Lecture 16: Earthquake induced landslide; Landslide hazard mapping; Tsunami hazard, Consideration for tsunami hazard mapping

Topics

- Landslides
- Causes of Landslides
- Earthquake Induced Landslides
- Methods for Landslide Evaluation
- Newmark Sliding Block Analysis
- Preventive Measures for static landslide
- What is a tsunami?
- How does it Occur?
- Major Tsunami's in the World
- What is the highest known tsunami?
- Possible locations of Plate Boundaries
- Tsunami Hazard Assessment (THA)
- Probabilistic Tsunami Hazards analysis
- PTHA Data and Modeling Requirements
- Tsunami hazard mapping

Keywords: *Landslide, Slope stability, Tsunami, Inundation*

Topic 1

Landslides

- The term “landslide” describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these.

- The materials may move by falling, toppling, sliding, spreading, or flowing. Figure 16.1 shows a graphic illustration of a landslide, with the commonly accepted terminology describing its features.

- The various types of landslides can be differentiated by the kinds of material involved and the mode of movement. A classification system based on these parameters is shown in Table 16.1. Other classification systems incorporate additional variables, such as the rate of movement and the water, air, or ice content of the landslide material.

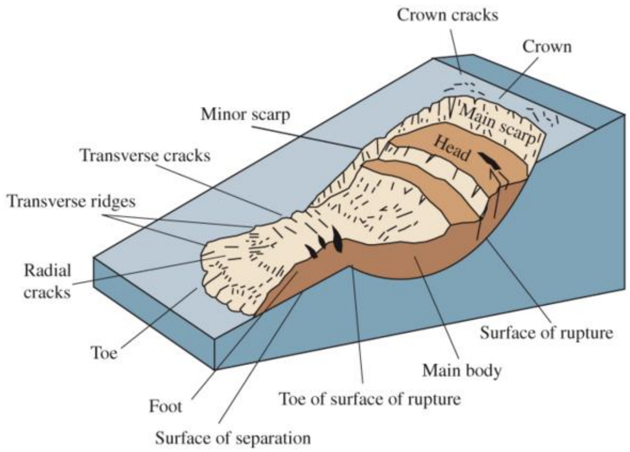


Figure 16.1: An idealized slump-earth flow showing commonly used nomenclature for labeling the parts of a landslide. Source: USGS

Table 16.1 Types of landslides. Abbreviated version of Varnes' classification of slope movements (Varnes, 1978). Source: USGS.

Type of Movement		Type of Material		
			Engineering Soils	
		Bed Rock	Predominantly Coarse	Predominantly Fine
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock Topple	Debris topple	Earth topple
Slides	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow (soil creep)
Complex		Combination of two or more principal types of movement		

- Although landslides are primarily associated with mountainous regions, they can also occur in areas of generally low relief. In low-relief areas, landslides occur as cut-and-fill failures (roadway and building excavations), river bluff failures, lateral spreading landslides, collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. The most common types of landslides are described as follows and are illustrated in Figure 16.2.

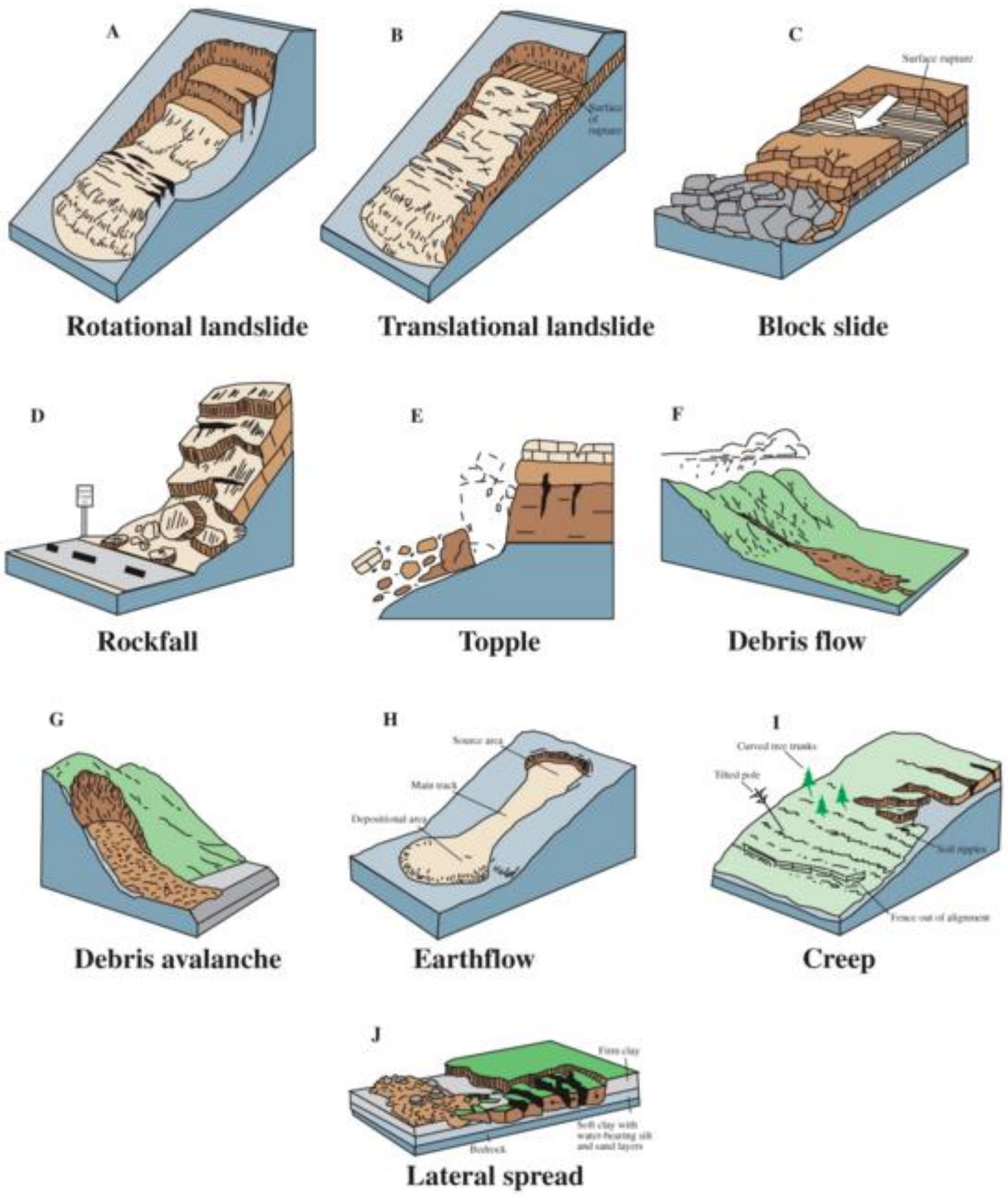


Figure 16.2. The most common types of landslides. Source: USGS

SLIDES: Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides.

- **Rotational slide**: This is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (Figure 16.2A).

- **Translational slide**: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (Figure 16.2B). A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass (Figure 16.2C).

- **FALLS**: Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs (Figure 16.2D). Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

- **FLOWS:** There are five basic categories of flows that differ from one another in fundamental ways.

- **Debris flow**: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope (Figure 16.2F). Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes.

- Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies. Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.

- **Debris avalanche**: This is a variety of very rapid to extremely rapid debris flow (Figure 16.2G).

- **Earthflows**: have a characteristic "hourglass" shape (Figure 16.2H). The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

- **Mudflow**: A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles. In some instances, for example in many newspaper reports, mudflows and debris flows are commonly referred to as "mudslides."

- **Creep**: Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep:

  (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature;
  (2) continuous, where shear stress continuously exceeds the strength of the material; and
  (3) progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (Figure 16.2I).

- **Lateral spreads**: Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain (Figure 16.2J). The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state.

- Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow.

- Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason. Combination of two or more of the above types is known as a complex landslide.

Topic 2

Causes of Landslides

Internal Causes:

- **Influence of slope**- Provides favorable condition for landslides; steeper slope are prone to slippage of land. It is known that most of the materials are stable upto certain angle- “Critical angle” or “angle of repose”.
- **Ground water or associated water**- Main factor responsible for slippage. Suppose the hard or massive rocks are underlained by softer rocks (shale or clay bed)
- When rain water percolates through some fractures or joints the clayey beds becomes very plastic and acts as slippery base, which enhance the chances of loose overburden to slip downward.
- Water is the most powerful solvent, which not only causes decomposition of minerals but also leaches out the soluble matter of the rock and reduces the strength.

- **Lithology**- rock which are rich in clay (montmorillonite, bentonite), mica, calcite, gypsum etc are prone to landslide because these minerals are prone to weathering.

- **Geological structures**- Occurrence of inclined bedding planes, joints, fault or shear zone are the planes of weakness, which create conditions of instability.

- **Human Influence-** undercutting along the hill slopes for laying roads or rail tracks can result into instability. Deforestation in the uplands, result into more erosion during the rainy season.

External factors

- Most common is the vibration resulted due to earthquakes; blasting to explosives; volcanic eruption etc.

- Earthquakes often initiate mass failures on large scale eg. 1897 Assam quake produced gigantic landslide ever recorded in the region.

Topic 3

Earthquake Induced Landslides

- Earthquakes can activate slope failures in the undulating terrains leading to landslides with catastrophic effects. These depend on several factors inherent to the soil conditions such as geology, hydro-geology, topography, and slope stability.

- The zonation of landslide hazard defining four degrees of hazards: “nil or low”, “moderate”, “high” and “very high” can be achieved through several ways – from simplistic analysis based on the preparatory factors i.e. soil and slope conditions, seismicity, water content, rainfall, etc. to pseudo-static analysis and finite-element methods for nonlinear behavior of the soil response. The deterministic landslide susceptible zones can be developed through preparatory factors without considering the triggering factors.

- Earthquake induced landslides can be divided into three main categories: disrupted slides and falls, coherent slides, and lateral spreads and flows. These depend on several factors inherent to the soil conditions such as

1. Past Landslides and Their Distribution
2. Bedrock
3. Slope Steepness or Inclination
4. Hydrologic Factor
5. Human-Initiated Effects
6. Geology
7. topography
8. proximity to drainage,
9. lithology,
10. proximity to faults,
11. geomorphologic/terrain units.

- **Past Landslides and Their Distribution** - Interpreting the likelihood of future landslide occurrences requires an understanding of conditions and processes controlling past landslides in the area of interest. This can be achieved by examining and mapping past landslide activity in the area. Geologic, topographic, and hydrologic circumstances associated with past landslides indicate which natural or artificially created circumstances are likely to produce landslides in the future.

- A primary consideration of the planner is the effect of existing land use on landslide activity. Certain types of landslides may be associated with specific land uses. For example, certain slides may only occur in road cuts or excavations. There may even be a critical height-to-inclination relationship for cutslopes below which these landslides will not occur.

- Field studies can provide insight into how different factors have contributed to failures. In some investigations special forms have been employed to ensure consistent collection of this ancillary information.

- **Bedrock** - Bedrock influences landslide occurrence in several ways. Weak, incompetent rock is more likely to fail than strong, competent rock. (See Figure 10-5 for an example of this.) On slopes where weak rock overlain by strong rock is exposed, the difference in strength increases the potential for landsliding in the stronger rock as well since the weak rock tends to erode and undermine the stronger rock.

- The strength of a rock mass depends on the type of rock and the presence and nature of discontinuities such as joints or other fractures. The more discontinuities present in bedrock, the greater the likelihood of rock instability.

- Rock type may exert control on landsliding by influencing the strength of surface material in the area. For example, soils (in the engineering rather than agricultural sense of the term) derived from schists or shales will contain high percentages of clay.

- These soils will have different strength characteristics than coarser-grained soils such as those derived from granitic bedrock. There are many ways, then, that rock type or structure contributes to the instability, which can be represented on a map.

- **Slope Steepness or Inclination** – The influence of slope steepness on landslide occurrence is the easiest factor to understand. Generally, steeper slopes have a greater chance of landsliding. This does not prevent failures from occurring on gentler slopes.

- Other factors may make a gentle slope especially sensitive to failure, and thus in this situation could be determined to have a relatively high hazard potential.

- For example, high ground water conditions occurring in sandy soils may liquefy during an earthquake. This can cause a landslide on a slope as gentle as 5 to 10 percent.

- Conversely, the steepest slopes may not always be the most hazardous. Steep slopes are less likely to develop a thick cover of superficial material conducive to certain types of landslides. Slope steepness can be mapped using generally available topographic maps.

- **Hydrologic Factor** - Water is recognized as an important factor in slope stability-almost as important as gravity. Information on water table levels and fluctuations is rarely available. To represent the hydrologic factor in landslide hazard assessments, indirect measures can be used which can be mapped to show the influence of the area's hydrology, such as vegetation, slope orientation (aspect), or precipitation zones.

- The type of vegetation and its density over an area will often reflect the variation in subsurface water. Certain species are water-loving or phreatophytes. Presence of these species shows near-surface water table conditions and springs. In mountainous regions, microclimatic differences produce different hydrologic conditions which in turn result in plant communities that vary according to the moisture available to the slope and its distribution throughout the year.

- Slope orientation (aspect) refers to the direction a slope faces. It can be an indirect measure of climatic influence on the hydrologic characteristics of the landscape. Important characteristics associated with landslides are related to such factors as subsurface recharge resulting from prevailing winds and their influence on local frontal storms or accumulated snow.

- In other cases, a slope may experience more freeze/thaw cycles or wet/dry cycles which can reduce the strength of the soil and make the area more susceptible to landslides. In general, due to the complexity of these factors and existing development activities, there is usually no direct observable correlation between slope orientation and landslide hazard.

- **Human-Initiated Effects** - In addition to natural phenomena, human activities may increase the natural tendency for a landslide to occur. Landslides which result from development activities are usually the result of increasing moisture in the soil or changing the form of a slope.

- Development activities such as cutting and filling along roads and the removing of forest vegetation are capable of greatly altering slope form and ground water conditions (Swanson and Dyrness, 1975). These altered conditions may significantly increase the degree of landslide hazard present (Varnes, 1985, and Sidle, Pearce, and O'Loughlin, 1985).

- For example, converting a forested area to grassland or one where crops are cultivated can increase the moisture in the soil enough to cause landslide problems (DeGraff, 1979). Or building a road which cuts off the toe of a steep slope can increase landslide susceptibility. It is possible to reduce the potential impact of natural landslide activity and limit development-initiated landslide occurrence by early consideration of these effects (Kockelman, 1985).

Topic 4

Methods for Landslide Evaluation

- Landslides/slope movements are predominant in hilly and mountainous terrain whereas liquefaction can occur in valleys and low-lying areas with high water table where fine sands and silts exist in loose condition (Fig. 16.3). In hilly regions, slopes can be composed of soils and/or weathered or competent rocks.

- **Slope Stability Analysis for Soils** - Earthquakes can cause slope movement. The liquefaction of soil can cause flow failures and/or lateral spreading. It is also possible that even if soil is not liquefied there could still be weakening of soil and deformation of the slope due to the action of inertial forces during earthquake.

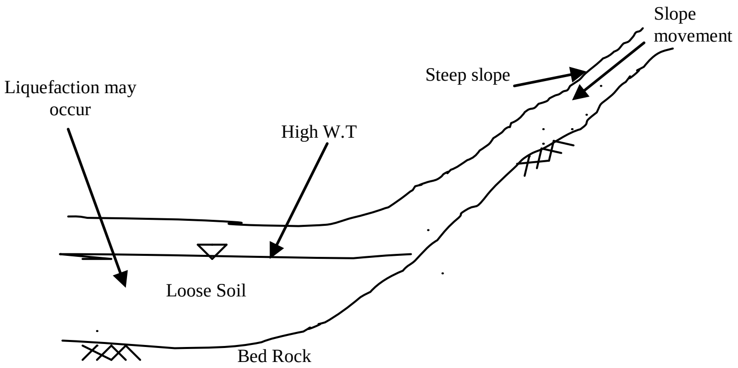


Fig. 16.3: Most common areas of slope movement and liquefaction

- The type of analysis should be based on the occurrence of liquefaction and/or development of pore water pressures (factor of safety against the liquefaction (FSL).

  Case 1: Where soil is not expected to liquefy and also no significant pore water pressure is developed (say, FSL>2.0), only inertial slope stability analyses like pseudostatic slope stability analysis (based on limit equilibrium methods) or dynamic slope stability analysis (based on finite element or finite difference methods) are performed. If FOS falls below one, the deformations can be estimated by Newmarks sliding block analysis (displacement based analysis).

  Case 2: Where soil is not expected to liquefy and there is sufficient development of pore water pressures (say, 1.0<FSL<2.0), effective stress slope stability analysis is used to check the slope stability.

  Case 3: If soil liquefies during the design earthquake ($FSL \leq 1.0$), flow slide analysis or lateral spreading analysis is to be carried out depending upon the type of mode of failure. Slope stability is analysed assuming no strength for liquefied soil and post liquefaction residual strengths for the remaining soil. In case of lateral spreading, weakening slope analysis is to be carried out.
- Slope stability analysis can be broadly classified based on methodology into three categories.
  1. Based on limit equilibrium approaches,
  2. Displacement-based analysis and,
  3. Stress-deformation methods.

- Important slope stability methods under each of these categories are presented below.

- **Pseudo-static Analysis -** Pseudo-static methods of seismic slope stability analysis involve the use of a destabilizing horizontal seismic coefficient (k) within a conventional limit equilibrium slope stability calculation.

- It is the most commonly used inertial slope stability analysis and is it is initially proposed by Terzaghi (1950). The advantages of this method are that it is easy to understand and apply, and that the method is applicable for both total stress and effective stress slope stability analyses.

- This method ignores the cyclic nature of earthquake and treats it as if it applied a static force upon the slope. In this method, a lateral force that acts through the centroid of the sliding mass in an out of slope direction is applied.

- The unknowns in this method are weight of the sliding mass (W) and the seismic coefficient (kh). The selection of seismic coefficient is done based on peak ground acceleration and earthquake magnitude. For details further details on the section of appropriate seismic coefficient, one may refer to BIS 1893-1984.

- The pseudo-static lateral force (Fh) is calculated using

$$Fh = kh.W \qquad (16.1)$$

$$Kh = a\max/g \qquad (16.2)$$

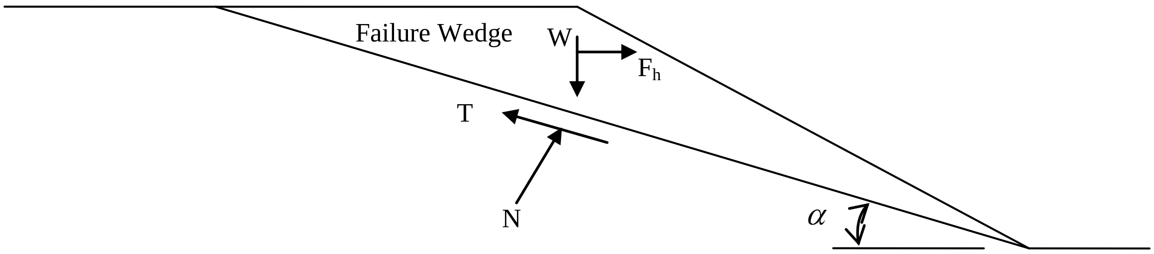


Fig. 16.4: Pseudostatic stability analysis

- **Stress-Deformation Methods of Analysis** - Even though pseudo-static and displacement based methods are most commonly used, they provide relatively crude indices of slope performance. Whereas stress deformation methods implemented in dynamic finite element and finite difference computer codes provides better insight.

- These methods employ nonlinear inelastic soil models formulated in terms of effective stresses, which allow modeling of the generation, redistribution and dissipation of excess pore water pressures during and after earthquake shaking.

- Weakening Slope Stability Analysis: This is the preferred method for those soils that will experience reduction in shear strength during an earthquake (Case ii and Case iii). If the liquefaction occurs in or under a sloping soil mass, the entire soil mass can flow or translate laterally to the unsupported slide in a phenomenon termed as flow slide.

- The analysis for the occurrence of flow slides can be performed using limit equilibrium methods or stress deformation methods based on effective stresses analysis considering excess pore water pressures generated. Flow slides occur if the factor of safety in these methods falls below one.

- Lateral spreading is caused due to the liquefaction of soil behind a retaining wall and subsequent increase in pressure on the retaining wall or gently sloping or flat ground surfaces.

- A commonly used approach for predicting the amount of horizontal ground displacement resulting from liquefaction induced lateral spreading is to use the empirical method developed by Bartlett and Youd (1995).

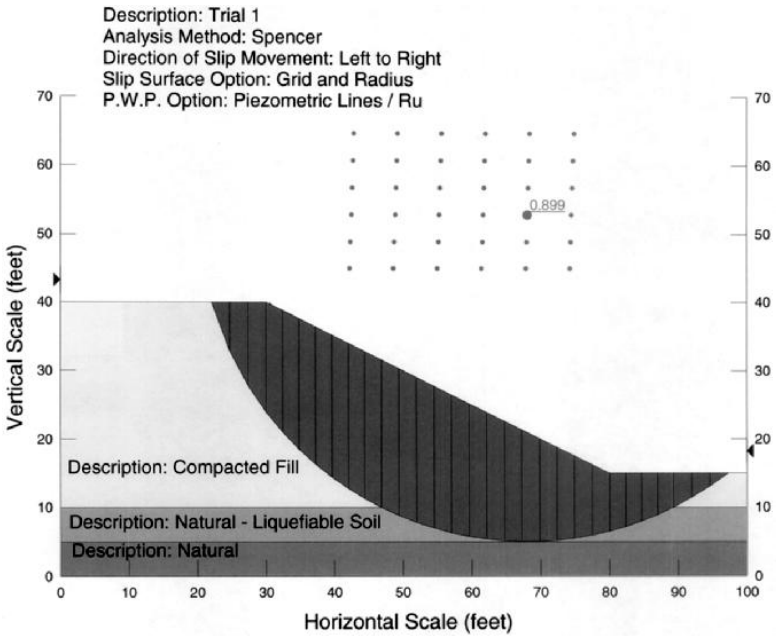
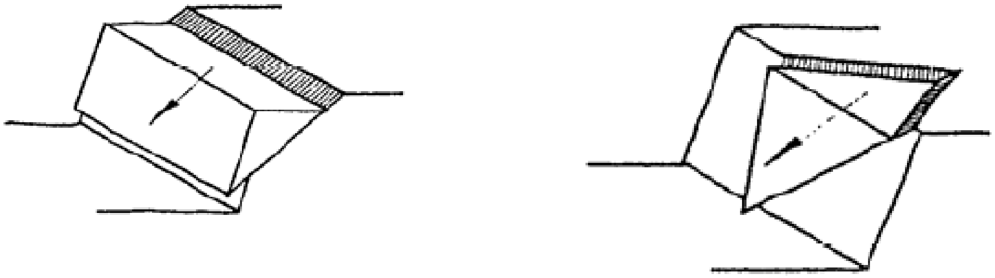


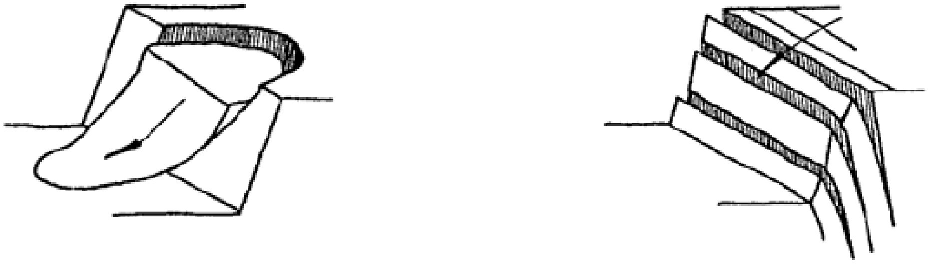
Fig. 16.5: Slope stability analysis for the weakening condition (ru = 1.0) using the Slope/W computer program (Geo-Slope 1991).

- **Slope Stability Analysis for Rock Slopes** - Some of the modes of failure in rock slopes are depicted in Fig. 16.6. A brief description of these failure modes is given below.

   1. **Plane failure**: It is the phenomenon of a block of rock sliding on a single plane. It occurs when a discontinuity dips in a direction close to that of the face and magnitude of the dip is greater than the angle of friction for the discontinuity.
   2. **Wedge failure**: It is a general case for slope faces in fractured rock masses. It occurs when orientation of two discontinuities results in a line of intersection that dips in a direction close to that of the face and the dip of this line is significantly greater than the angle of friction for discontinuities.
   3. **Circular Failure**: Generally, it occurs when the material is weak (as in soil slopes) or when the rock mass is heavily jointed or broken (as in a waste rock dump).
   4. **Block toppling**: This type of failure occurs when long slender rock blocks (e.g. tabular or columnar blocks) dip into the face at relatively steep angles and rest on a basal discontinuity which dips out of the face at an angle less than the angle of friction for that discontinuity.



(a) Plane failure (b) Wedge failure



(c) Circular failure (d) Block toppling

Fig. 16.6: Modes of failure in fractured rock masses (After Hoek and Bray, 1981)

Topic 5

Newmark Sliding Block Analysis

- In the pseudostatic method inertial forces induced by earthquake shaking are represented in terms of pseudostatic accelerations, ah and av, and associated inertial forces, Fh and Fv:

$$F_h = \frac{a_h}{g} W = k_h W \qquad F_v = \frac{a_v}{g} W = k_v W \qquad (16.3)$$

- where a_h and a_v are the horizontal and vertical accelerations, respectively, associated with a particular level of earthquake shaking, and k_h and k_v are nondimensional pseudostatic earthquake coefficients. W is the weight of the failed mass. These forces can be incorporated into any limit equilibrium analysis procedure to determine an equivalent overall factor of safety. For example, in terms of the Ordinary Method of Slices (Figure 16.7), the factor of safety is expressed as:

$$FS = \frac{\text{resisting force}}{driving force} = \frac{\sum_{n}^{M} cb + [(W - F_v)\cos\alpha - F_h \sin\alpha]\tan\phi}{(W - F_v)\sin\alpha + F_h \cos\alpha} \qquad (16.4)$$

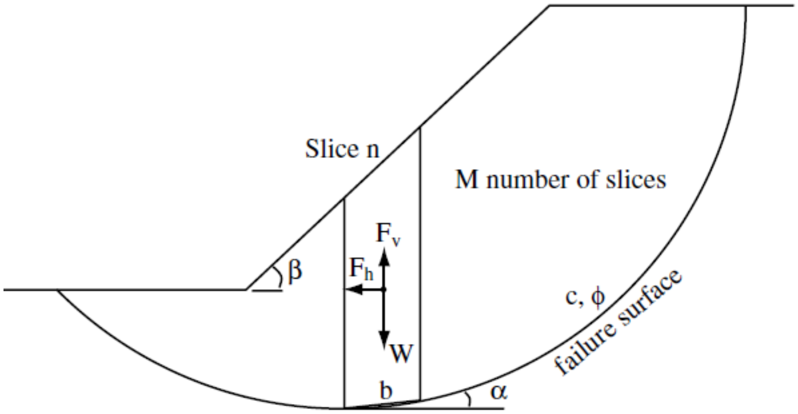


Fig. 16.7: Ordinary Method of Slices for slope stability analysis with pseudostatic seismic forces.

Table: 16.2 Typical Values of Kh and FS for use in Stability Calculations

k_h	FS	Comments	Source
0.10	>1.0	Major earthquake	U.S. Army Corps of Engineers (1982)
0.15	>1.0	Great earthquake	
0.05-0.15	>1.0	Standard of practice; somewhat larger for critical conditions	State of California
0.15-0.25	>1.0	Standard of practice	Japan

0.15	>1.15	With a 20% strength reduction	Seed (1979a)
⅓ to ½ PGA	>1.0		Marcuson and Franklin (1983)
½ PGA	>1.0	With a 20% strength reduction	Hynes-Griffin and Franklin (1984)
Source: Adapted from Abramson, L.W., T.S. Lee et al. 2002. Slope Stability and Stabilization Methods. New york, John Wiley and Sons.			

- where c and φ are the Mohr-Coulomb strength parameters along the failure surface and the summation is carried out over all M slices. Compared to the nonseismic case, F_h clearly results in a reduction of the FS.

- On the other hand, the effect of F_v is less pronounced because it appears with the same sign in both the numerator and the denominator. As a result, it is common to neglect F_v altogether.

- Most modern commercial limit equilibrium slope stability programs allow for this type of pseudostatic analysis. The difficulty arises in selecting appropriate values of kh and FS. Because kh represents the inertial shaking effects, it is reasonable to assume that it should be related in some fashion to the peak horizontal acceleration amax (PHA).
- In general, slope deposits are compliant to various degrees and amax only occurs over a very short period of time. Therefore, in practice kh is taken as a fraction of the maximum acceleration. Considerable judgment is required in selecting appropriate values of kh.

- A number of suggestions can be found in the literature [Seed, 1979a; U.S. Army Corps of Engineers, 1982; Marcuson and Franklin, 1983; Hynes-Griffin and Franklin, 1984; Abramson et al., 2002] and some of these are listed in Table 16.2.

- The value of kh is often prescribed in local codes. Although easy to conduct, the pseudostatic approach is quite simplistic. It attempts to represent complex dynamic behavior in terms of static forces.

- Stability is expressed in terms of an overall factor of safety. The implicit assumption is that the soil is rigid-perfectly plastic and unchanging. This does not represent an appropriate approach in cases where significant excess pore pressures may accumulate or where strength degradation due to seismic loading is in excess of approximately 15% [Kramer, 1996].

- Displacements associated with time-varying inertial forces can be estimated, to a first degree, with the procedure proposed by Newmark [1965], which represents an extension of the pseudostatic approach. An analogy is made between failure along a given sliding surface in a slope and a block initially resting on an inclined surface (Figure 16.8).

- The block is subjected to horizontal inertial forces kh(t)W that correspond to seismic motions propagating through the slope deposit. Displacement is initiated when the sum of the downslope static and inertial forces equals the strength developed at the interface between the block and the inclined plane.

- This condition occurs when the factor of safety is 1.0 and corresponds to a yield coefficient ky and a yield acceleration ay = ky.g. When the block is subjected to an interval with acceleration larger than ay , it will begin to move relative to the plane (Figure 16.8).

- The corresponding velocities and displacements can be obtained through integration of the acceleration record in excess of ay . The assumption is that the sliding mass constitutes a rigid body. This assumption is only appropriate for slopes where soils are very stiff or where the motion is of low frequency.

- Where this is not the case careful consideration must be given in selecting an appropriate accelerogram. This may be done by carrying out a site response analysis and determining acceleration series at various points along the potential failure surface.

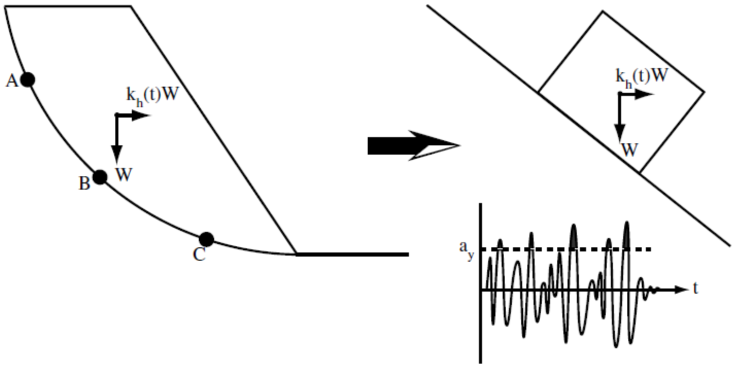


Fig. 16.8: Newmark sliding block method.

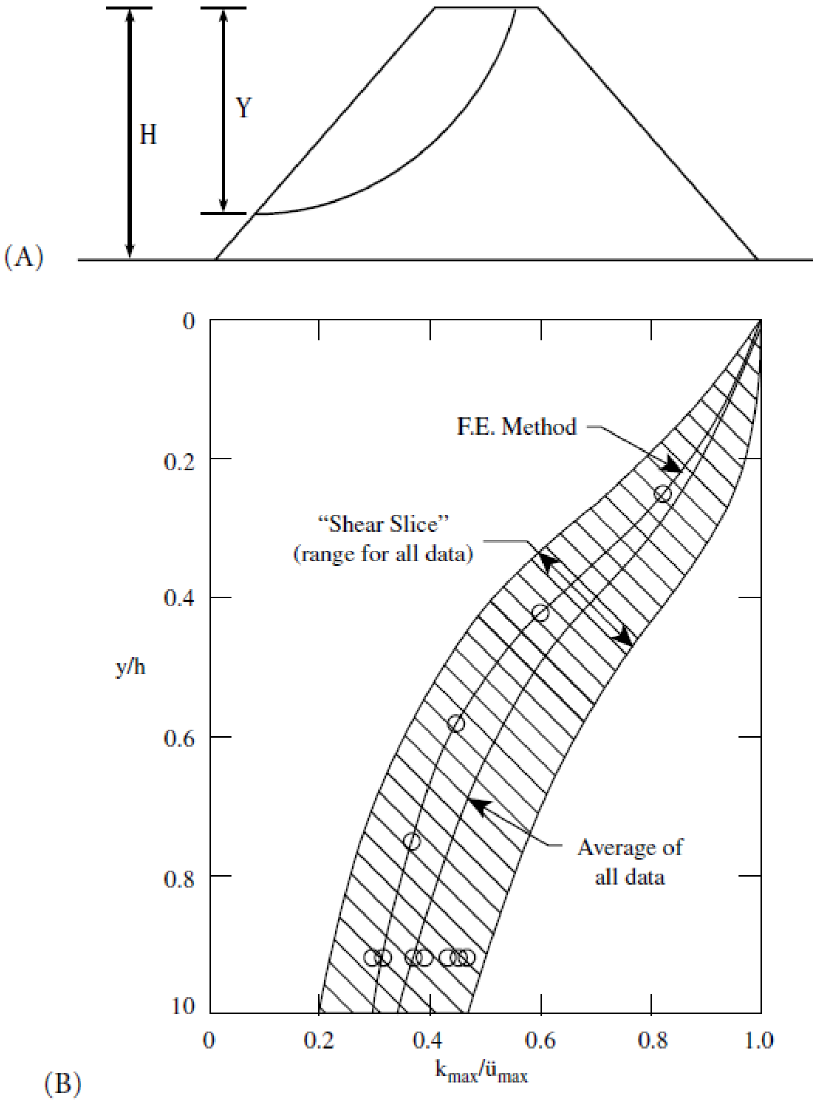
- An average horizontal equivalent acceleration (HEA) can be developed for use with the Newark sliding block method. With reference to Figure 16.8, this would be computed as:

$$HEA(t) = \frac{m_A a_A(t) + m_B a_B(t) + m_C a_C(t)}{m_A + m_B + m_C} \qquad (16.5)$$

- Where m represents the mass of soil in each slice above the point where the acceleration response a (t) is given. Conversely, a dynamic finite element analysis can be conducted to calculate average accelerations over finite lengths of the potential failure surface based on integration of the time-dependent stresses.

- These acceleration time series can in turn be used as input for the sliding block analysis. A number of computer programs are available that can carry out such an analysis, including QUAD-4 [Idriss et al., 1973] and FLUSH [Lysmer et al., 1975].

- Makdisi and Seed [1978] developed a simplified procedure to estimate permanent horizontal displacements of earth dams and embankments. These are determined with the aid of the charts in Figure 16.9.



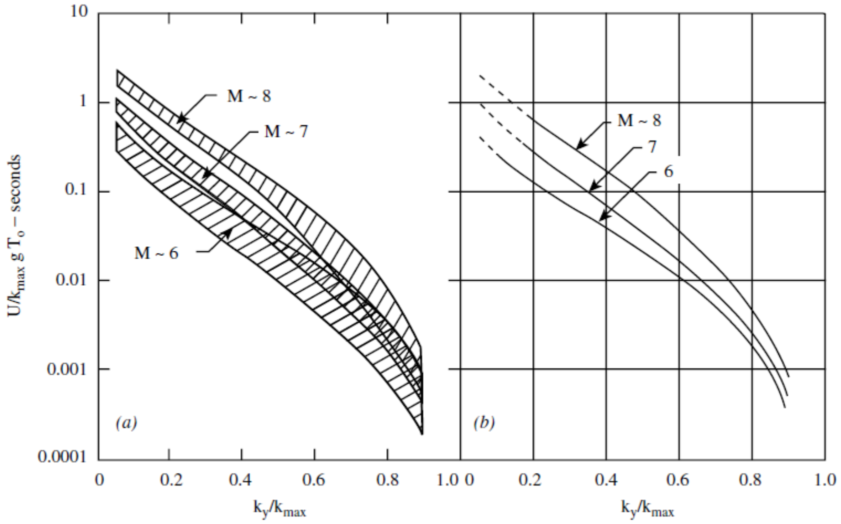


Fig 16.9: Simplified procedure to estimate permanent horizontal displacements of earth dams and embankments. (From Makdisi, and Seed, 1978).

- The analysis is based on the dynamic response of embankments subjected to a range of ground motions representing earthquakes of various magnitudes. Makdisi and Seed calculated the distribution of average maximum acceleration with depth below the crest of the embankment (Figure 16.9).

- Displacements were estimated by comparing the acceleration at depth to the corresponding yield acceleration by means of a Newmark-type sliding block analysis. The yield acceleration was taken as 80% of the undrained shear strength of the soil. Results of the sliding block analysis are summarized in Figure 16.9C, from which the horizontal displacement can be calculated for any failure surface extending a distance y below the crest.

- T_o is the fundamental period of the dam, which can be obtained by means of an approximate shear beam analysis [Gazetas, 1982] or other two-dimensional dynamic response modeling approach.

- Although widely used, it is important to note that the Makdisi-Seed procedure is based on a limited set of case studies and, strictly speaking, should only be applied to dams and embankment slopes with seismic motions corresponding to earthquake magnitudes in the range of 6.5 to 8.5 where the PGA at the base of the embankment is at least 0.2g.

- A number of equivalent-linear procedures have been suggested to estimate approximate permanent displacements in dams and slopes [Lee, 1974; Serff et al., 1976]. Their most appealing quality is that they retain the simplicity of linear material behavior. They work well, provided that pore pressures remain relatively low and that seismic motions do not induce excessive levels of material nonlinearity [Finn, 2001].

- However, it is likely that in the future more reliance will be placed on stress-based finite element and other similar numerical procedures that directly incorporate inelastic soil behavior.

- A sufficient number of two- and three-dimensional analyses have been conducted using constitutive models ranging from simple hysteretic to complex elasto-plastic models to validate this approach [Prevost et al., 1985; Finn, 1988; Griffiths and Prevost, 1988; Marcuson et al., 1992]. Computer codes such as TARA-3 [Finn et al., 1986], PLAXIS [Brinkgreve and Vermeer, 1988], and QUAKE/W [Quake/W, 2001] have been developed to carry out these types of analysis.

Topic 6

Preventive Measures for static landslide

- Landslides can occur slowly or rapidly. They can generally be predicted by observing areas known to be unstable and by taking into account the meteorological conclitions (bad weather).

- Preventive measures consist of developments and constructions intended to avoid or at least limit landslides through stabilising work: terracing, drainage anchoring, deep injections into the soil or by the construction of retaining dikes to hold back or divert landslides, tunnels, shafts, etc. Planting trees in unstable areas is also an efficient preventive measure.

- As regards long term security measures it is important that legislation on land development requires a systematic appraisal of the potential natural dangers. Before establishing residential areas and granting planning permission for buildings the natural dangers must be taken into account. These measures will be complemented by the constant monitoring of unstable areas and by an obligation to upkeep forests and vegetation and to maintain high altitude waterways (water falls, silting basins, dikes etc.).

- The damaging effects of landslides will primarily be avoided or limited by taking the following preventive and protective measures:

    1. Monitoring (observatories or specialist institutes) constantly or randomly unstable areas representing a major threat.
    2. Establishing one or several information and alarm centres to inform the authorities and the public.

3. Imposing building restrictions, forbiding people from staying in restricted areas and banning traffic on certain routes (road, rail, etc.)
4. Erecting buildings and developing infrastructures that will prevent or limit landslides and protect the population.
5. Planning the evacuation of populations eventually at risk.
6. Establishing well equipped and trained disaster management and rescue teams which will include geologists.

Topic 7

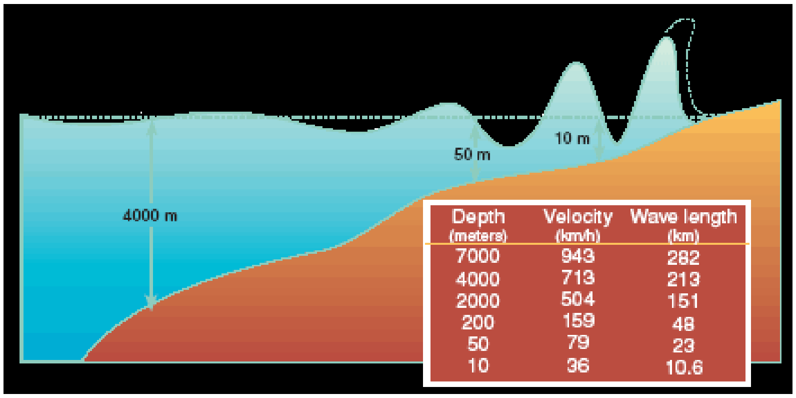
What is a tsunami?

- A tsunami is a series of waves, made in an ocean or other body of water by an earthquake, landslide, volcanic eruption, or meteorite impact. Tsunamis can cause huge destruction when they hit coastlines. “tidal waves”, are not Tsunami waves.

- Tsunami waves are different from the waves you can usually find rolling into the coast of a lake or ocean. Those waves are made by wind offshore and are quite small compared with tsunami waves. A tsunami wave in the open ocean can be more than 100 km across. That’s roughly the length of 1000 American football fields! Tsunami waves are huge and can travel very quickly, at about 700 km/hr, but they are only about one meter high in the open ocean.

- As a tsunami wave travels into the shallower water near the coast, it slows and grows in height. Even though a tsunami may be barely visible at sea, it may grow to be many meters high near the coast and have a tremendous amount of energy. When it finally reaches the coast, a tsunami may appear as a rapidly rising or falling tide or a series of waves with a maximum height of up to 30 meters.

- A few minutes before a tsunami wave hits, the water near shore may move away, exposing the ocean floor. Often the first wave may not be the largest, and additional waves may arrive at the coast every 10 to 60 minutes. They move much faster than a person can run. The danger from a tsunami can last for several hours after the arrival of the first wave. Unlike other waves, tsunami waves typically do not curl and break.



Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

Fig 16.10: shows how the shape of a tsunami wave changes as it moves into shallower water.

Topic 8

How does it Occur?

- Undersea earthquakes, which typically occur at boundaries between Earth's tectonic plates, cause the water above to be moved up or down. Tsunami waves are formed as the displaced water, which acts under the influence of gravity, attempts to find a stable position again.

- Undersea landslides, which can be caused by large earthquakes, can also cause tsunami waves to form as water attempts to find a stable position.

- Undersea volcano eruptions can create enough force to uplift the water column and generate a tsunami.

- Asteroid impacts disturb the water from above, as momentum from falling debris is transferred to the water into which the debris falls.

- Near the source of submarine earthquakes, the seafloor is "permanently" uplifted and down-dropped, pushing the entire water column up and down. The potential energy that results from pushing water above mean sea level is then transferred to horizontal propagation of the tsunami wave (kinetic energy).

- Within several minutes of the earthquake, the initial tsunami is split into a tsunami that travels out to the deep ocean (distant tsunami) and another tsunami that travels towards the nearby coast (local tsunami). The deep-ocean tsunami travels faster than the local tsunami near shore.

- When the local tsunami travels over the continental slope the amplitude increases and the wavelength decreases. As the deep ocean tsunami approaches a distant shore, amplification and shortening of the wave will occur, just as with the local tsunami.

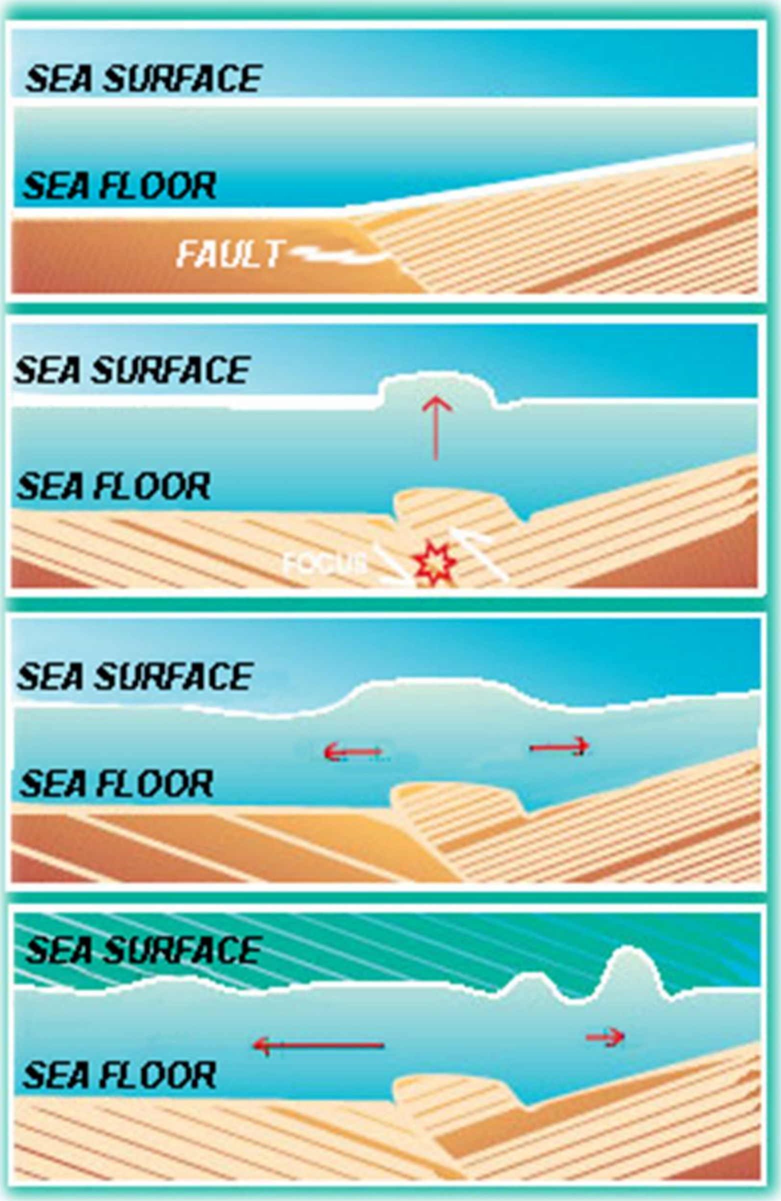


Fig 16.11: When movement along a fault moves the seafloor upward, water is also pushed upward and becomes tsunami waves. As the waves approach shallower water, they become higher.

Topic 9

Major Tsunami's in the World

- 18 November 1929, Mw 7.4, Newfoundland, Canada
- 1 April 1946, Mw 8.1, Aleutian Islands, USA
- 4 November 1952, Mw 9.0, Kamchatka, Russia
- 9 March 1957, Mw 9.1, Aleutian Islands, USA
- 22 May 1960, Mw 9.5, Chile
- 28 March 1964, Mw 9.2, Alaska, USA
- 29 November 1975, Mw 7.2, Kalapana, Hawaii, USA
- 16 August 1976, Mw 8.1, Moro Bay, Philippines
- 19 August 1977, Mw 8.0, Sunda Islands, Indonesia
- 12 December 1979, Mw 7.7, Narino, Colombia
- 26 May 1983, Mw 7.9, Sea of Japan
- 10 June 1996, Mw 7.9, Andreanov, USA
- 26 December 2004, Mw 9.3, Sumatra, Indonesia

http://www.ngdc.noaa.gov/nndc/struts/results?&t=102564&s=37&d=37

Topic 10

What is the highest known tsunami?

- On the night of July 9, 1958 an earthquake along the Fairweather Fault in the Alaska Panhandle loosened about 40 million cubic yards (30.6 million cubic meters) of rock high above the northeastern shore of Lituya Bay.

- This mass of rock plunged from an altitude of approximately 3000 feet (914 meters) down into the waters of Gilbert Inlet (see map below). The impact generated a local tsunami that crashed against the southwest shoreline of Gilbert Inlet.

- The wave hit with such power that it swept completely over the spur of land that separates Gilbert Inlet from the main body of Lituya Bay. The wave then contiuned down the entire length of Lituya Bay, over La Chaussee Spit and into the Gulf of Alaska. (Fig 16.12)

- The force of the wave removed all trees and vegetation from elevations as high as 1720 feet (524 meters) above sea level. Millions of trees were uprooted and swept away by the wave. This is the highest wave that has ever been known.

Topic 11

Possible locations of Plate Boundaries

- Tsunamis occur most frequently in the Pacific, particularly along the "Pacific Ring of Fire ". This zone is found at the northern edge of the Pacific Plate and refers to the geologically most active fields of the earth. Figure 16.13 shows historic location of Tsunami in world map.

- Several times a year, strong earthquakes of at least 7 on the Richter scale result in tsunamis. Japan, for example, is hit by a tsunami at least once a year. From observations of scientists and historical sources, we know today that Tsunamis can occur in all larger seas of the world. Thus, fatal tsunamis occur in geologically less active oceans such as the Atlantic, the Indian Ocean or the Mediterranean as well.

- Great danger exists in densely populated areas or in vacation areas in which a tsunami can endanger millions of human lives. Indeed Tsunamis occur more seldom in for example the Mediterranean than in the Pacific Ocean, but that is exactly why one must not underestimate or minimize the danger. Looking back to the year 1755 one can see that the tsunami triggered by the earthquake off Lisbon is accountable for the majority of the 70 000 deaths.

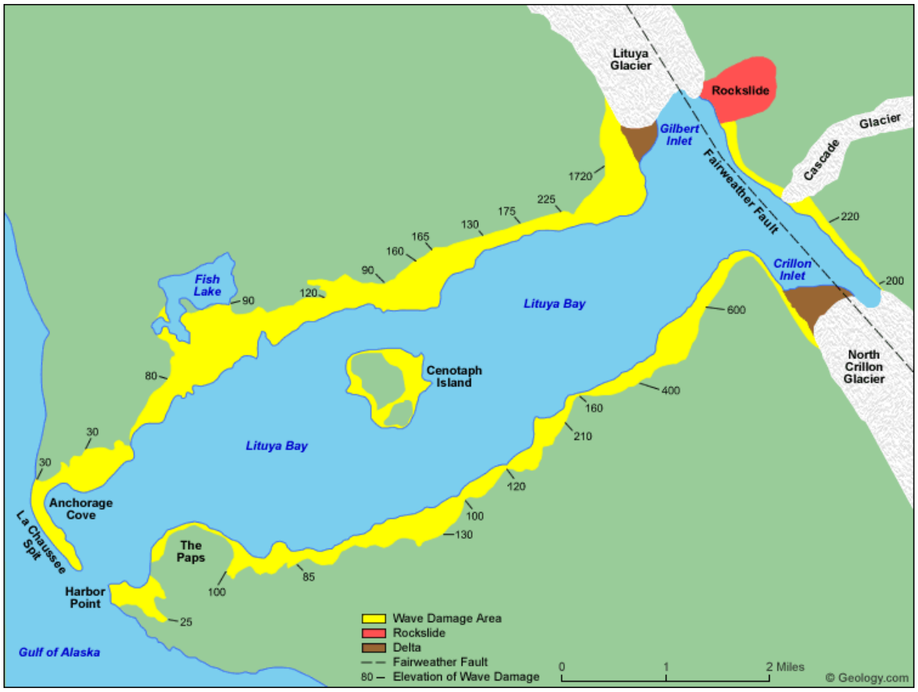


Fig 16.12: Detail Map: Lituya Bay, Alaska, The largest recorded tsunami was a wave 1720 feet tall in Lituya Bay, Alaska

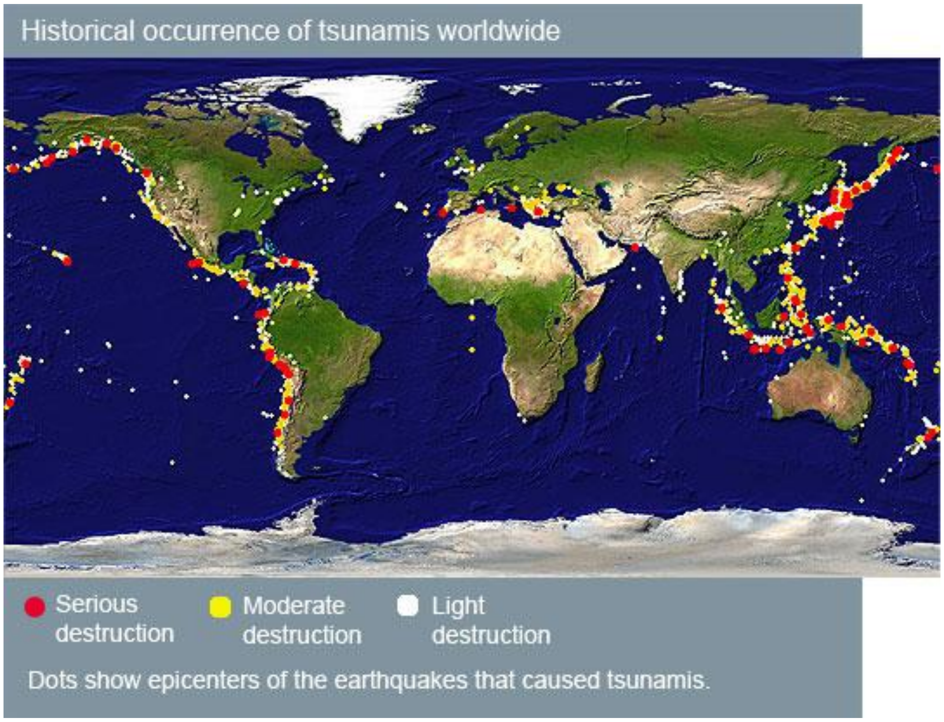


Fig 16.13: Historical occurrence of Tsunamis worldwide

Topic 12

Tsunami Hazard Assessment (THA)

- Existing methods of tsunami hazard assessment fall into three main categories. The first is application of a simple historical determinism method that generally means just mapping of what was happened in the past. The method implies the mapping of tsunami run-up effects historically known for a particular coastal area, to represent (with some corrections) the highest possible run-up to be expected in the future.

- The second category consists of straightforward historical stochastic approach which is construction of a statistical model to reproduce available historical observations. This method is entirely based on available run-up statistics and does not consider any seismotectonic of the source area. An application of the historical stochastic method consists of the following basic steps:

  1. Compilation of historical catalog tsunami observation (run-ups and tide-gauge measurements) for a particular site;
  2. Assuming type of statistics and calculation of tsunami run-up frequency function (empirical frequency of recurrence);

3. Calculation of “tsunami hazard function” (historical exceedance rate function)
4. Obtaining annual probability of exceedance for different run-up values.

- The primary disadvantage of the stochastic method is its unreliability at lower annual probabilities than the inverse period of the catalog. This reliability can be extended somewhat by fitting a distribution to the tail (in which case the method is called “the parametric historic method”), but this does not relieve concerns that issues as seismic gaps or uncertainties in tectonics have been neglected.

- However, the most severe limitation of this method is that it is inapplicable for areas with limited or no historical tsunami observations (that is very common situation along the most part of the western and northern Indian Ocean coastline and the whole coast of Australia).

- The third method is based on the fully deterministic “scenario” approach and on intensive application of numerical models for calculation of tsunami generation, propagation and flooding. This method uses a single-valued event (a design earthquake) to occur at the most probable (or most dangerous) location.

- The parameter of this event is determined on the basis of “expert judgment” and their uncertainties are rarely taken into account. Tsunami run-up heights at the site of interest implied by such an event are then calculated.

- The frequency of event occurrence is usually not taken into account (or evaluated in very crude way), and there is no formal and open way of treating uncertainties. This method is widely used for calculation of tsunami inundation maps for coastal cities and other critical facilities located at close proximity of the coastline.

Topic 13

Probabilistic Tsunami Hazards analysis

- Probabilistic Tsunami Hazard Analysis was rarely considered until recently i.e., since the occurrence of the 2004 Indian Ocean Tsunami.

- PTHA is based on Probabilistic Seismic Hazard Analysis, which is widely used for insurance, planning and design purposes. PSHA considers the probability that some measure of earthquake ground motion, such as Peak Ground Acceleration, may be exceeded at a location of interest.

- The implementation of PTHA used here, which was described by Thio et al. (2008), instead considers the probability that a tsunami wave height will be exceeded immediately offshore at a location of interest. Like almost all implementations of PSHA, the theoretical development of PTHA begins with the assumption that events causing a tsunami exceeding some height follow a time-independent Poisson process.

- Under this assumption, the probability of at least one event occurring in t years that has an offshore tsunami height h greater than hcrit at the location of interest i is:

$$P^{i}(h \geq h_{crit}) = 1 - \exp(-\phi^{i}(h_{crit})t) \qquad (16.6)$$

- where Φi(hcrit) is the annual mean number of events per year that will cause an offshore tsunami height exceeding hcrit at the location of interest i. Φi(hcrit) is also known as the annual frequency of exceedence.

- The reciprocal of Φi(hcrit) is known as the 'return period', ζi(hcrit) = 1/Φi(hcrit). Φi(hcrit) is calculated as the sum over all source zones of the mean number of earthquakes resulting in tsunamis satisfying h > hcrit at the location of interest:

$$\phi^{i}(h_{crit}) = \sum_{j} N_j(M \geq M^{i}_{crit}) \qquad (16.7)$$

- Here Nj (M ≥ Micrit) is the annual number of earthquakes that occur in source zone j, whose magnitude exceeds Micrit, which is the magnitude of an earthquake that produces a tsunami whose offshore height is hcrit at location i.

- Micrit here will be determined by numerically modelling tsunamis from various magnitude earthquakes to the coast.

- The calculation of the functional form of Nj (M ≥ Micrit) can be based on the historic occurrence of subduction zone earthquakes and/or a relationship between the frequency and magnitude of earthquakes, such as the well-known Gutenburg-Richter law.

Topic 14

PTHA Data and Modeling Requirements

- Tsunami hazard models have been available for some time. They generally work by virtually converting the energy released by a subduction earthquake into a vertical displacement of the ocean surface. The resulting wave is then propagated across a sometimes vast stretch of ocean using a relatively coarse linear model based on bathymetries with a typical resolution of two arc minutes.

- The maximal wave height at a fixed contour line near the coastline (say, 50 metres) is then reported as the hazard to communities ashore. Models such as Method of Splitting Tsunamis (MOST) (Titov & Gonzalez 1997) and the URS

Corporation's Probabilistic Tsunami Hazard Analysis (Somerville et al 2005) follow this paradigm.

- Figure 16.14 shows typical data used for Tsunami modeling

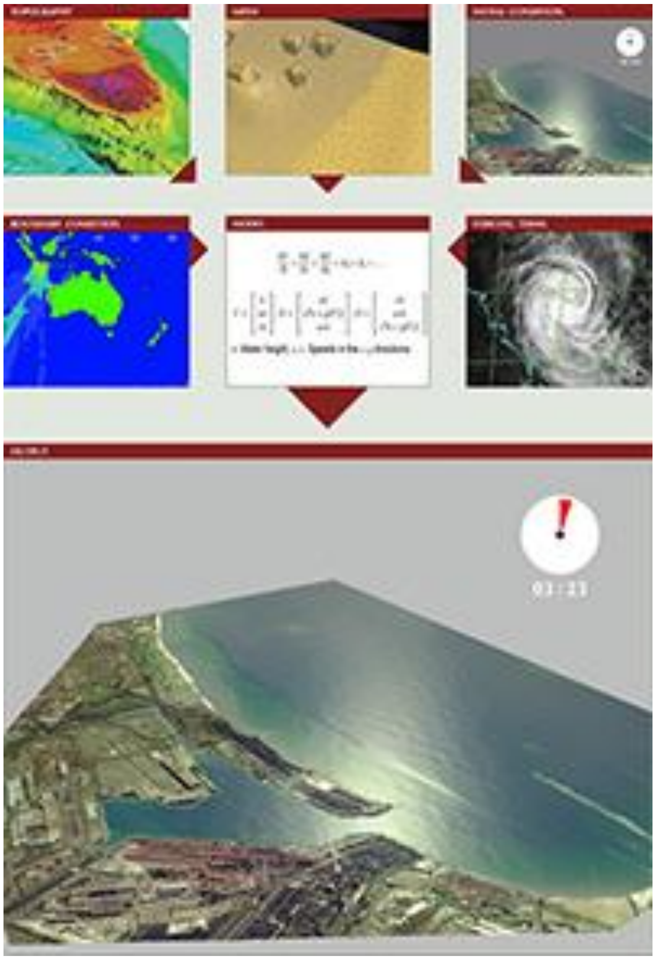


Fig 16.14: Data requirements for an ANUGA simulation include topography of the study area, a triangular mesh, definition of initial and boundary conditions, and any forcing terms, such as wind stress. Boundary conditions could capture incoming waves from a range of sources, such as output from other models, runoff or tidal variations. (Larger image [JPG 1.5mb])

- The severity of a hydrological disaster is critically dependent on complex bathymetric and topographic effects near the area of interest. For example, during the 1993 Okushiri Island tsunami, a very large runup was observed at one specific location, whereas surrounding areas received much less inundation (Matsuyama et al 1999).

- Estimating the impact of a tsunami on a particular community therefore requires modelling of the nonlinear process by which waves are reflected and otherwise shaped by the local bathymetries and topographies.

- These complex effects generally require elevation data of much higher resolution than is used by the linear models, which typically use data resolutions in the order of hundreds of metres (sufficient to model long-wavelength tsunamis in open water). The data resolution used by nonlinear inundation models, by contrast, is typically in the tens of metres.

Topic 15

Tsunami hazard mapping

- A tsunami is a series of waves with long wavelength and period (time between crests) which can vary from a few minutes to over an hour. Tsunamis are generated by any large, impulsive displacement of the sea bed level.

- Earthquakes generate tsunamis by vertical movement of the sea floor. If the sea floor movement is horizontal, a tsunami is not generated. Earthquakes of $M > 6.5$ are critical for tsunami generation.

- Tsunamis are also triggered by landslides into or under the water surface, and can be generated by volcanic activity and meteorite impacts. On the average, there are two tsunamis per year somewhere in the world which cause damage near the source.

- Approximately every 15 years a destructive, Pacific-wide tsunami occurs. Tsunamis are among the most destructive of coastal hazards and as was witnessed in the Indian Ocean tsunami of 26 December 2004, in which a single event can cause loss of life of the order of 300,000 and damage of several billion US dollars (Nirupama, 2008).

- Tsunami hazard assessment is usually not coupled with seismic microzonation. The main reason for potential loss due to Tsunami is unpreparedness and unawareness about the Tsunami in the coastal regions because of very large return period.

- So unpredictable damages and human loss in the coast region can be minimized if knowledge of Tsunami run-up and inundation studies are available. Also these results are useful to plan Tsunami warring system in coastal cities. The following simple steps can be followed to map Tsunami run-up and inundation area:

1. Collection of seismic information such as past earthquake in the coastal regions, earthquake sources and tsunami records using literatures in and around the study area.
2. Preparation of Tsunamigenic sources map for study area.
3. Estimation maximum probable potential earthquake produced by each Tsunamigenic sources.
4. Estimation of source parameters for maximum tsunamigenic earthquake.
5. Tsunami hazard analysis and determination of probable Tsunami generation
6. Tsunami run-up estimation for probable Tsunami with modeling sea and land floor terrain
7. Mapping of tsunami Inundation area for probable tsunami waves
8. Mapping the Tsunami hazard area based on probable tsunami for maximum Tsunamigenic earthquake for the region.

- Many Tsunami assessment models are available free in the WebPages after Indian Ocean Tsunami (December 26, 2004). Proper models can be selected based on available data and used to map Tsunami Hazard mapping.

- The impact of Tsunami can be evaluated using a tsunami intensity scale, which was introduced by Papadopoulos and Imamura (2001). (Table 16.3)

- The waves generated in a closed or semi closed basins are known as Seiches. These can be generated because of the rupture of the basin ground, landslides etc. in the case of seiches the height of waves (1 to 2 m) will be less than the tsunami waves.

- The rock slide during the filling of the reservoir of the Vajont Dam in 1963, a huge rock slide (about 200 M m3) and the subsequent siche over topped the dam and created huge damage in the down stream side (Towhata, 2008).

- Specialized investigation must be done to identify the areas prone to flooding due to tsunami and seiches. The flooding data thus obtained should be used in microzonation work of regions vulnerable to flooding. The two types of zones with respect to flooding due to tsunami and seiches are:

    1. High hazard – Potential flooding areas obtained from the above mentioned method.
    2. Low hazard – Other areas.

Table 16.3: Tsunami Intensity Scale (Papadopoulos and Imamura 2001)

Scale	Rank	Brief description (tsunami height is a rough value)
I	Not felt.	
II	Scarcely felt	Few people on board small vessels feel it. There occurs no damage
III	Weak	Observed by a few people on the coast, but no damage
IV	Largely observed	Observed by most people on the coast
V	Strong	Few people are frightened and try to escape. Minor effects of wave on the coast
VI	Slightly damaging	Tsunami height may be 2 m. Damage and flooding to some extent
VII	Damaging	4 m high tsunami. Many people are frightened and try to escape. Objects overturn and drift, and many wooden structures are damaged
VIII	Heavily damaging	4 m high wave. All people escape but a few are washed away. Few large ships are moved towards the shore. Most wooded buildings are washed away or destroyed
IX	Destructive	8 m high tsunami. Many people are washed away. Many large ships are moved significantly, and sand beach is eroded remarkably. Light damage in reinforced concrete buildings
X	Very destructive	8 m high tsunami. Most people are washed away. Buildings are damaged
XI	Devastating	16 m high tsunami. Flooding makes many objects drift and transport them into the sea. Buildings are damaged.
XII	Completely devastating	32 m high tsunami. Most reinforced-concrete buildings are damaged

Lecture 16 Earthquake induced landslide; Landslide hazard mapping; Tsunami hazard, Consideration for tsunami hazard mapping