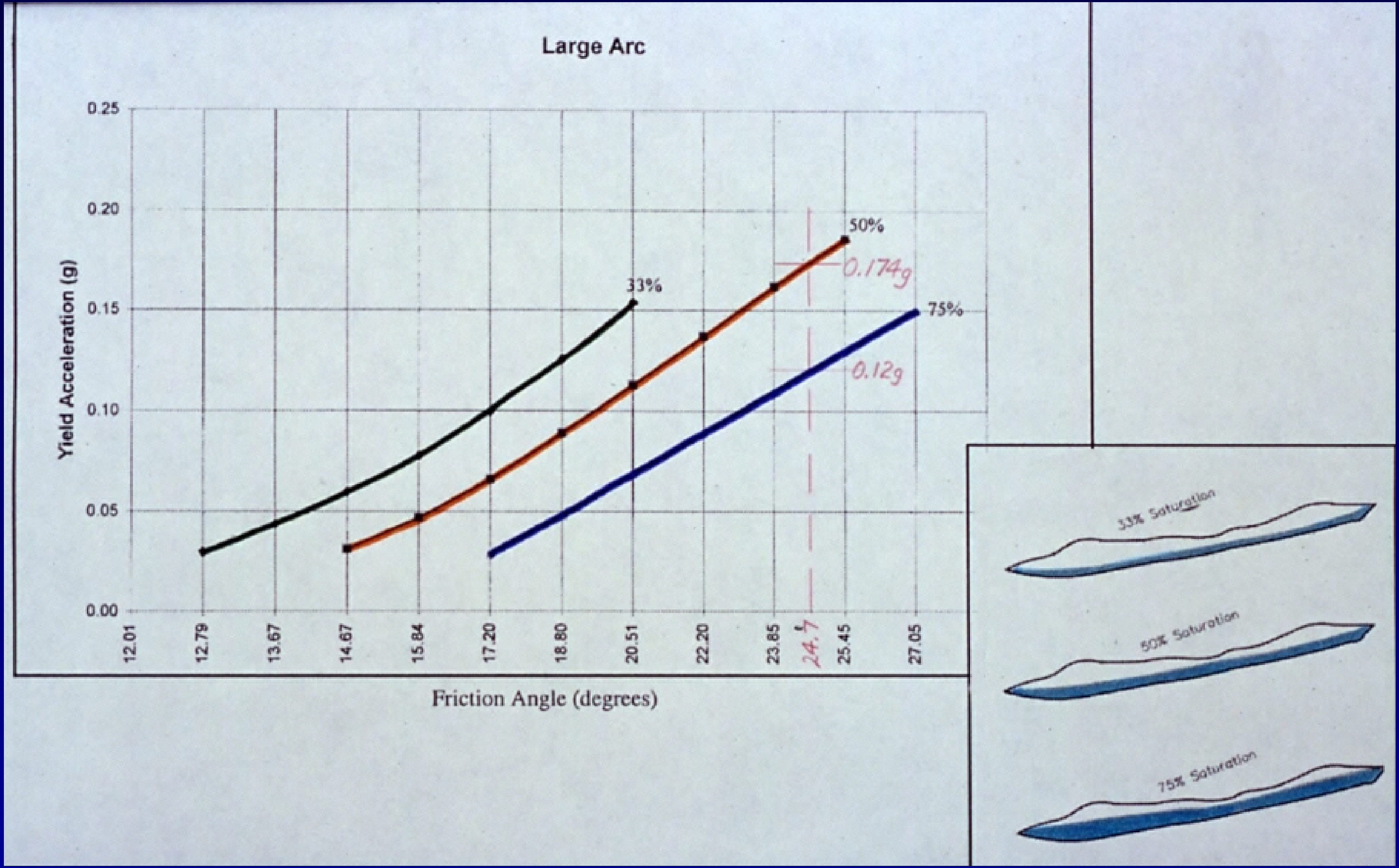
- Any dynamic analysis should evaluate small, medium and large portions of the dynamic system being modeled. $L_1$ = 550’; $L_2$ = 1100’; $L_3$ = 2000’



- A series of rigid block analyses allows yield accelerations to be determined for a range of water contents within the smallest earthflow. For friction angle 24.7$^o$ , $k_y$ = 0.072g

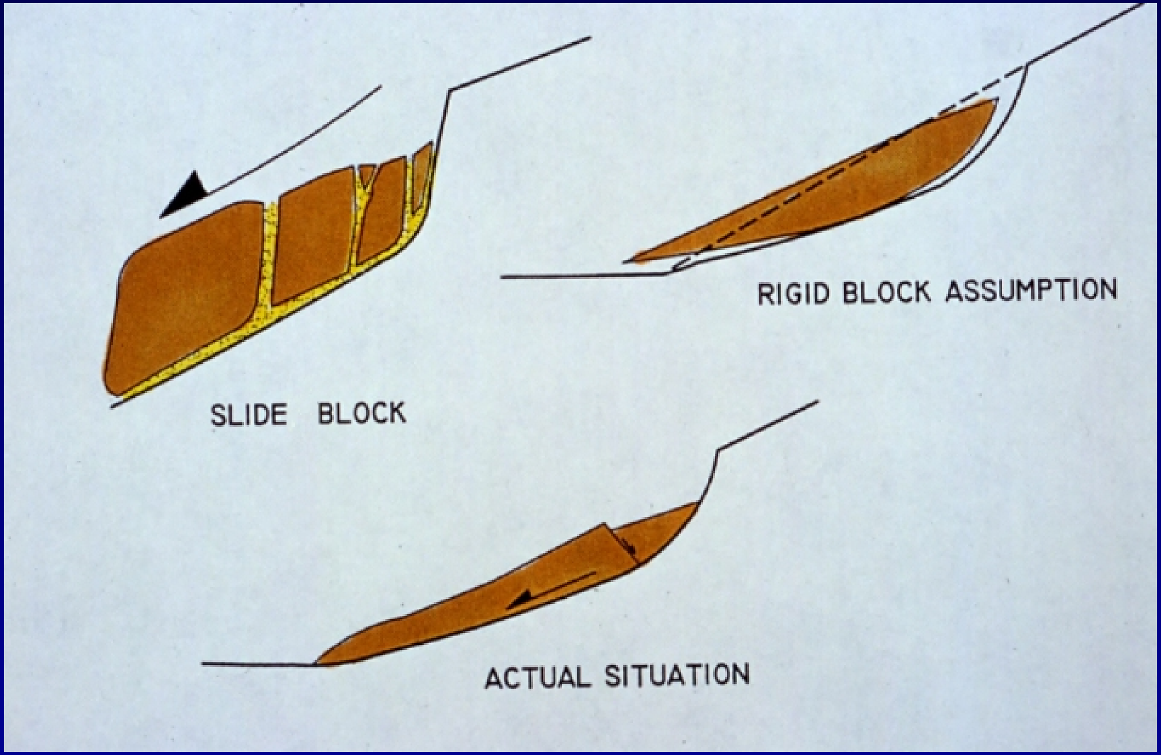


- Rigid block analyses for the medium sized earthflow, having a base length of 1100 feet. The yield acceleration for phi of $24.7^{o}$ was $k_y = 0.210$g



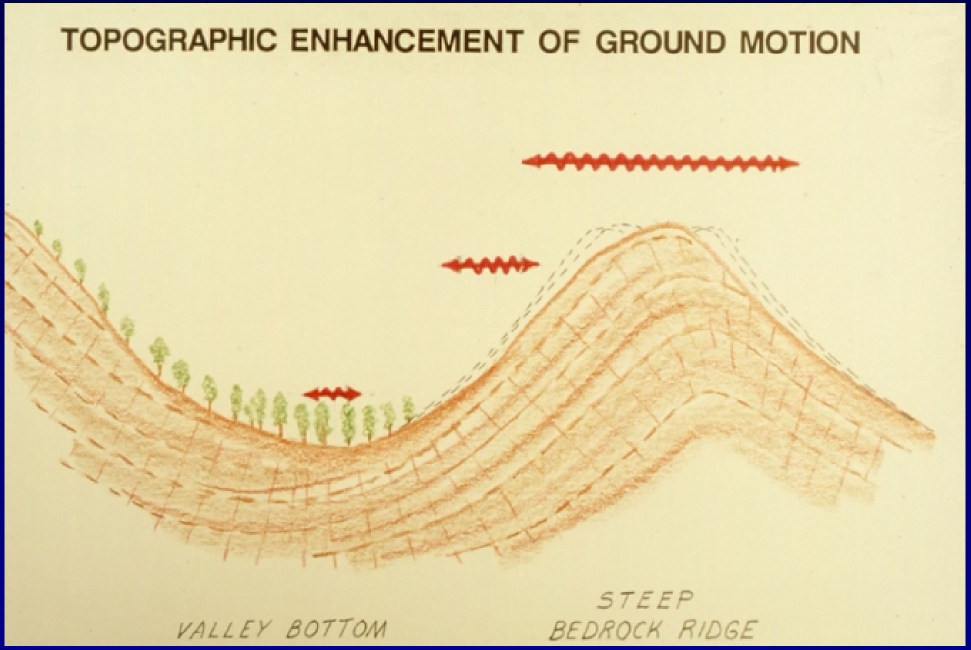
- Rigid block analyses for the largest earthflow lobe, having a base length of 2000 feet. The yield acceleration for phi of 24.7° was $k_y = 0.174g$

# Appropriateness of Pseudostatic Methods



- Rigid block assumptions should not be used to model EQ-induced movements of large dormant landslide complexes

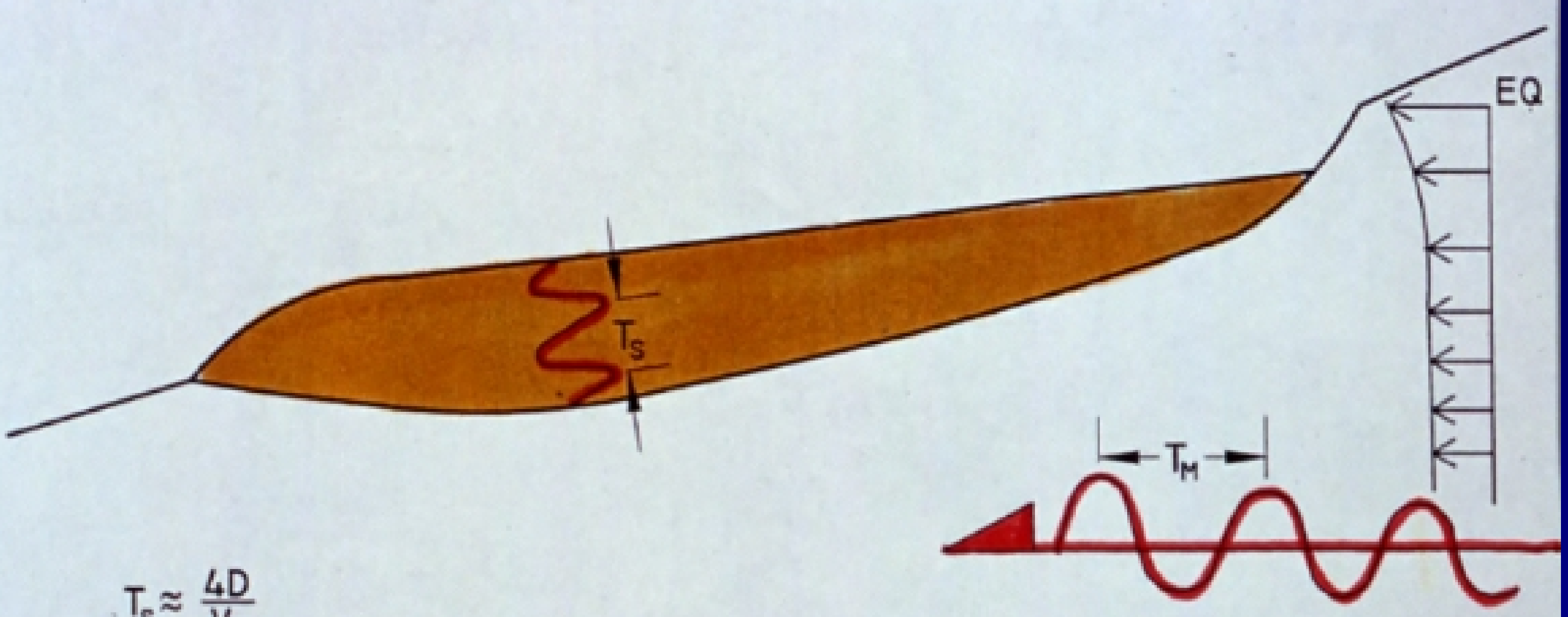
# TOPOGRAPHIC ENHANCEMENT



- Steep-sided bedrock ridges tend to amplify ground motions, causing greater structural damage and triggering shallow block slides.

- Earthquake-induced landslides triggered by the January 1994 Northridge Earthquake
- These surficial slides can be analyzed using the Newmark sliding block method
- Note the preferential orientation of the sliding

# FUNDAMENTAL PERIOD OF THE SLIDE MASS, $T_S$

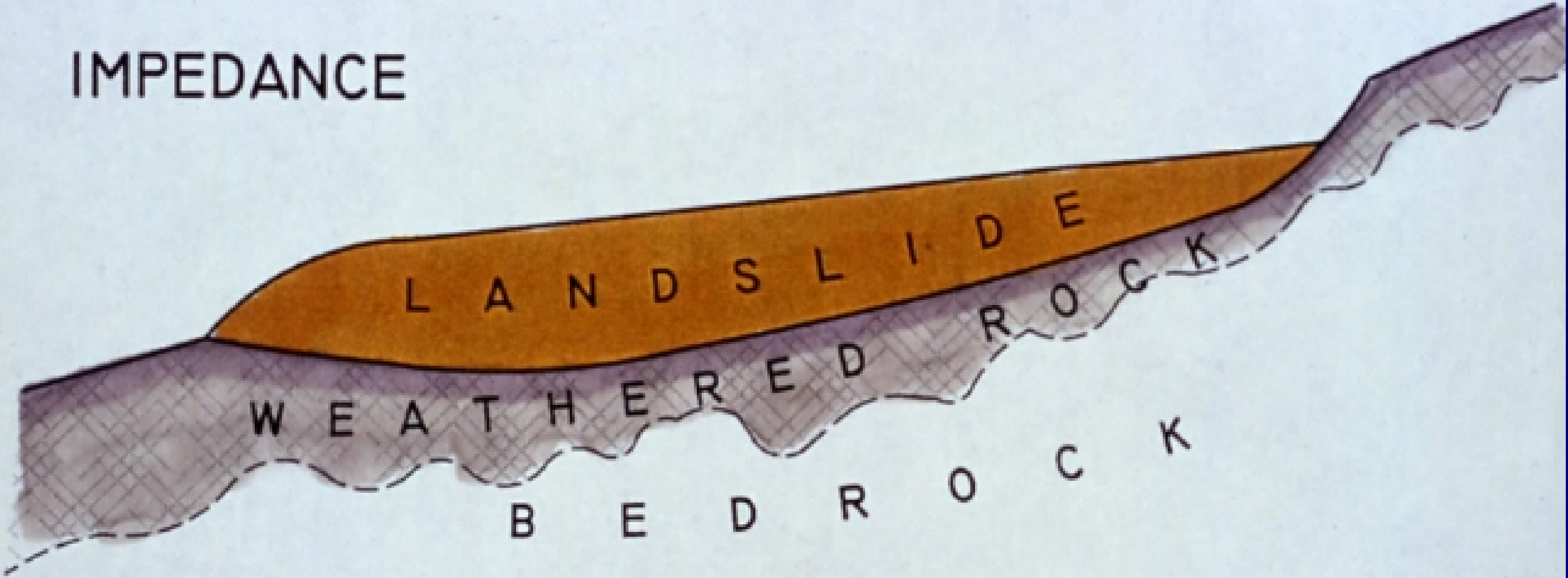


$$T_S \approx \frac{4D}{V_S}$$

$T_M$ = INPUT FOUNDATION MOTION

FIG 5 - ANY DYNAMIC ANALYSIS BEGINS BY CONSIDERING THE FUNDAMENTAL PERIOD OF THE SLIDE MASS AND THE PREDOMINANT PERIOD OF THE INPUT GROUND MOTION. IF INPUT MOTION IS NEAR RESONANCE, MASSIVE GROUND AMPLIFICATION WOULD RESULT. D = DEPTH OF THE SLIDE MASS.

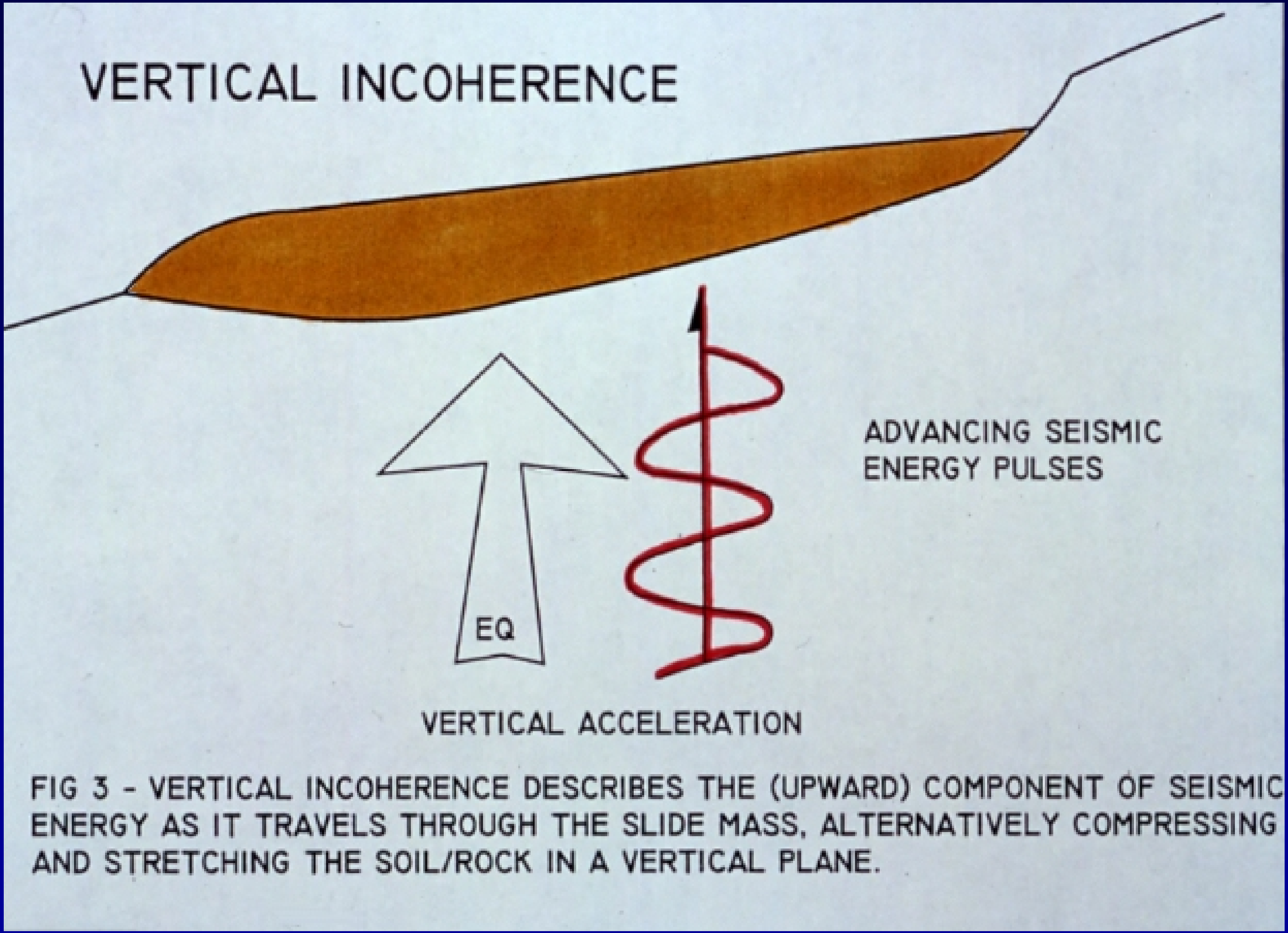
# IMPEDANCE



IMPEDANCE RATIO

$$IR = \frac{\rho_{FOUNDATION} \; (V_S)_{BEDROCK}}{\rho_{LANDSLIDE} \; (V_S)_{LANDSLIDE}}$$

FIG 6 - IF THICK SEQUENCES OF SOFT MATERIAL OVERLIE STIFF MATERIAL, SOME DYNAMIC AMPLIFICATION OF THE EARTHQUAKE ENERGY CAN BE EXPECTED IN THE SOFT MATERIAL.



# VERTICAL INCOHERENCE

FIG 3 - VERTICAL INCOHERENCE DESCRIBES THE (UPWARD) COMPONENT OF SEISMIC ENERGY AS IT TRAVELS THROUGH THE SLIDE MASS, ALTERNATIVELY COMPRESSING AND STRETCHING THE SOIL/ROCK IN A VERTICAL PLANE.

# LATERAL INCOHERENCE

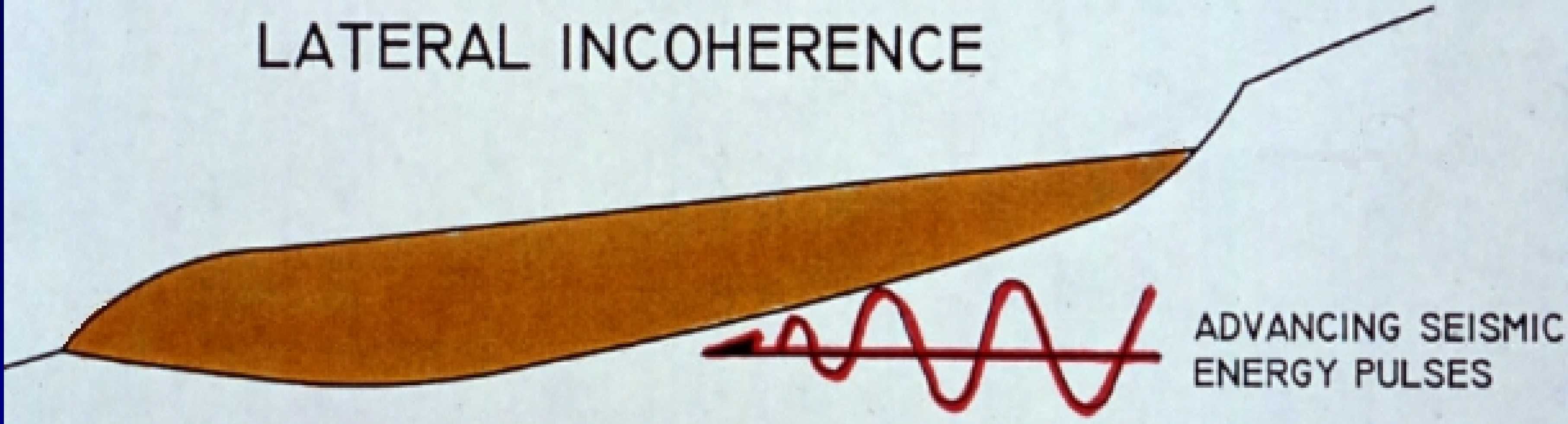
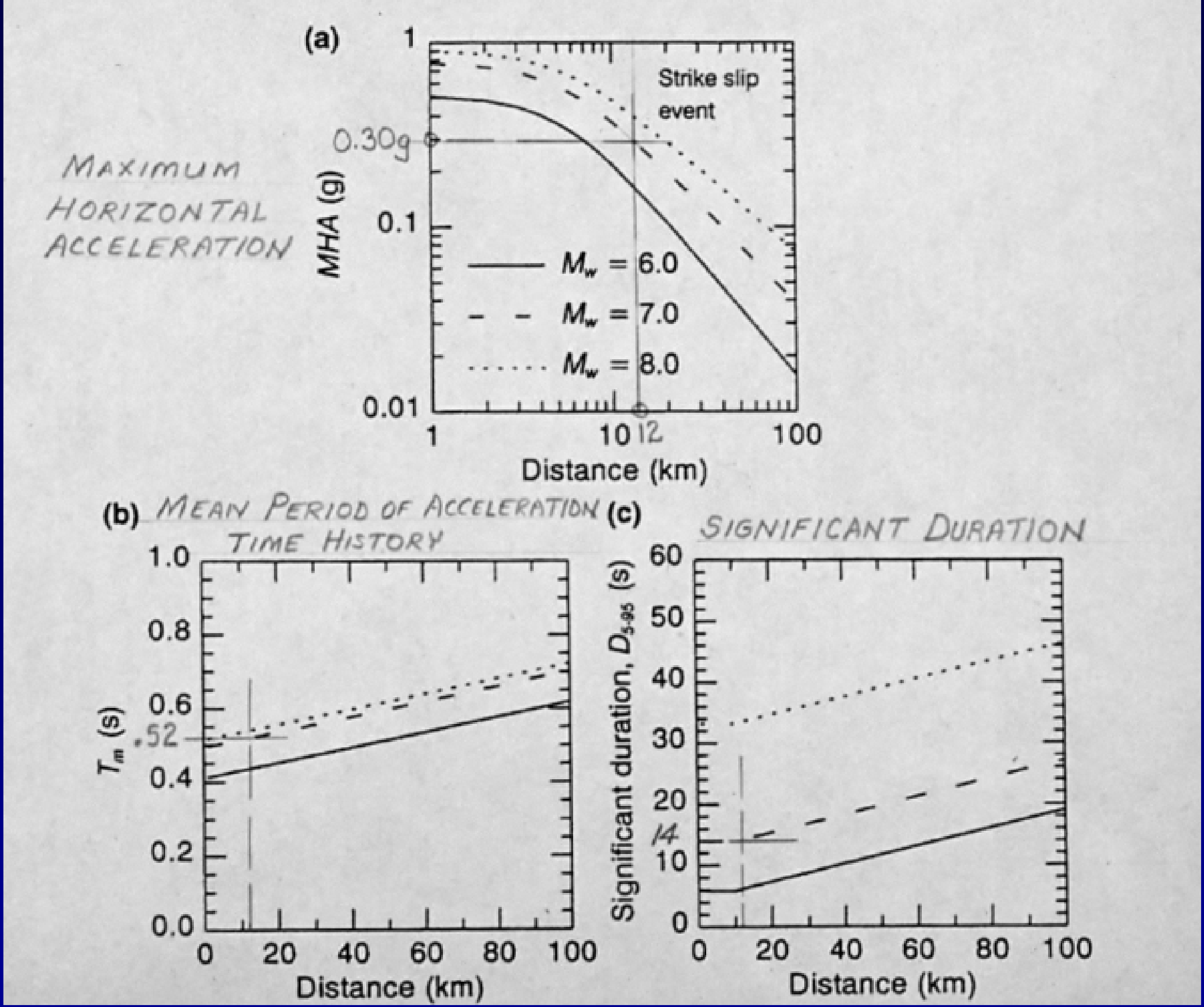
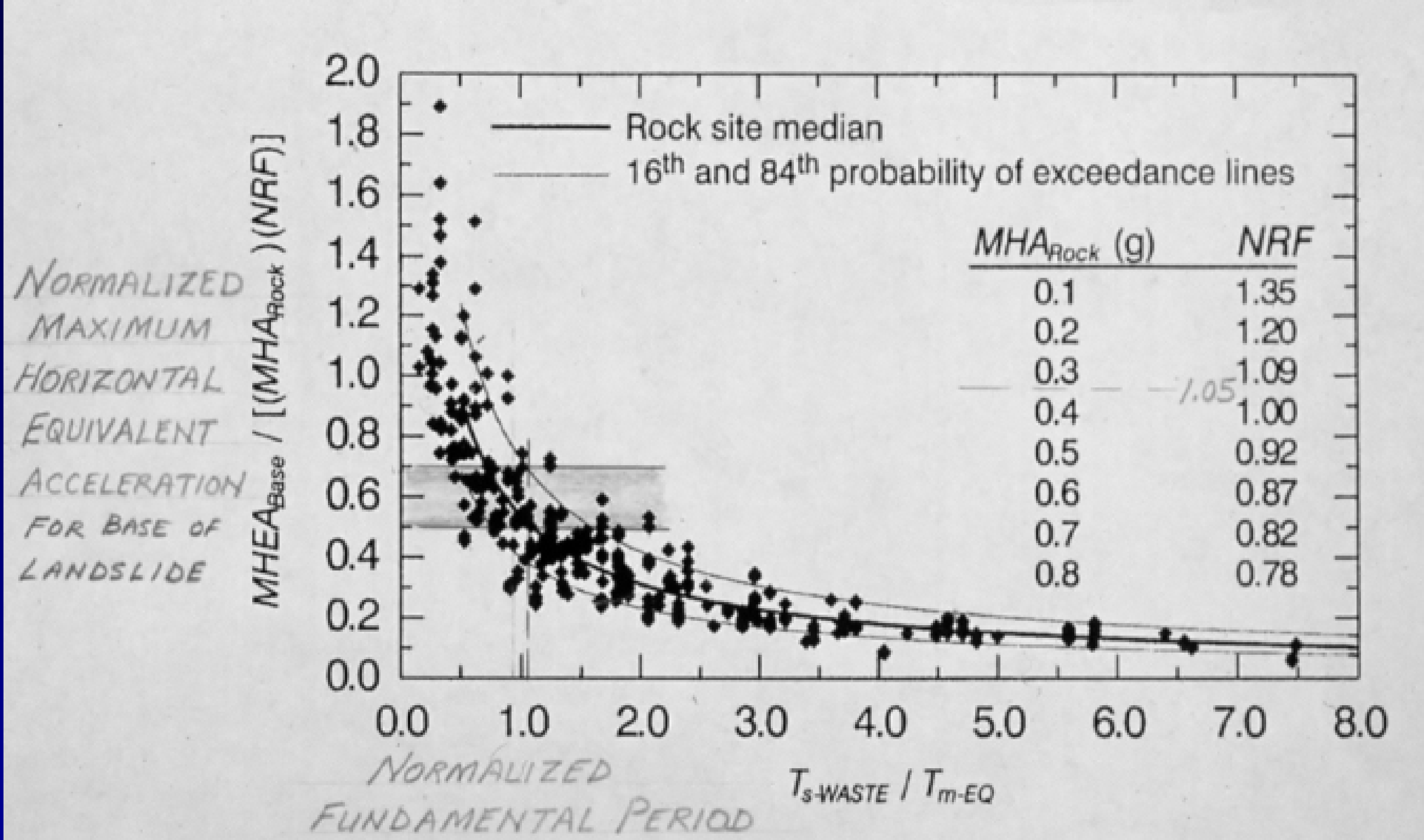


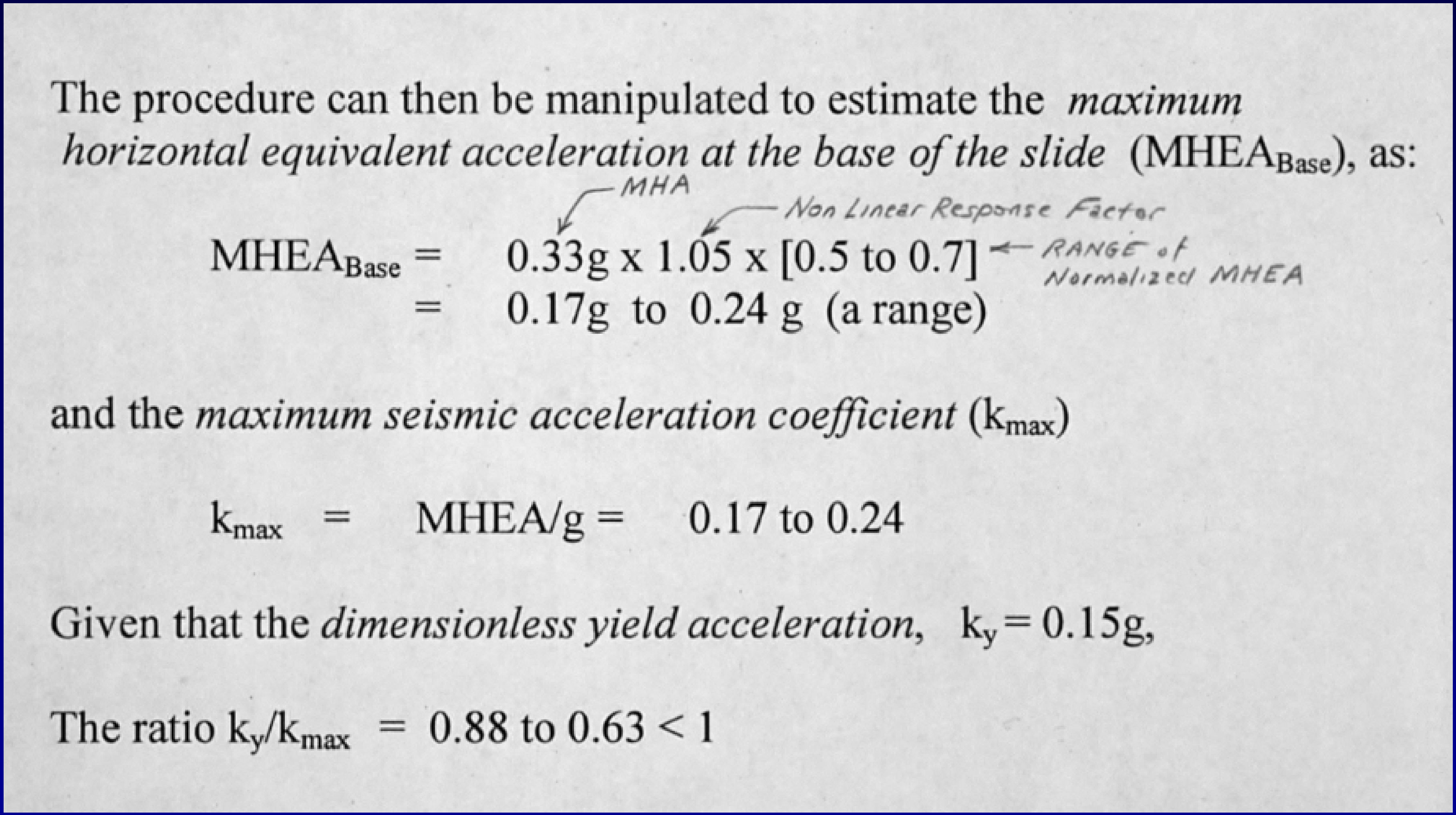
FIG 4 - AS SEISMIC ENERGY PULSES THROUGH THE SLIDE, IT ALTERNATIVELY STRETCHES AND COMPRESSES THE GROUND MASS. IF THE SLIP SURFACE IS LONG, THE MAXIMUM SEISMIC FORCE CANNOT BE EXERTED ALONG THE ENTIRE BOUNDARY AT ANY GIVEN INSTANT. AN EQUIVALENT ACCELERATION MUST BE USED TO DESCRIBE THE OVERALL IMPACT OF SEISMIC LOADING.



- We can perform a screening analysis of the dynamic system by evaluating fundamental dynamic parameters and comparing these with existing data from earthquakes



- We need to know the Maximum Horizontal Equivalent Acceleration at the base of the landslide, known as the $\mathrm{MHEA}_{\mathrm{base}}$



The procedure can then be manipulated to estimate the *maximum horizontal equivalent acceleration at the base of the slide* ($MHEA_{Base}$), as:

$$MHEA_{Base} = \overset{\text{MHA}}{0.33g} \times \overset{\text{Non Linear Response Factor}}{1.05} \times [0.5 \text{ to } 0.7] \leftarrow \text{RANGE of Normalized MHEA}$$

$$= 0.17g \text{ to } 0.24\,g \text{ (a range)}$$

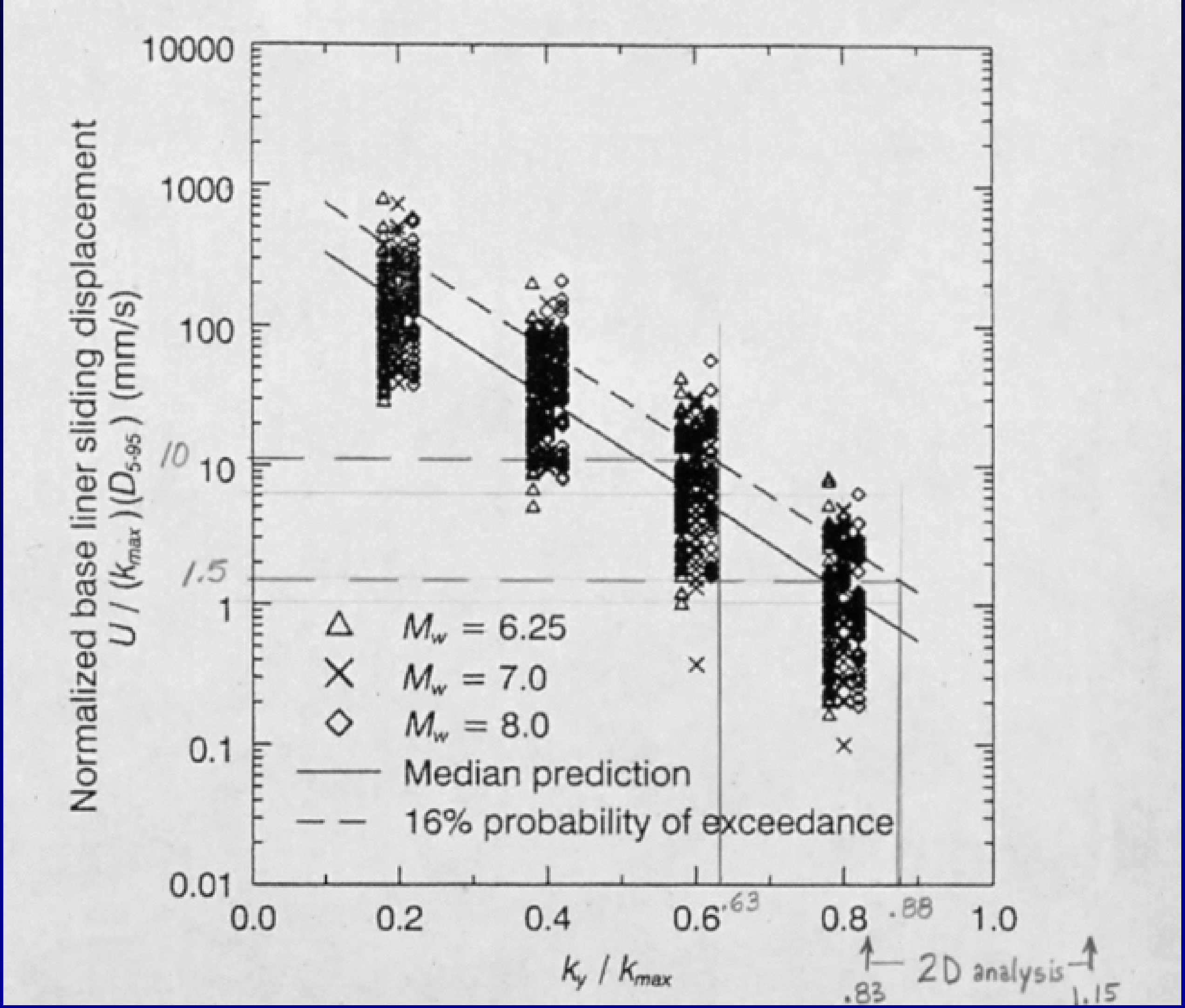
and the *maximum seismic acceleration coefficient* ($k_{max}$)

$$k_{max} = MHEA/g = 0.17 \text{ to } 0.24$$

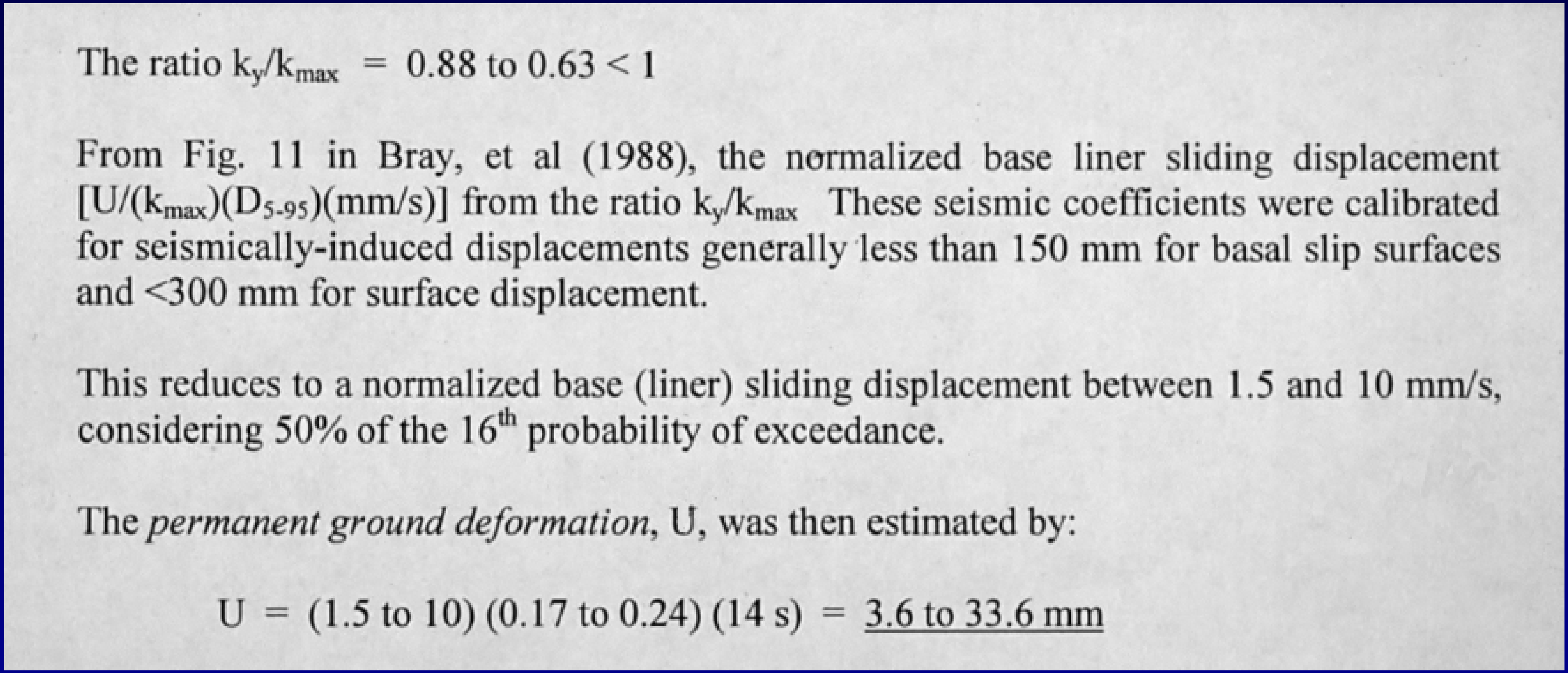
Given that the *dimensionless yield acceleration*, $k_y = 0.15g$,

The ratio $k_y/k_{max} = 0.88 \text{ to } 0.63 < 1$

- The range of $k_y$ /$k_{max}$ allows us to the normalized base sliding displacement for a large range of earthquake motions



- For the Mission Peak earthflows, the range of normalized base sliding displacement was between 1.5 and 10.



The ratio $k_y/k_{max}$ = 0.88 to 0.63 < 1

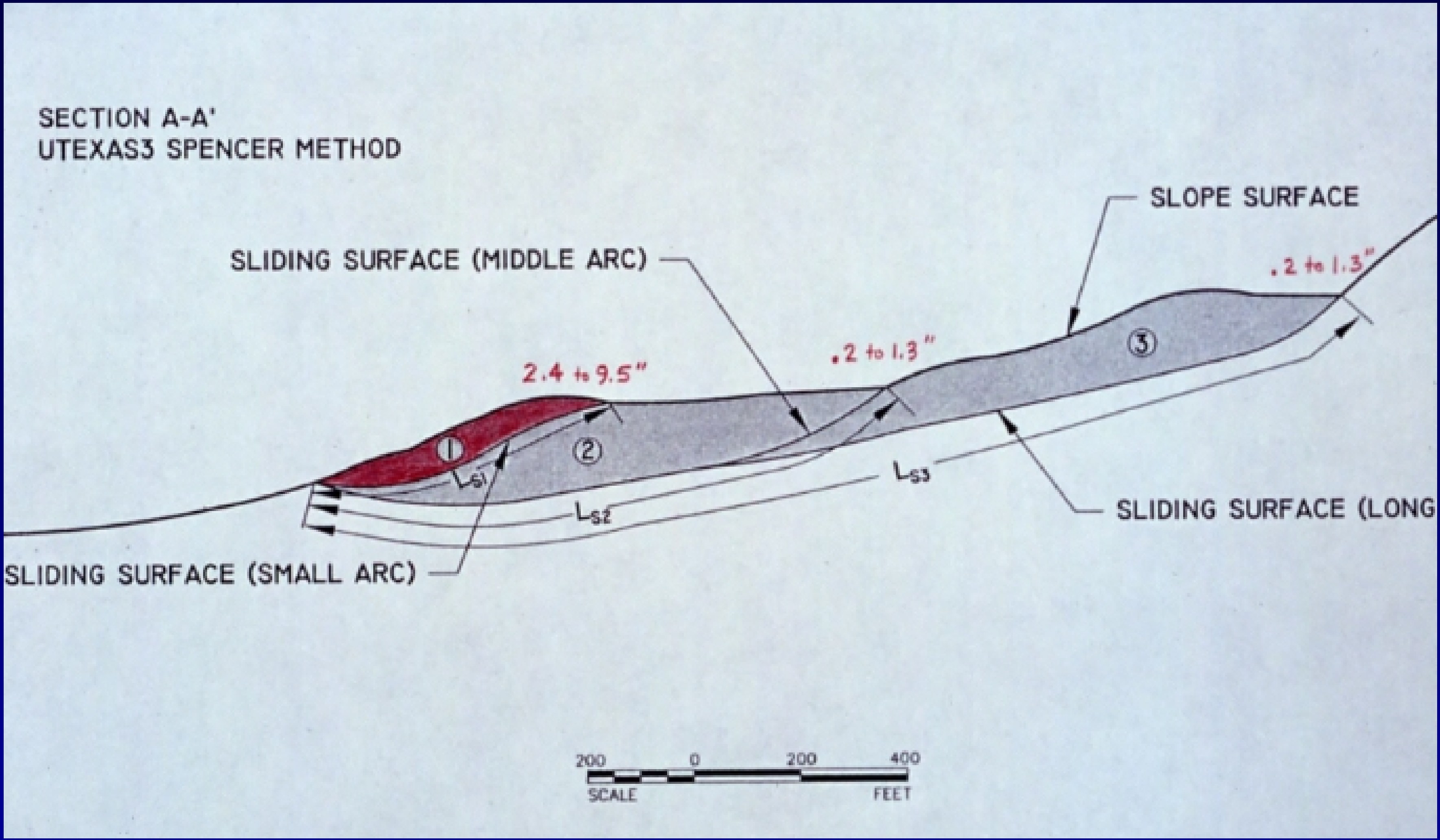
From Fig. 11 in Bray, et al (1988), the normalized base liner sliding displacement $[U/(k_{max})(D_{5\text{-}95})(mm/s)]$ from the ratio $k_y/k_{max}$ These seismic coefficients were calibrated for seismically-induced displacements generally less than 150 mm for basal slip surfaces and <300 mm for surface displacement.

This reduces to a normalized base (liner) sliding displacement between 1.5 and 10 mm/s, considering 50% of the 16th probability of exceedance.

The *permanent ground deformation*, U, was then estimated by:

$$U = (1.5 \text{ to } 10)\,(0.17 \text{ to } 0.24)\,(14\text{ s}) = \underline{3.6 \text{ to } 33.6\text{ mm}}$$

- For this case, the expected range of permanent ground deformation is between 3.6 and 33.6 mm



- Permanent ground deformations increase with decreasing size of the earthflow, because of lateral incoherence.