Ground Improvement for Mitigation of Failure Risks to Existing Embankment Dams

by

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SCOPE OF THE LECTURE

- Types of distress and failure of existing embankment dams and their causes
- Why so many existing embankment dams require fixing
- Available ground improvement methods and basis for selecting among them
- Illustrative case histories
- Recent trends in design and ground improvement method applications
- Some major unresolved problems

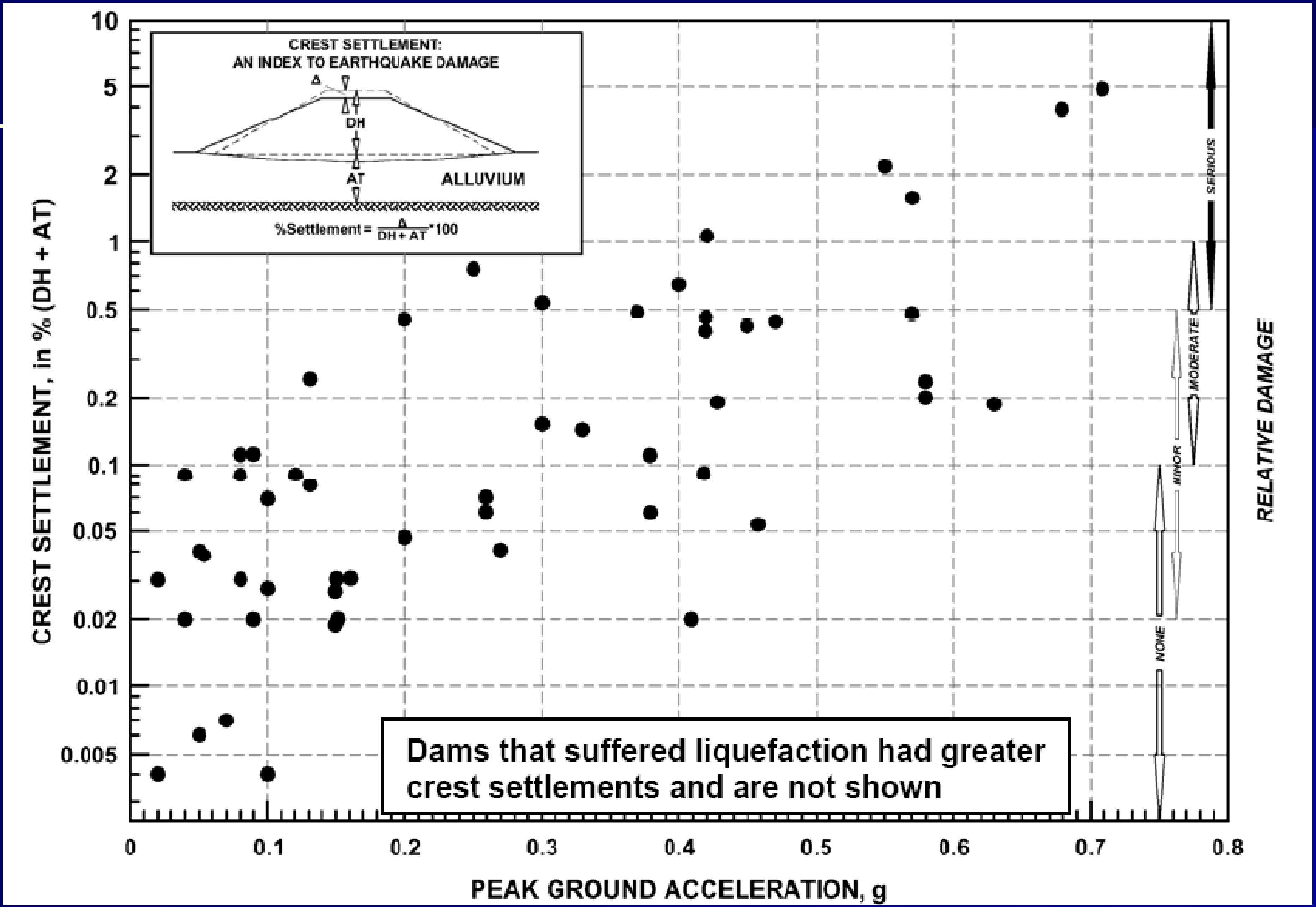
TYPES OF DISTRESS AND FAILURE OF EXISTING EMBANKMENT DAMS AND THEIR CAUSES

- Excessive Settlement
- Liquefaction of embankment and foundation materials
- Large Deformations
- Cracking and opening of seepage paths
- Damage to control structures

Loss of freeboard and overtopping as a result of:

- Crest settlement from compression of the embankment and foundation
- Crest settlement from loss of embankment stability and lateral displacement
- Crest settlement from liquefaction in the embankment and/or foundation and lateral spreading

Almost all embankment dams undergo some settlement as a result of an earthquake



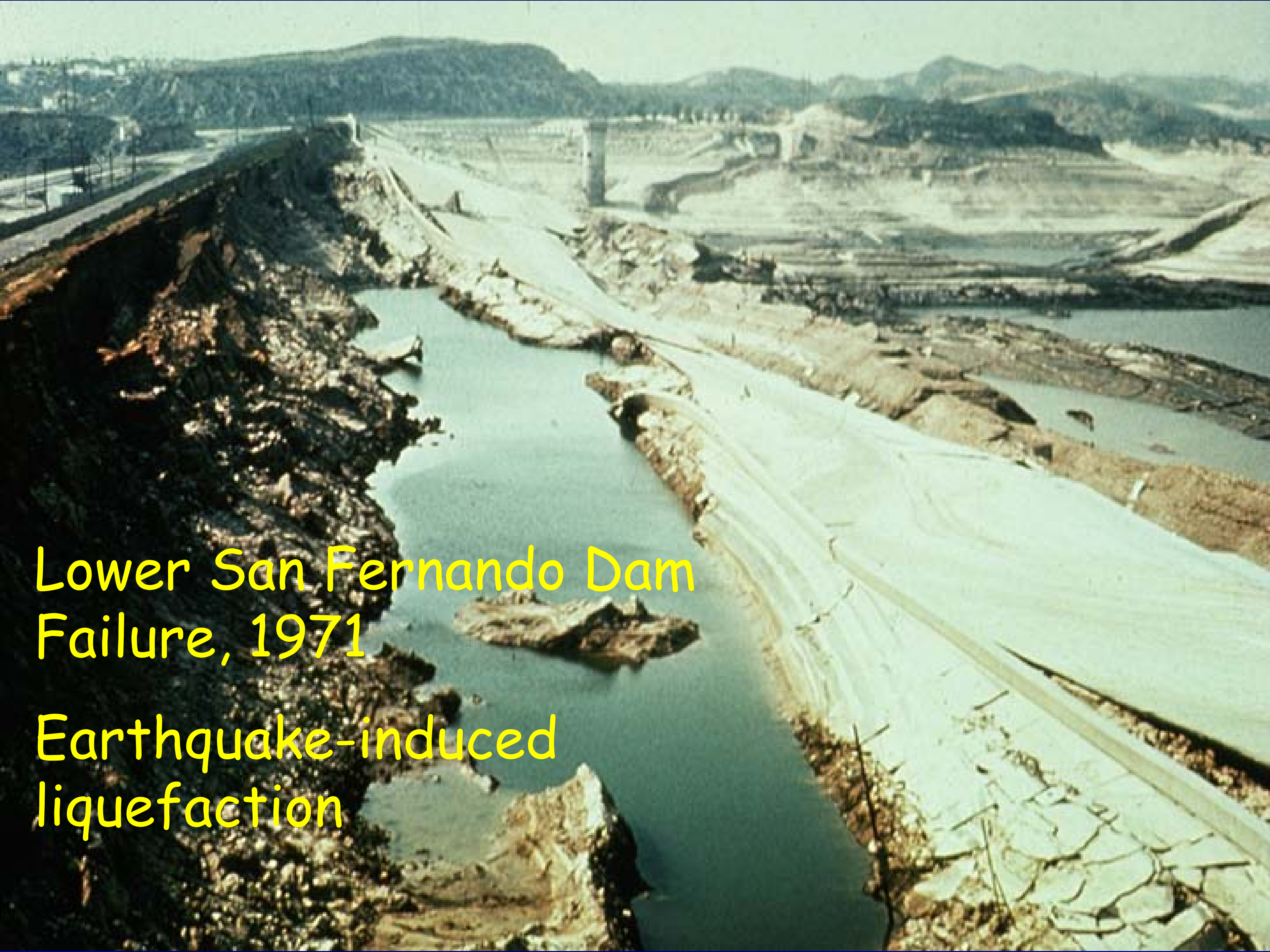
Dams that suffered liquefaction had greater crest settlements and are not shown

(Modified and redrawn from Swaisgood, 1998)

Fort Peck Dam Failure in 1933 – static liquefaction of a loose sand embankment fill

(not caused by an earthquake)

Failure of Fort Peck Dam - static liquefaction of a loose sand embankment fill



Lower San Fernando Dam Failure, 1971

Earthquake-induced liquefaction

1971 Slide – Lower San Fernando Dam

Photo taken during reservoir emptying after the earthquake to protect the large population at risk downstream

Seepage and Piping (initiated by cracking and differential movements):

- Within and through the embankment as a result of cracking of the core and inadequate protective filters
- Seepage and piping through the foundation as a result of cracking of cutoff walls and seepage control blankets
- Piping along conduits as a result of differential ground movements

Settlement and cracking at Hebgen Dam, MT in 1959 EQ

Transverse crack in a long, low dam near Anchorage caused by the Great Alaska EQ of 1964 (from Sherard, 1973)

Loss of Reservoir Control can result from:

- Loss of spillway
- Damage to spillway gates
- Damage to inlet and outlet works

WHY DO SO MANY DAMS NEED REMEDIATION?

- Many were built on sedimentary deposits now known to be susceptible to liquefaction
- Many dams were built using methods now known to yield embankments that have poor stability; e.g. hydraulic filling
- Aging dam inventory and the deteriorating effects of time on the condition of the dam and appurtenant structures
- Much more is known about how dams can be adversely impacted by seismic shaking
- Escalation of estimated seismic risk
- Larger populations in the downstream floodplain now and in the future
- Higher standards for dams built today – stricter regulatory requirements

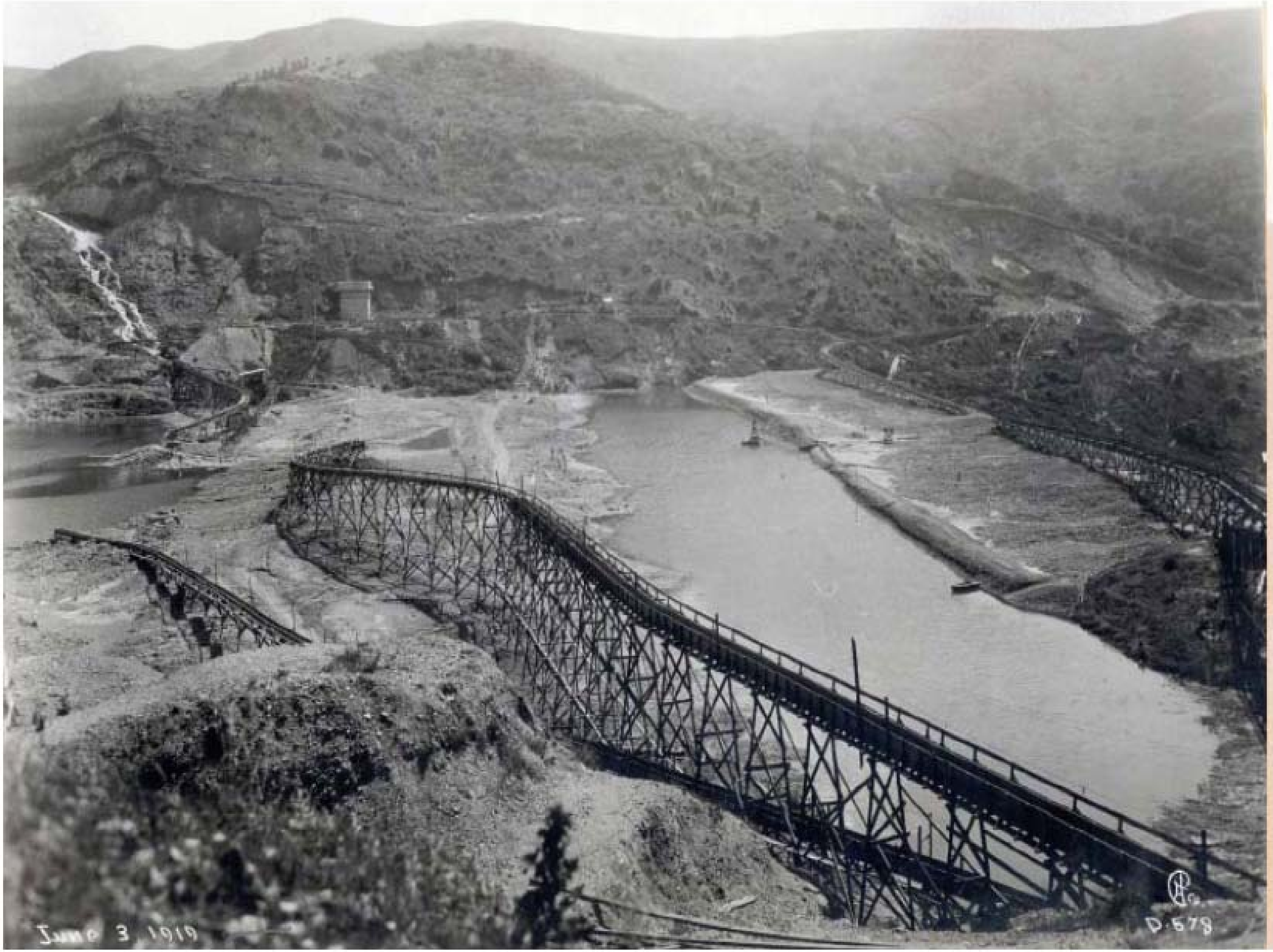
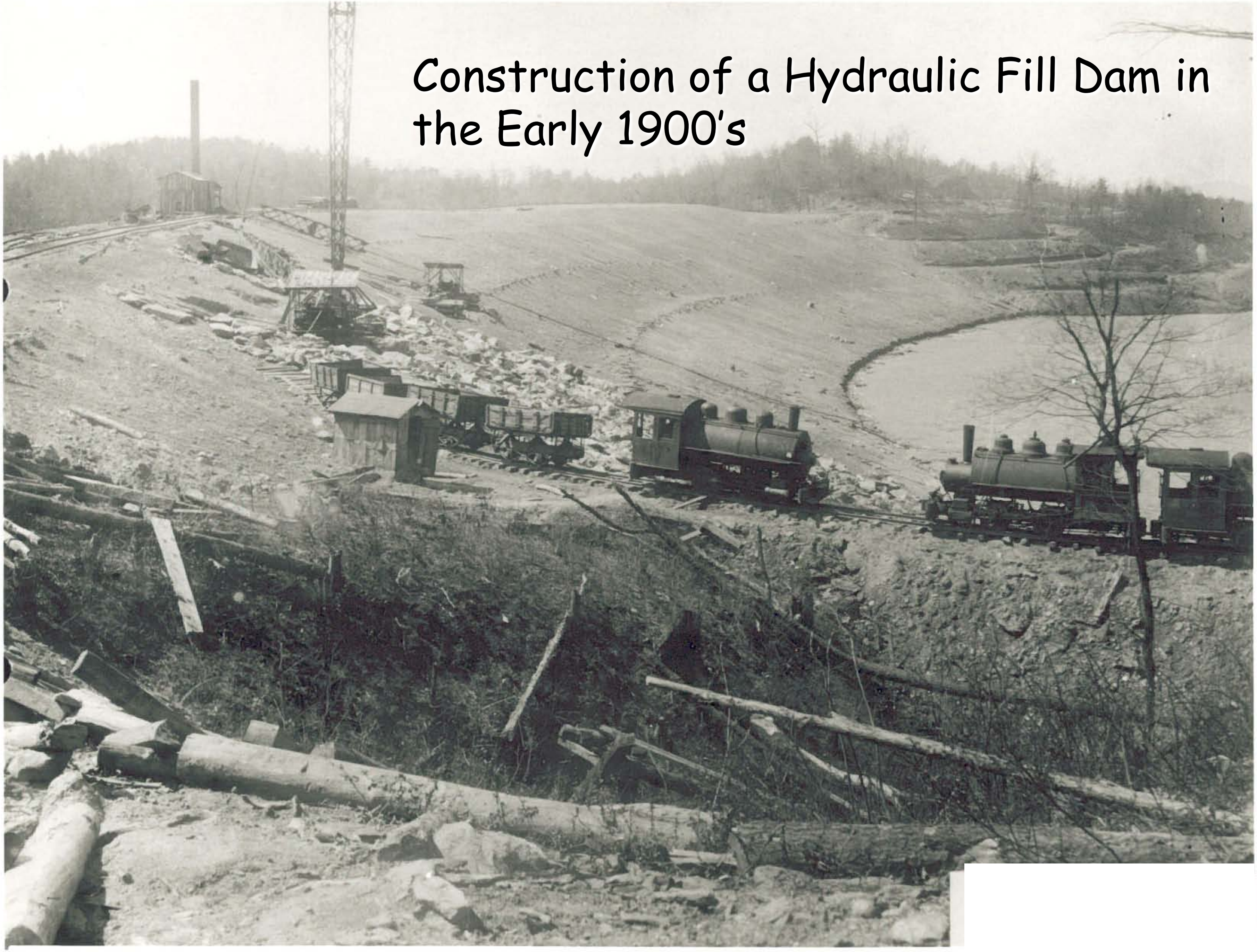
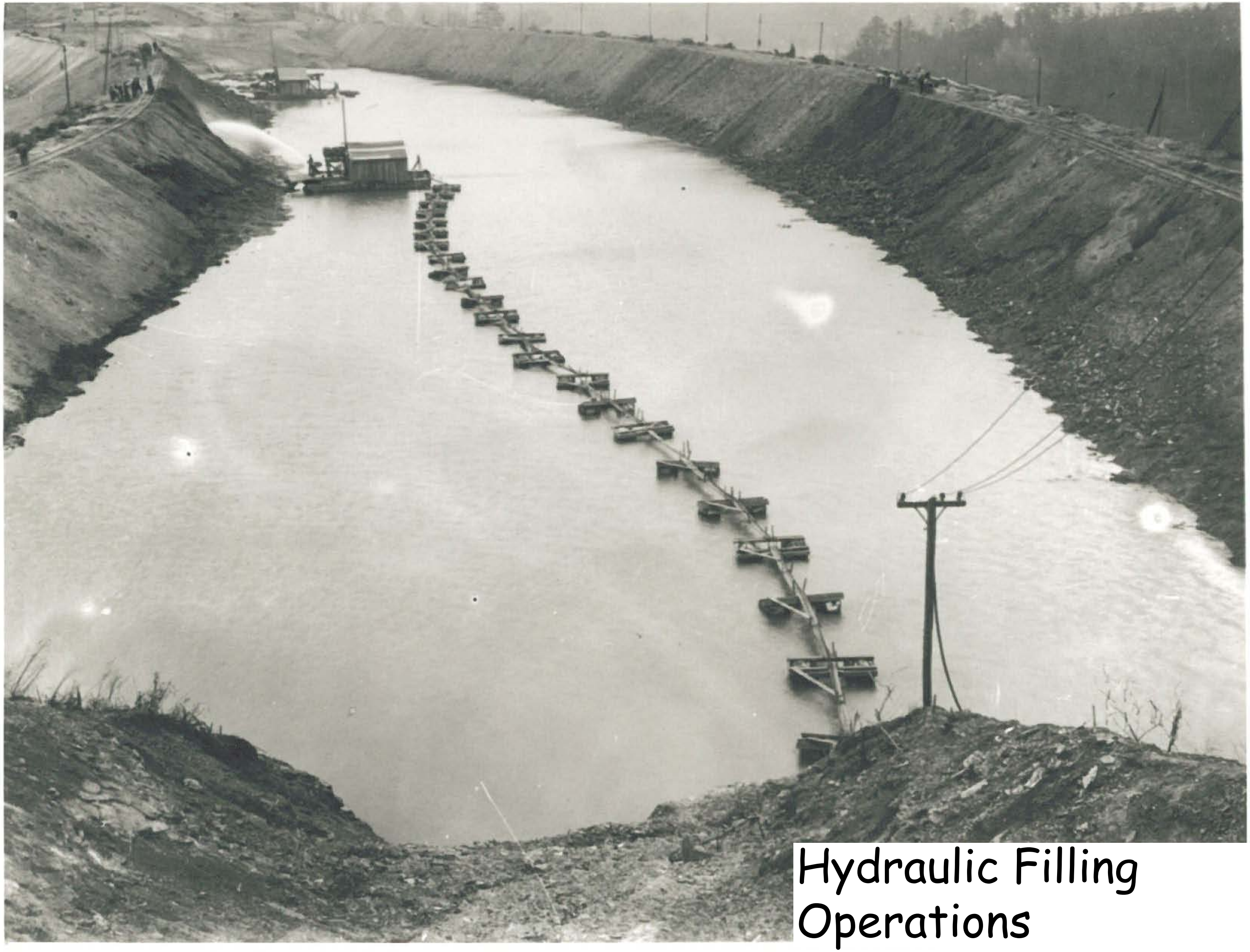


Fig. 2. Hydraulic filling during construction of San Pablo Dam near Oakland, CA in 1919 (Photo courtesy of East Bay Municipal Utility District)

Construction of a Hydraulic Fill Dam in the Early 1900's

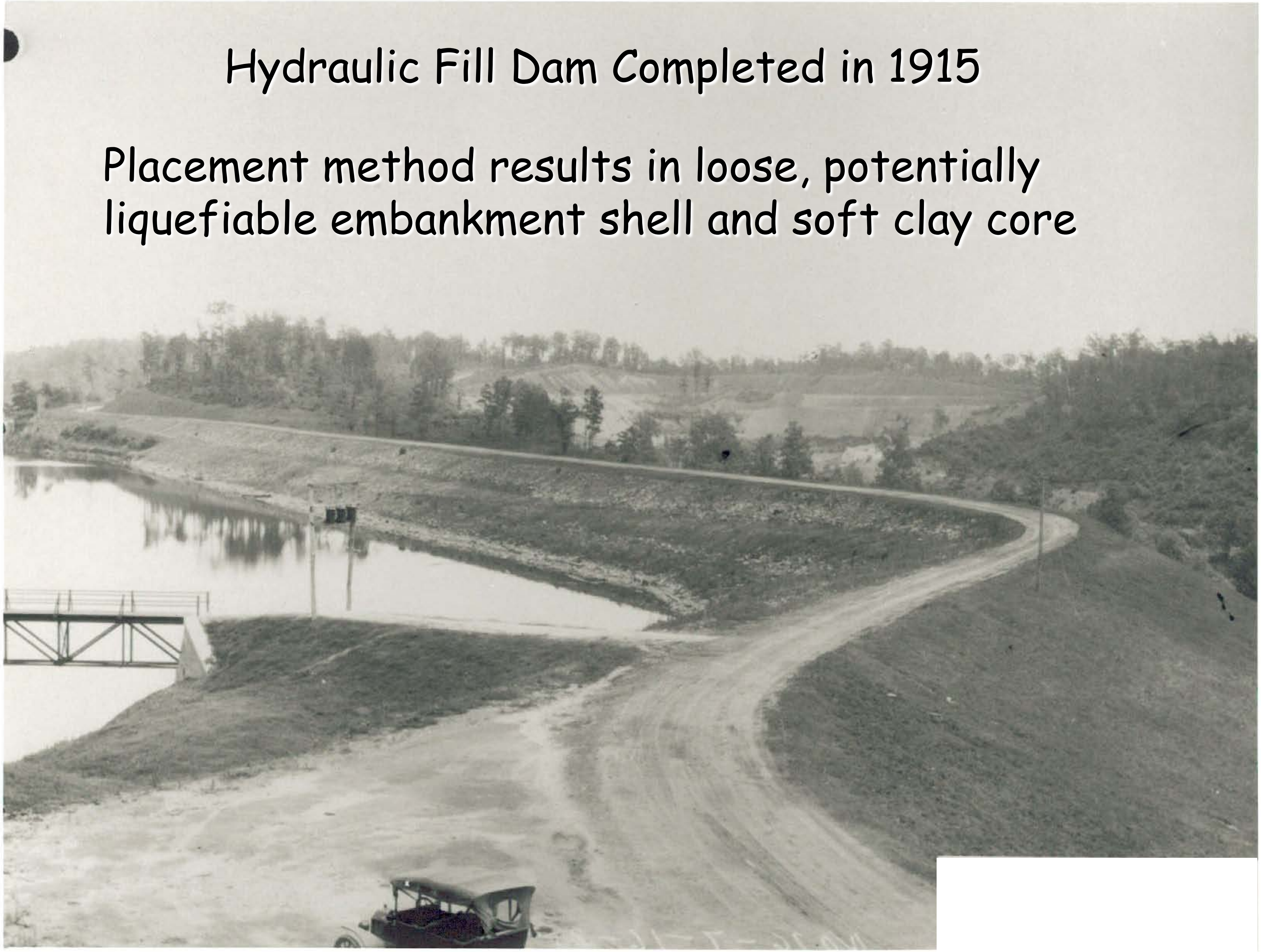




Hydraulic Filling Operations

Hydraulic Fill Dam Completed in 1915

Placement method results in loose, potentially liquefiable embankment shell and soft clay core



Steps in the Evaluation of Dam Safety

1. Review project history – site conditions, construction records, as-built conditions, maintenance records, etc.
2. Assess current conditions of the foundation, embankment and appurtenant structures
3. Determine site seismicity and estimate the ground motions
4. Determine hydraulic demands; e.g., PMF, Reservoir levels
5. Develop best estimate site characterization models for the dam and its foundation
6. Do simple/approximate analyses for estimation of possible liquefaction, deformations, and cracking
7. Do the results indicate the possibility of failure or near-failure by any conceivable failure mode?
8. If so, then more refined analyses and a risk assessment are necessary.
9. If the risk is greater than acceptable limits, then begin development of protective and remedial strategies

Methods and Problems in Characterization of the Site and Existing Dam Conditions

- Accurate definition of the foundation rock and soil strata types, geometry and properties
- Definition of the embankment internal geometry and material properties – design, construction records and photographs, field explorations
- In-situ tests – types, applications and limitations
- Laboratory tests – types, applications and limitations
- Geophysical methods – types, applications and limitations

(Data from different sources do not always provide a clear, consistent indication of liquefaction potential or residual strength)

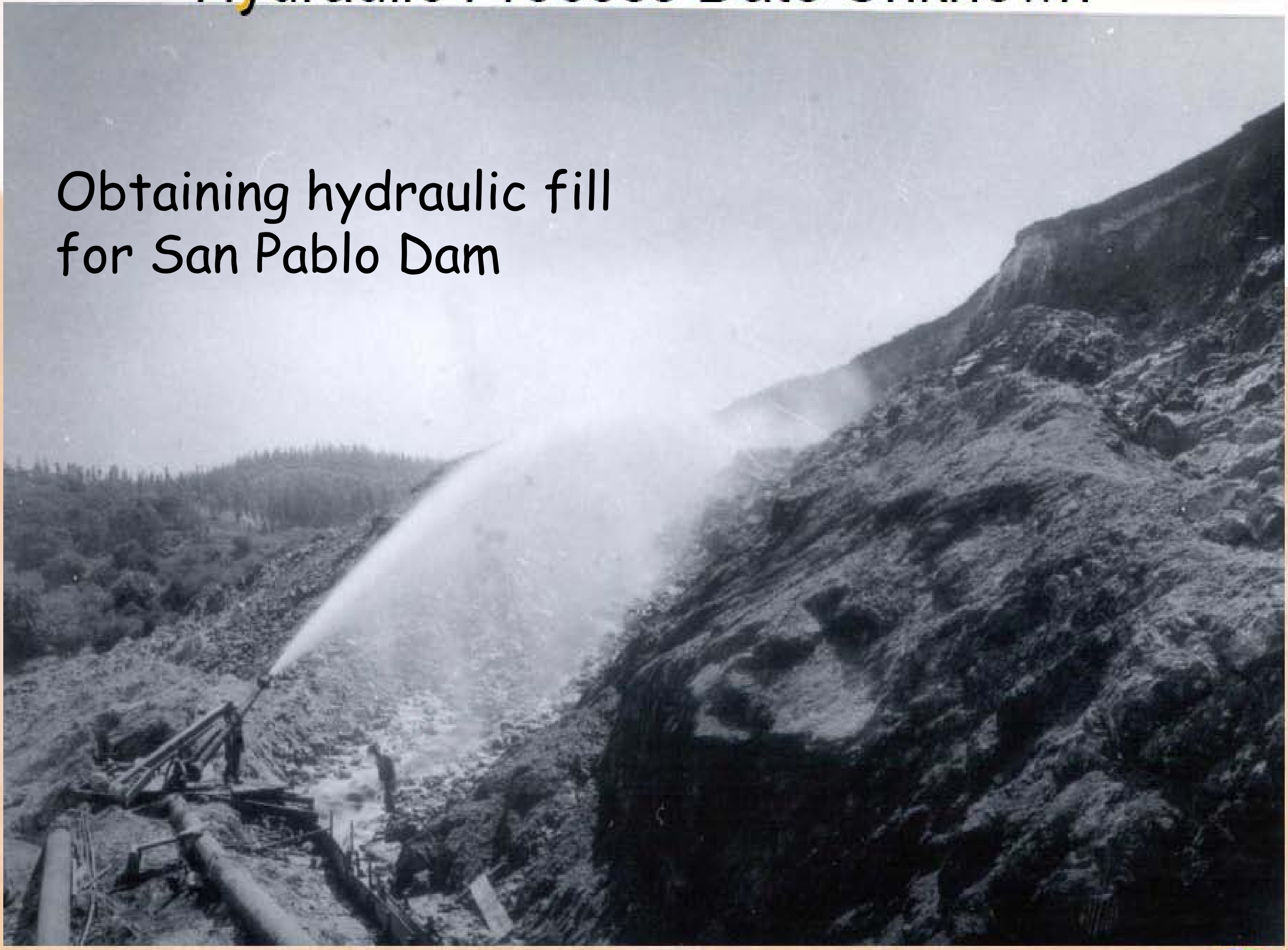
3D Aerial View

SAN PABLO DAM, CALIFORNIA

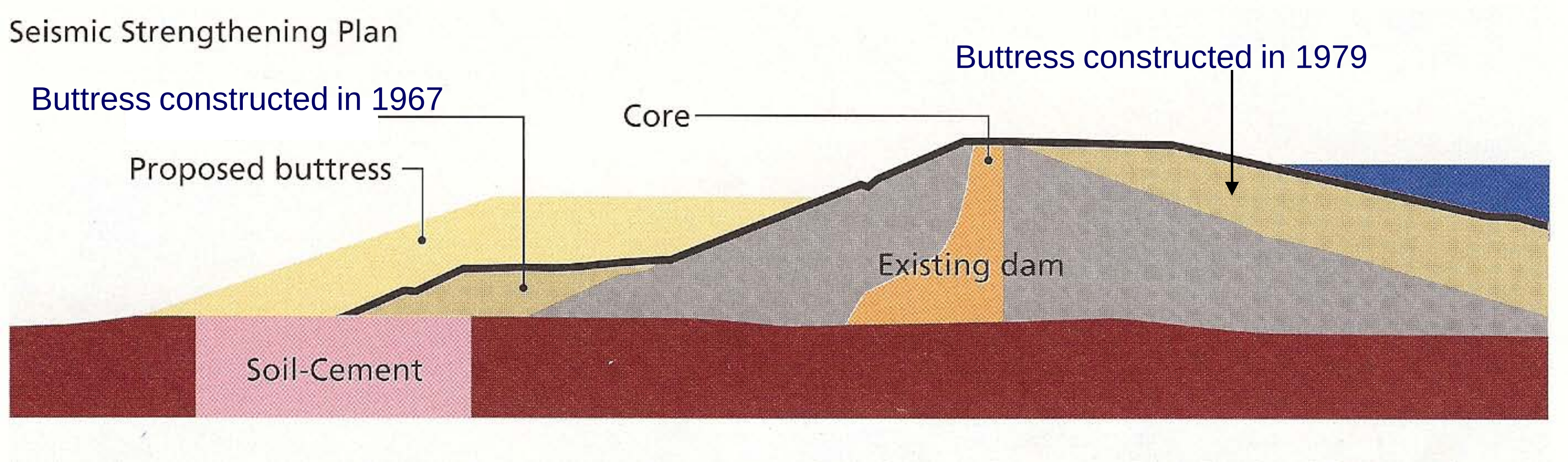
San Pablo Dam - A Case of Misidentified materials

- 170-ft high, 125-ft wide, 1200-ft long hydraulic fill dam completed in 1921
- Founded on alluvial sediments; some zones susceptible to liquefaction
- Embankment of hydraulic fill material that consisted of weathered sandstone and shale
- Evaluations in 1960's and again in 1970's assumed a liquefiable embankment, evidently because it was a hydraulic fill, and included tests on sandy embankment samples - resulted in a small DS buttress in 1967 and large US buttress to bedrock in 1979
- Reevaluation in 2004 assumed liquefiable embankment and indicated excessive slumping and overtopping in M7.25 EQ on Hayward Fault
- Considered completely rebuilding the dam- would require draining the reservoir
- Chose an in-place alternative instead, with Cement Deep Soil Mixing (CDSM) in the foundation and a large DS buttress fill.
- Extensive field (mostly CPT) and lab testing programs revealed that the embankment material was fine-grained and not susceptible to liquefaction.
- As a result a considerably smaller zone of CDSM and reduced buttress was used.

Hydraulic Process Date Unknown



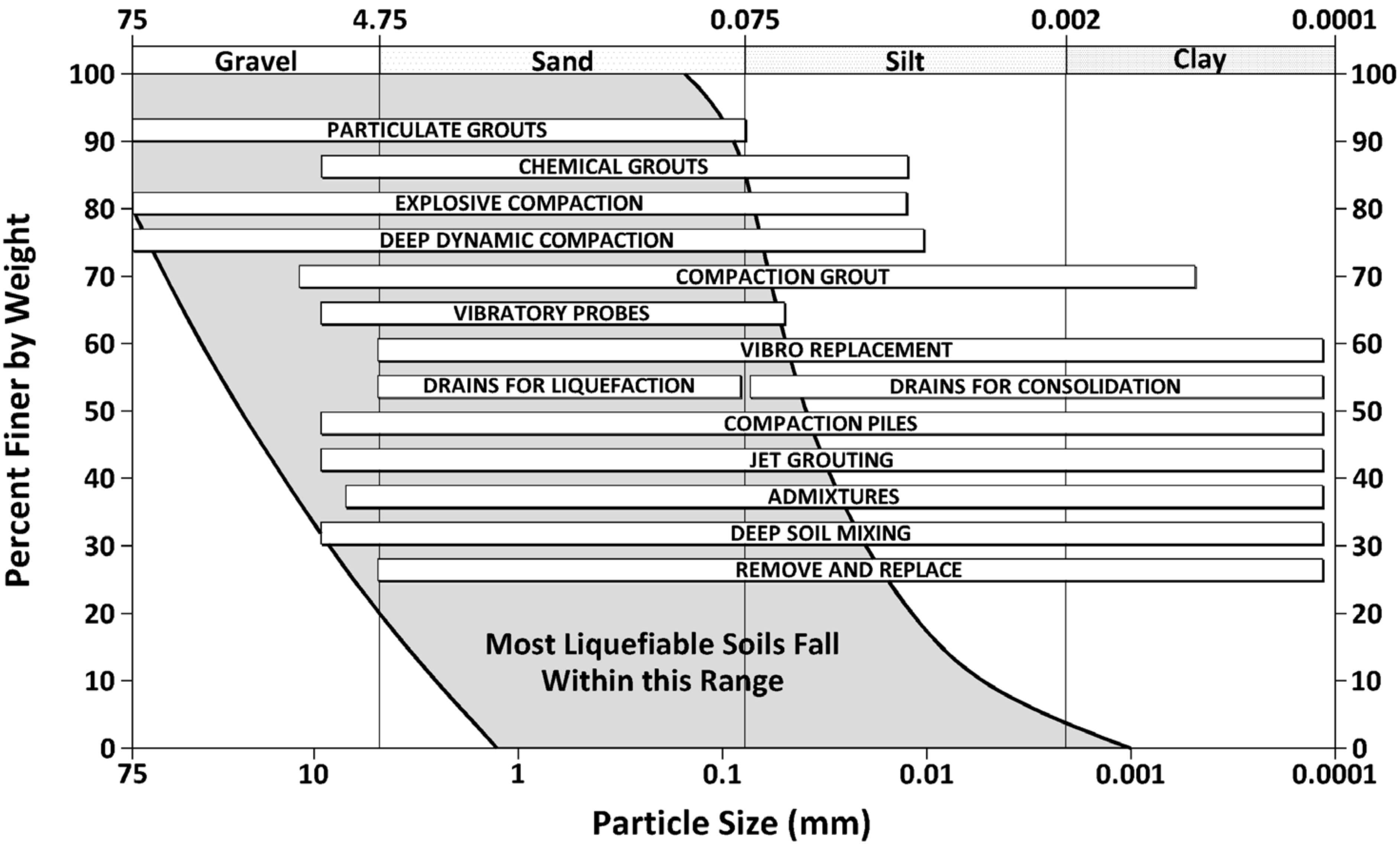
Obtaining hydraulic fill for San Pablo Dam



Construction of third retrofit of San Pablo Dam began in Fall 2008 (see *Civil Engineering,* October 2008) – now complete (2010)

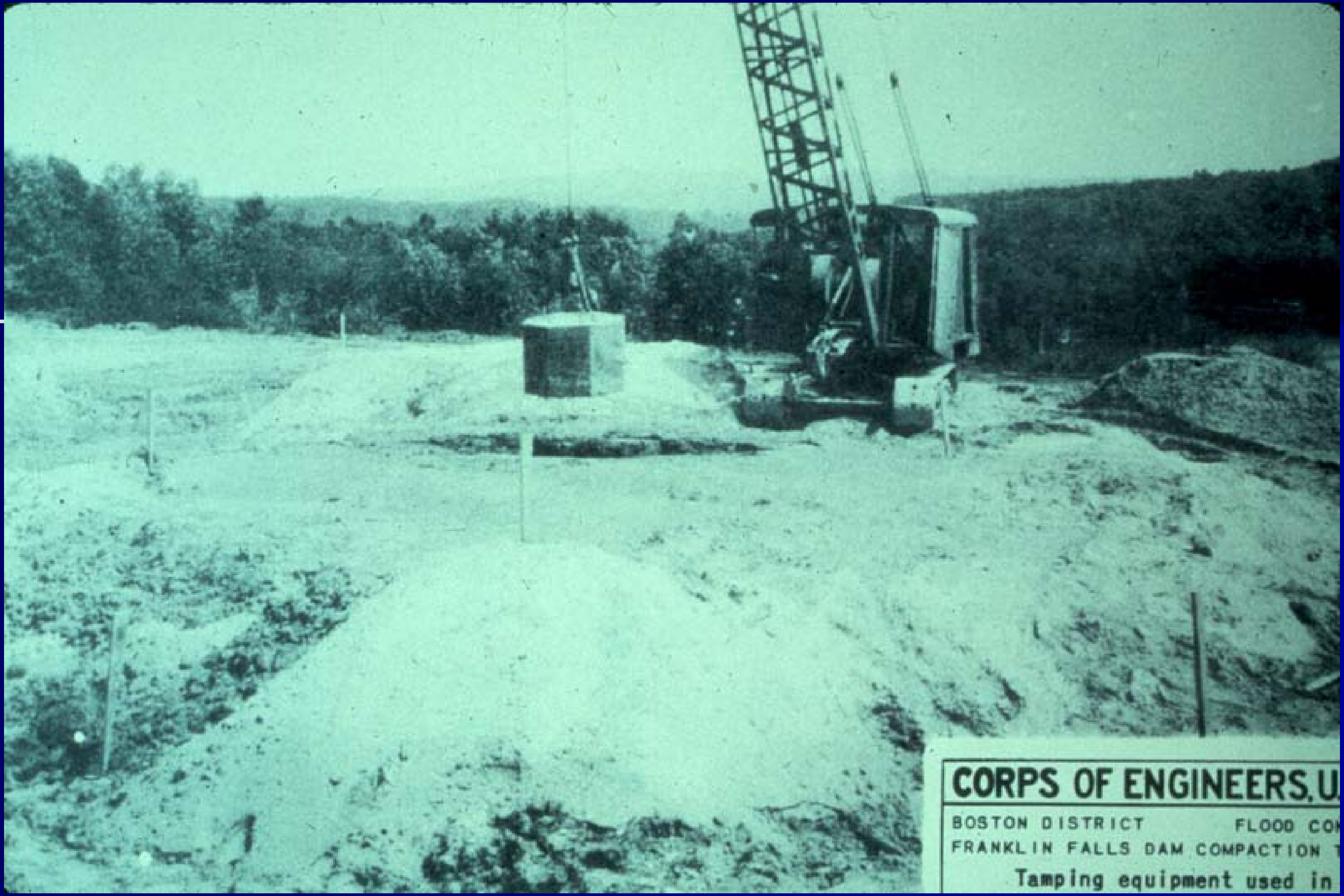
SAN PABLO DAM: Remediated (2009) using Cement Deep Soil Mix Block and Downstream Berm

Ground Improvement Methods Used for Strengthening Dams and Their Foundations



Ground Improvement Methods for Mitigation of Seismic Risk to Existing Embankment Dams and Their Foundations

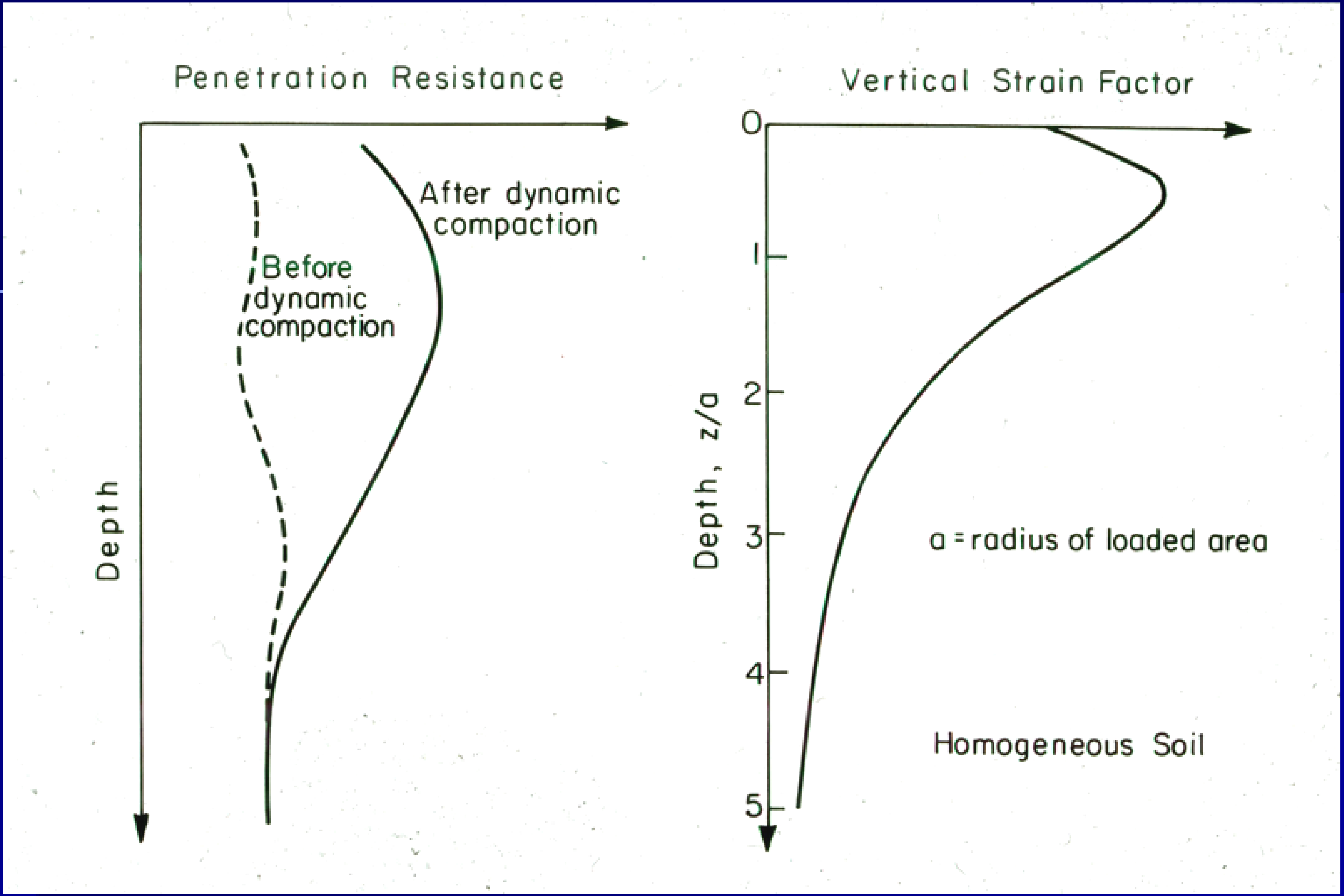
Roller compaction at Mt. St. Helens Sediment Retention Dam, WA – Embankments constructed using **modern equipment and methods** would not be expected to be vulnerable to damage under seismic loadings – but this has not always been the case.



An experimental program of compaction by dropping a heavy concrete block was done by the U.S. Army Corps of Engineers in the mid-1930's during construction of the Franklin Falls Dam in New Hampshire.

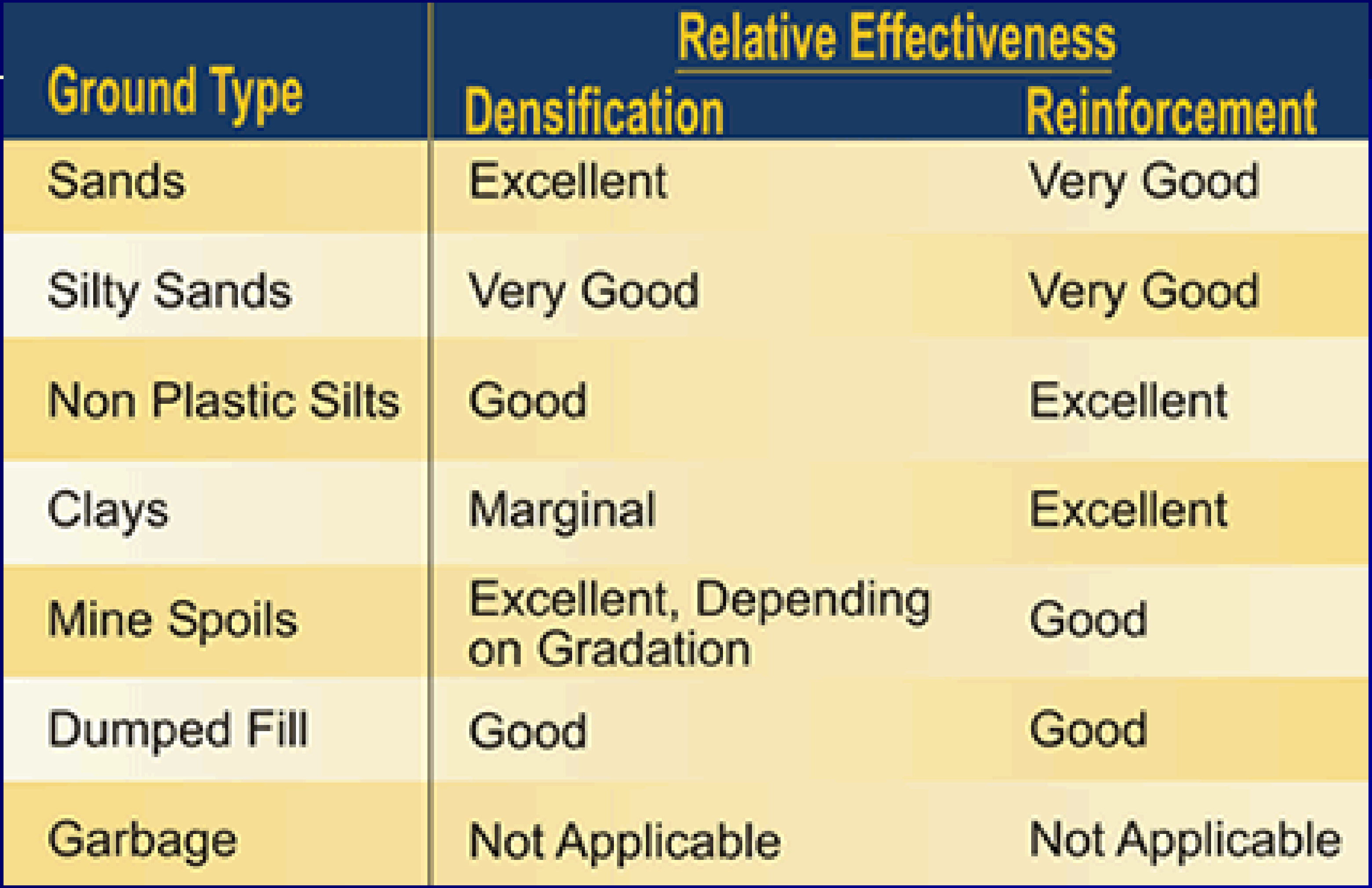
Deep Dynamic Compaction

Courtesy of DGI-Menard



Variation of improvement with depth after DDC is consistent with the strain distribution beneath the weight impact point. Upper limit for densification by DDC is about 35 feet.

Effectiveness of DDC in Different Soils



Ground Type	Relative Effectiveness	
	Densification	Reinforcement
Sands	Excellent	Very Good
Silty Sands	Very Good	Very Good
Non Plastic Silts	Good	Excellent
Clays	Marginal	Excellent
Mine Spoils	Excellent, Depending on Gradation	Good
Dumped Fill	Good	Good
Garbage	Not Applicable	Not Applicable

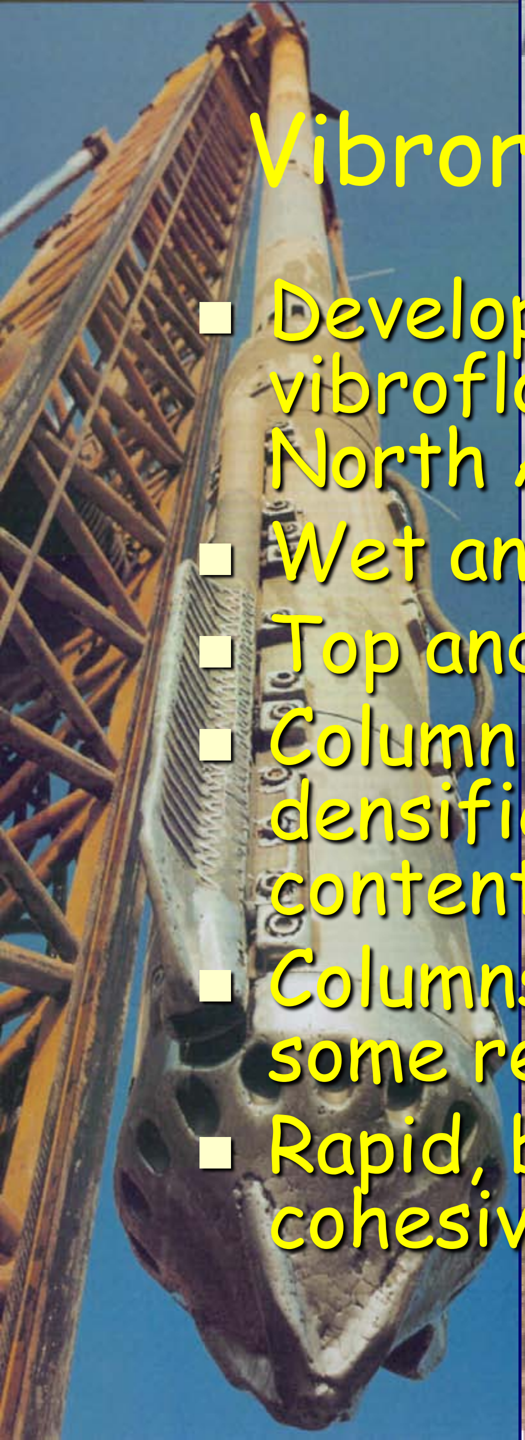
From Hayward Baker

Vibrocompaction

Nicholson Construction,
Vibrofoundations, Inc.

Slide Courtesy Russell A. Green

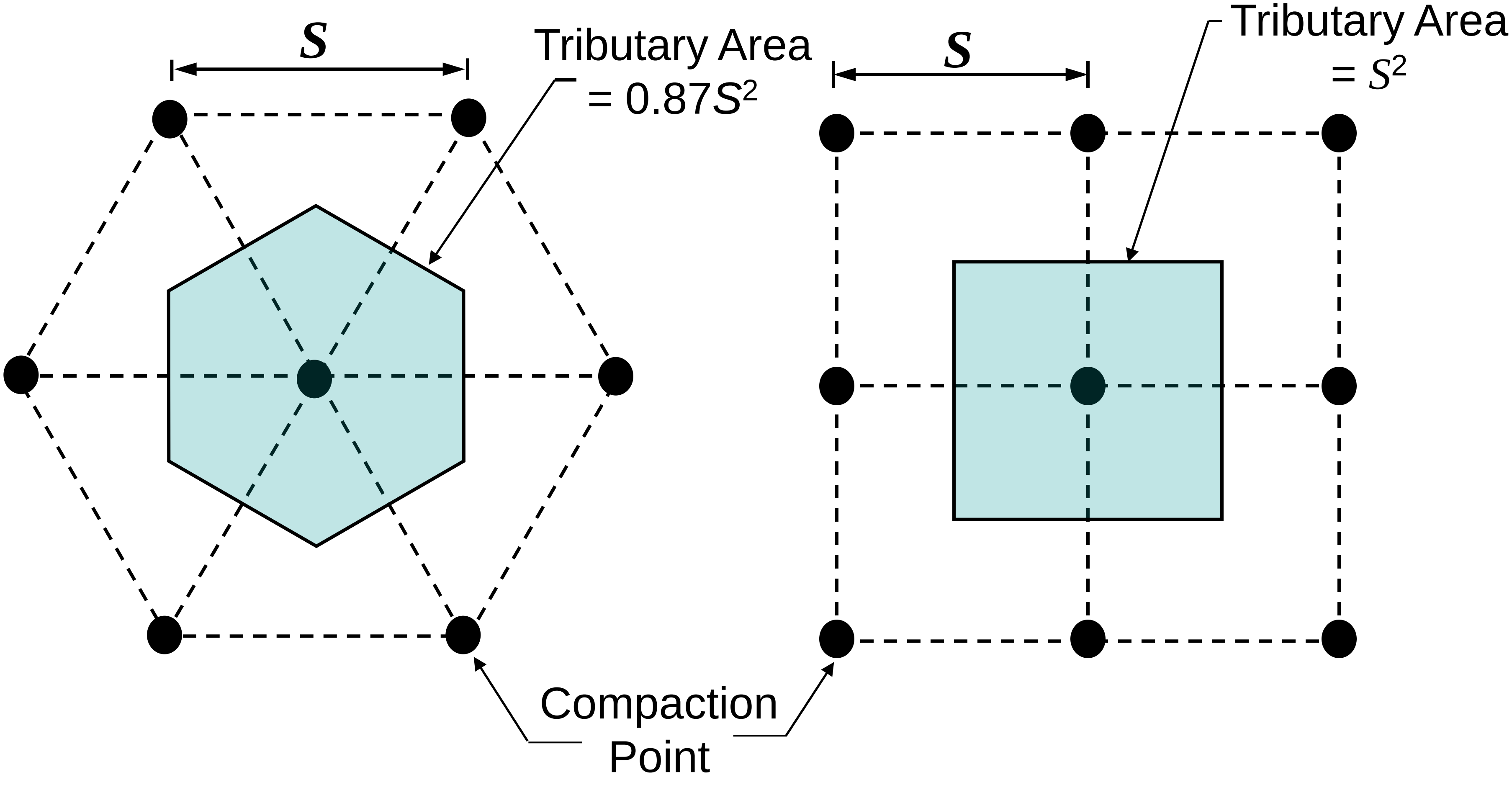
Vibroreplacement Stone Columns



- Developed based on German (1930's) vibroflotation technology, introduced to North America in 1940's
- Wet and dry methods to depths of 100 ft
- Top and bottom feed
- Column installation can provide densification of matrix soil (if fines content not excessive)
- Columns can enhance drainage and provide some reinforcement
- Rapid, but difficult to penetrate stiff cohesive soils

Compaction pile construction at Tablachaca Dam in Peru

Typical Patterns used to Treat Large Areas



S

Tributary Area = 0.87S^2

S

Tributary Area = S^2

Compaction Point

Triangular Pattern

Square Pattern

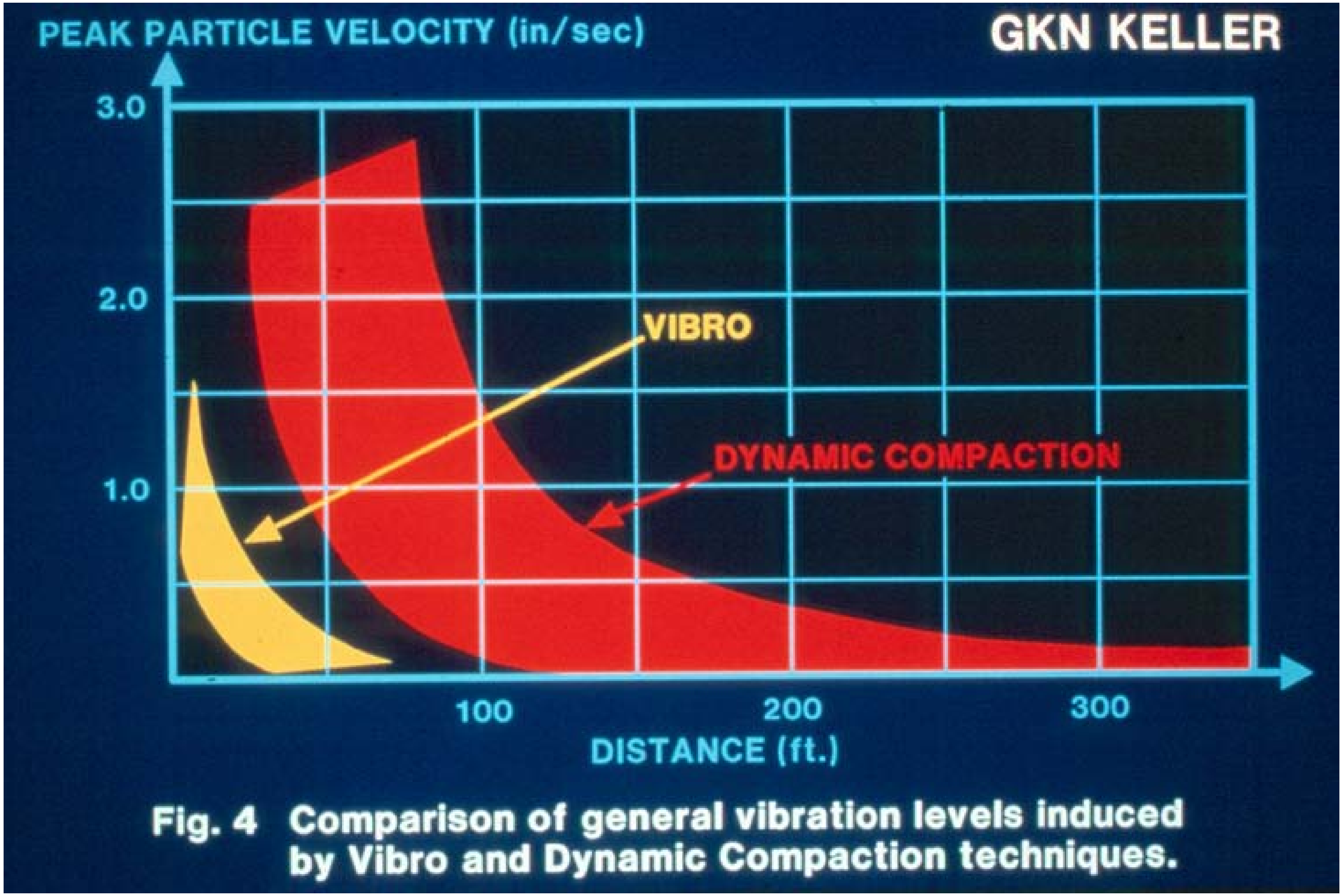


Fig. 4 Comparison of general vibration levels induced by Vibro and Dynamic Compaction techniques.

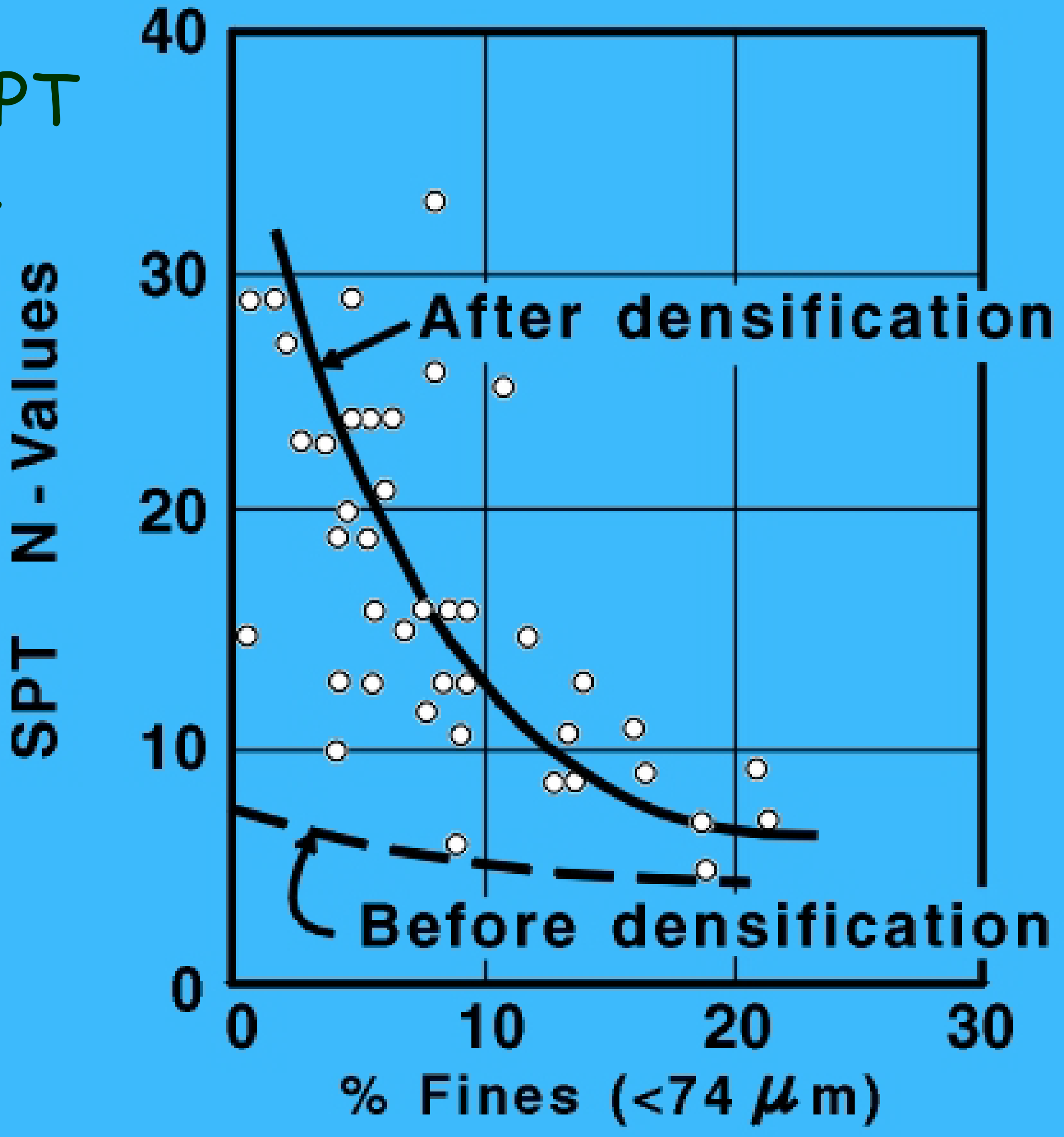
Each DDC impact influences a much greater volume of ground than the zone of influence of a probe during vibro-compaction. Much larger spacing (several meters) can be used between DDC impact points than the spacing for vibrocompaction probe points.

Expected Vibro-Compaction, Vibro-replacement and Rammed Aggregate Results

	Relative Effectiveness		
Ground Type	**Densification**	**Reinforcement**	**Drainage***
Sands	Excellent	Very Good	Good
Silty Sands	Very Good	Very Good	Very Good
Non-plastic Silts	Good	Excellent	Very Good
Clays	Marginal	Excellent	Excellent
Mine Spoils	Depends on gradation	Good	Depends on gradations
Dumped Fill	Good	Good	Depends on gradations

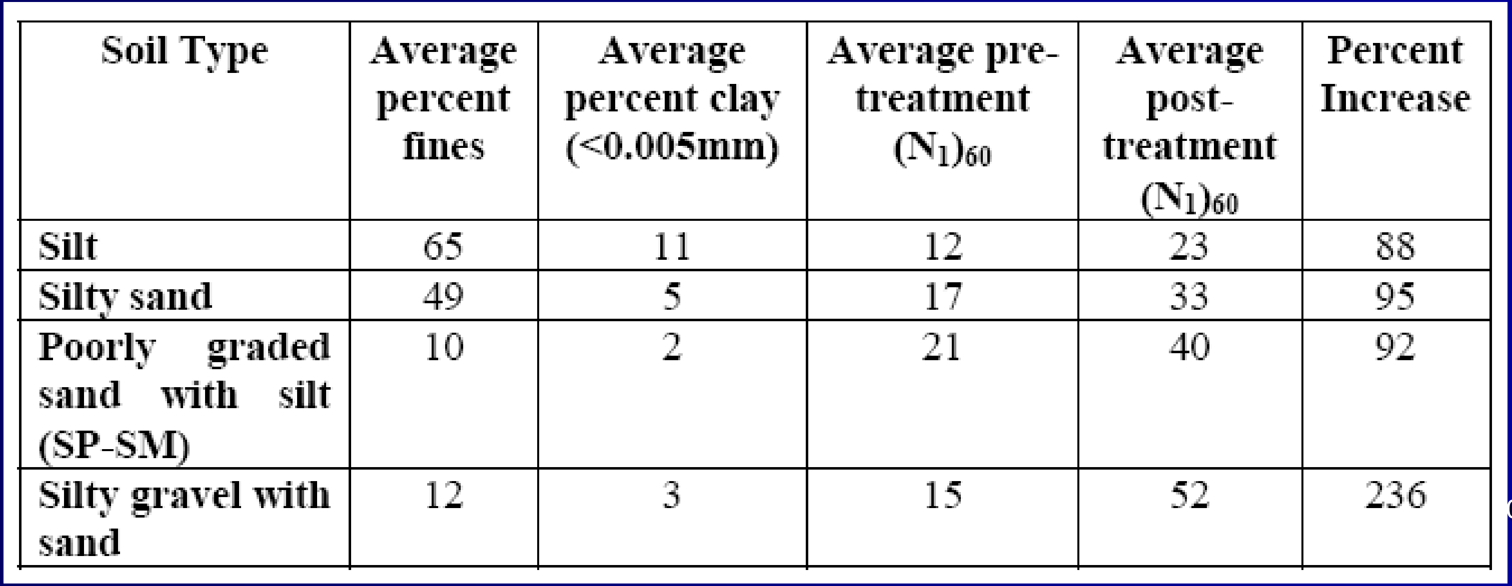
*Assumes no fines mixed into columns

Effect of fines on SPT resistance



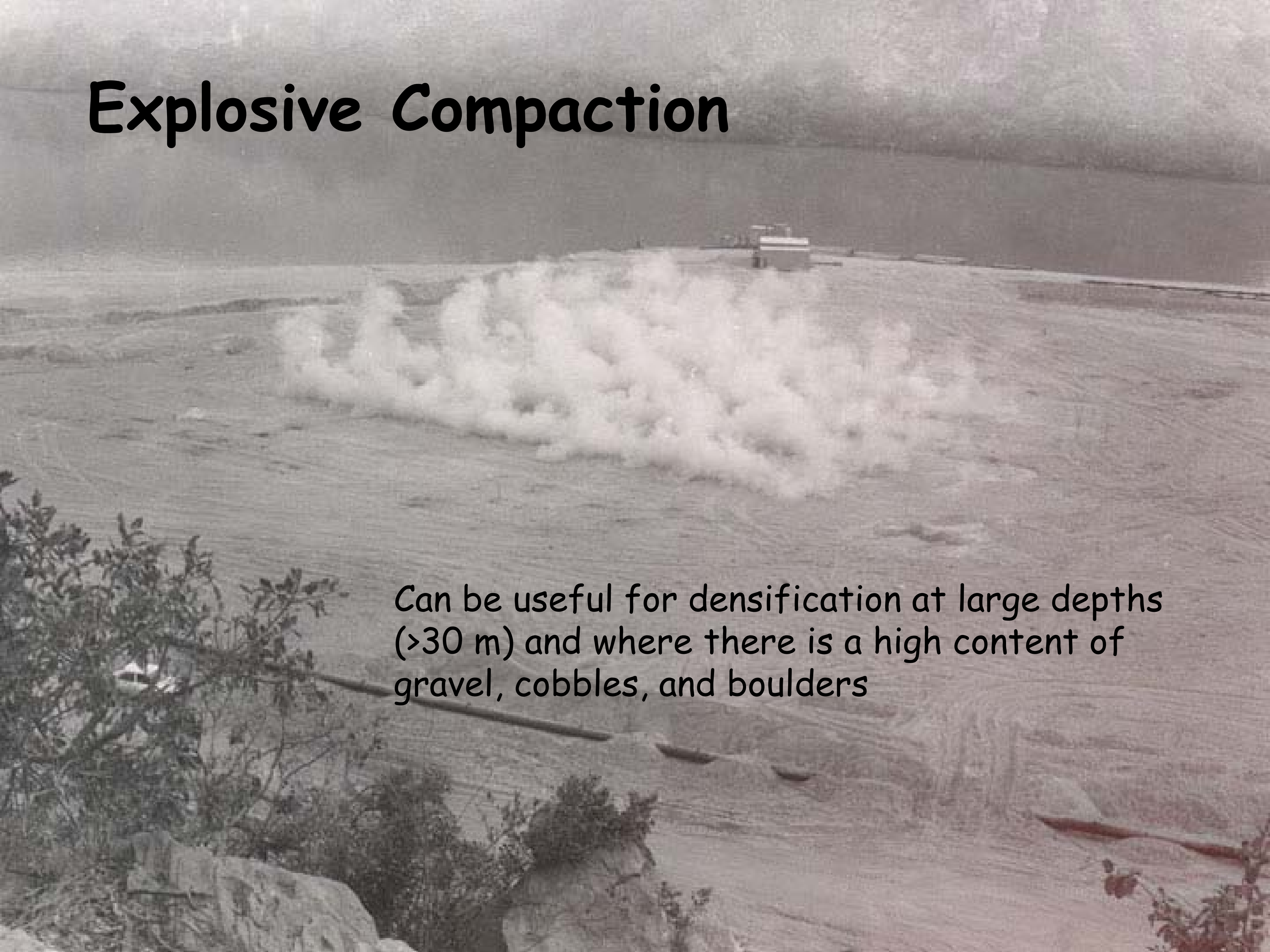
Closely-spaced Prefabricated Vertical Drains Installed **Prior** to Treatment by Vibratory or Impact Methods Can be Effective for Improvement of Higher Fines Content Soils: Salmon Lake Dam, Washington is an example (Luehring, et al 2001)

- 60-ft thick deposit of silty foundation material
- Fines content to > 60%
- Prefabricated vertical (wick) drains on 3 or 6-ft centers to depth of 58-61 ft between dry, bottom-feed stone column located on 6-ft centers
- Column diameters of 3.0 or 3.75 ft; replacement ratios of 22 or 35 %



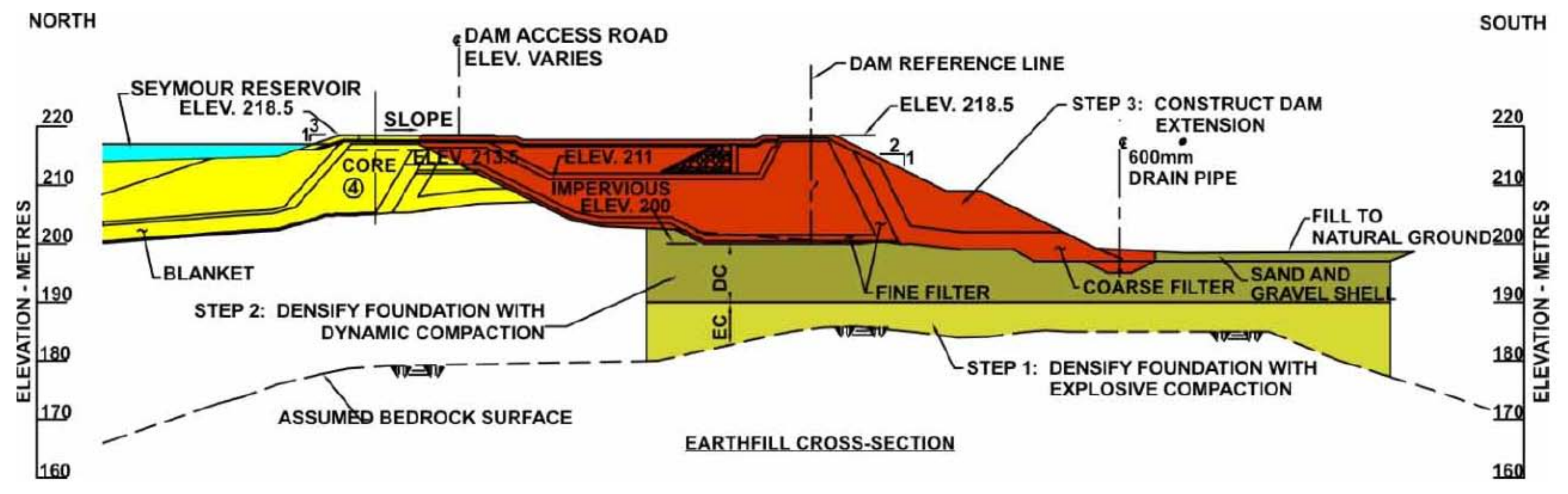
Soil Type	Average percent fines	Average percent clay (<0.005mm)	Average pre-treatment $(N_1)_{60}$	Average post-treatment $(N_1)_{60}$	Percent Increase
Silt	65	11	12	23	88
Silty sand	49	5	17	33	95
Poorly graded sand with silt (SP-SM)	10	2	21	40	92
Silty gravel with sand	12	3	15	52	236

Explosive Compaction



Can be useful for densification at large depths (>30 m) and where there is a high content of gravel, cobbles, and boulders

Seymour Falls Dam prior to Seismic Upgrade
(Siu et al., **13th World Conference on Earthquake Engineering, Vancouver,** 2004)



Foundation Densification by Explosive Compaction and Deep Dynamic Compaction at Seymour Falls Dam prior to Construction of New Embankment

(Siu et al., **13th World Conference on Earthquake Engineering, Vancouver,** 2004)

Densification of a high gravel and cobble content layer at Seymour Falls Dam, BC – note gas and water ejecting from blast holes (from Elliott, et al)

Deep Dynamic Compaction at Seymour Falls Dam

Most drops were 25 tonnes from 25 meters

Ave. energy was 550 tonne-m/sq m.

(from Murray, et al, 2005)

Seymour Falls Dam after Remediation

New earthfill dam and gravity wall extension, with the original earthfill dam showing as a grassy ridge along the top; the concrete slab and buttress dam is at right. (Canadian Consulting Engineer, October 2007)

Comparative Costs

Actual cost depends on project size, location, depth of treatment, mobilization, local conditions, availability of contractors, etc.

A relative cost of 1 may be of the order of $(3-4)/m^3 of improved ground.

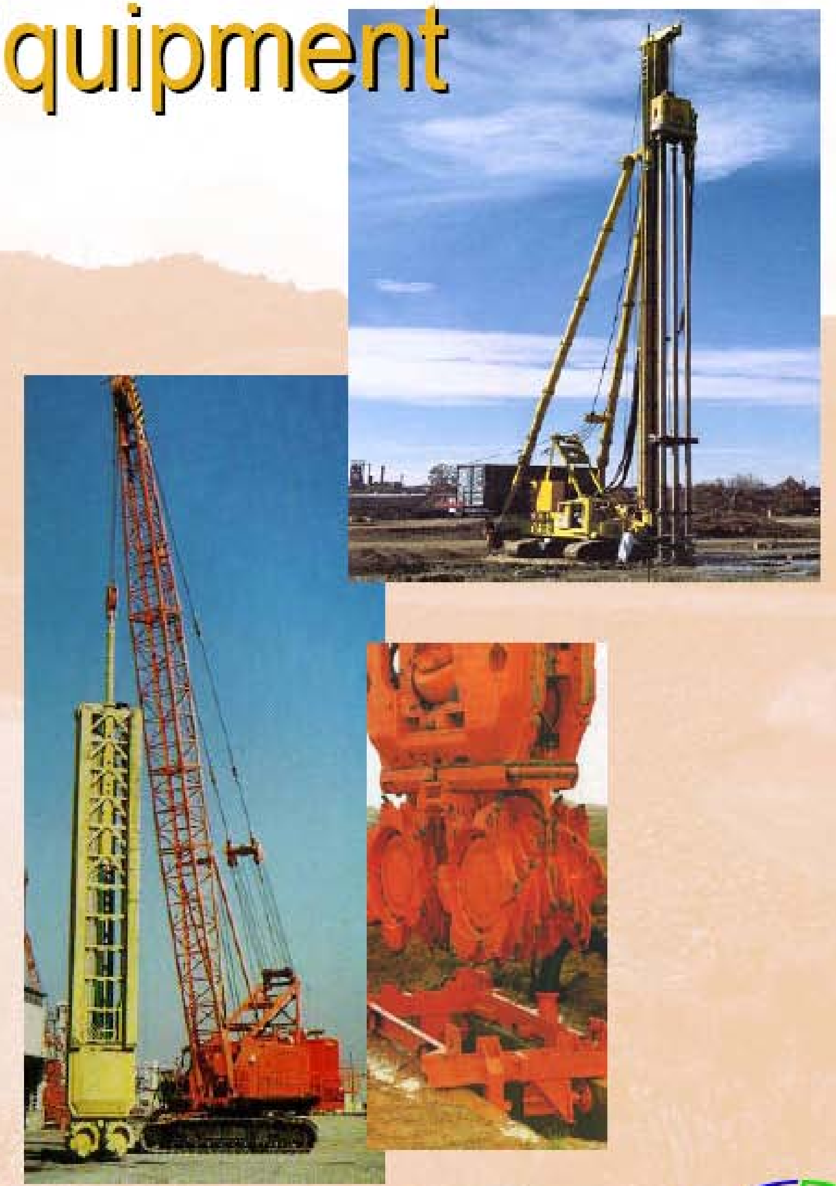
Comparative Costs of Vibro-Densification Methods:	
Treatment Method	**Relative Cost (per unit volume)**
Deep Dynamic Compaction	0.5 - 2
Vibro-Replacement	3 - 10
Vibro-Compaction	2 - 10
Vibratory Probe	~3
Blasting (EC)	0.25 - 1

Deep soil mixing at Jackson Lake Dam

(First large-scale use of DSM in the U.S.)

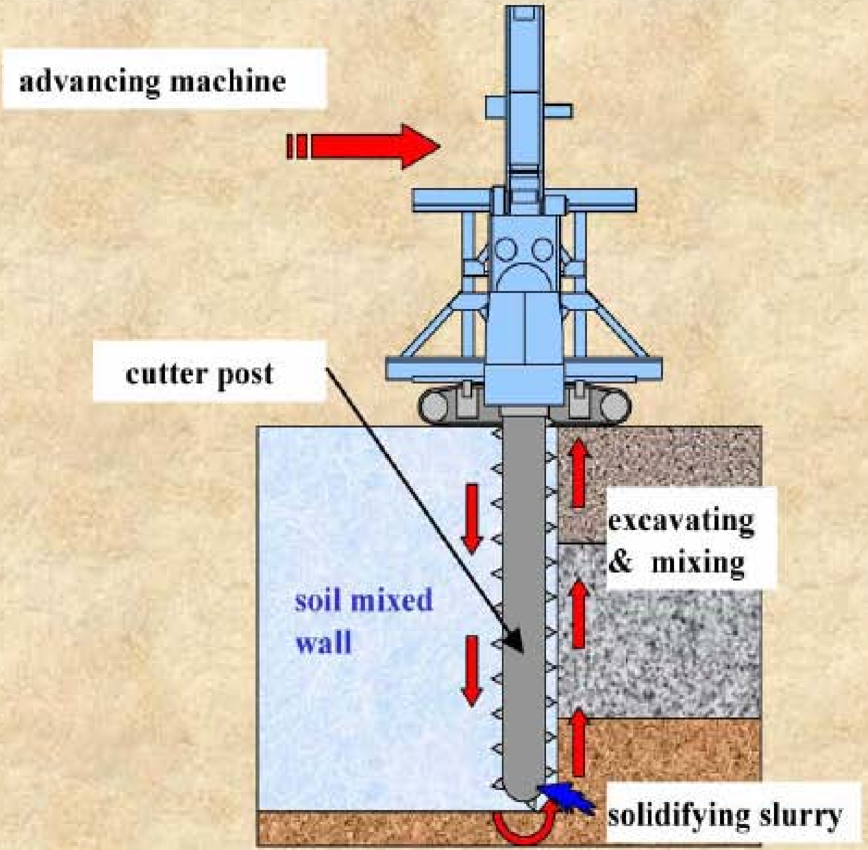
CDSM Equipment

- Multi-Axis Augers
- TRD
- Hydro-Mill



Multi-Axis Augers

TRD – Trench Cutting Re-Mixing Deep Wall Method



advancing machine

cutter post

excavating & mixing

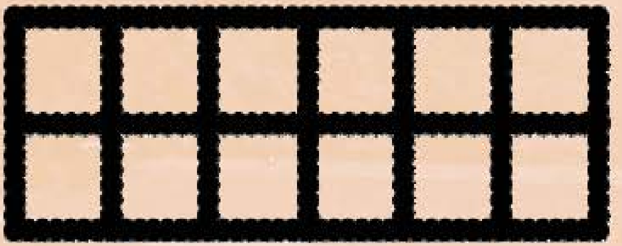
soil mixed wall

solidifying slurry

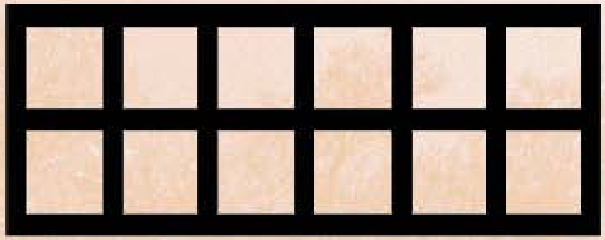
starter cutter post

Typical Arrangement of CDSM Elements

TWO-WAY GRID

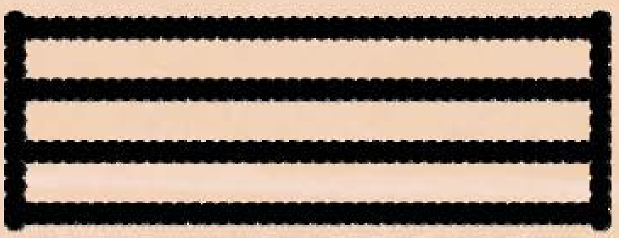


Multi-Auger Walls



Smooth Walls

SHEAR WALLS WITH END PANELS



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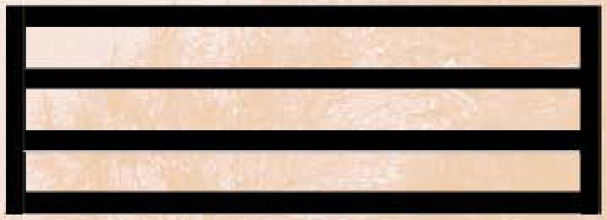
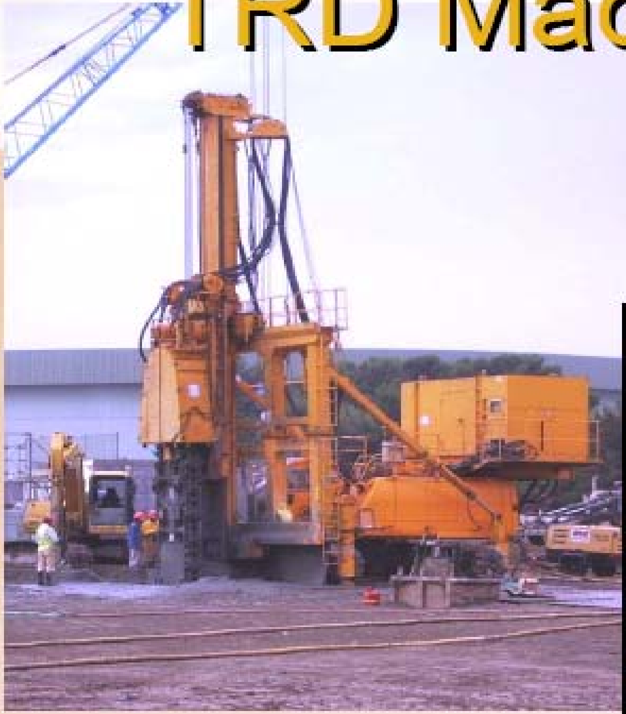


Smooth Walls

TRD Machine in Operation



Excavated TRD Walls

Schematic of Jet Grouting

Cement Deep Soil Mix and Jet Grout Columns at a Recent (2006) Dam Downstream Test Section

Jet Grout and CDSM Columns at a Recent (2006) Dam Test Section

Selection of most appropriate method(s) depends on many factors, including:

- Soil type and suitable methods for improving it
- Level of improvement needed
- Magnitude of improvement attainable by a method
- Required depth and thickness of treatment
- Areal extent of treatment
- Accessibility of the site
- Environmental considerations
- Time and cost considerations
- Local experience
- Confidence in method effectiveness (QA/QC)
- Construction risks
- Long-term monitoring and performance requirements

METHODS FOR EVALUATION OF IMPROVED GROUND

- Surface settlement and heave
- Backfill quantities
- Sampling of admixture treated soil
- Penetration tests: SPT, CPT, BPT, DMT
- Shear wave velocity
- Undisturbed samples
- Hydraulic conductivity (in-situ)
- Construction data records (power, energy input, pressures, quantities, rates, etc.)
- "Can see a lot just by watching"

QA/QC requirements for improved ground

- During construction, observations should be made and recorded at each improvement location, including:
  - Ground surface movements
  - Volume of backfill material used
  - Grout take
  - Amount of energy or pressure expended
  - Consistency, unit weight, viscosity of mixed in-situ materials and spoils returned to the ground surface
- After construction, in-situ methods such as SPT, CPT and/or shear wave velocity testing can be performed to verify that the level of improvement is achieved.
- Laboratory testing can also be used to verify some types of improvement