CONTINUING EDUCATION COMMITTEE

SLIDES ON LEARNING FROM EARTHQUAKES

SET II: LESSONS FROM GEOTECHNICAL ENGINEERING

SOURCES OF INFORMATION

1. Earthquake Engineering Research Institute, 1986, Reducing Earthquake Hazards: Lessons Learned from Earthquakes, Publication 86-02, El Cerrito, California, Chapter 2.

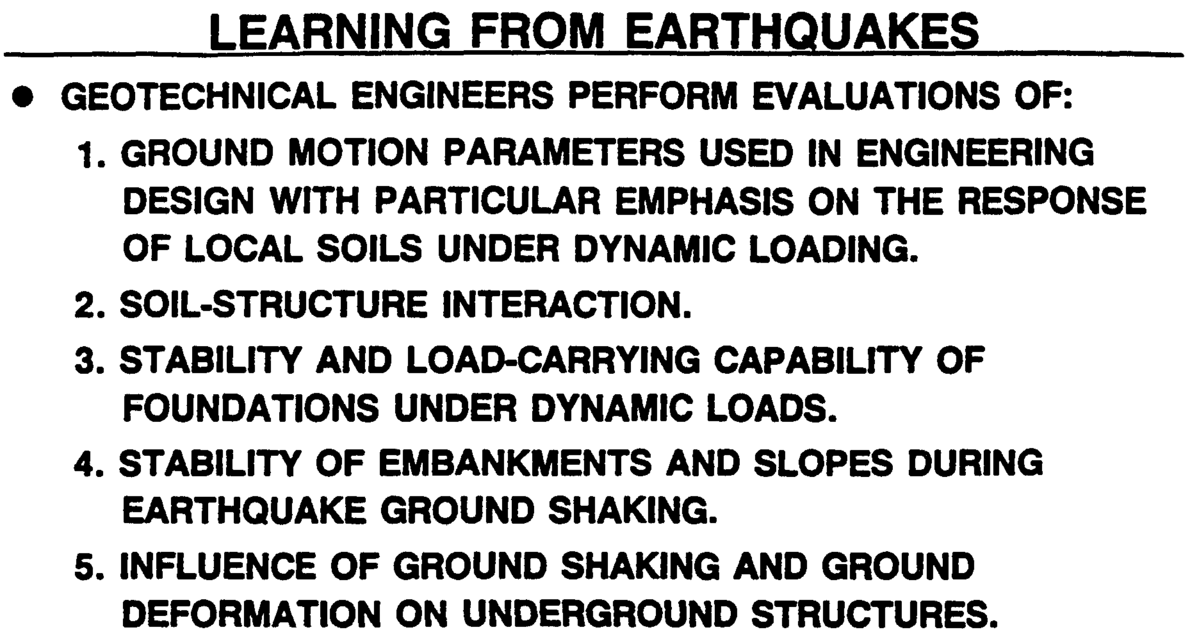
2. National Research Council, 1985, Liquefaction of Soil During Earthquake Committee on Earthquake Engineering, National Academy Press, Washington, D.C. 240 p.

3. National Research Council - 1982, Earthquake Engineering Research--1982, Committee on Earthquake Engineering Research, National Academy Press, Washington, D.C., 240 p.

INFORMATION FOR EACH SLIDE

1. SLIDE IDENTIFICATION NUMBER: LFE II-1

   SUMMARY OF WHAT SLIDE DEPICTS:



LEARNING FROM EARTHQUAKES

- **GEOTECHNICAL ENGINEERS PERFORM EVALUATIONS OF:**
  1. **GROUND MOTION PARAMETERS USED IN ENGINEERING DESIGN WITH PARTICULAR EMPHASIS ON THE RESPONSE OF LOCAL SOILS UNDER DYNAMIC LOADING.**
  2. **SOIL-STRUCTURE INTERACTION.**
  3. **STABILITY AND LOAD-CARRYING CAPABILITY OF FOUNDATIONS UNDER DYNAMIC LOADS.**
  4. **STABILITY OF EMBANKMENTS AND SLOPES DURING EARTHQUAKE GROUND SHAKING.**
  5. **INFLUENCE OF GROUND SHAKING AND GROUND DEFORMATION ON UNDERGROUND STRUCTURES.**

2. SLIDE IDENTIFICATION NUMBER: LFE II:-2

SUMMARY OF WHAT THE SLIDE DEPICTS:

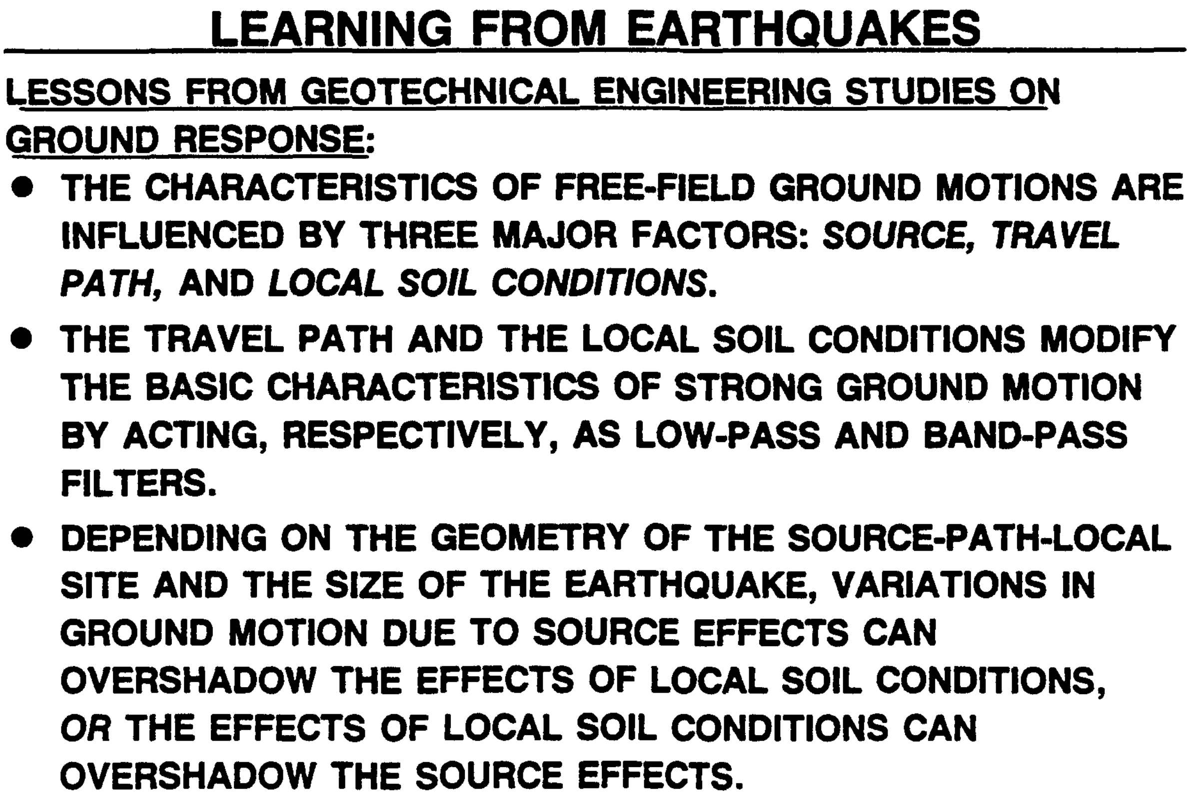
Important site effects evaluated by the geotechnical engineer include:

1. Site Amplification - In an earthquake, the soil column under the right conditions can modify the ground shaking experienced by the structure. Examples of enhanced ground motion by site amplification include the lake-bed zone of Mexico City. This zone has been shown to amplify the ground motion, relative to a site underlain by rock, in a narrow period band centered around 2 seconds. Deamplification can also occur under the right conditions.
2. Liquefaction - Soil liquefaction has been observed in almost all large earthquakes, and in some cases such as the 1964 Niigata, Japan earthquake and the 1964 Prince William Sound, Alaska earthquake has caused much damage.
3. Landslides - Examples of landslides include the destructive Turnagain Heights landslide during the 1964 Prince William Sound, Alaska earthquake.

Each phenomenon will be illustrated later.

3. SLIDE IDENTIFICATION NUMBER - LFE II-3

SUMMARY OF WHAT THE SLIDE DEPICTS:



LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES ON GROUND RESPONSE:

- **THE CHARACTERISTICS OF FREE-FIELD GROUND MOTIONS ARE INFLUENCED BY THREE MAJOR FACTORS: *SOURCE, TRAVEL PATH,* AND *LOCAL SOIL CONDITIONS*.**
- **THE TRAVEL PATH AND THE LOCAL SOIL CONDITIONS MODIFY THE BASIC CHARACTERISTICS OF STRONG GROUND MOTION BY ACTING, RESPECTIVELY, AS LOW-PASS AND BAND-PASS FILTERS.**
- **DEPENDING ON THE GEOMETRY OF THE SOURCE-PATH-LOCAL SITE AND THE SIZE OF THE EARTHQUAKE, VARIATIONS IN GROUND MOTION DUE TO SOURCE EFFECTS CAN OVERSHADOW THE EFFECTS OF LOCAL SOIL CONDITIONS, *OR* THE EFFECTS OF LOCAL SOIL CONDITIONS CAN OVERSHADOW THE SOURCE EFFECTS.**

4. SLIDE IDENTIFICATION NUMBER - LFE II-4

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows a schematic illustration of the total earthquake-earth-building system. Three elements of the system are emphasized and will be described in other slides.

1) the source - key source parameters include the magnitude, depth to the brittle-plastic transition zone in the earth's crust where earthquakes tend to nucleate, and source directivity,

2) the wave propagation path - key path parameters include epicentral or hypocentral distance and the specific dissipation, Q, and

3) the local soil column or site geology - key site parameters include the thickness, softness and geometry of the soil-rock column.

Physical parameters of the source, path, and site can modify the amplitude and spectral composition of the ground motion load on a building.

Soil-structure interaction is another important consideration.

5. SLIDE IDENTIFICATION NUMBER: LFE II-5

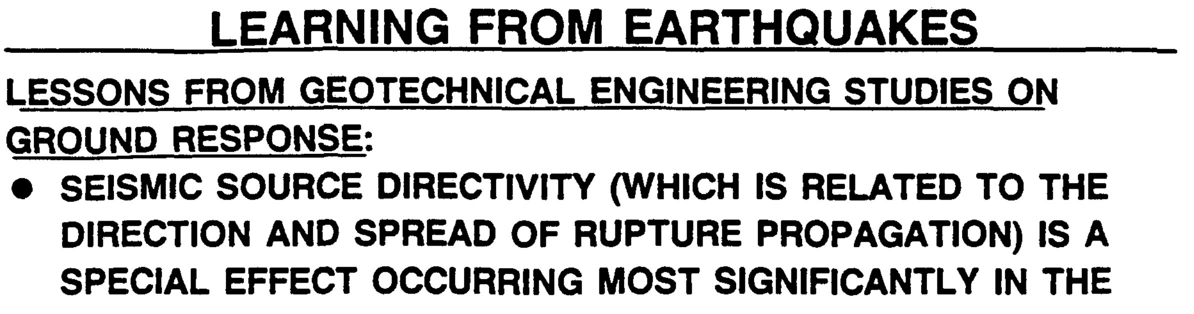
SUMMARY OF WHAT THE SLIDE DEPICTS:

A catalog of important ground motion parameters that are considered in earthquake-resistant design or in the analysis of strong motion accelerograms includes:

1) distance to the fault,
2) length of the fault rupture,
3) peak amplitude of acceleration (and displacement derived from the accelerogram),
4) frequency content (spectral acceleration, spectral velocity, and spectral displacement),
5) duration,
6) direction of the fault rupture, and
7) pulse characteristics.

6. SLIDE IDENTIFICATION NUMBER: LFE II-6

SUMMARY OF WHAT THE SLIDE DEPICTS:



LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES ON GROUND RESPONSE:

- **SEISMIC SOURCE DIRECTIVITY (WHICH IS RELATED TO THE DIRECTION AND SPREAD OF RUPTURE PROPAGATION) IS A SPECIAL EFFECT OCCURRING MOST SIGNIFICANTLY IN THE NEAR FIELD (WITHIN 15 KM OF THE SOURCE), ALTHOUGH IT HAS ALSO BEEN OBSERVED IN THE FAR FIELD. DIRECTIVITY CAUSES AMPLIFICATION OF LOW-FREQUENCY GROUND MOTION.**

- **NEAR-FIELD RECORDS CAN CONTAIN A LOW-FREQUENCY PULSE CORRESPONDING TO THE "FLING" OF THE FAULT, A UNIDIRECTIONAL GROUND DISPLACEMENT NEAR THE RUPTURING FAULT.**

7. SLIDE IDENTIFICATION NUMBER: LFE II-7

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows the S16° E component of horizontal ground acceleration recorded at Pacoima dam in the magnitude 6.4 1971 San Fernando, California, earthquake. The peak acceleration was 1.24 g. The derived values of peak velocity and displacement were 114 cm/sec and 38 cm.

The duration is shown in two ways; 12 seconds by the bracketed duration equal to or greater than 5 percent of g in the center and 7 seconds by 90 percent of the integral of the acceleration squared at the bottom.

This record stimulated research on: a) the effects of rock, soil, and topography on ground motion, b) duration, c) effective peak acceleration, and d) the "killer pulse" and break out phases associated with the fling of the fault and the effect of surface fault rupture.

8. SLIDE IDENTIFICATION NUMBER: LFE II-8

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide describes the importance of site effects, showing what happened in the August 1966 Varto, Turkey Earthquake. Eleven of fourteen reinforced concrete buildings built on an old river channel collapsed; whereas, twelve similar buildings built on a gravel bench remained standing. Similar results have been observed in many earthquakes throughout the world. Other examples include the 1965 Caracas, Venezuela earthquake and the 1957 and 1985 Mexico earthquakes.

The key parameters are the softness, thickness, and topography of the soil-rock column. The primary issue that is debated is nonlinear versus linear response.

9. SLIDE IDENTIFICATION NUMBER: LFE II-9

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows two accelerograms recorded in Mexico City during the magnitude (M_s) 8.1 September 19, 1985, Mexico earthquake. The earthquake occurred 400 km west of Mexico City at a depth of nucleation of about 18 km as a consequence of subduction along the Middle American Trench between the North American and Cocos tectonic plates. The Tacubaya site in Mexico City, underlain by stiff rock-like material, experienced a peak horizontal (E-W) acceleration of 3.5 percent of g; whereas the SCT (Communications Center) site, underlain by the soft, former lake-bed sediments, experienced long duration ground motions having a peak horizontal (E-W) acceleration of 17 percent of g.

The lake-bed sediments amplified the ground motion and soil-structure resonance contributed to the damage of 5,728 5-21-story buildings constructed in the lake-bed zone of Mexico City.

Such phenomena were also experienced in the July 28, 1957, Mexico earthquake. They were a warning of what would happen in 1985.

Other Sources of Information

Stone, W. C., Yokel, F. Y., Celebi, M., Hanks, T., and Leyendecker, E. V., 1987; Engineering Aspects of the September 19, 1985 Mexico Earthquake, National Bureau of Standards, Building Science Series, 165, U.S. Government Printing Office, Washington, D.C. 207 p.

10. SLIDE IDENTIFICATION NUMBER: LFE II-10

SUMMARY OF WHAT THE SLIDE DEPICTS

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES ON SOIL-STRUCTURE INTERACTION:

- **SEISMIC SOIL-STRUCTURE INTERACTION CONSISTS OF TWO PHYSICAL EFFECTS:**
    1. ***KINEMATIC INTERACTION EFFECT*—CAUSED BY THE SCATTERING OF THE SEISMIC WAVES AT THE FOUNDATION OF THE STRUCTURE. SIZE AND GEOMETRY OF THE STRUCTURE'S BASE ARE THE MOST IMPORTANT FACTORS.**
    2. ***INERTIAL INTERACTION EFFECT*—CAUSED BY THE COUPLED DYNAMIC SYSTEM OF THE STRUCTURE AND THE FOUNDATION MEDIUM. CONTRAST OF THE INERTIAL PROPERTIES OF THE STRUCTURE RELATIVE TO THOSE OF THE FOUNDATION MEDIUM IS THE MOST IMPORTANT FACTOR.**

11: SLIDE IDENTIFICATION NUMBER: LFE II-11

SUMMARY OF WHAT THE SLIDE DEPICTS:

Liquefaction is a phenomenon associated primarily, but not exclusively, with the behavior of saturated, cohesionless soils during earthquake ground shaking. Soil liquefaction causes a temporary loss of strength or stiffness that result in ground deformation, settlement, and tipping of buildings, landslides, and failure of earth dams.

Soil liquefaction has been observed in almost all large earthquakes.

The 1964 Niigata, Japan and 1964 Prince William Sound, Alaska earthquakes brought soil liquefaction to the attention of engineers.

12. SLIDE IDENTIFICATION NUMBER: LFE II-12

SUMMARY OF WHAT THE SLIDE DEPICTS:

The slide shows a sketch of water-saturated sand grains and illustrates the process of liquefaction. Shear deformations indicated by large arrows brought about by earthquake ground shaking distort the granular structure causing some loosly packed groups to collapse, as indicated by the small arrows. Each collapse transfers stress from grain to grain contacts to the pore water, increasing the pressure in that water. When pore-water pressures reach a critical level (grain-to-grain contact stresses approach zero), the granular material suddenly behaves as a liquid rather than a solid. At this point, liquefaction has taken place.

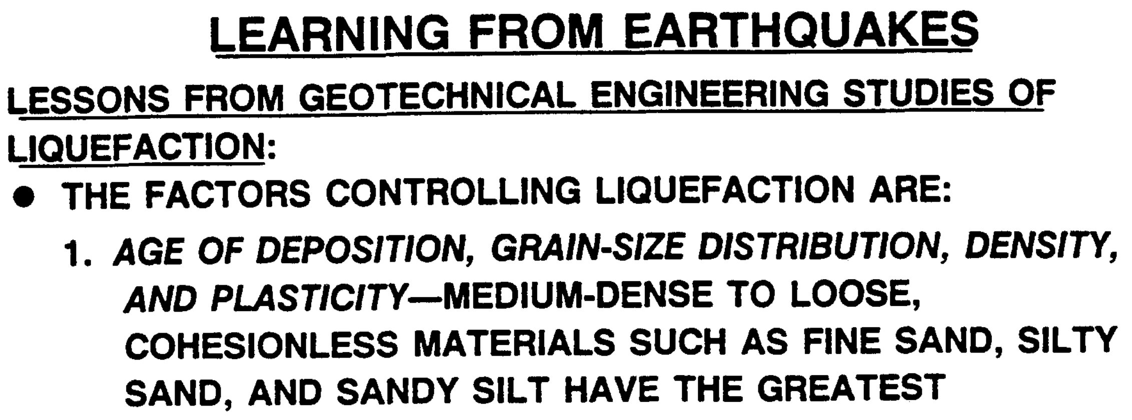
13. SLIDE IDENTIFICATION NUMBER: LFE II-13

SUMMARY OF WHAT THE SLIDE DEPICTS:

Photograph of San Francisco, California showing areas where liquefaction and lateral spreading (to be defined later) took place during the 1906 earthquake. Lateral spreads disrupted many buildings and severed several water mains. Lack of water hampered efforts to contain the fire that broke out during the earthquake.

14. - 15. SLIDE IDENTIFICATION NUMBER: LFE II-14 and 15

SUMMARY OF WHAT THE SLIDE DEPICTS:



LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF LIQUEFACTION:

- **THE FACTORS CONTROLLING LIQUEFACTION ARE:**
  1. ***AGE OF DEPOSITION, GRAIN-SIZE DISTRIBUTION, DENSITY, AND PLASTICITY*—MEDIUM-DENSE TO LOOSE, COHESIONLESS MATERIALS SUCH AS FINE SAND, SILTY SAND, AND SANDY SILT HAVE THE GREATEST**

SUSCEPTIBILITY, ESPECIALLY IF DEPOSITED IN THE PAST FEW HUNDRED YEARS BY FLUVIAL, LITTORAL, OR EOLIAN PROCESSES. MATERIALS HAVING A SIGNIFICANT CLAY CONTENT ARE GENERALLY RESISTANT TO LIQUEFACTION. COARSE-GRAINED MATERIALS CAN LIQUEFY, BUT THEIR PORE PRESSURES TEND TO DISSIPATE RAPIDLY.

2. *PENETRATION RESISTANCE*—RELATIONS BASED ON THE STANDARD PENETRATION TEST SHOW THAT SUSCEPTIBILITY TO LIQUEFACTION INCREASES AS THE PENETRATION RESISTANCE OF THE MATERIAL DECREASES.
3. *GROUND SHAKING*—AS THE STRENGTH AND DURATION OF GROUND MOTION INCREASES, THE LIKELIHOOD OF LIQUEFACTION OF SUSCEPTIBLE MATERIALS INCREASES. THE TRIGGERING THRESHOLD IS ABOUT MMI V-VI. SEVERITY INCREASES AS INTENSITY (AND MAGNITUDE) INCREASES.

16. SLIDE IDENTIFICATION NUMBER: LFE II-16

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF LIQUEFACTION:

- LIQUEFACTION CAN CAUSE THE FOLLOWING TYPES OF GROUND FAILURE:
    1. *FLOW FAILURES*—MASSIVE DISPLACEMENT OF COMPLETELY LIQUEFIED SOIL OR BLOCKS OF INTACT EARTH RIDING ON A LAYER OF LIQUEFIED SOIL. FLOW FAILURES, THE *MOST CATASTROPHIC* GROUND FAILURE CAUSED BY LIQUEFACTION, CAN MOVE OVER A DISTANCE OF KILOMETERS AT SPEEDS UP TO TENS OF KILOMETERS PER HOUR. THEY USUALLY DEVELOP IN LOOSE, SATURATED SAND AND SILTY SAND ON SLOPES GREATER THAN 5 PERCENT.

17. SLIDE IDENTIFICATION NUMBER: LFE II-17

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF LIQUEFACTION:

2. *LATERAL SPREADS*—LATERAL DISPLACEMENT OF SURFICIAL SOIL LAYERS OVERLYING A LIQUEFIED LAYER. LATERAL SPREADS ARE THE *MOST COMMON* GROUND FAILURE CAUSED BY LIQUEFACTION. LATERAL DISPLACEMENTS GENERALLY RANGE FROM A METER OR LESS TO SEVERAL METERS. THEY DEVELOP ON VERY GENTLE SLOPES RANGING FROM 0.5 PERCENT TO 5 PERCENT, AND HAVE CAUSED MORE DAMAGE THAN ANY OTHER TYPE OF EARTHQUAKE-INDUCED GROUND FAILURE.

18. SLIDE IDENTIFICATION NUMBER: LFE II-18

SUMMARY OF WHAT THE SLIDE DEPICTS:

Alaska railroad bridge compressed and buckled by lateral spreading of flood-plain deposits toward the river channel during the 1964 Prince William Sound, Alaska earthquake. Lateral spreads are caused by loss of strength in a subsurface sand layer because of liquefaction. This loss of strength allows overlying sediments to move laterally down very gently slopes (usually between 0.3 and 5 degrees) in response to a combination of gravitational and earthquake loads.

More than 250 bridges were damaged or destroyed in Alaska in 1964 as a consequence of lateral spreading induced by the earthquake.

19. SLIDE IDENTIFICATION NUMBER: LFE II-19

SUMMARY OF WHAT THE SLIDE DEPICTS:

Lateral spreads caused distortion of railroad tracks in the 1964 Prince William Sound, Alaska earthquake.

20. SLIDE IDENTIFICATION NUMBER: LFE II-20

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF LIQUEFACTION:

3. *SLUMPS*—THIS TYPE OF GROUND FAILURE COMMONLY OCCURS IN STEEP RIVER BANKS UNDERLAIN BY LIQUEFIED SEDIMENT. THE WIDTH OF THE FAILURE MAY BE SEVERAL TIMES THE HEIGHT OF THE BANK AND VERTICAL DISPLACEMENTS MAY BE A LARGE FRACTION OF THE HEIGHT.

21. SLIDE IDENTIFICATION NUMBER: LFE II-21

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF LIQUEFACTION:

4. *LOSS OF SHEAR STRENGTH*—THIS TYPE OF GROUND FAILURE ALLOWS HEAVY STRUCTURES TO SETTLE OR TIP AND LIGHTWEIGHT, BURIED STRUCTURES TO RISE BUOYANTLY.

22. SLIDE IDENTIFICATION NUMBER: LFE II-22

SUMMARY OF WHAT THE SLIDE DEPICTS:

Four-story apartment buildings in Niigata, Japan that settled and tipped as much as 60 degrees because of loss of strength is supporting soils during the 1964 Niigata earthquake. Loss of bearing strength was caused by liquefaction of a sand layer that extends 10 to 15 feet below the base of the foundation. Most of the buildings were later jacked back into an upright position, underpinned with piles, and reused.

The peak ground acceleration did not exceed 0.1 g in the earthquake.

23. SLIDE IDENTIFICATION NUMBER: LFE II-23

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF STRENGTH LOSS IN SENSITIVE CLAY:

- **THE LARGE LANDSLIDES THAT OCCURRED IN ANCHORAGE, ALASKA, DURING THE 1964 EARTHQUAKE WERE DUE PRIMARILY FROM LOSS OF STRENGTH IN THE BOOTLEGGER COVE CLAY FORMATION, WHICH WAS VERY SENSITIVE (SENSITIVITIES AS HIGH AS 40) TO THE LONG DURATION, STRONG GROUND SHAKING.**
- **THE TYPES OF GROUND FAILURE GENERATED BY LIQUEFACTION MAY ALSO BE GENERATED BY LOSS OF STRENGTH IN SENSITIVE CLAY.**
- **THE DURATION AND STRENGTH OF THE GROUND SHAKING DIRECTLY INFLUENCE THE GENERATION OF LOSS OF STRENGTH AND FAILURE IN SENSITIVE CLAY. CLAYS HAVING SENSITIVITIES GREATER THAN 8 ARE CLASSIFIED AS EXTRA SENSITIVE.**

24. SLIDE IDENTIFICATION NUMBER: LFE II-24

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows ground deformation and damage at the upper part of five major landslides that developed in Anchorage, Alaska, during the 1964 Prince William Sound, Alaska earthquake. The landslides were induced by a combination of loss of strength in sensitive (quick) clay layers and liquefaction of sand and silt lenses in the Bootlegger Cove Formation.

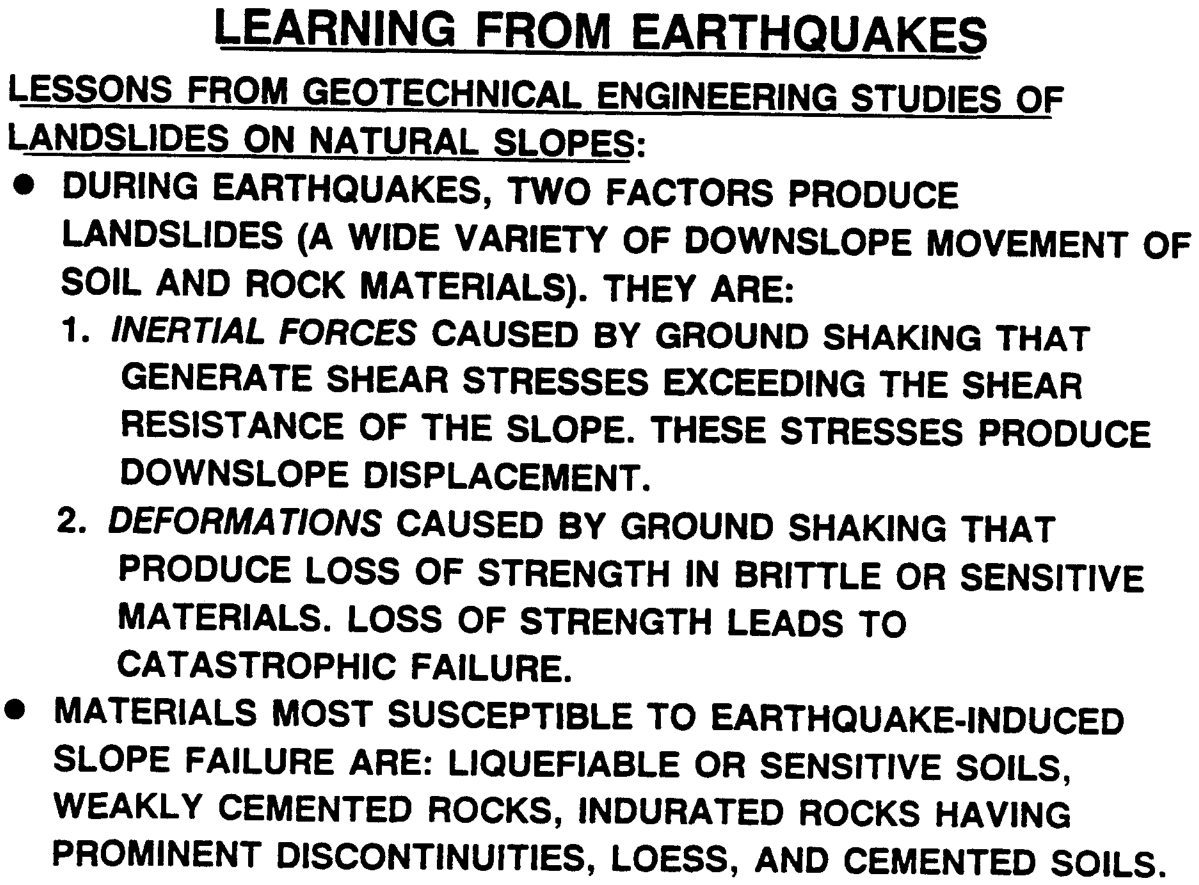
25. SLIDE IDENTIFICATION NUMBER: LFE II-25

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows the destruction caused by the Turnagain Heights landslide in Anchorage that was triggered during the 1965 Prince William Sound, Alaska earthquake. The long (up to 4 minutes of perciptible motion duration of strong ground shaking was an important causative factor.

26. SLIDE IDENTIFICATION NUMBER: LFE II-26

SUMMARY OF WHAT THE SLIDE DEPICTS:



LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF LANDSLIDES ON NATURAL SLOPES:

- DURING EARTHQUAKES, TWO FACTORS PRODUCE LANDSLIDES (A WIDE VARIETY OF DOWNSLOPE MOVEMENT OF SOIL AND ROCK MATERIALS). THEY ARE:
  1. *INERTIAL FORCES* CAUSED BY GROUND SHAKING THAT GENERATE SHEAR STRESSES EXCEEDING THE SHEAR RESISTANCE OF THE SLOPE. THESE STRESSES PRODUCE DOWNSLOPE DISPLACEMENT.
  2. *DEFORMATIONS* CAUSED BY GROUND SHAKING THAT PRODUCE LOSS OF STRENGTH IN BRITTLE OR SENSITIVE MATERIALS. LOSS OF STRENGTH LEADS TO CATASTROPHIC FAILURE.
- MATERIALS MOST SUSCEPTIBLE TO EARTHQUAKE-INDUCED SLOPE FAILURE ARE: LIQUEFIABLE OR SENSITIVE SOILS, WEAKLY CEMENTED ROCKS, INDURATED ROCKS HAVING PROMINENT DISCONTINUITIES, LOESS, AND CEMENTED SOILS.

27. SLIDE IDENTIFICATION NUMBER: LFE II-27

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows an aerial view of the Madison Canyon landslide in southwestern Montana induced by the 1959 Hebgen Lake earthquake. Rocks from the mountaintop dropped about 1,300 feet and reached a speed of about 100 miles per hour before striking the valley floor and riding up the opposite valley wall. The lake filling the valley is Earthquake Lake.

28. SLIDE IDENTIFICATION NUMBER: LFE II-28

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF LANDSLIDES ON NATURAL SLOPES:

- **MOST EARTHQUAKE-INDUCED LANDSLIDES INVOLVE MATERIALS THAT HAVE *NOT* PREVIOUSLY FAILED. EXCEPT FOR LATERAL SPREADS, EXISTING LANDSLIDES ARE SELDOM REACTIVATED, AND IF THEY ARE, THEY GENERALLY MOVE ONLY SHORT DISTANCES.**
- **STEEPNESS OF SLOPE DIRECTLY INCREASES SUSCEPTIBILITY TO SLOPE FAILURE, ALTHOUGH LATERAL SPREADS COMMONLY OCCUR ON GENTLE SLOPES. SLOPES THAT HAVE BEEN OVERSTEEPENED BY EROSION, ROAD CUTS, ETC., ARE VERY VULNERABLE TO FAILURE.**
- **THE THRESHOLD OF GROUND SHAKING REQUIRED TO TRIGGER VARIOUS TYPES OF LANDSLIDES IS MMI VI-VII.**

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING STUDIES OF GROUND SETTLEMENT:

- STRONG GROUND SHAKING HAS COMPACTED LOOSE COHESIONLESS MATERIALS AND CAUSED DIFFERENTIAL GROUND SETTLEMENTS RANGING FROM 5 CENTIMETERS TO MORE THAN A METER.
- THE AMOUNT OF DIFFERENTIAL SETTLEMENT IS A FUNCTION OF SEVERAL FACTORS INCLUDING: THICKNESS AND RELATIVE DENSITY OF THE SOIL LAYER, THE FABRIC OF THE SOIL, AND THE GENERATION OF PORE WATER PRESSURES DURING THE COMPACTION PROCESS IN WHICH THE IN SITU INTERNAL STRUCTURE (PACKING) OF THE SOIL IS REARRANGED BY VIBRATIONS.

30. SLIDE IDENTIFICATION NUMBER: LFE II-30

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON BUILDING DAMAGE FROM FOUNDATION FAILURE:

- EXAMINATIONS OF FOUNDATIONS BENEATH DAMAGED AND UNDAMAGED BUILDINGS IN THE 1964 PRINCE WILLIAM SOUND, ALASKA, 1971 SAN FERNANDO, CALIFORNIA, AND 1979 IMPERIAL VALLEY, CALIFORNIA, EARTHQUAKES HAVE SHOWN THAT VERY FEW FOUNDATIONS (SHALLOW OR DEEP) OUTSIDE OF THE ZONES OF SURFACE FAULTING, LIQUEFACTION, OR LANDSLIDES HAVE SUFFERED LOCAL, SMALL-SCALE FAILURE LEADING TO DAMAGE OF THE SUPERSTRUCTURE.
- AN EXCEPTION IS THE FAILURE OF SOME DEEP FOUNDATIONS IN THE SEPTEMBER 19, 1985 MEXICO EARTHQUAKE. CYCLIC LOADS INCLUDING UPLIFT FORCES WEAKENED THE SOFT CLAY SUPPORTING THE FRICTION PILES, ALLOWING THE LOADED PILES TO PENETRATE AND IN SOME CASES PULL OUT OF THE GROUND. THESE EFFECTS LED TO SETTLEMENT, TILTING, AND FAILURE OF THE SUPERSTRUCTURE.

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON BRIDGE DAMAGE FROM GROUND FAILURE:

- THE MAJOR GEOTECHNICAL FACTORS CONTRIBUTING TO DAMAGE TO BRIDGES IN THE 1906 SAN FRANCISCO, CALIFORNIA, THE 1964 PRINCE WILLIAM SOUND, ALASKA, 1964 AND 1979 IMPERIAL VALLEY, CALIFORNIA, EARTHQUAKES ARE:
    1. LIQUEFACTION OF SATURATED SOILS IN RIVER CHANNELS AND FLOOD PLAINS.
    2. INCREASED LATERAL EARTH PRESSURES.
    3. SLOPE INSTABILITY.
    4. SETTLEMENT OF APPROACH FILLS.

32. SLIDE IDENTIFICATION NUMBER: LFE II-32

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows failure of a bridge in the 1964 Prince William Sound, Alaska earthquake.

33. SLIDE IDENTIFICATION NUMBER: LFE II-33

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON EMBANKMENT DAMS AND FILLS:

- MOST ENGINEERED, MECHANICALLY COMPACTED EMBANKMENTS OR FILLS OF EARTH AND ROCKFILL MATERIALS HAVE PERFORMED WELL UNDER GROUND SHAKING IN PAST EARTHQUAKES. THE NOTABLE EXCEPTIONS ARE EMBANKMENTS AND FILLS OF SATURATED, LOOSE, FINE-GRAINED, COHESIONLESS MATERIALS WHICH ARE SUSCEPTIBLE TO LIQUEFACTION, LOSS OF STRENGTH, AND SETTLEMENT. THESE PHENOMENA CAUSE: 1) THE DAM TO SLIDE ON ITS FOUNDATION, 2) SLOPE FAILURES, 3) LOSS OF DESIGN FREEBOARD, AND 4) THE DISPLACEMENT AND FAILURE OF OUTLET WORKS.
- IN ADDITION TO GROUND SHAKING, RESERVOIRS ARE POTENTIALLY SUSCEPTIBLE TO RUPTURING FROM FAULT DISPLACEMENTS, REGIONAL UPLIFT, LANDSLIDES, AND SEICHES.

34. SLIDE IDENTIFICATION NUMBER: LFE II-34

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON EMBANKMENT DAMS AND FILLS:

- THE PERFORMANCE OF EARTH EMBANKMENT DAMS DEPENDS PRIMARILY ON SOIL TYPES, DEGREE OF SATURATION, DENSITY, AND THE STRENGTH AND DURATION OF THE GROUND SHAKING.
- OBSERVED FAILURES HAVE OCCURRED AFTER THE GROUND SHAKING CEASED.
- EMBANKMENTS FOR ROADWAYS, DIKES, AND BUILDING PADS HAVE SUFFERED SETTLEMENT, CRACKING, AND SLOPE FAILURE.
- SETTLEMENT OF FILLS ADJACENT TO BRIDGE ABUTMENTS IS A COMMON SOURCE OF FAILURE.
- AREAS OF EMBANKMENTS THAT ARE PARTICULARLY SUSCEPTIBLE TO SLOPE FAILURE ARE: 1) SLOPING MARGINS OF FILLS WHERE COMPACTION IS TYPICALLY POOR, AND 2) SLOPING CONTACTS BETWEEN THE IN-PLACE MATERIAL AND FILL, TYPICAL OF CUT-AND-FILL OPERATIONS.

35. SLIDE IDENTIFICATION NUMBER: LFE II-35

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON EMBANKMENT DAMS AND FILLS:

- GROUND SHAKING IN PAST EARTHQUAKES HAS CAUSED TWO TYPES OF FAILURES IN EMBANKMENT DAMS:
    1. SEVERE LOSS OF STRENGTH IN THE EMBANKMENT OR FOUNDATION MATERIALS (FOR EXAMPLE, SHEFFIELD DAM AND LOWER SAN FERNANDO DAM IN THE 1925 SANTA BARBARA, CALIFORNIA, AND THE 1971 SAN FERNANDO, CALIFORNIA, EARTHQUAKES).

2. **SETTLEMENT OR PLASTIC DEFORMATION OF EMBANKMENT OR FOUNDATION MATERIALS LEADING TO LOSS OF FREEBOARD OR CRACKING OF THE EMBANKMENT (FOR EXAMPLE, HEBGEN LAKE IN THE 1959 HEBGEN LAKE, MONTANA, EARTHQUAKE AND SEVERAL DAMS IN THE SEPTEMBER 19, 1985 MEXICO EARTHQUAKE).**

36. SLIDE IDENTIFICATION NUMBER: LFE II-36

SUMMARY OF WHAT THE SLIDE DEPICTS:

This slide shows the near failure of the Lower San Fernando dam during the 1971 San Fernando, California earthquake. Part of the upstream face of this 140-ft-high earth dam lost strength and slipped beneath the water. Eighty thousand people in Los Angeles were evacuated for several days until the water level was lowered.

Although no strong motion accelerographs were recorded during the earthquake at the dam, analysis of a seismoscope recond obtained there by Ron Scott (1973) suggested a peak acceleration of as much as 0.55 to 0.6 g.

(Note: See Bulletin of Seismological Society of America, v. 63, p. 1637-1661)

37. SLIDE IDENTIFICATION NUMBER: LFE II-37

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON UNDERGROUND STRUCTURES:

- **TUNNELS HAVE PERFORMED VERY WELL DURING PAST EARTHQUAKES, EXCEPT IN THOSE CASES WHEN THE TUNNEL HAS BEEN INTERSECTED BY FAULT DISPLACEMENTS OR LANDSLIDES. ONLY MINOR DAMAGE HAS OCCURED IN ROCK TUNNELS WHEN THE GROUND ACCELERATIONS WERE LESS THAN 0.4 G. DAMAGE TO LININGS AND PORTALS FROM STRONG GROUND SHAKING HAS GENERALLY BEEN ASSOCIATED WITH POOR CONSTRUCTION PRACTICES SUCH AS: 1) USE OF BRICK OR UNREINFORCED CONCRETE LINERS, 2) LACK OF GROUT BETWEEN WOOD LAGGING AND THE OVERBREAK, AND 3) DISCONTINUITIES IN STIFFNESS.**
- **THE SEVERITY OF DAMAGE TO TUNNELS GENERALLY INCREASES WITH: 1) FAULT AND GROUND DISPLACEMENTS, AND 2) DURATION OF THE GROUND SHAKING.**
- **DEEP TUNNELS GENERALLY PERFORM BETTER THAN SHALLOW TUNNELS.**

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON RETAINING STRUCTURES AND LINED CHANNELS:

- SURFACE FAULT RUPTURES CAUSED MOST OF THE MAJOR DAMAGE TO VERTICAL-WALLED FLOOD CONTROL CHANNELS DURING THE 1971 SAN FERNANDO, CALIFORNIA, EARTHQUAKE. DAMAGE WAS GREATEST NEAR THE RUPTURE ZONE AND DECREASED RAPIDLY AS DISTANCE FROM THE RUPTURE ZONE INCREASED.
- IRRIGATION CANALS AND DITCHES AND OTHER CHANNELS LINED WITH UNREINFORCED CONCRETE ARE VERY SUSCEPTIBLE TO DAMAGE FROM DIFFERENTIAL GROUND DISPLACEMENT. EVEN IF THE DAMAGE IS MINOR, LEAKING WATER (OR FLUIDS) CAN ERODE SUPPORTING EMBANKMENTS AND TRIGGER GREATER DAMAGE.

39. SLIDE IDENTIFICATION NUMBER: LFE II-39

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON RETAINING STRUCTURES AND LINED CHANNELS:

- MOST RETAINING STRUCTURES THAT HAVE COLLAPSED OR EXPERIENCED DAMAGE DURING PAST EARTHQUAKES ARE WATERFRONT STRUCTURES EXTENDING BELOW THE WATER SURFACE. ONLY A FEW CASES OF DAMAGE HAVE BEEN REPORTED FOR RETAINING STRUCTURES CONSTRUCTED ABOVE THE GROUND WATER TABLE.
- THE MOST SIGNIFICANT SOURCE OF DAMAGE TO PORT AND HARBOR FACILITIES HAS BEEN THE BUILD UP OF EXCESSIVE LATERAL PRESSURES APPLIED TO QUAY WALLS AND BULKHEADS BY BACKFILL MATERIALS AS A CONSEQUENCE OF LIQUEFACTION OR LOCAL SLIDING.
- PORT AND HARBOR FACILITIES ARE TYPICALLY DESIGNED FOR A HIGHER LEVEL OF RISK THAN OTHER TYPES OF ENGINEERED STRUCTURES BECAUSE OF PAST EXPERIENCES.

40. SLIDE IDENTIFICATION NUMBER: LFE II-40

SUMMARY OF WHAT THE SLIDE DEPICTS:

LEARNING FROM EARTHQUAKES

LESSONS FROM GEOTECHNICAL ENGINEERING ON RETAINING STRUCTURES AND LINED CHANNELS:

- THE FAILURE MECHANISMS FOR RETAINING STRUCTURES ARE COMPLEX AND INCLUDE:
    1. INCREASED LATERAL PRESSURES.
    2. DYNAMIC WATER PRESSURES.
    3. LOSS OF BEARING STRENGTH.
    4. INCREASED AXIAL AND LATERAL STRESSES ON PILES.
    5. SLOPE INSTABILITY.
    6. LIQUEFACTION,
- FEW REPORTS HAVE BEEN MADE OF DAMAGE TO RETAINING WALLS CAUSED DIRECTLY BY GROUND SHAKING.
- THE STRUCTURAL CONFIGURATIONS, INCLUDING THE ANCHOR SYSTEMS, ARE IMPORTANT IN CONTROLLING DAMAGE TO PORT AND HARBOR FACILITIES.