Lecture 19: Liquefaction

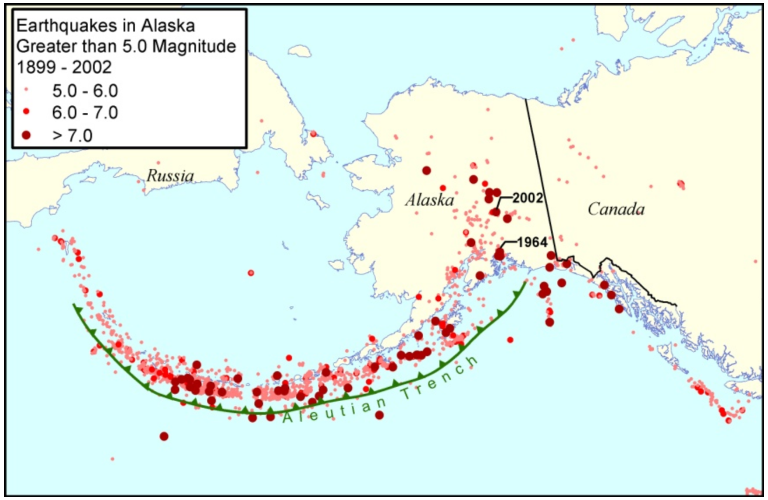
Key Questions

1. What types of sediments are most susceptible to liquefaction?
2. What determines the “shear strength” of sediments?
3. Why do liquefiable sediments have to be saturated with water?
4. Why does ground shaking due to earthquakes amplify in soft sediments?
5. What is lateral spreading?
6. Why is the Bellingham waterfront susceptible to these hazards?


Niigata Japan, 1964 liquefaction

Liquefaction

Alaska Earthquake of March 28, 1964



Alaska Earthquake of March 28, 1964

http://cee.uiuc.edu/sstl/education/liquefaction/HOUSE.html

http://www.smate.wwu.edu/teched/geology/eq-general.html

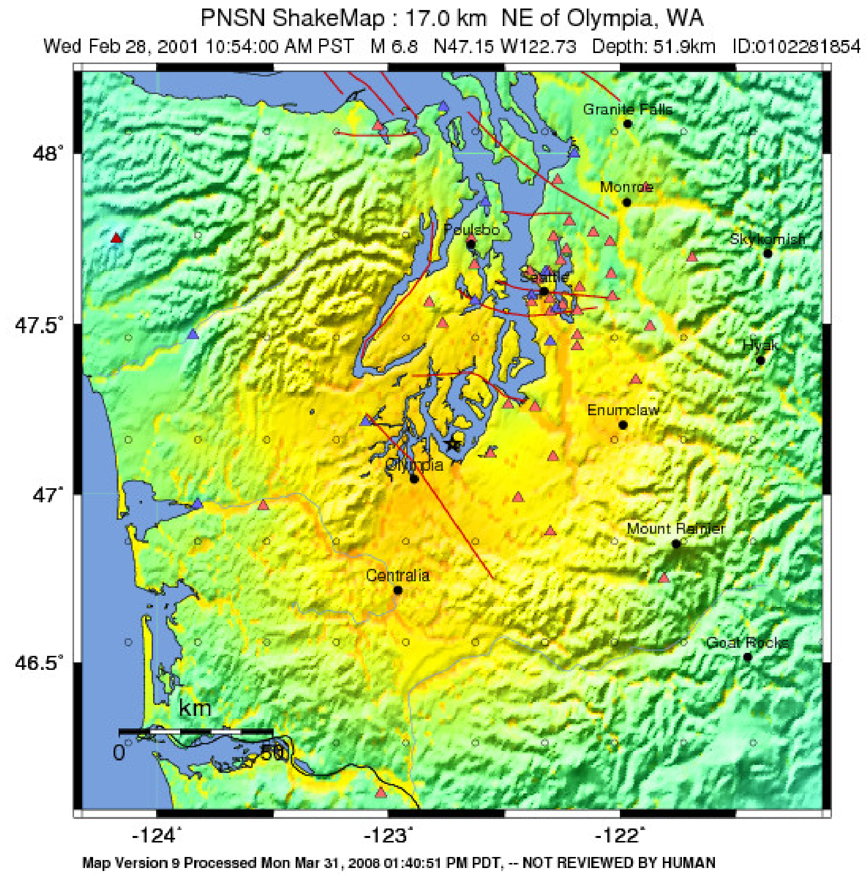
Earthquake of July 29, 1967, Caracas, Venezuela

http://www.smate.wwu.edu/teched/geology/eq-general.html

Nisqually Earthquake: Liquefaction

Nisqually earthquake 02/28/2001: Olympia, WA

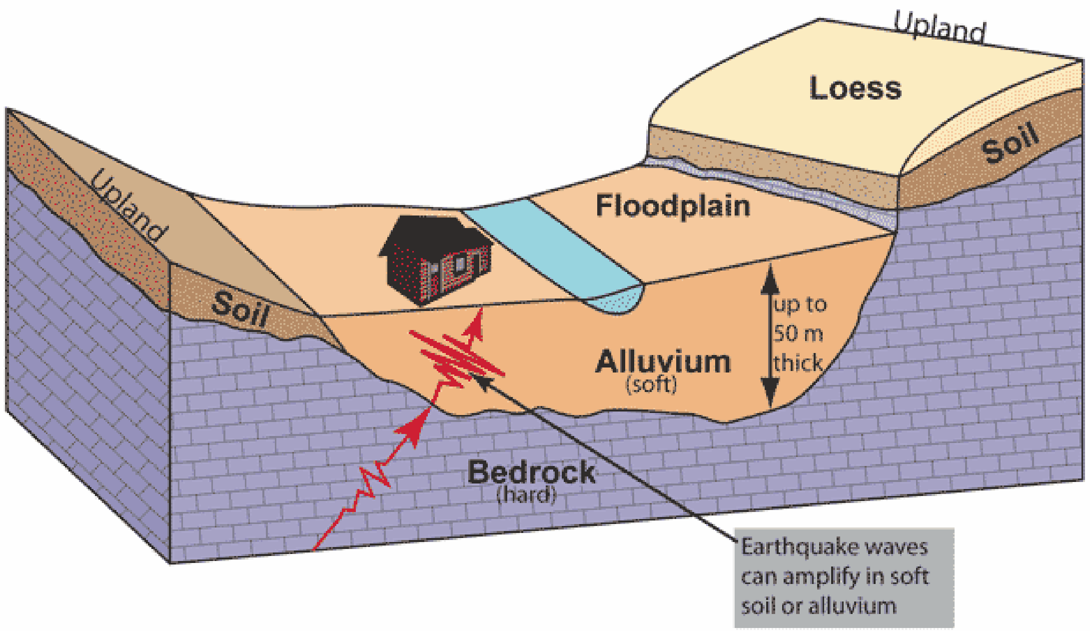
Liquefaction is initiated by ground shaking from EQs
(Nisqually Earthquake, February 28 2001)

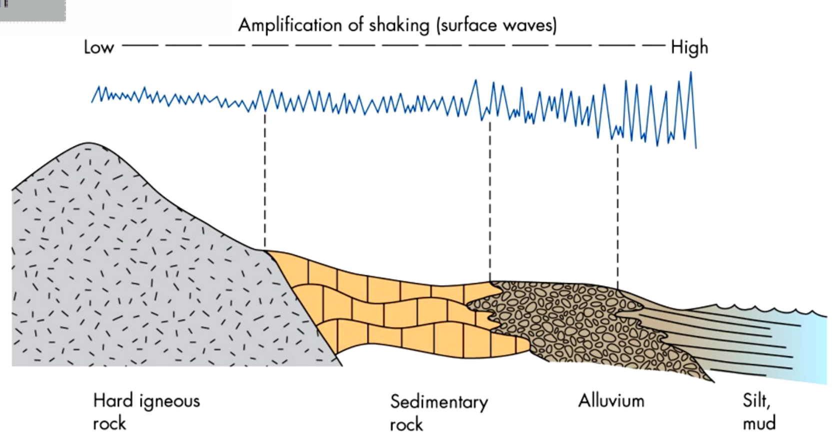


PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

http://www.ess.washington.edu/shake/0102281854/intensity.html

Ground shaking is amplified in soft, unconsolidated sediments

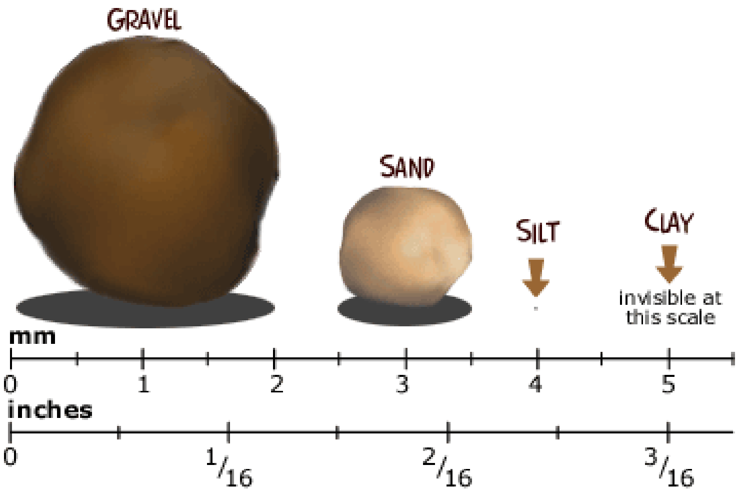




Keller, E.A., Introduction to Environmental Geology, 3rd Ed. 2005, Pearson Prentice Hall

Liquefaction occurs in **saturated** **sand** or **silts**

USDA Soil Classification



Geological factors that influence the degree of liquefaction in a saturated sand or silt include:

1) depositional environment or type of sediment

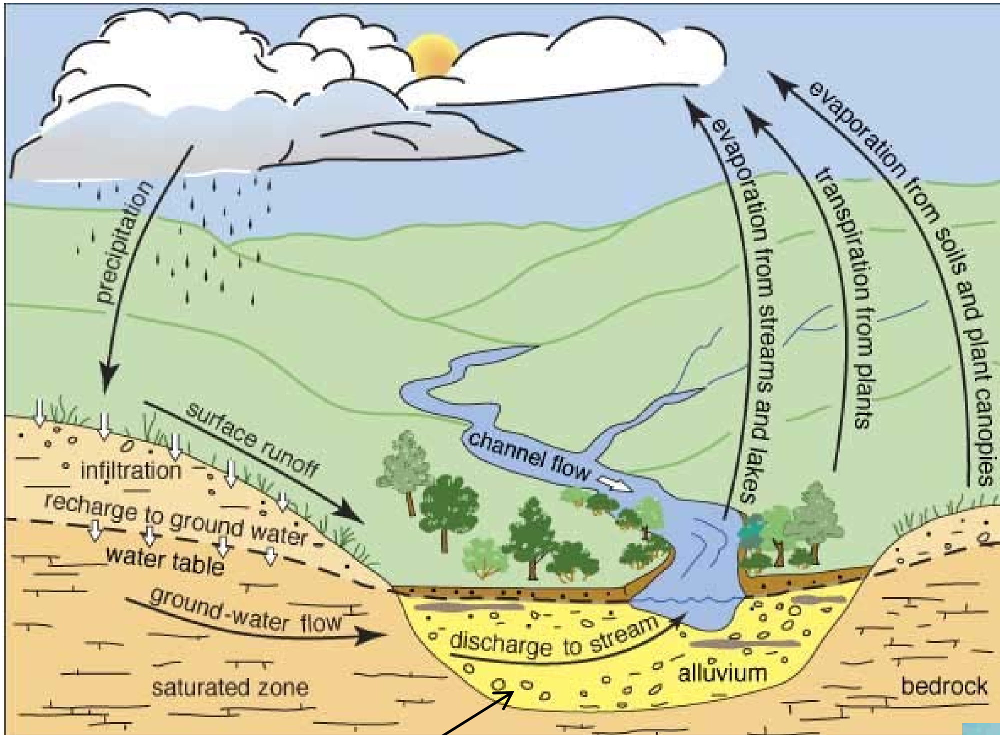
→ alluvial deposits are typically porous “loose” sands and silts

2) age

→ young alluvial deposits are typically more porous (higher susceptibility)

→ older deposits become more compacted and cemented (lower susceptibility

3) ground shaking magnitude



alluvium – unconsolidated, loose, sediments deposited by a river

Copper River, Alaska

Liquefaction Susceptibility and Site Class Maps of Washington State, By County

by Stephen P. Palmer,
Sammantha L. Magsino,
Eric L. Bilderback,
James L. Poelstra,
Derek S. Folger,
and Rebecca A. Niggemann

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Open File Report 2004-20
September 2004

This report has not been edited or reviewed for conformity with Division of Geology and Earth Resources standards and nomenclature

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

Table 2. Correlations of age and type of geologic deposit with liquefaction susceptibility, modified from Youd and Perkins (1978).

Type of deposit	General distribution of cohesionless sediments	Likelihood that cohesionless sediments, when saturated, would be susceptible to liquefaction (by age of deposit)			
		< 500 yr	Holocene	Pleistocene	Pre-Pleistocene
river channel	locally variable	very high	high	low	very low
flood plain	locally variable	high	moderate	low	very low
alluvial fan and plain	widespread	moderate	low	low	very low
marine terraces and plains	widespread	--	low	very low	very low
lacustrine and playa	variable	high	moderate	low	very low
colluvium	variable	high	moderate	low	very low
dunes	widespread	high	moderate	low	very low
loess	variable	high	high	high	unknown
glacial till	variable	low	low	very low	very low
tuff	rare	low	low	very low	very low
beach (high wave energy)	widespread	moderate	low	very low	very low
beach (low wave energy)	widespread	high	moderate	low	very low
uncompacted fill	variable	very high	--	--	--
compacted fill	variable	low	--	--	--

Palmer, S. P., S. L. Magsino, E. L. Bilderback, J. L. Poelstra, D. S. Folger, and R. A. Niggemann. Liquefaction Susceptibility and Site Class Maps of Washington State, By County, Washington Division of Geology and Earth Resources, Open File Report 2004-20, September 2004.

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loess	variable	high	high	high	unknown
glacial till	variable	low	low	very low	very low
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Whatcom County Glacial Deposits

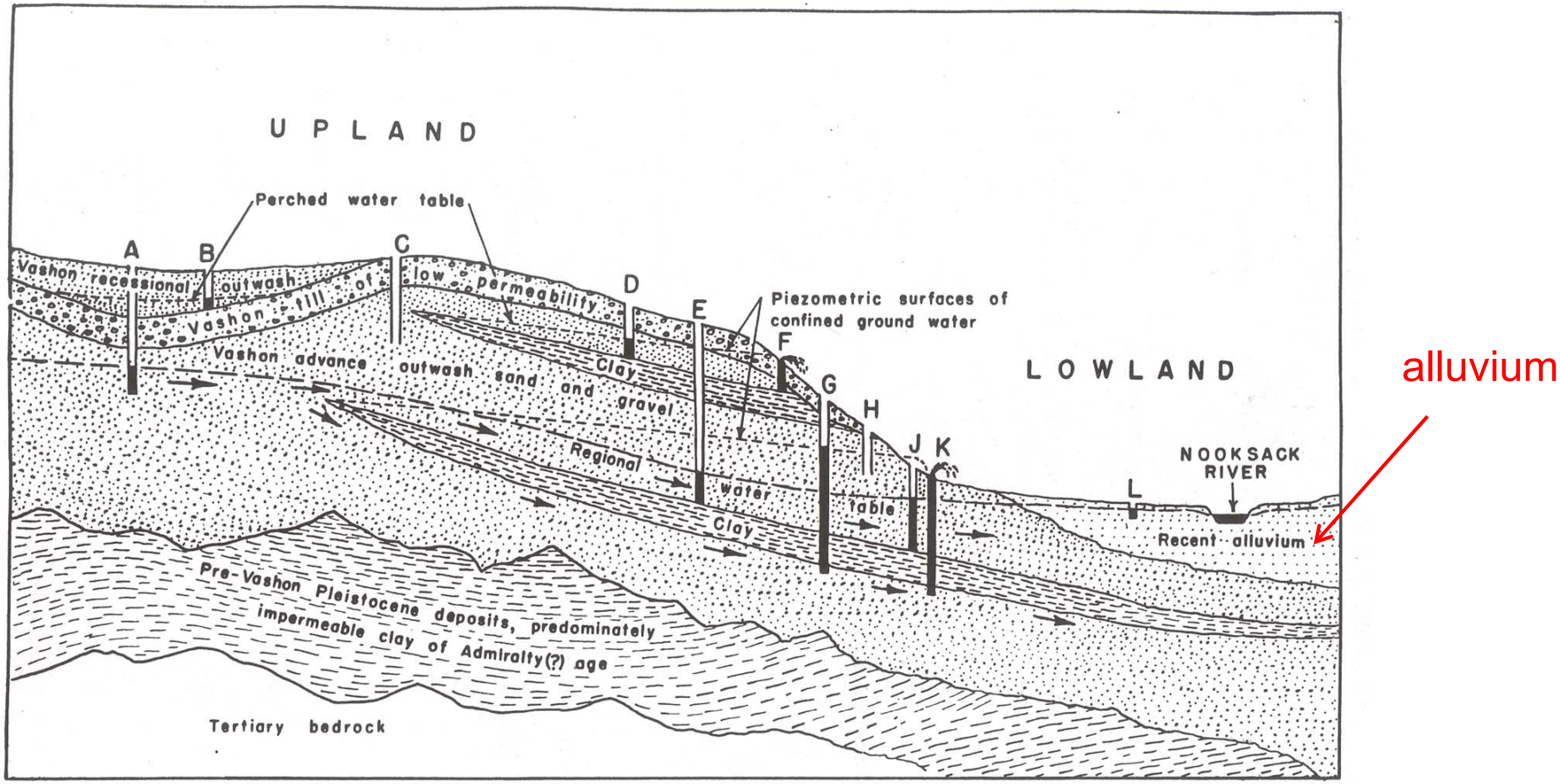
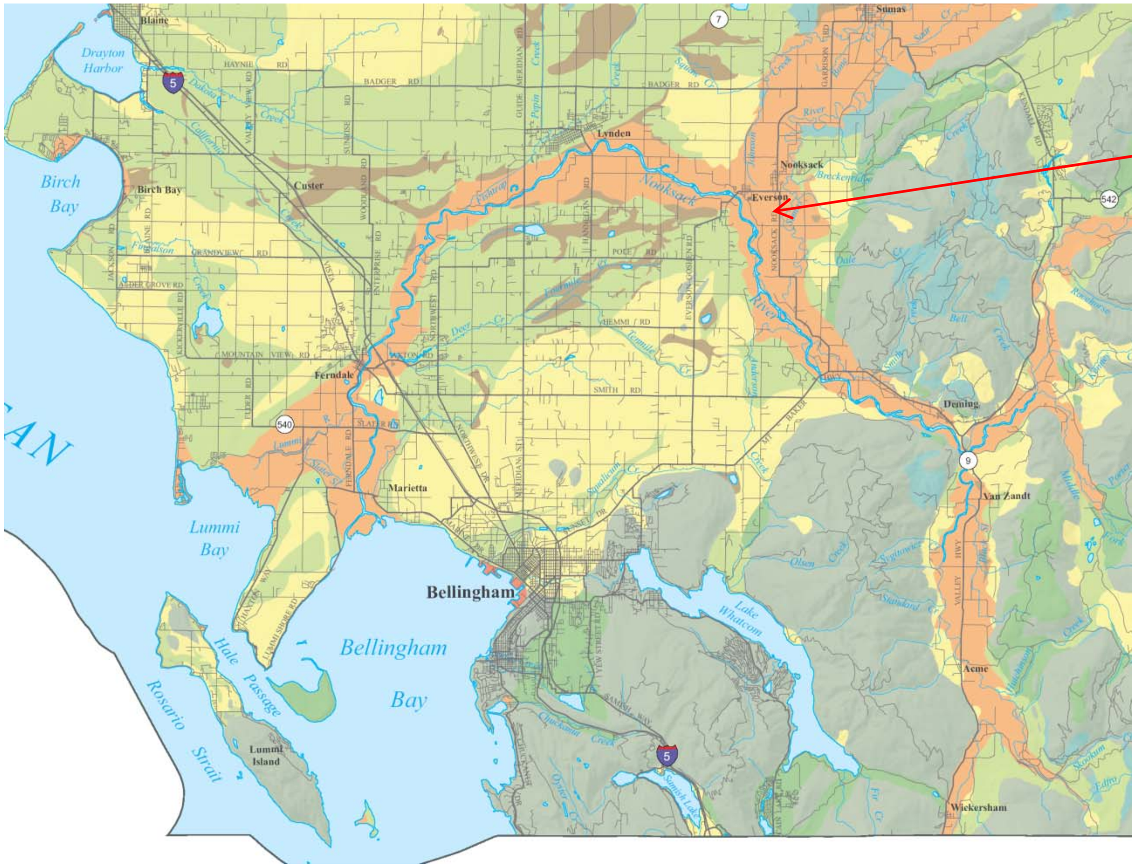


Figure 11. GENERAL CONDITIONS OF GROUND-WATER OCCURRENCE WITHIN THE LOWER NOOKSACK RIVER BASIN. Vertical scale exaggerated. Arrows indicate direction of ground-water movement.



EXPLANATION

- Liquefaction susceptibility: HIGH
- Liquefaction susceptibility: MODERATE to HIGH
- Liquefaction susceptibility: MODERATE
- Liquefaction susceptibility: LOW to MODERATE
- Liquefaction susceptibility: LOW
- Liquefaction susceptibility: VERY LOW to LOW
- Liquefaction susceptibility: VERY LOW
- Bedrock
- Peat deposit — Peat is not susceptible to liquefaction but may undergo permanent displacement or loss of strength as a result of earthquake shaking.
- Water
- Ice

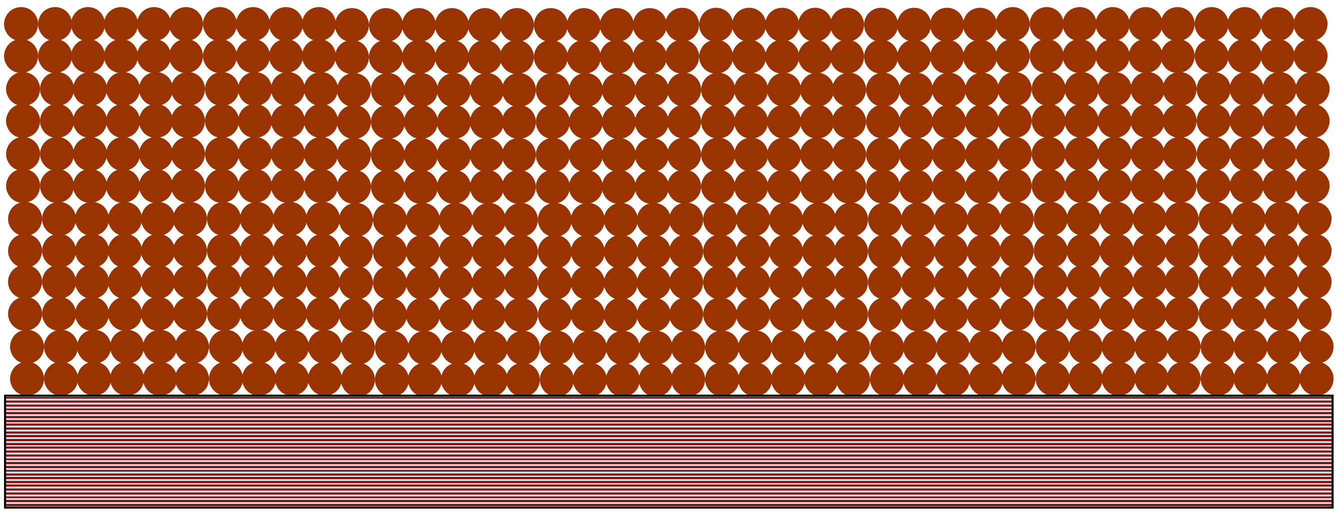
This explanation is standardized for this series of county-based liquefaction maps; some categories may not appear on this map.

Palmer, S. P., S. L. Magsino, E. L. Bilderback, J. L. Poelstra, D. S. Folger, and R. A. Niggemann. Liquefaction Susceptibility and Site Class Maps of Washington State, By County, Washington Division of Geology and Earth Resources, Open File Report 2004-20, September 2004.

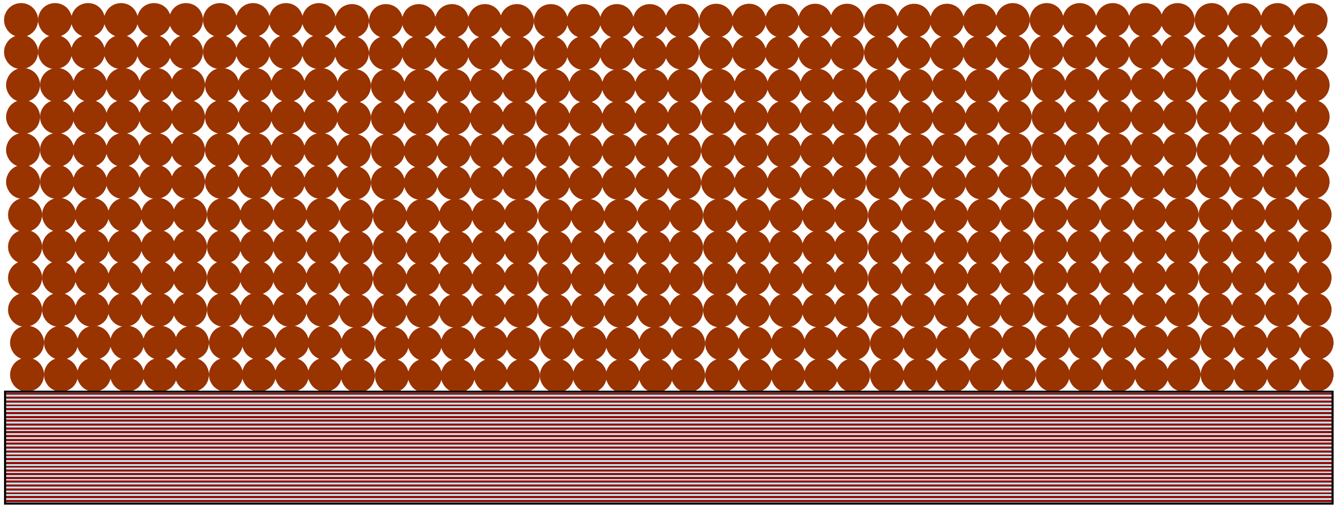
Liquefaction is the sudden loss of shear strength of a saturated sand or silt due to earthquake shaking

What determines shear strength of a sand or silt?

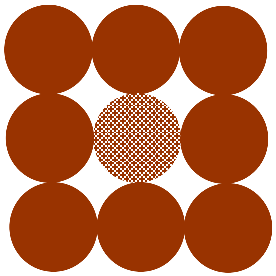
The shear strength is controlled by the degree of grain-to-grain contact (friction) in the sediment

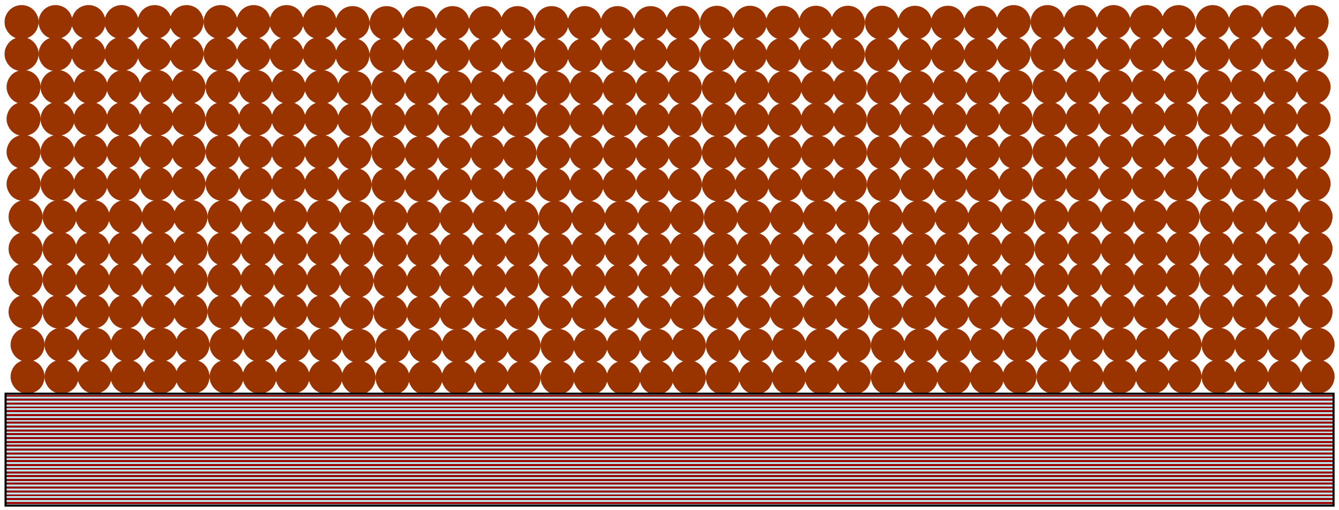


Grain-to-grain contact is partly controlled by packing

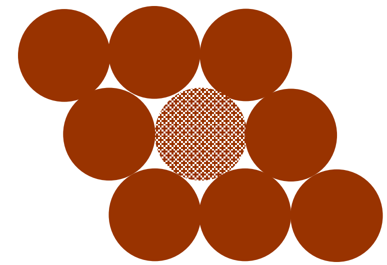


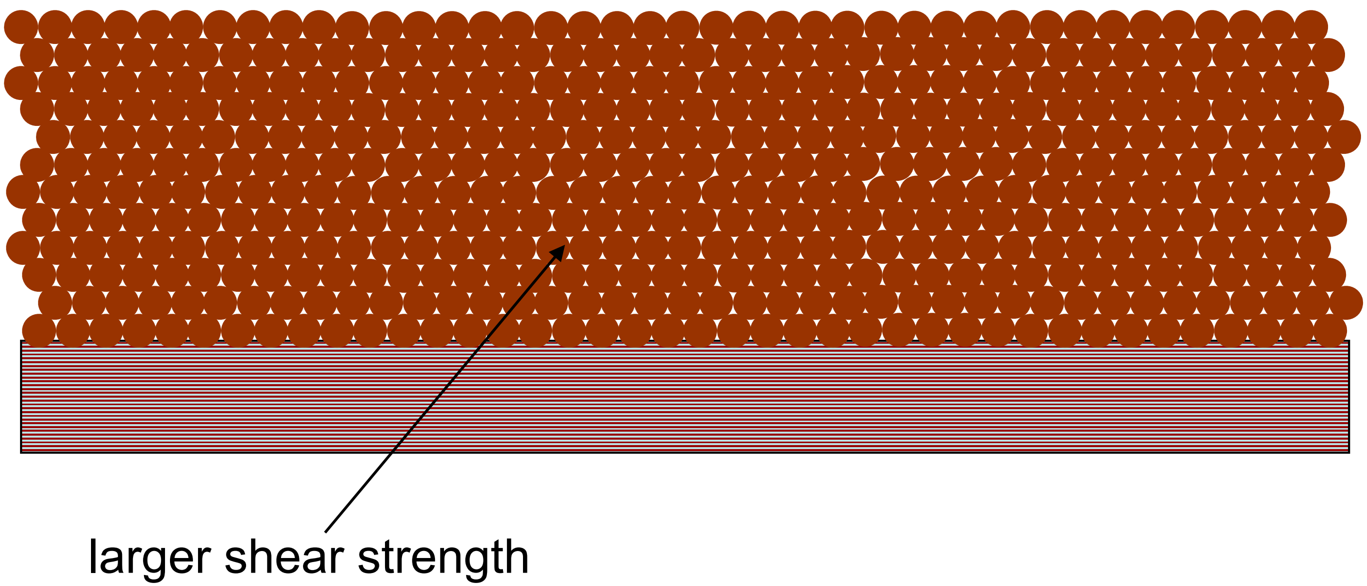
cubic packing: each grain touches 6 other grains



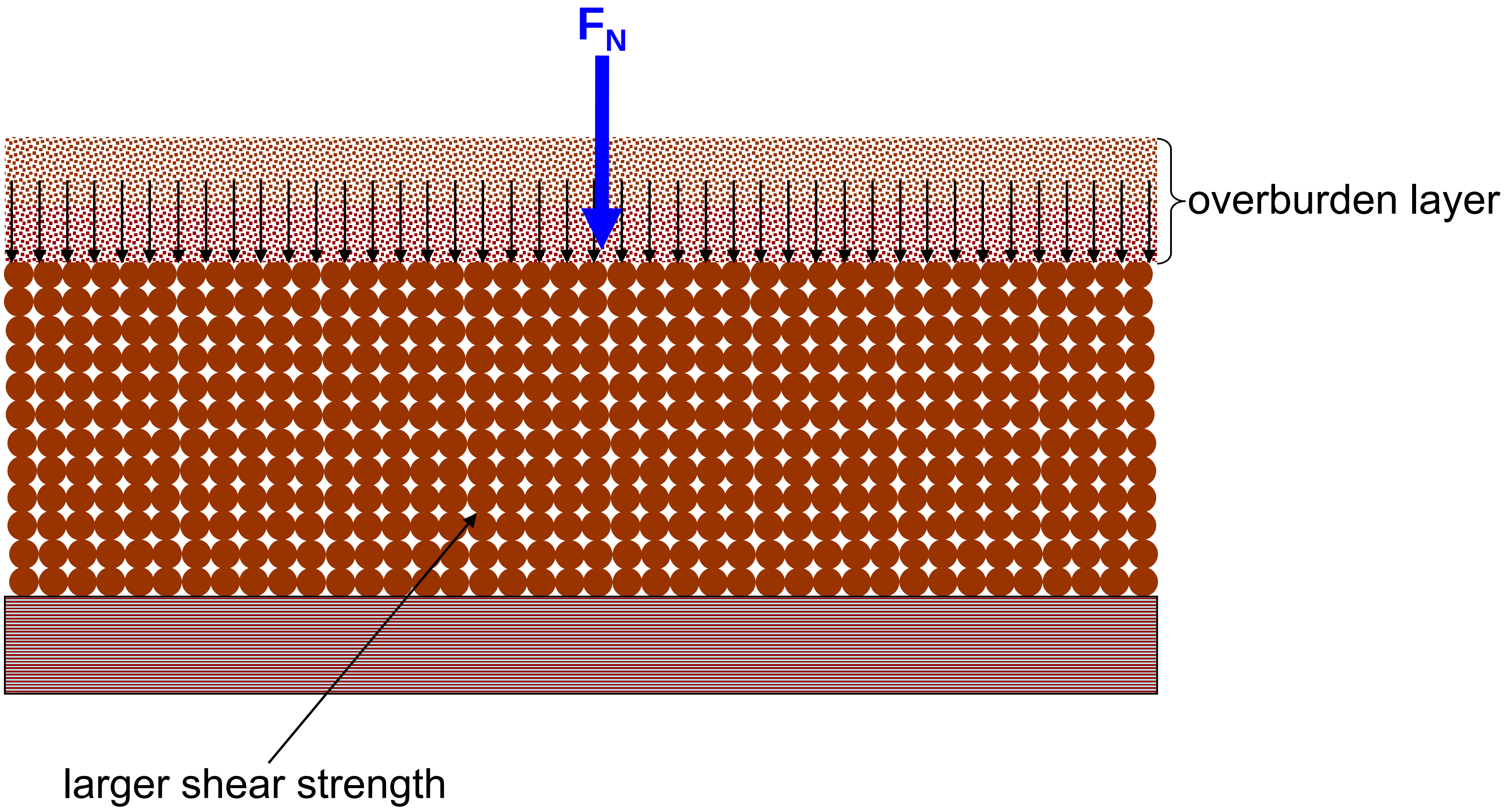


rhombohedron packing: each grain touches 12 other grains

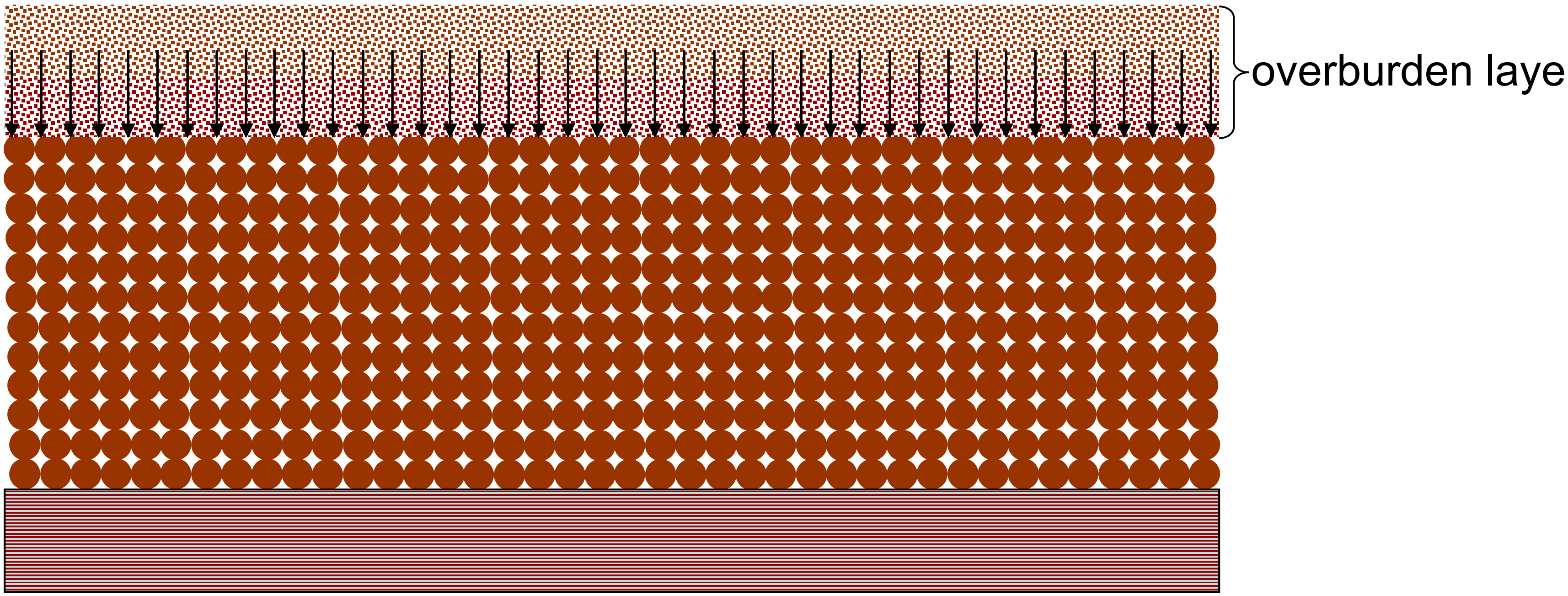




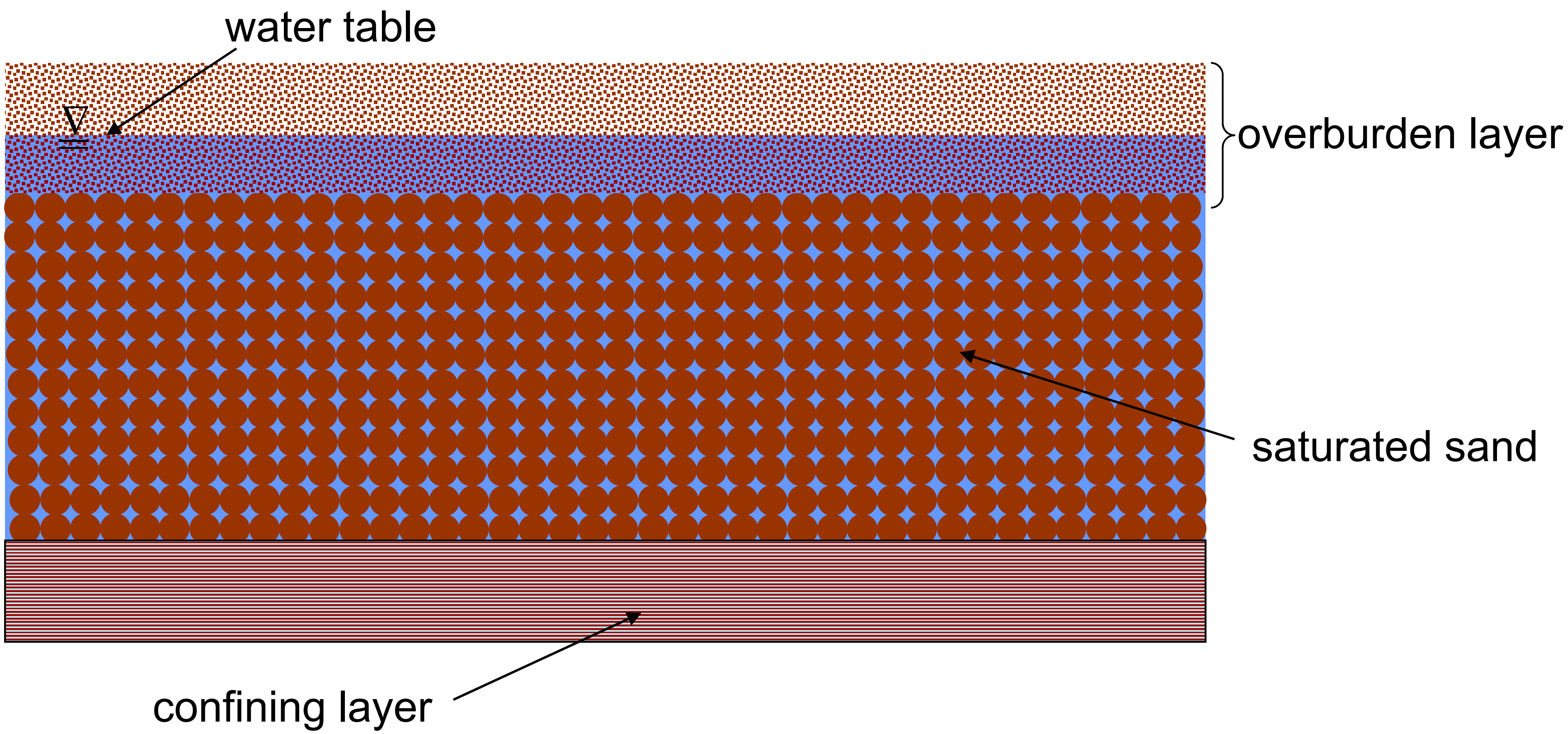
Overburden stress increases the grain-to-grain interaction, hence the shear strength

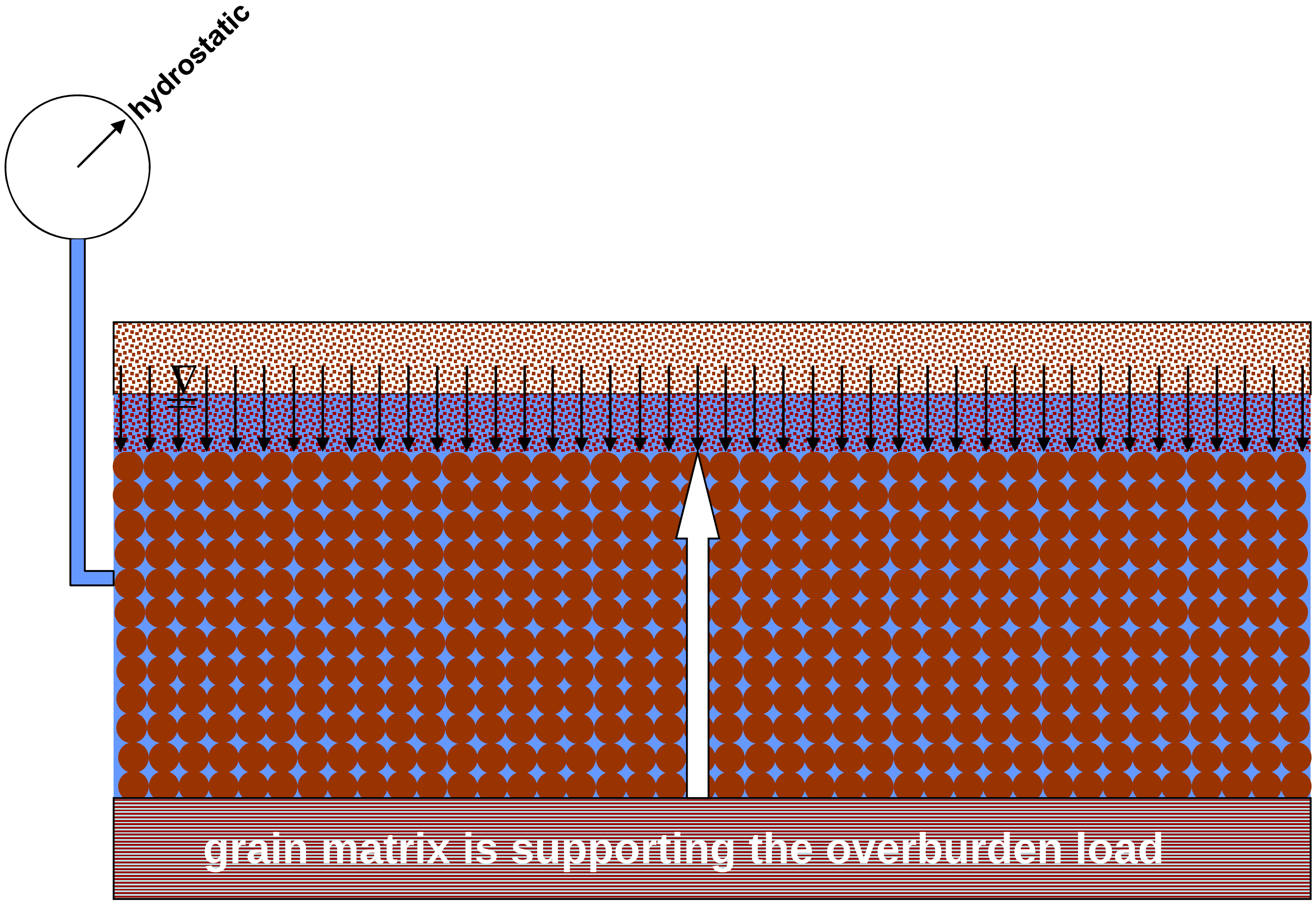


What causes the sand to lose shear strength during an earthquake?

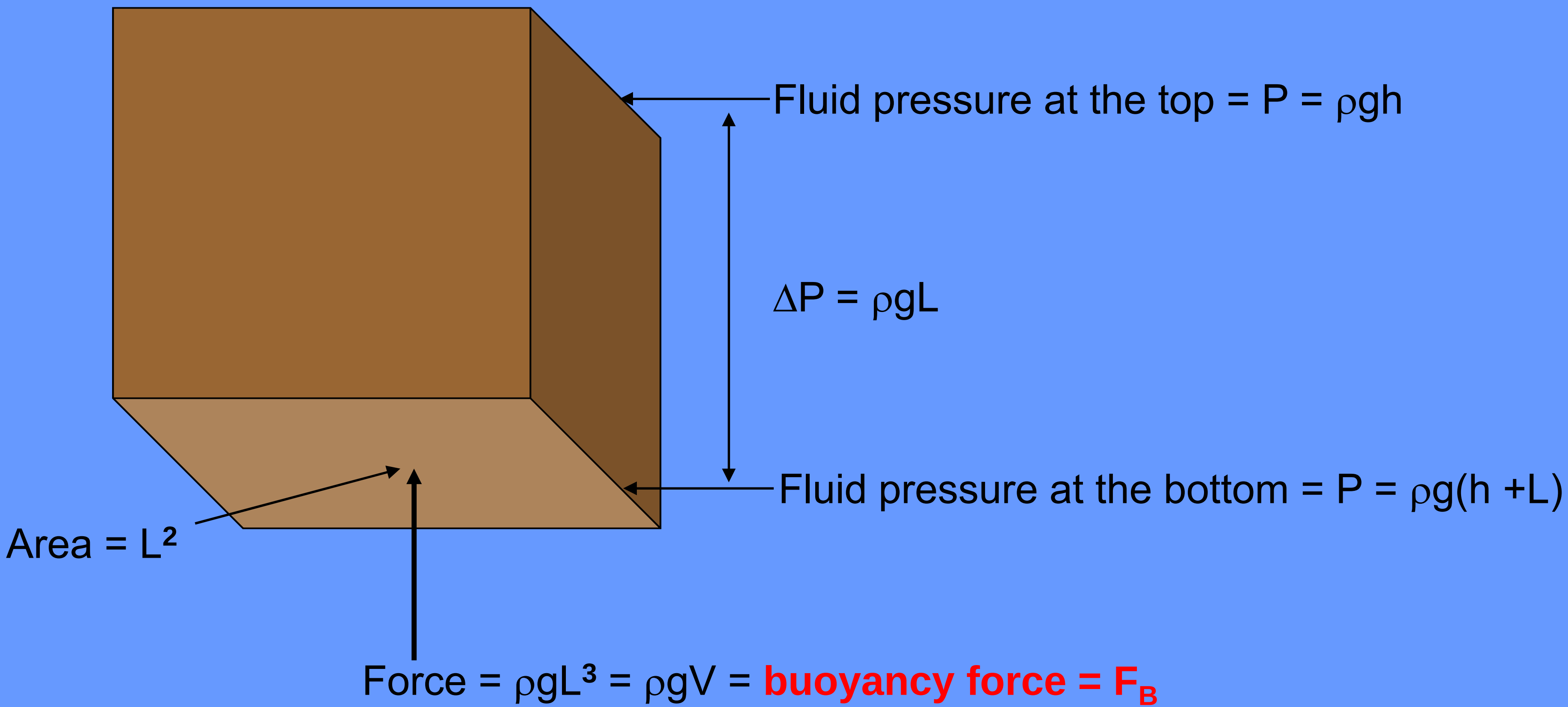


It starts with water

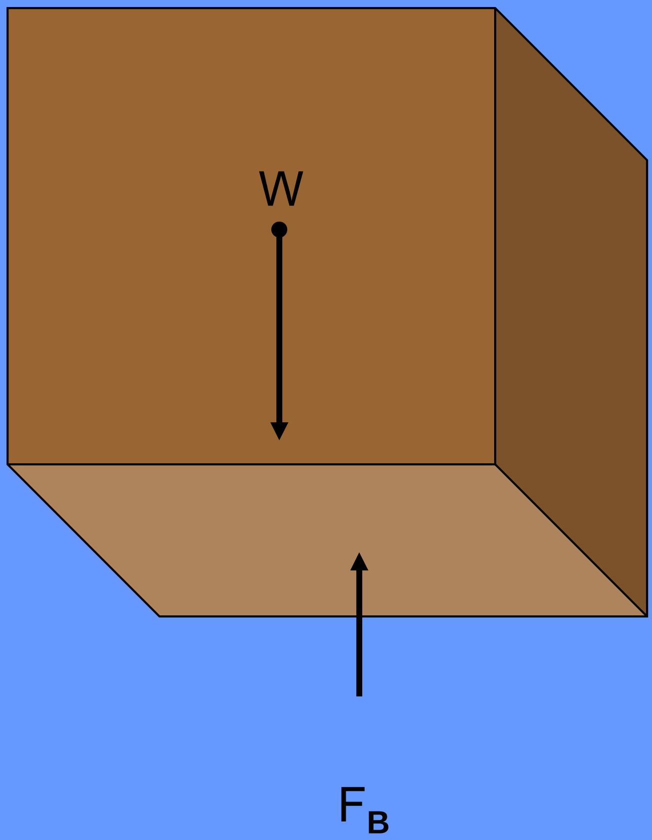



hydrostatic
grain matrix is supporting the overburden load

Cubic grain immersed in water (side length "L")



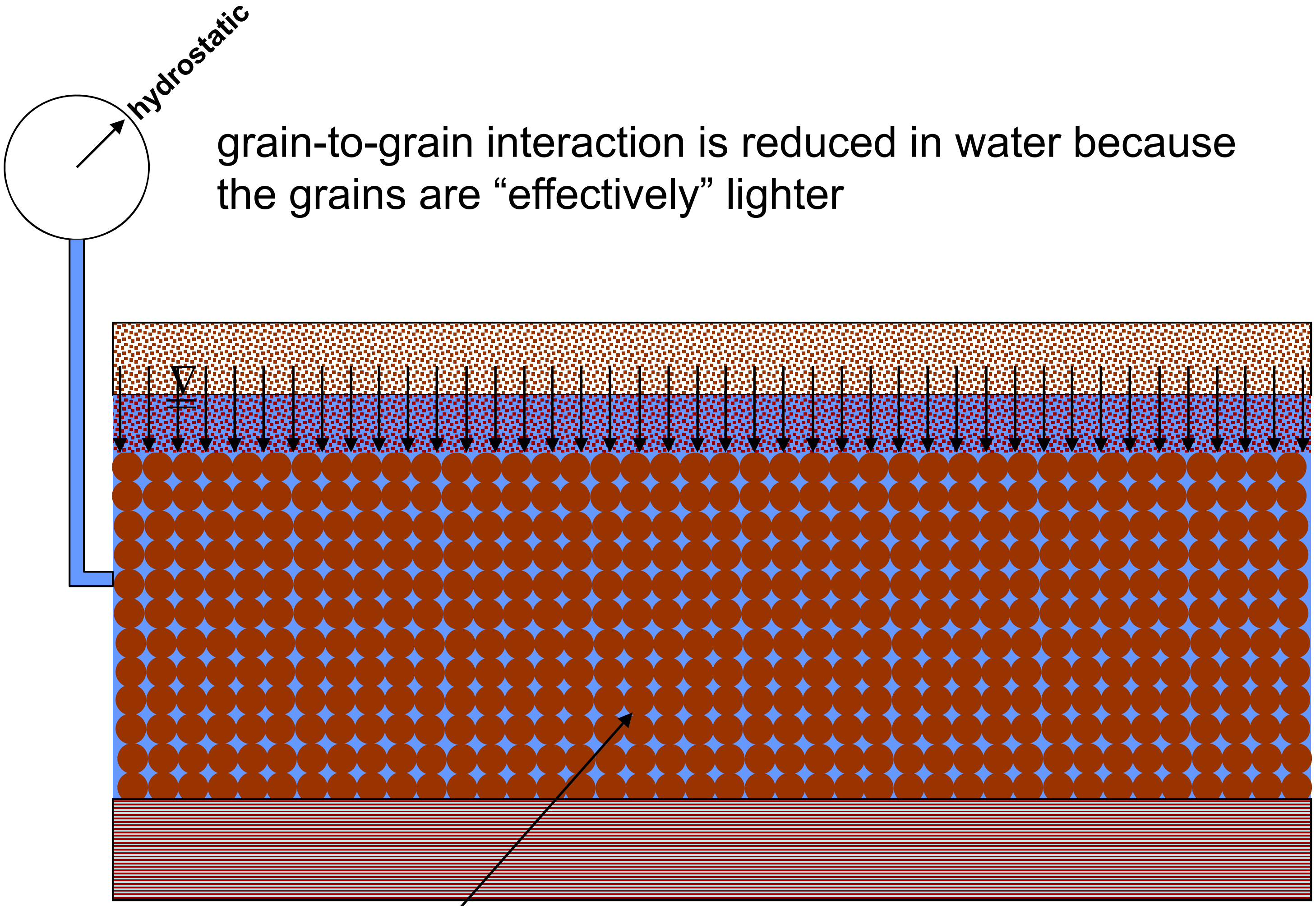
Cubic grain immersed in water



The grain weight is reduced by F_B

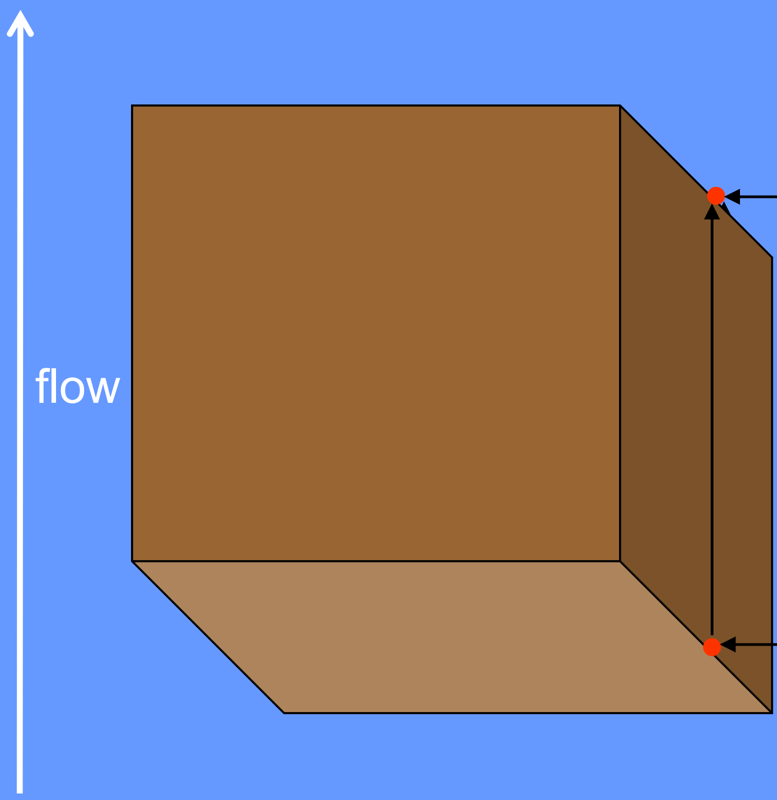
$$W_{new} = W - F_B$$

grain-to-grain interaction is reduced in water because the grains are "effectively" lighter



lower shear strength in water

Assume water is flowing vertically upward



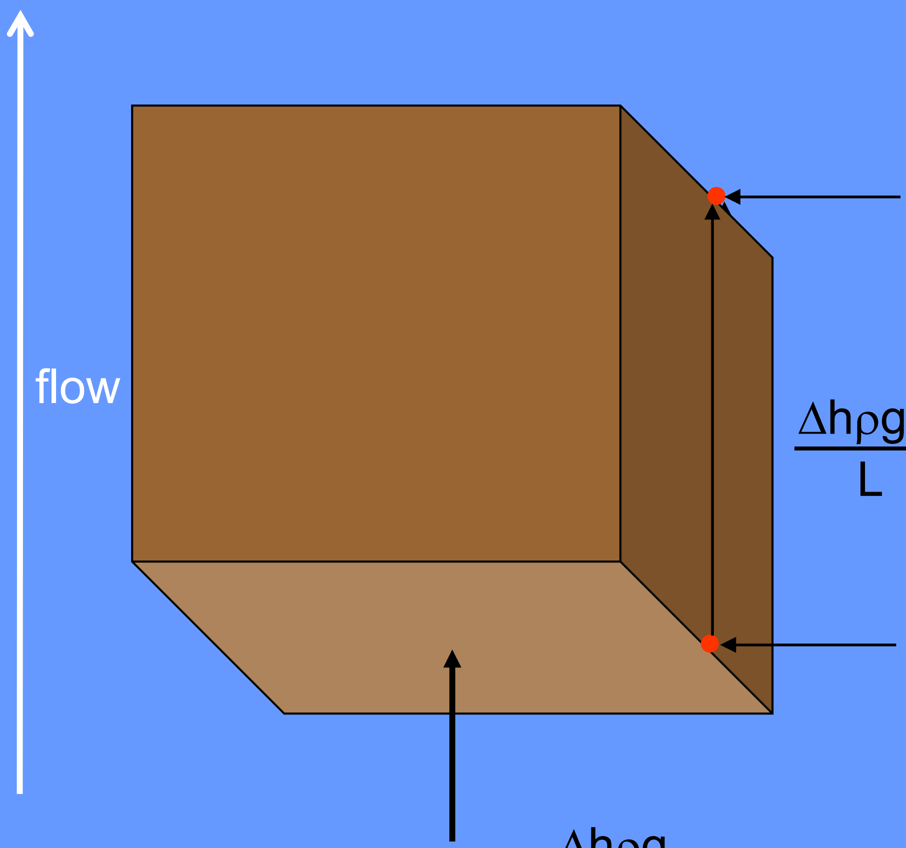
$h_B \rho g$ = energy at B

$\frac{\Delta h \rho g}{L}$ = change in energy over the distance L

$h_A \rho g$ = energy at A

Note: $\frac{\Delta h}{L}$ = hydraulic gradient

Assume water is flowing vertically upward



$h_B \rho g$ = energy at B

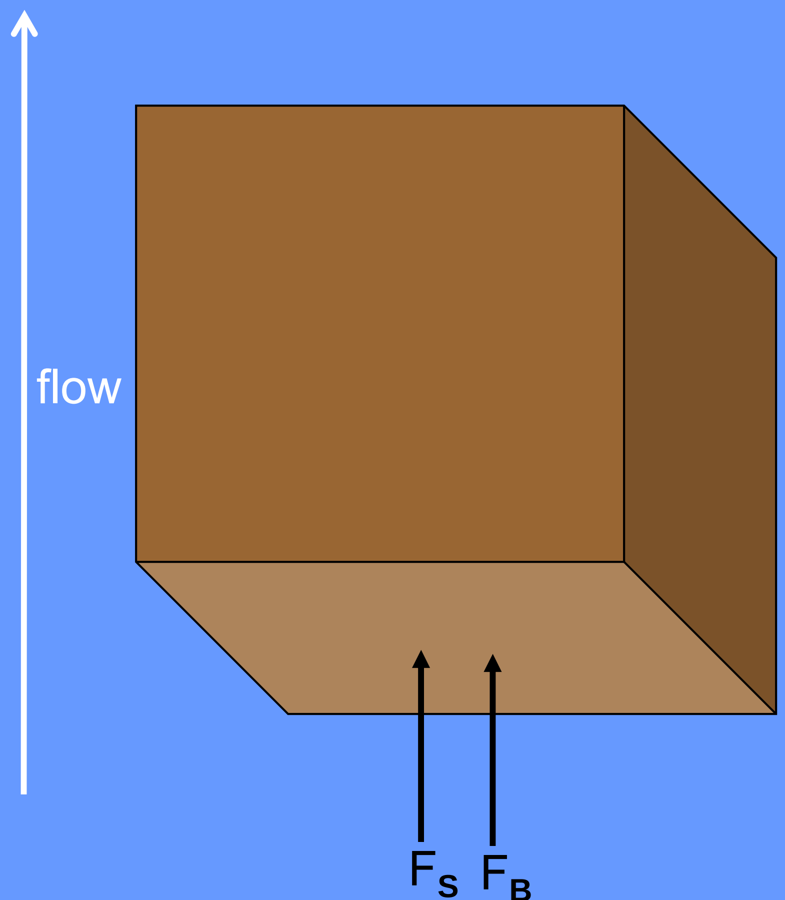
$\frac{\Delta h \rho g}{L}$ = change in energy over the distance L

$h_A \rho g$ = energy at A

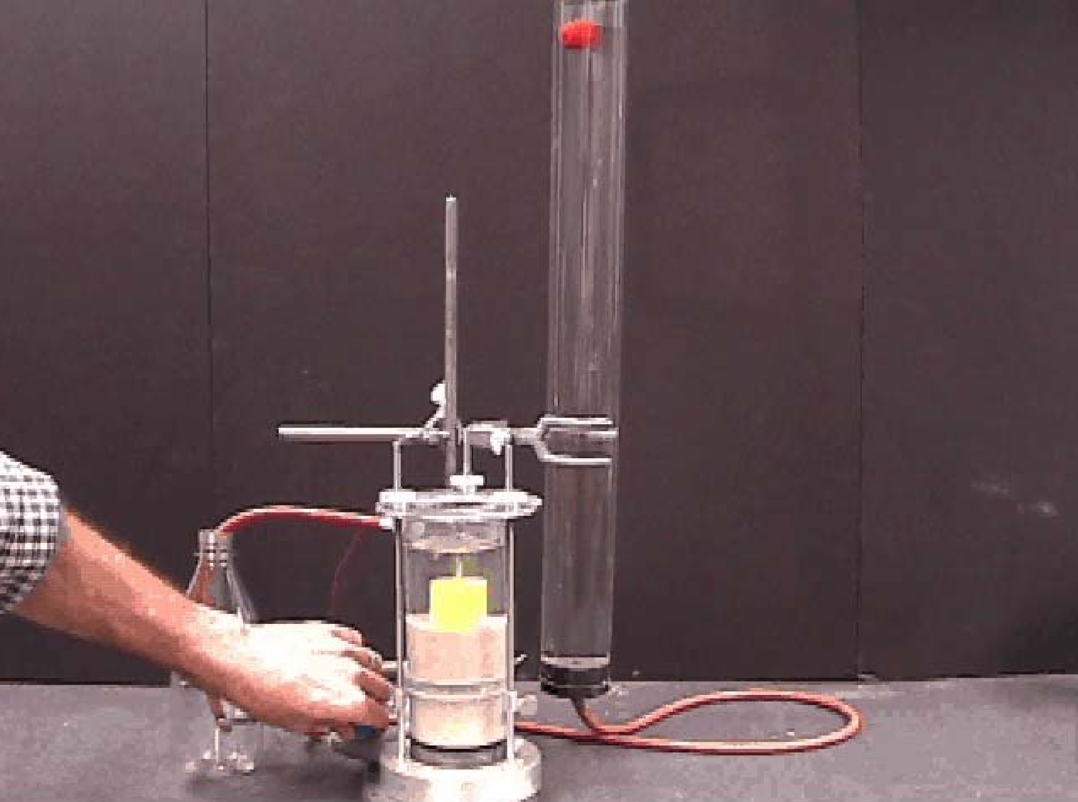
Force = $\frac{\Delta h \rho g}{L}$ = **seepage force = F_s**

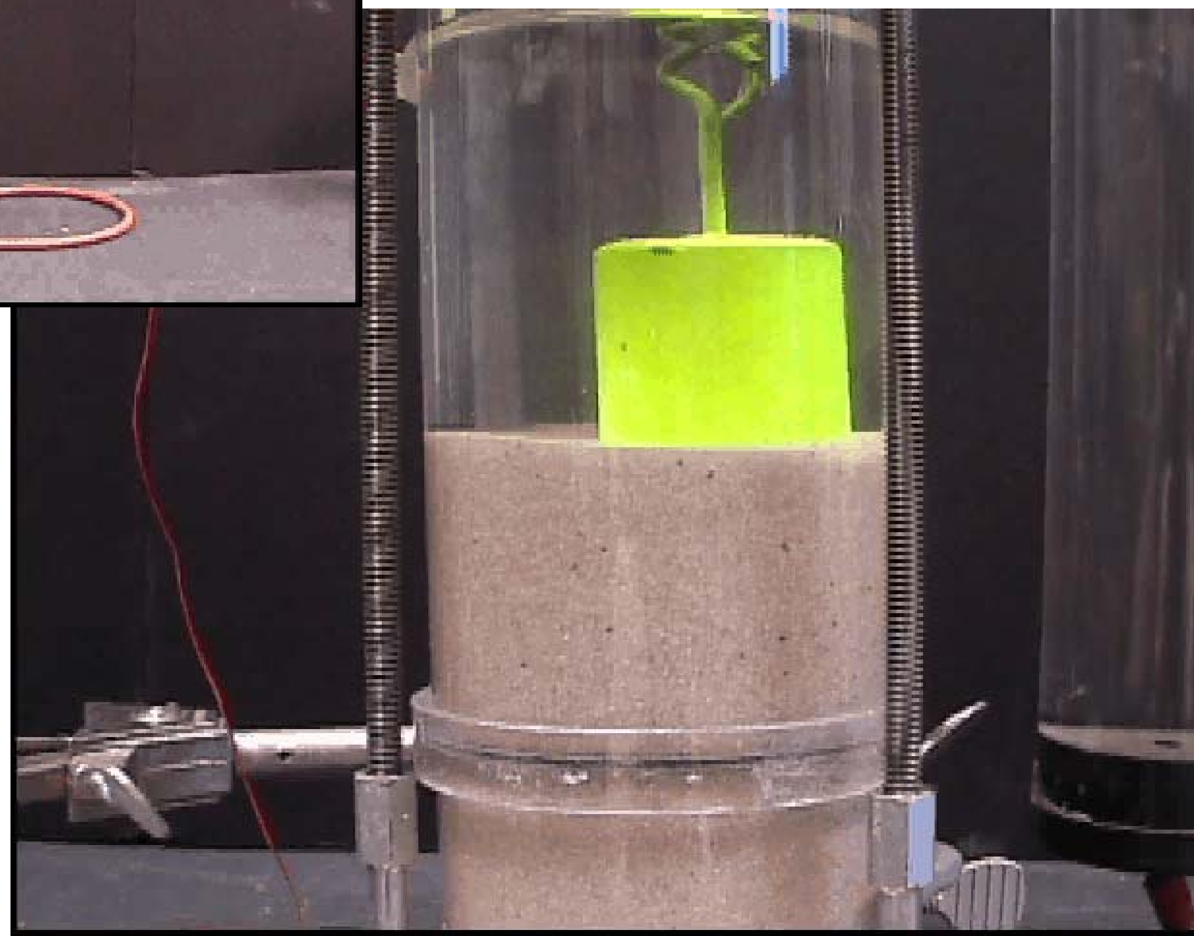
(per unit volume)

Assume water is flowing vertically upward

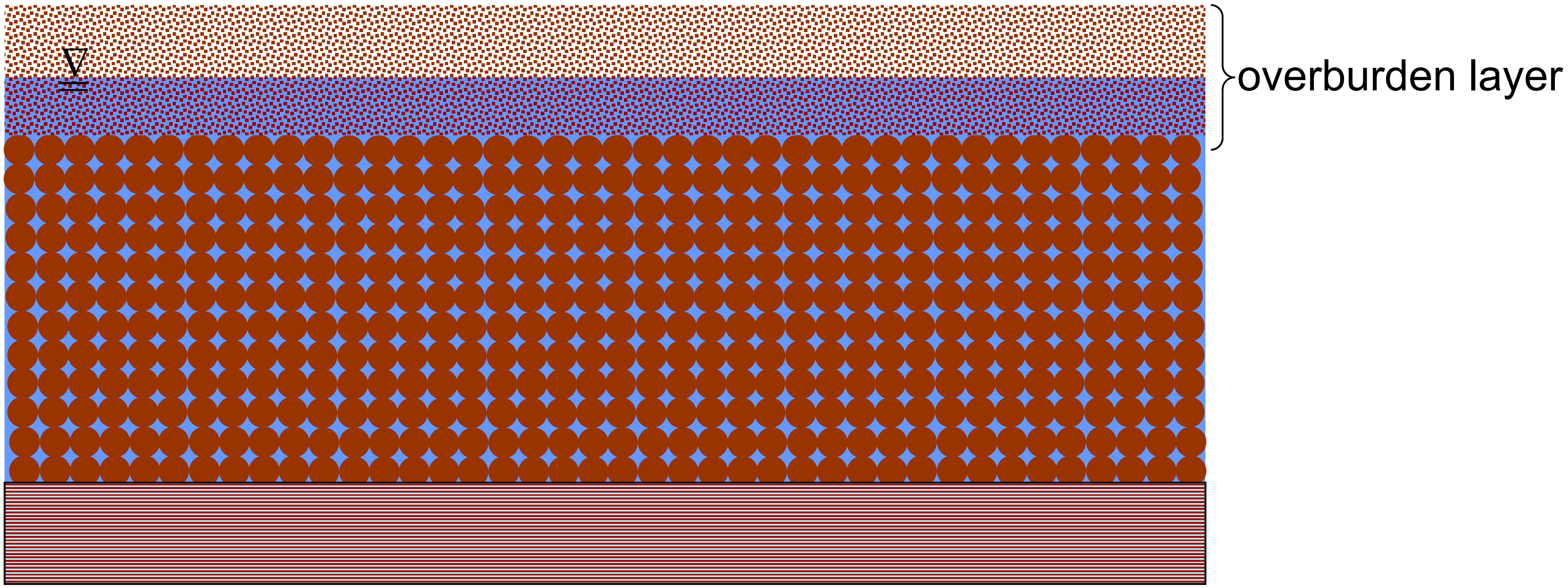


the grain will float if $F_S + F_B >$ grain weight

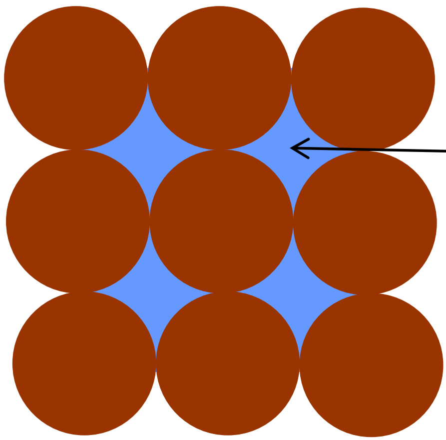




Liquefaction occurs in saturated silts and sands which have a high void space as a result of “loose” packing and uniform gain size



cubic packing (loosest possible packing)

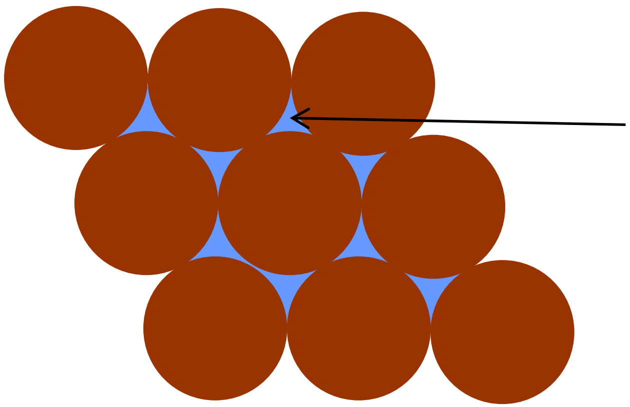


large void volume or “loose” sand

porosity = n = 47.64%

$$\text{porosity} = n = \frac{\text{void volume}}{\text{total volume}}$$

rhombohedron packing (tightest possible packing)



small void volume or “dense” sand

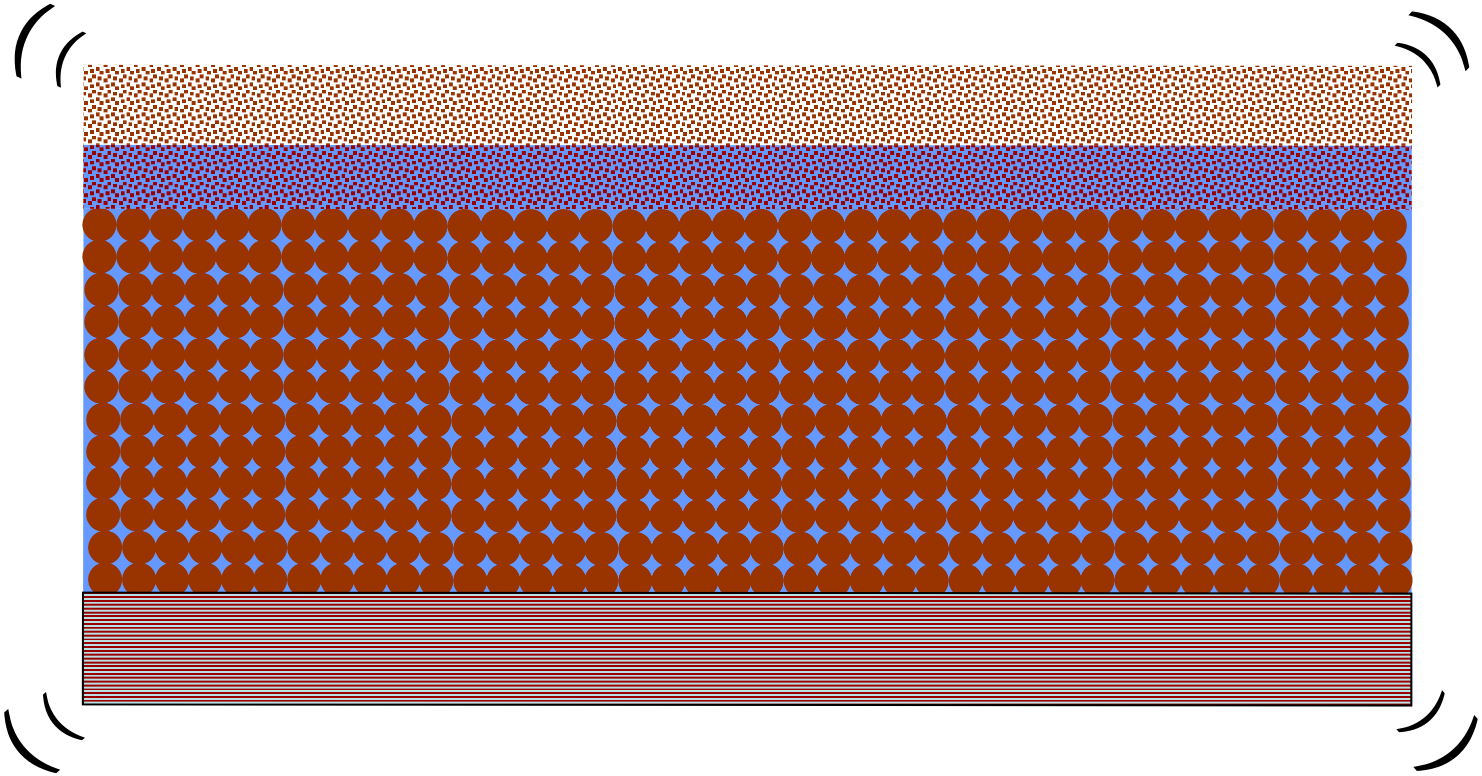
porosity = n = 28.95%

$$\text{porosity} = n = \frac{\text{void volume}}{\text{total volume}}$$

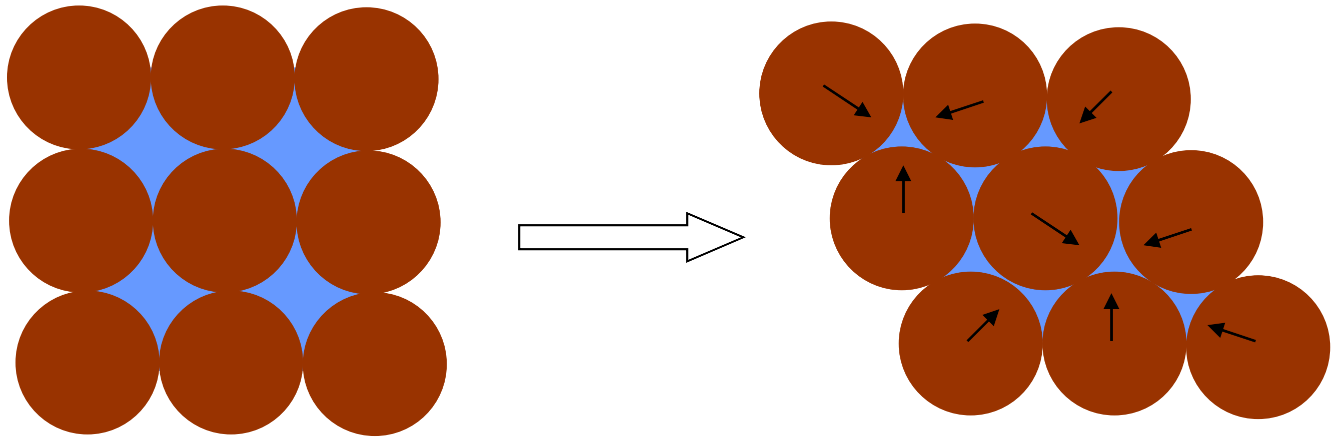
Relative Density (%)	Classification	
0 – 15	Very loose	high liquefaction susceptibility
15 – 35	Loose	
35 – 65	Medium dense	
65 – 85	Dense	
85 – 100	Very Dense	low liquefaction susceptibility

Coduto, D. P., Geotechnical Engineering Principles and Practice, 1999, Prentice Hall, Inc.

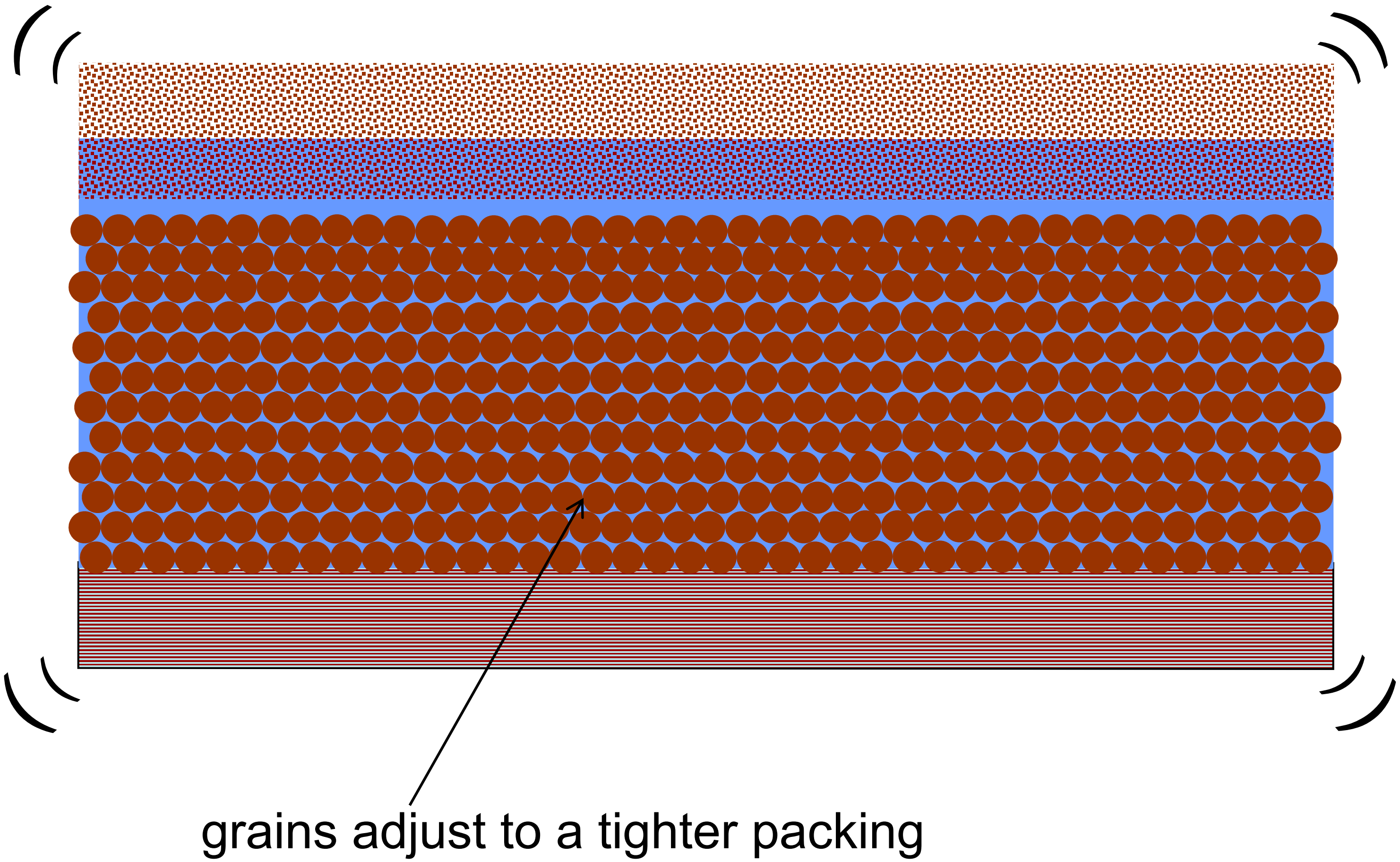
Earthquake shaking imparts shearing forces to the sediment



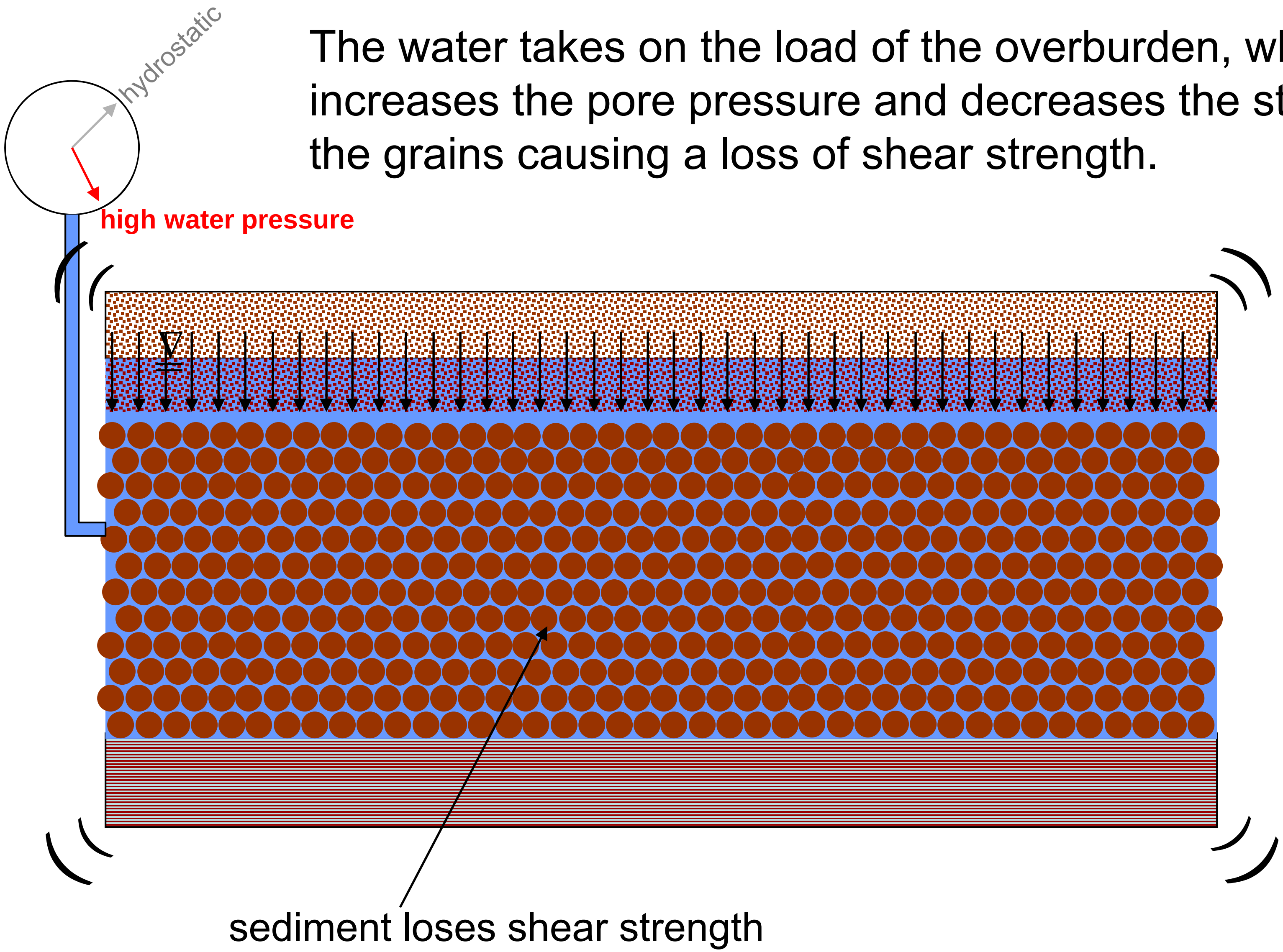
The tendency of loose sand is to attain a tighter denser packing, which compresses water in the pores spaces.

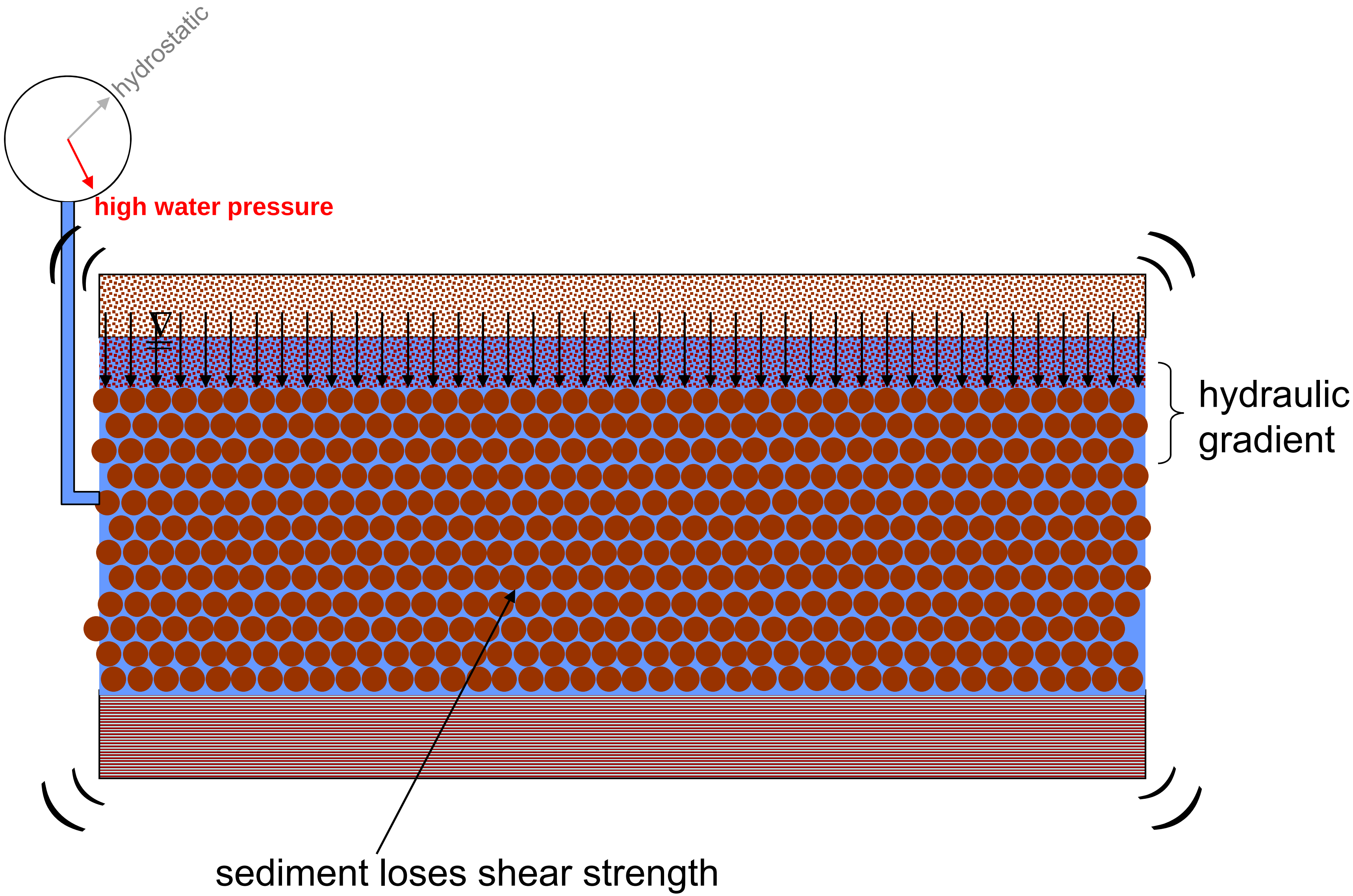


Rapid cyclic shaking doesn't allow the sand to drain fast enough

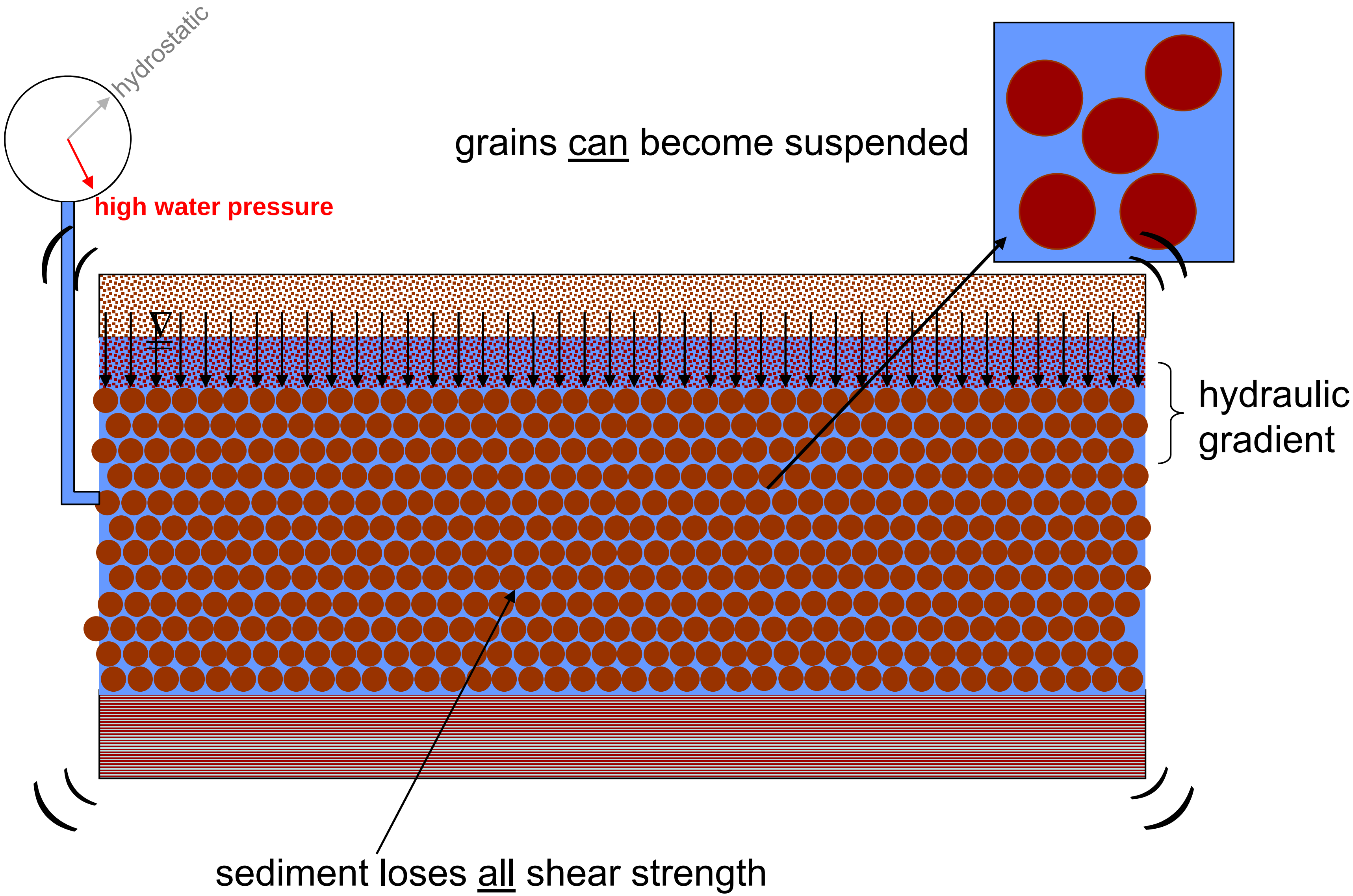


The water takes on the load of the overburden, which increases the pore pressure and decreases the stress on the grains causing a loss of shear strength.

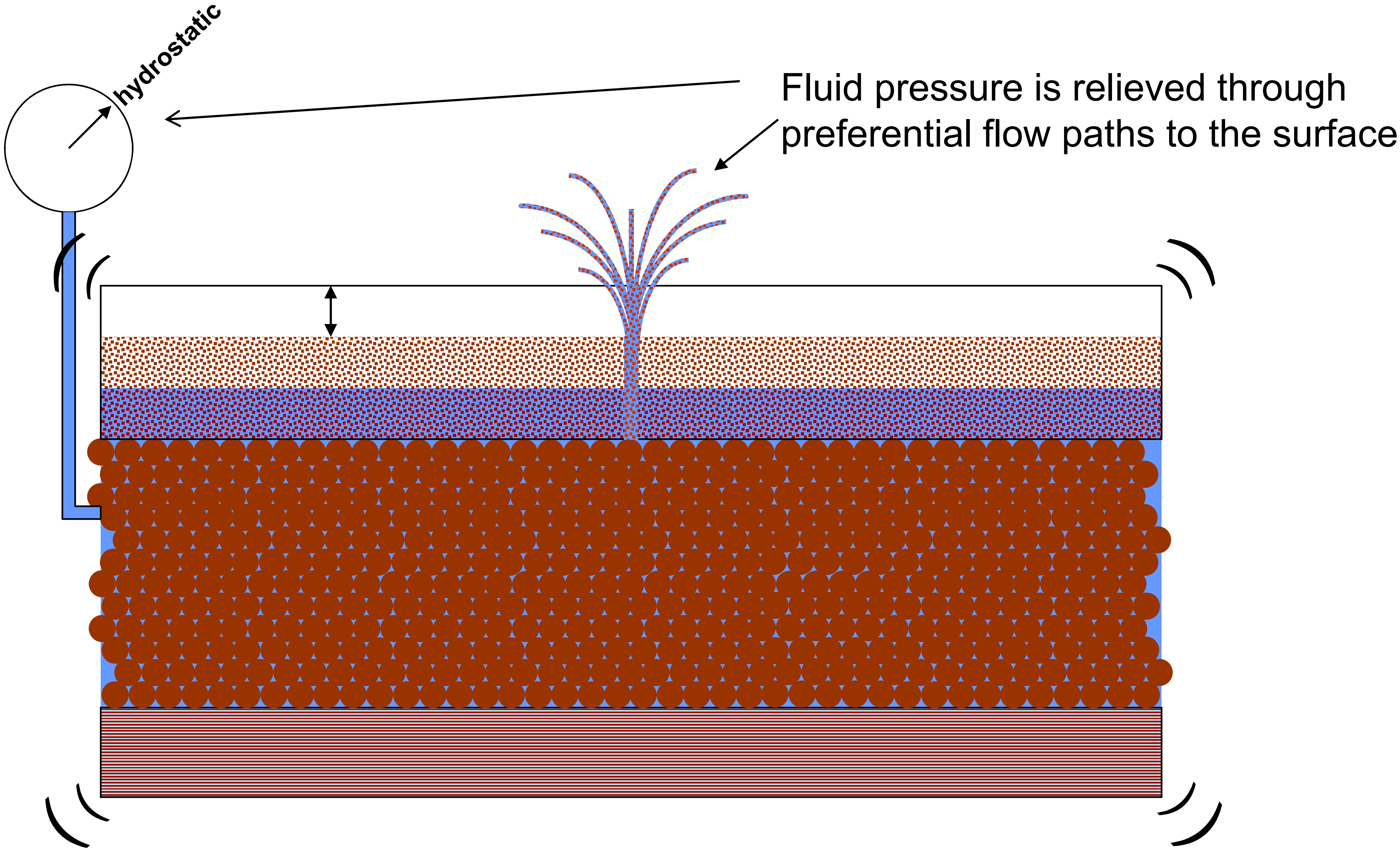


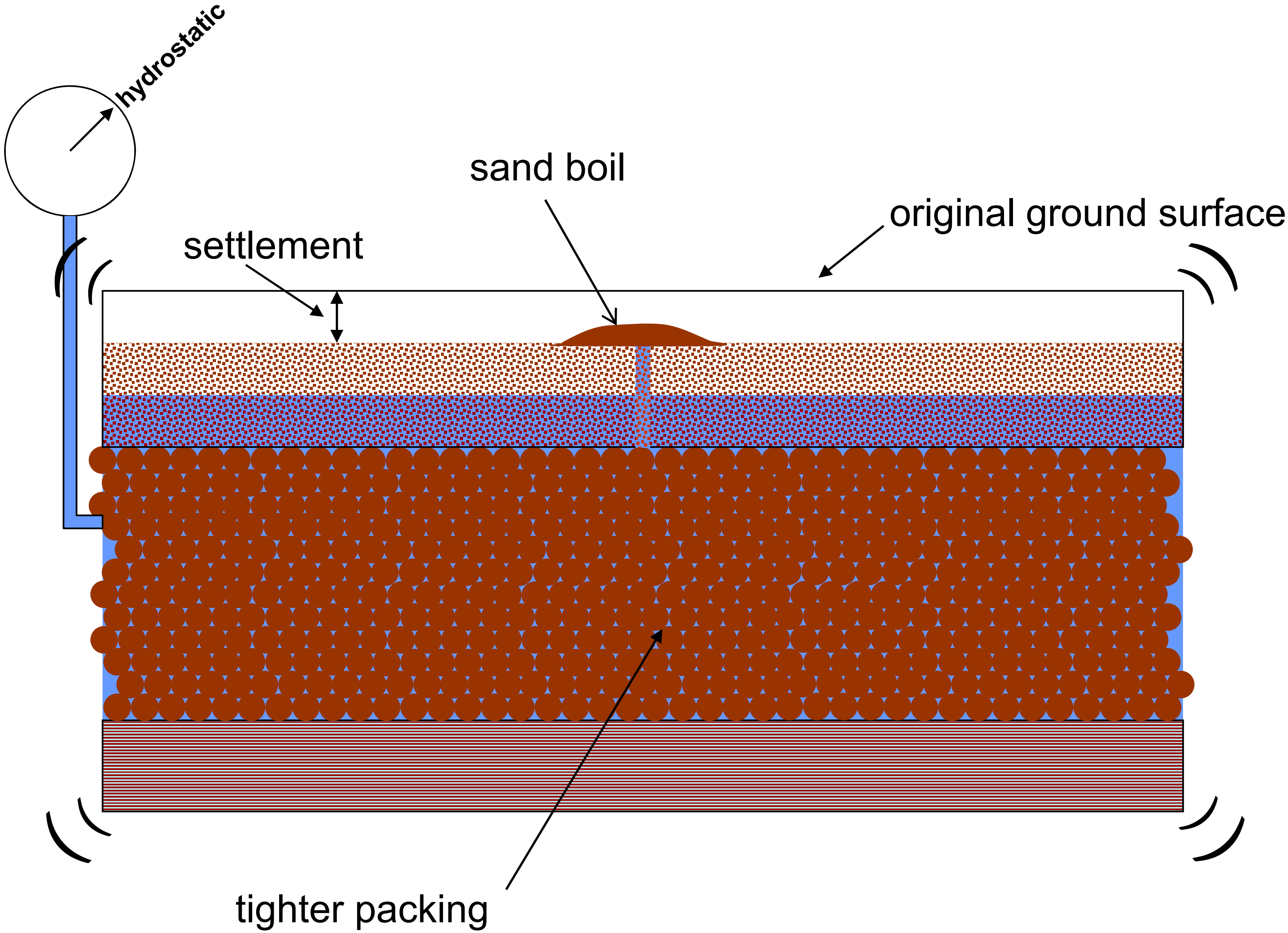


hydrostatic
high water pressure
hydraulic gradient
sediment loses shear strength

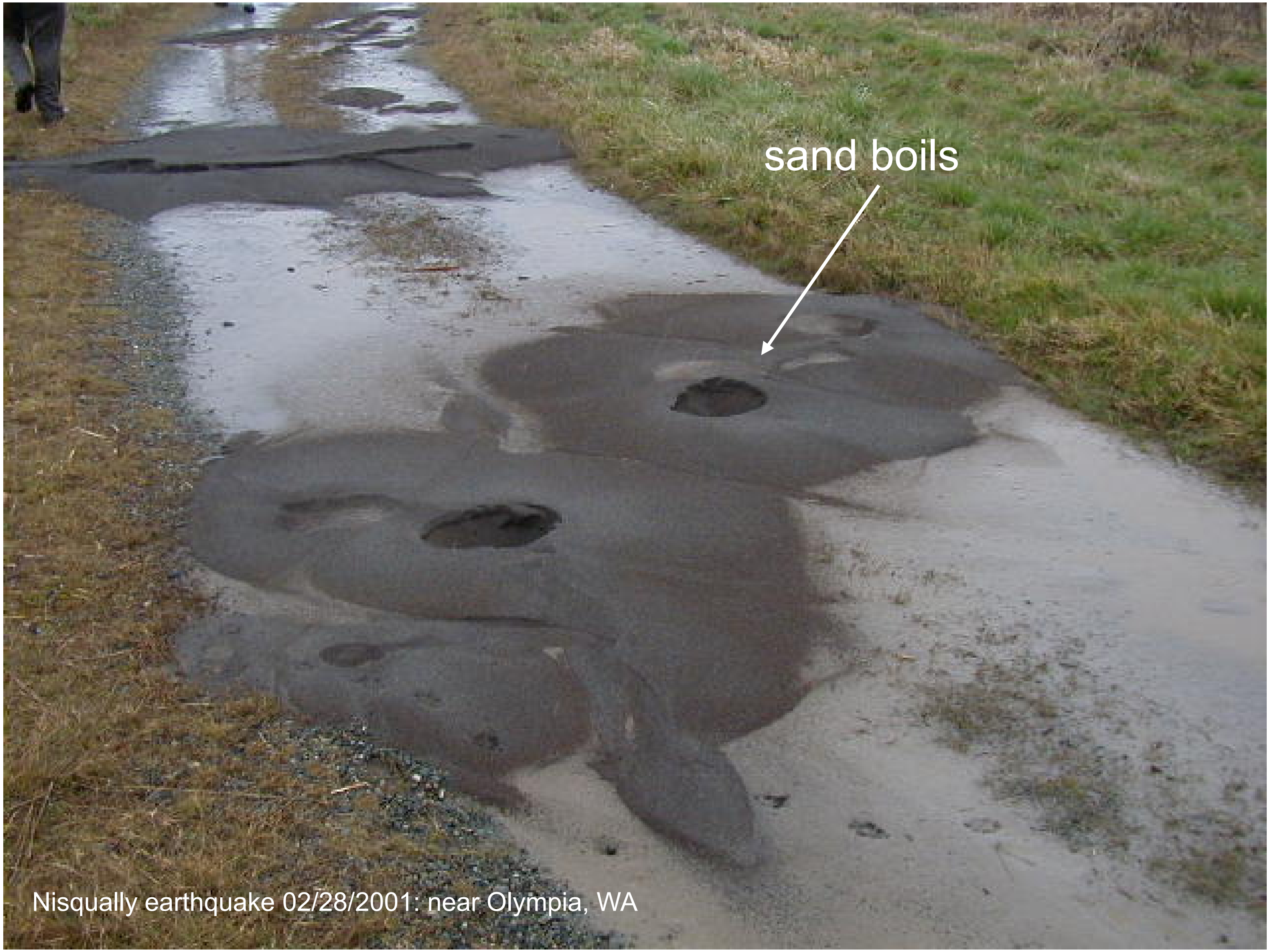

hydrostatic
high water pressure
grains can become suspended
hydraulic gradient
sediment loses all shear strength

Niigata, Japan, 1964: liquefaction damage


hydrostatic
Fluid pressure is relieved through
preferential flow paths to the surface



hydrostatic
sand boil
original ground surface
settlement
tighter packing


sand boils
Nisqually earthquake 02/28/2001: near Olympia, WA

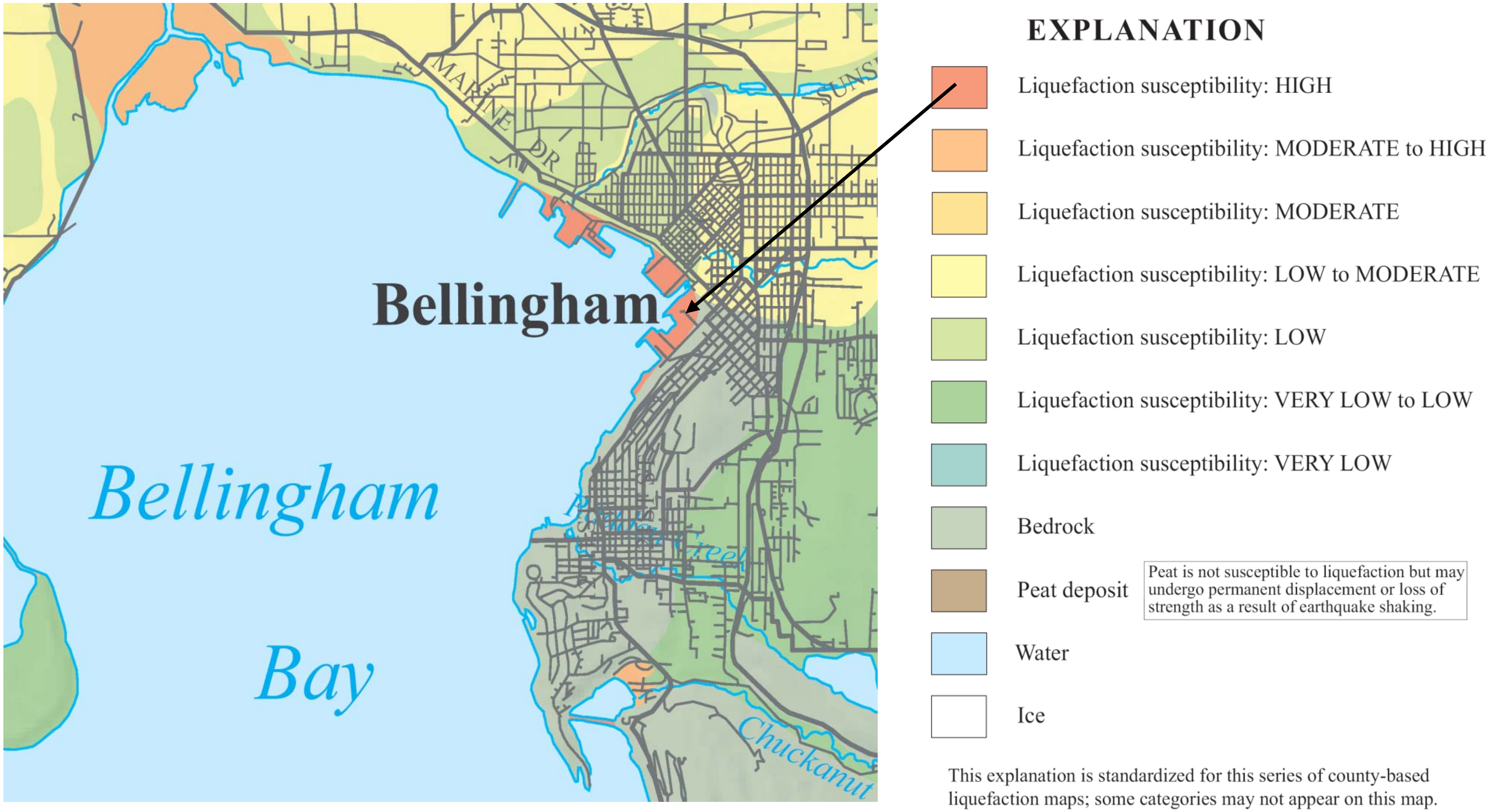
Nisqually earthquake 02/28/2001: near Olympia, WA

Lateral spreading occurs when liquefying sediments are on a slope

1965 M6.5 Seattle-Tacoma Earthquake

1995 M6.9 Kobe Earthquake

Photo by Donald Ballantyne/Steve Dickenson



Palmer, S. P., S. L. Magsino, E. L. Bilderback, J. L. Poelstra, D. S. Folger, and R. A. Niggemann. Liquefaction Susceptibility and Site Class Maps of Washington State, By County, Washington Division of Geology and Earth Resources, Open File Report 2004-20, September 2004.

Bellingham Waterfront: 2030???

Stratus Consultant Doug Graham's March 13, 2007 Campus Forum Presentation

Stephanie Bower, Architectural Illustration

Western Washington University plans on developing a section of the waterfront

Stratus Consultant Doug Graham's March 13, 2007 Campus Forum Presentation

Bellingham Bay: 1893

http://www.cob.org/waterfront/learnmore/lm_photo_gallery.htm

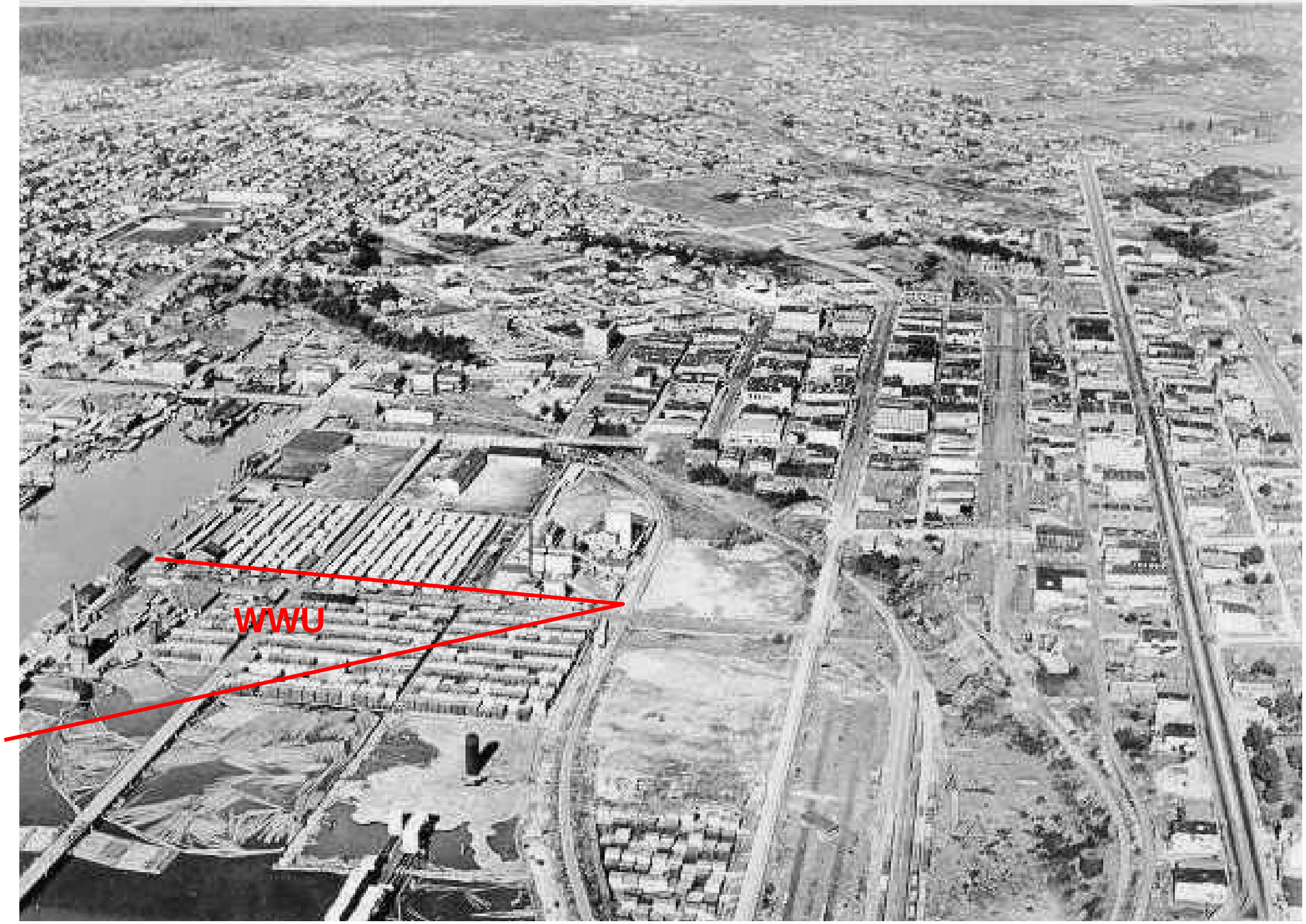
Bellingham Waterfront: 1912

Picture from an air balloon

Bellingham Waterfront: 1913

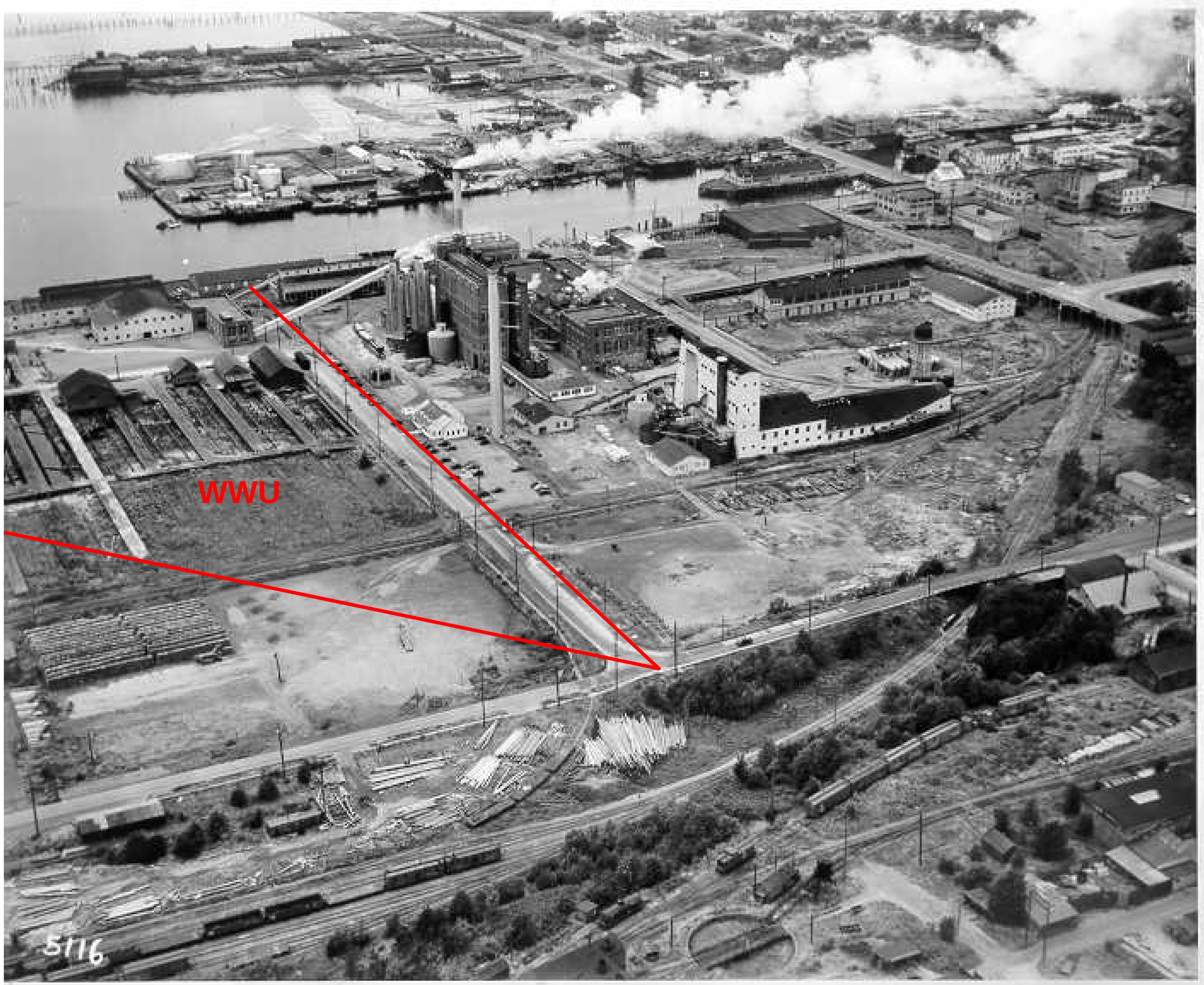
Whatcom Museum of History and Art

Bellingham Water Front: 1928



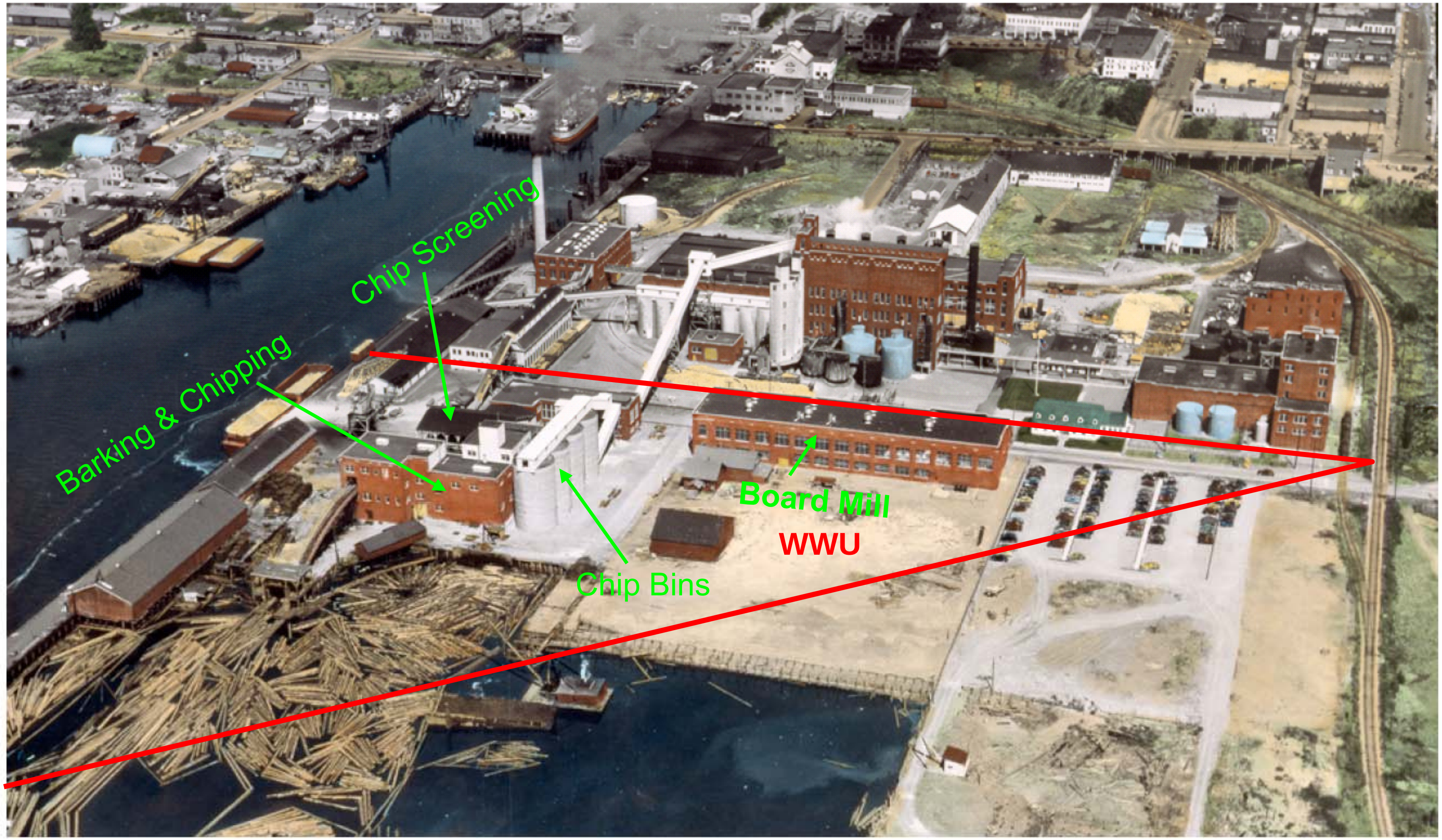
http://www.cob.org/waterfront/learnmore/lm_photo_gallery.htm

Bellingham Water Front: 1940



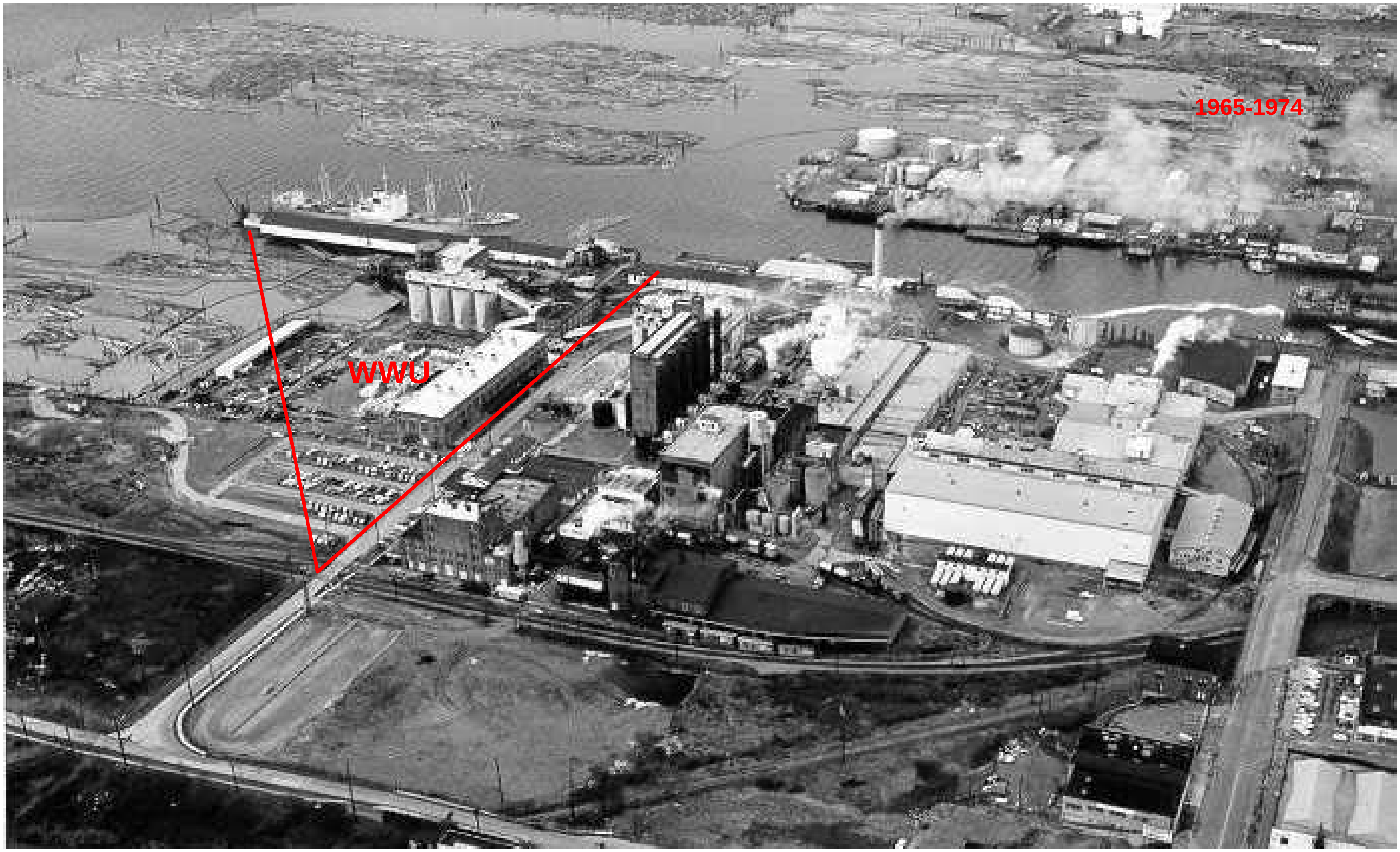
http://www.cob.org/waterfront/learnmore/lm_photo_gallery.htm

Bellingham Water Front: 1950



Port of Bellingham, Georgia Pacific Due Diligence Existing Building Assessment, RMC Architects, PLLC, September 2004: Mill Complex 1950

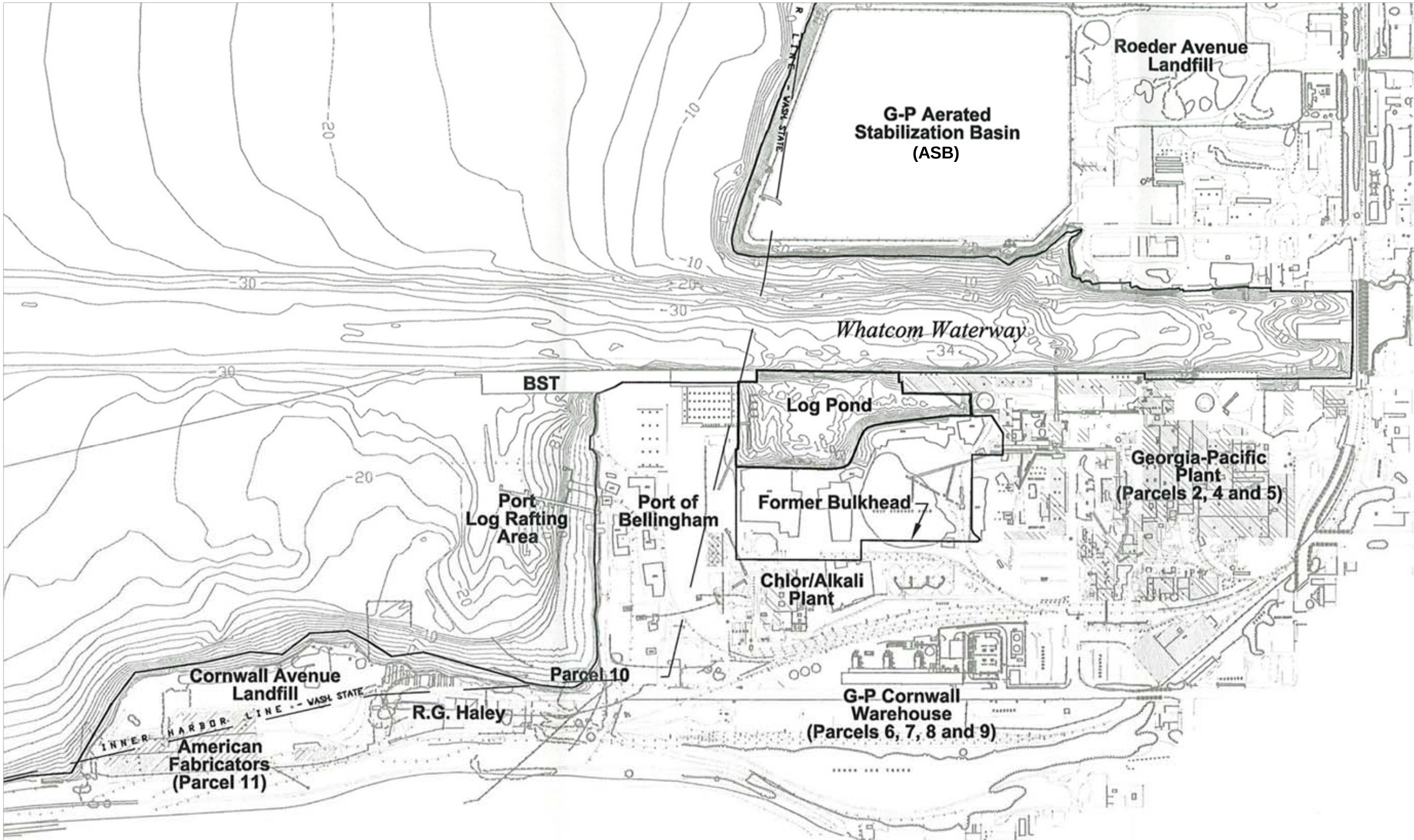
Bellingham Water Front: 1963



http://www.cob.org/waterfront/learnmore/lm_photo_gallery.htm

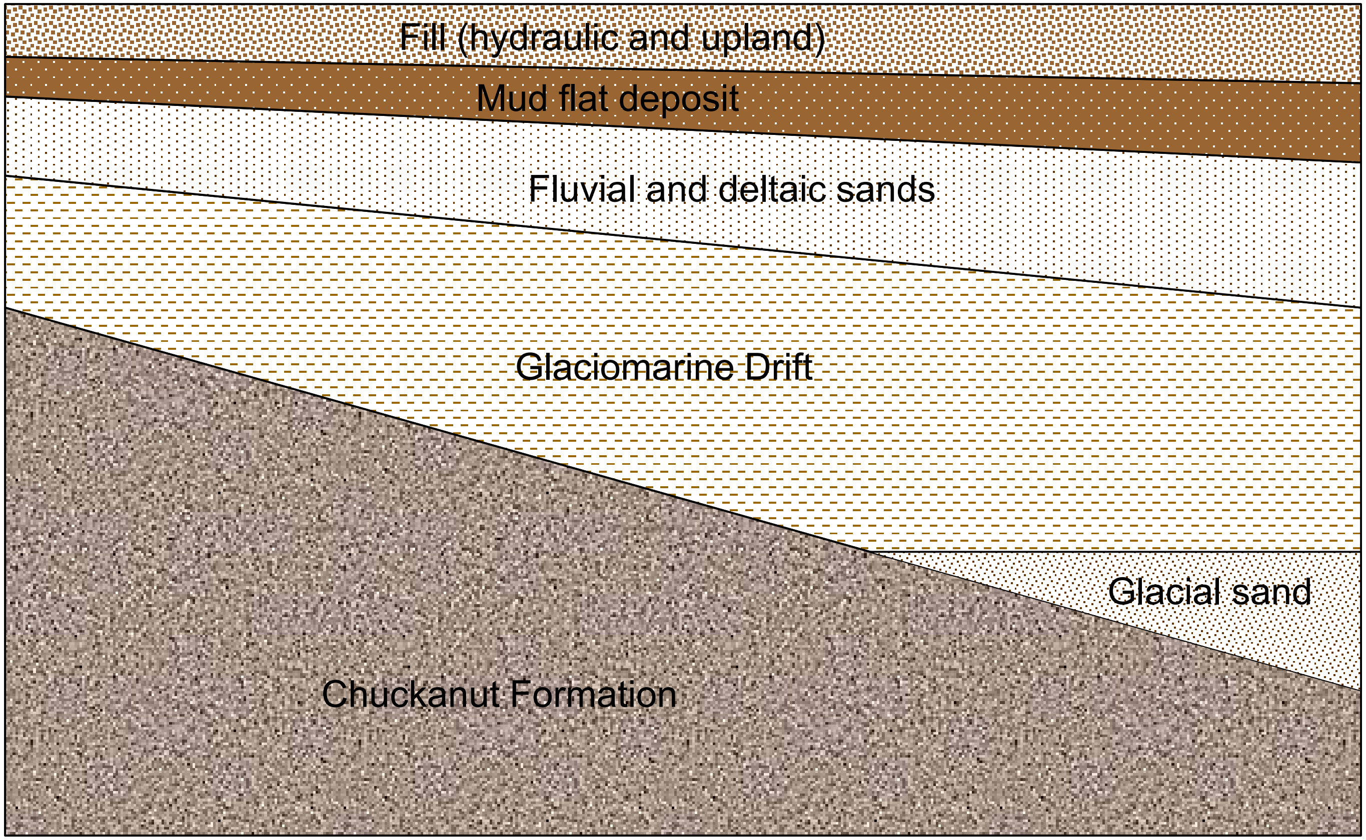
Bellingham Waterfront: 2004

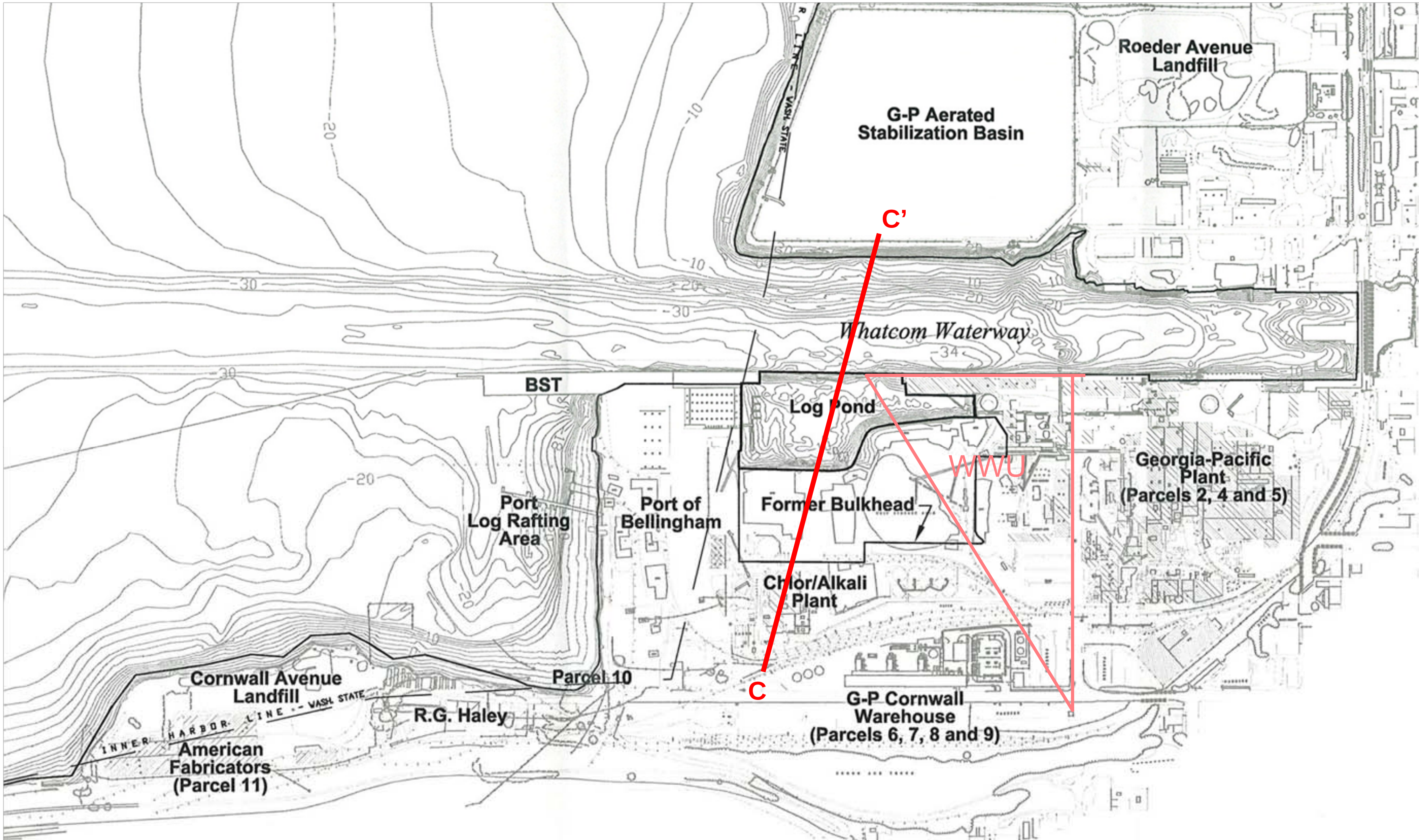
http://www.portofbellingham.com/library/images/0604261824_Whatcom_Waterway_Current_Conditions.jpg



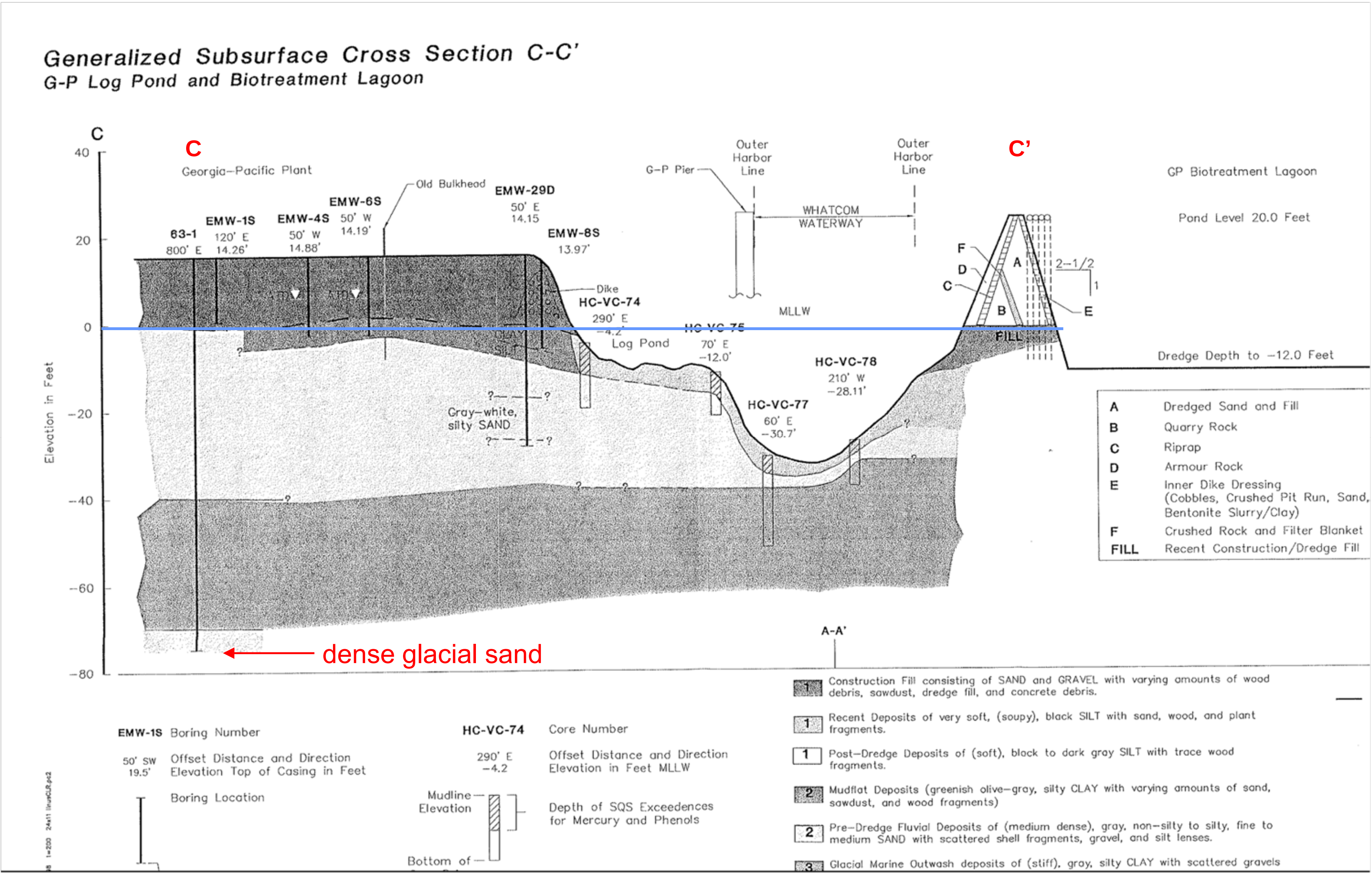
Phase II Environmental Assessment Georgia-Pacific Bellingham Operations, Aspect Consulting, LLC Project, September 3, 2004. Project No. 040088-002-08.

Generalized Stratigraphy





Phase II Environmental Assessment Georgia-Pacific Bellingham Operations, Aspect Consulting, LLC Project, September 3, 2004. Project No. 040088-002-08



Remedial Investigation and Feasibility Study Whatcom Waterway Bellingham, WA. Volume 1 Remedial Investigation Prepared for Georgia Pacific West by Anchor Environmental LLC and Hart Crowser Inc., July 25, 2000.

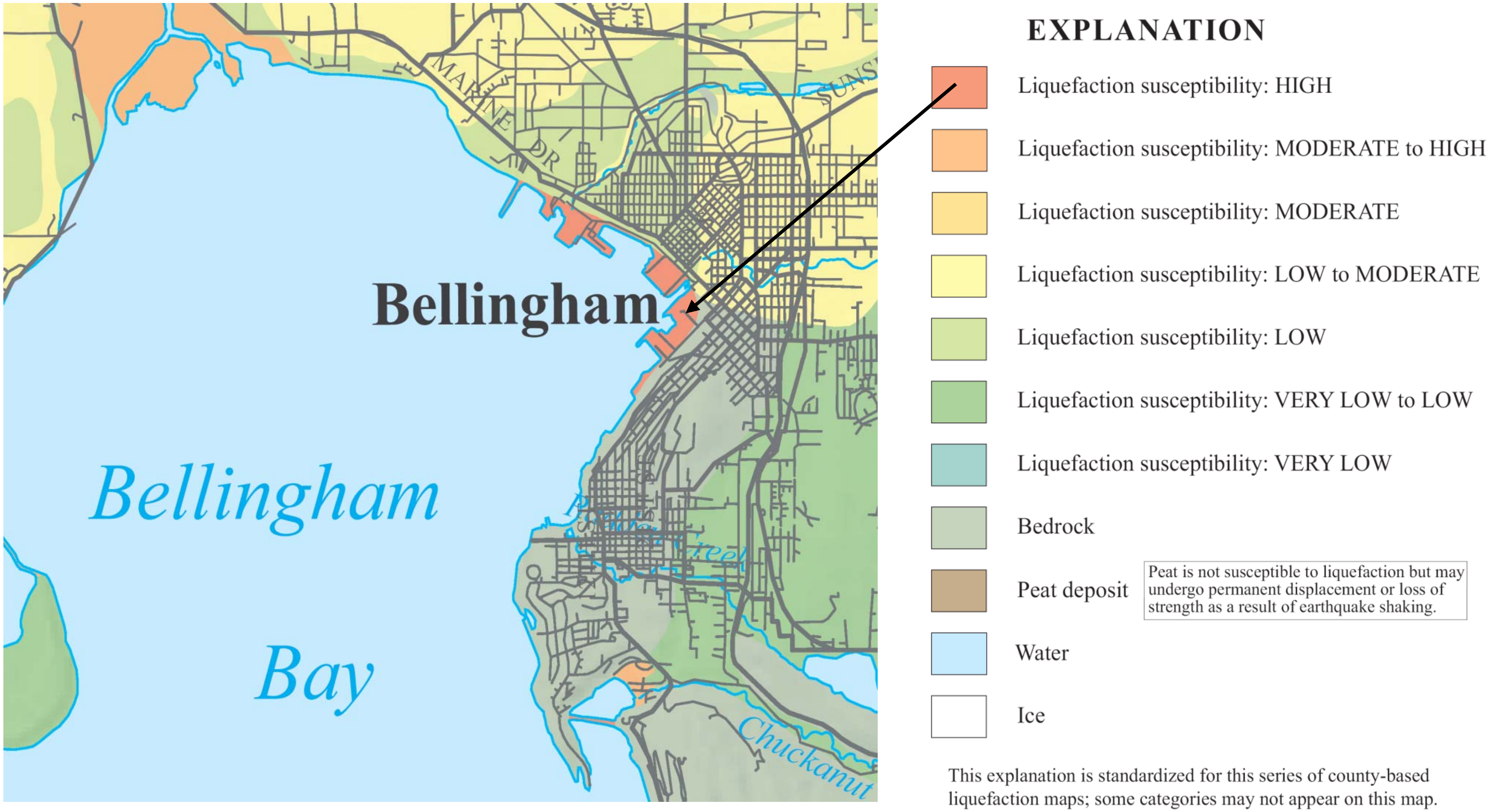
Relative Density (%)	Classification
0 – 15	Very loose
15 – 35	Loose
35 – 65	Medium dense
65 – 85	Dense
85 – 100	Very Dense

Coduto, D. P., Geotechnical Engineering Principles and Practice, 1999, Prentice Hall, Inc.

high liquefaction susceptibility

low liquefaction susceptibility

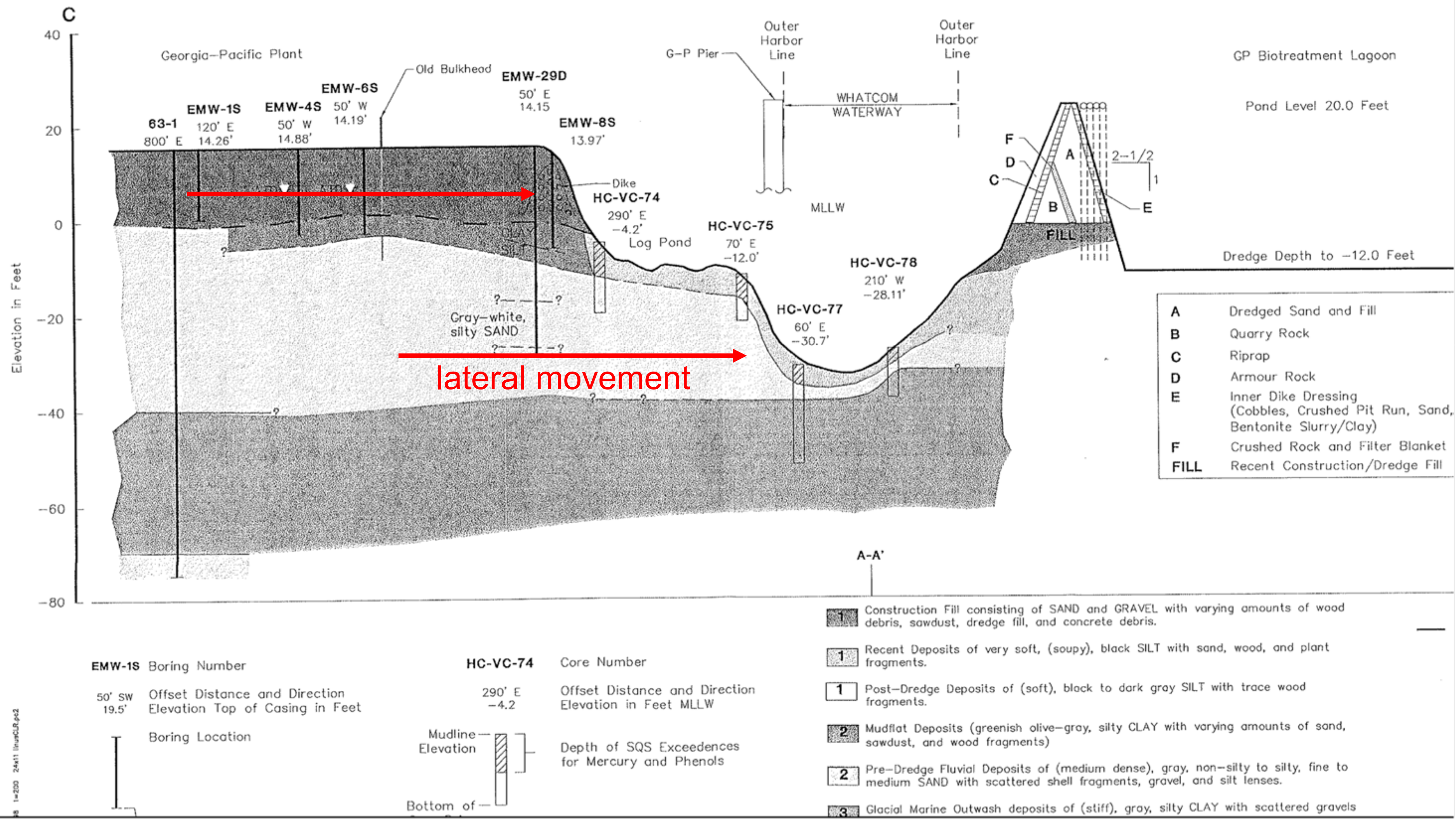
waterfront sands



Palmer, S. P., S. L. Magsino, E. L. Bilderback, J. L. Poelstra, D. S. Folger, and R. A. Niggemann. Liquefaction Susceptibility and Site Class Maps of Washington State, By County, Washington Division of Geology and Earth Resources, Open File Report 2004-20, September 2004.

Generalized Subsurface Cross Section C-C'

G-P Log Pond and Biotreatment Lagoon



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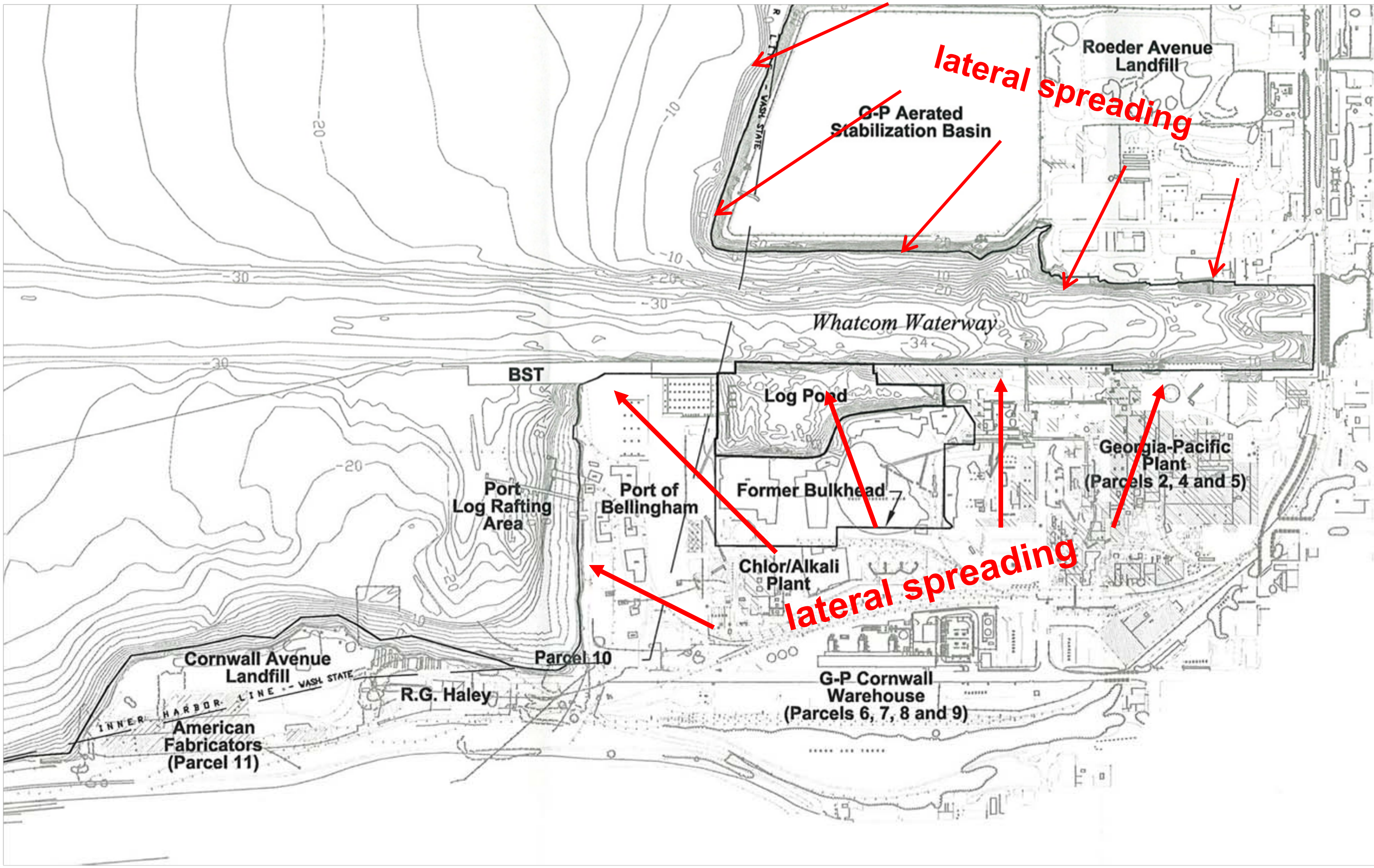


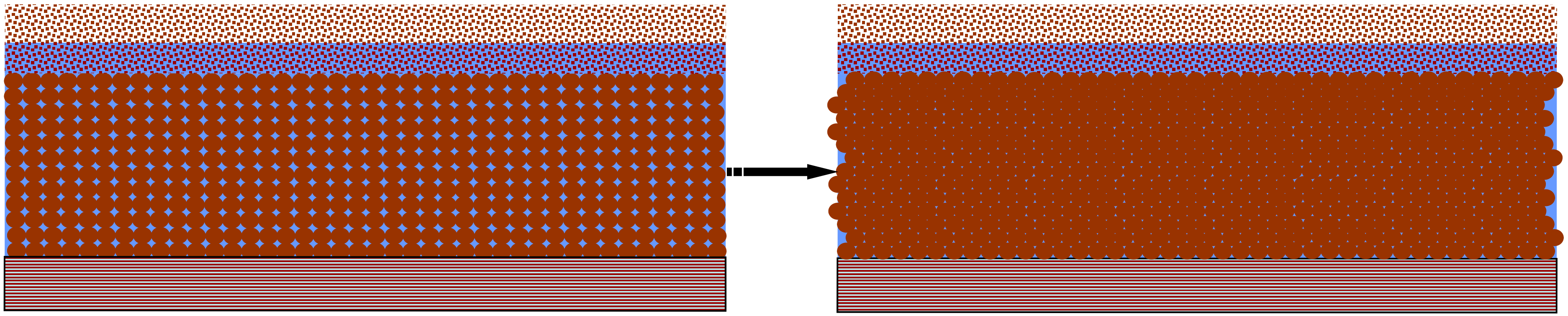
lateral spreading
Roeder Avenue Landfill
G-P Aerated Stabilization Basin
Whatcom Waterway
BST
Log Pond
Georgia-Pacific Plant (Parcels 2, 4 and 5)
Port Log Rafting Area
Port of Bellingham
Former Bulkhead
Chlor/Alkali Plant
lateral spreading
Cornwall Avenue Landfill
Parcel 10
R.G. Haley
G-P Cornwall Warehouse (Parcels 6, 7, 8 and 9)
American Fabricators (Parcel 11)
INNER HARBOR LINE - WASH. STATE

Seismic Site Response

- Liquefaction
  - 1 – 2 feet of settlement during design EQ
  - Subsidence occurs within fill and sand/deltaic soils

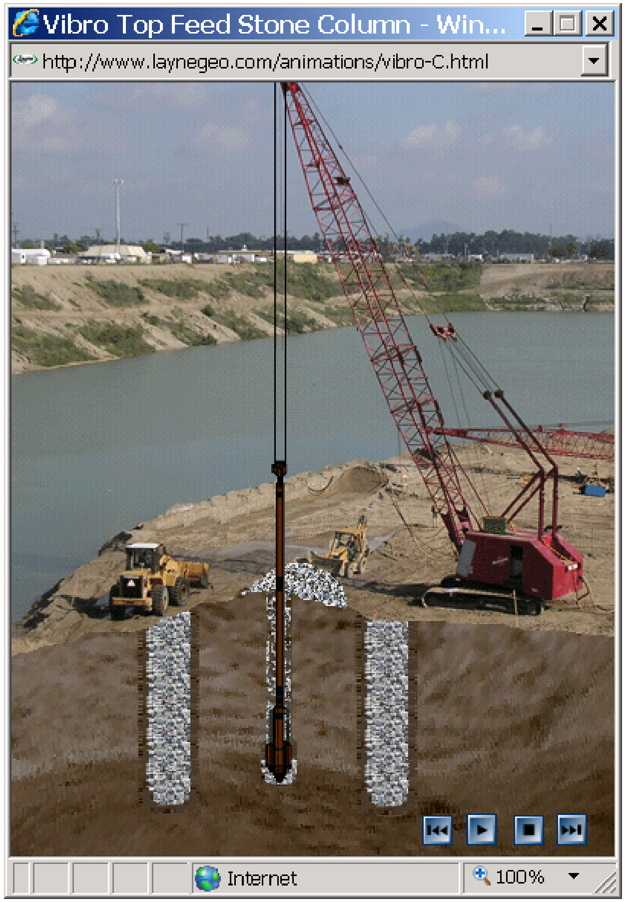
- Lateral spreading
  - Free face slope will move laterally
  - Lateral movement of surface toward creek

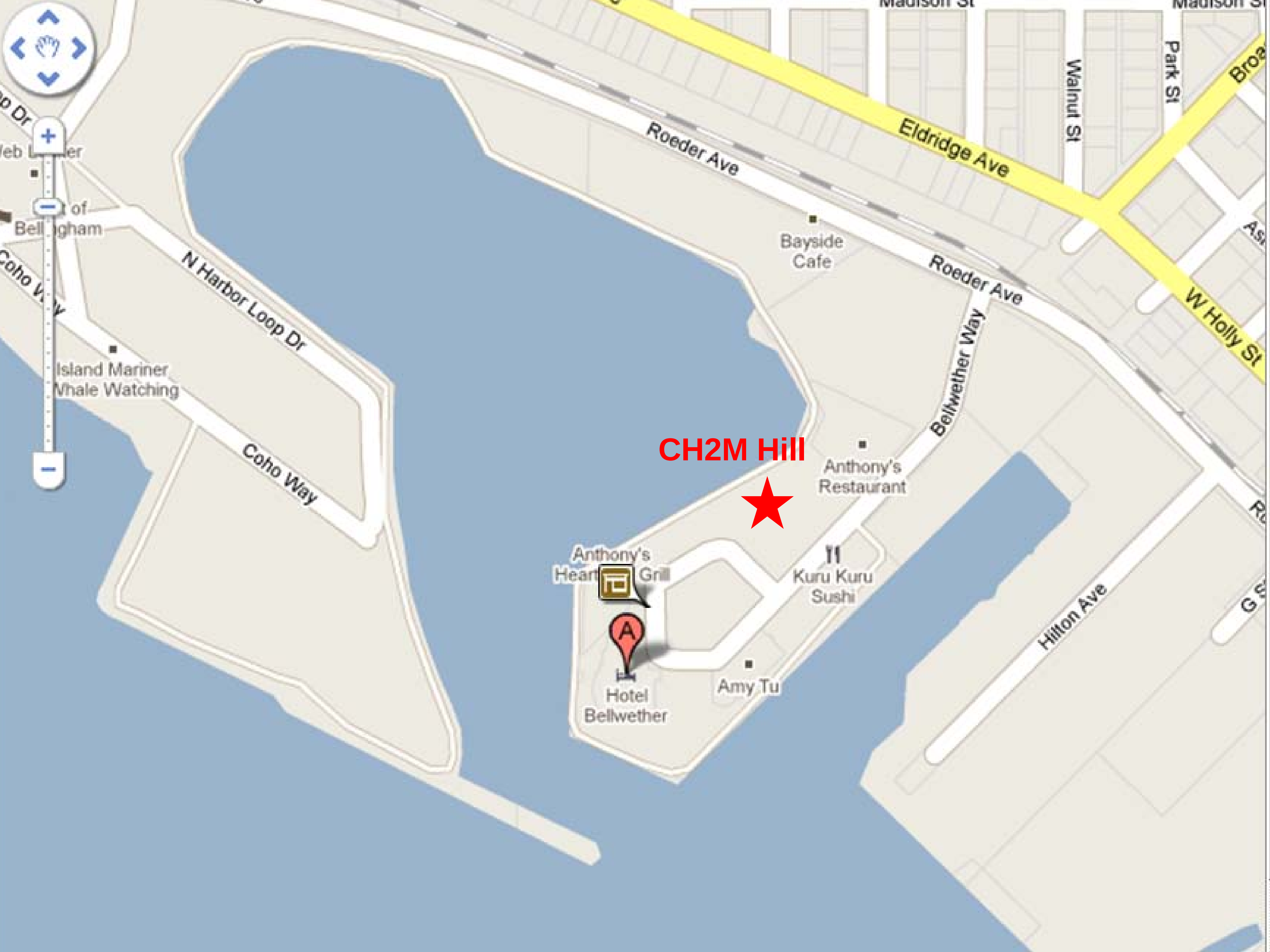
Mitigation will require the densification of loose sediments.



Site Mitigation Strategies

- Sheet pile wall (may have contamination containment dual role)
- Ground improvement near free face and/or under buildings
  - Stone columns to 40 – 50 feet (densify fill/beach/deltaic deposits)
  - Thick rip rap blanket
  - Jet grouting or compaction grouting
  - Grout mixing


Vibro Top Feed Stone Column - Win...
http://www.laynegeo.com/animations/vibro-C.html
Internet
100%

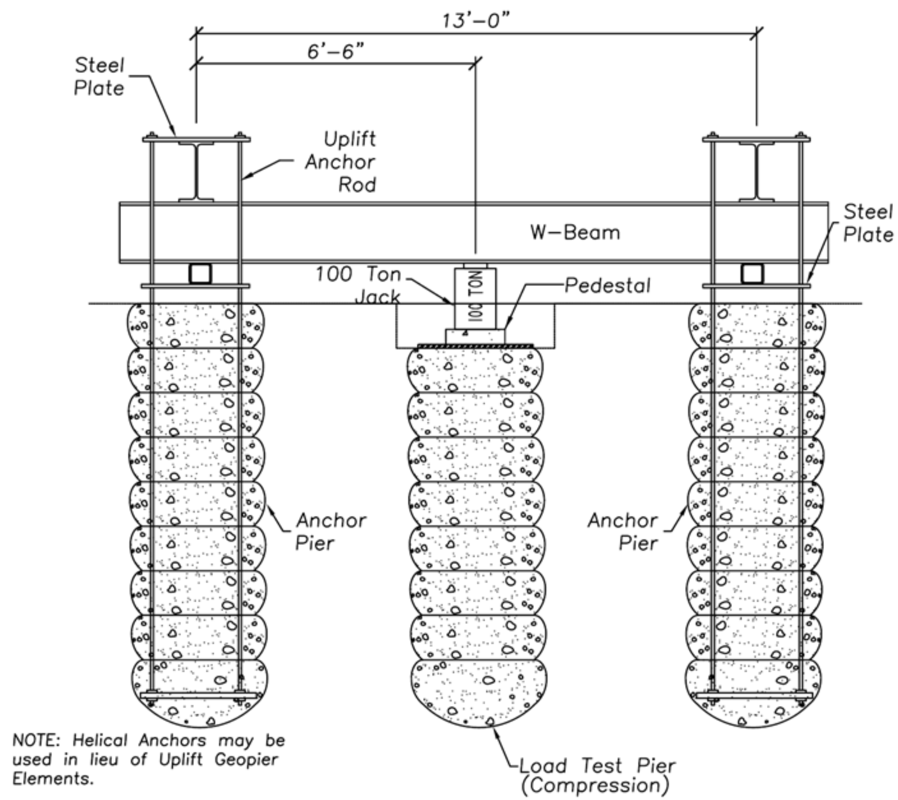


CH2M Hill
Roeder Ave
Eldridge Ave
Walnut St
Park St
W Holly St
Bayside Cafe
Bellwether Way
Anthony's Restaurant
Anthony's Hearthfire Grill
Kuru Kuru Sushi
Amy Tu
Hotel Bellwether
Hilton Ave
N Harbor Loop Dr
Coho Way
Island Mariner Whale Watching


CAT
NC


CAT
NC
RSC

Geopiers



2 MODULUS TEST SETUP

NOT TO SCALE

GP1.1

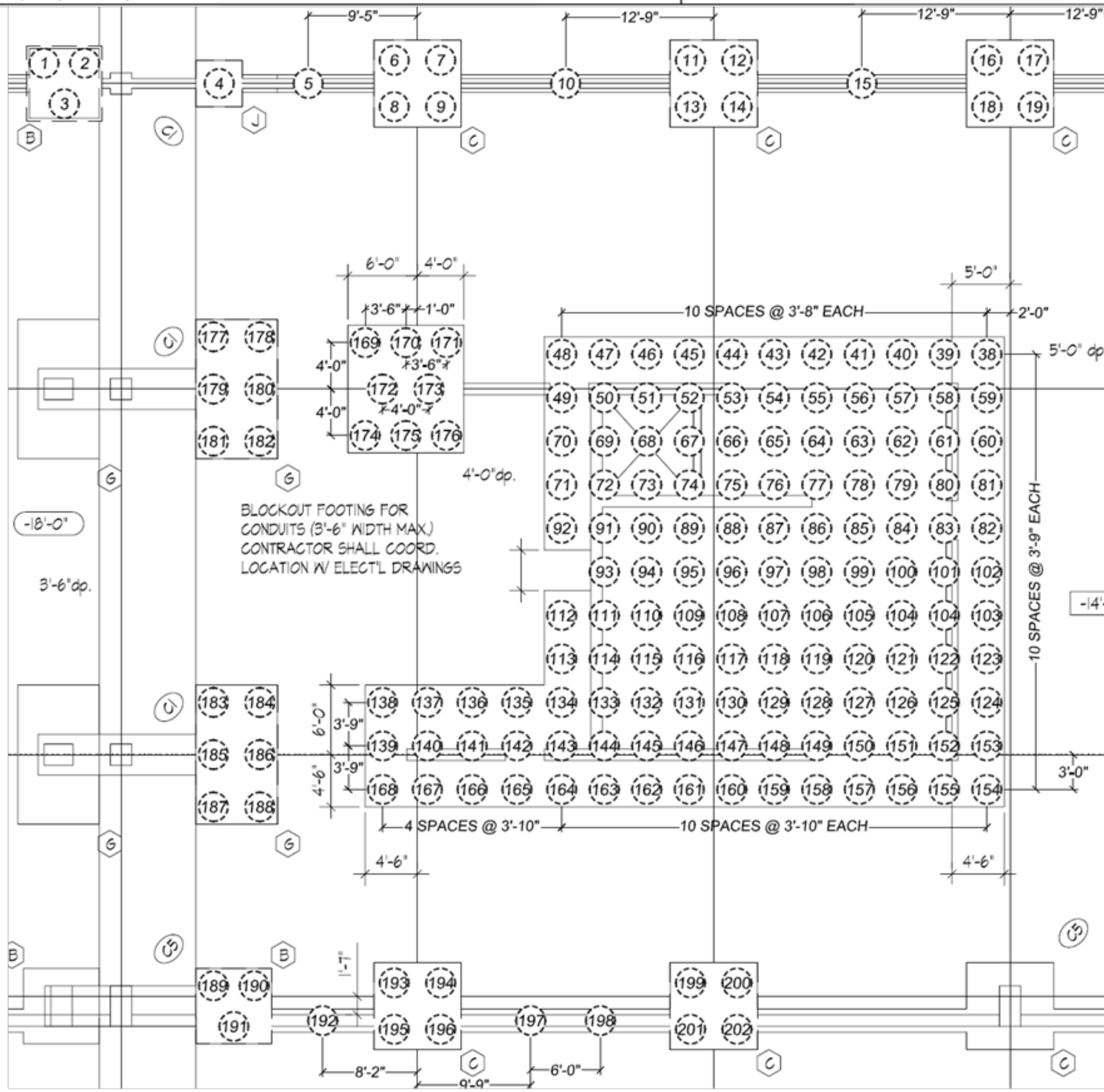
SHEET NUMBER

DATE 3/5/07

PROJECT NUMBER P06-GNW-239

GEOPIER Foundation Company - Northwest
40 Lake Bellevue, Suite 100
Bellevue, Washington 98005
ph: 425-646-2995
fax: 425-646-3118

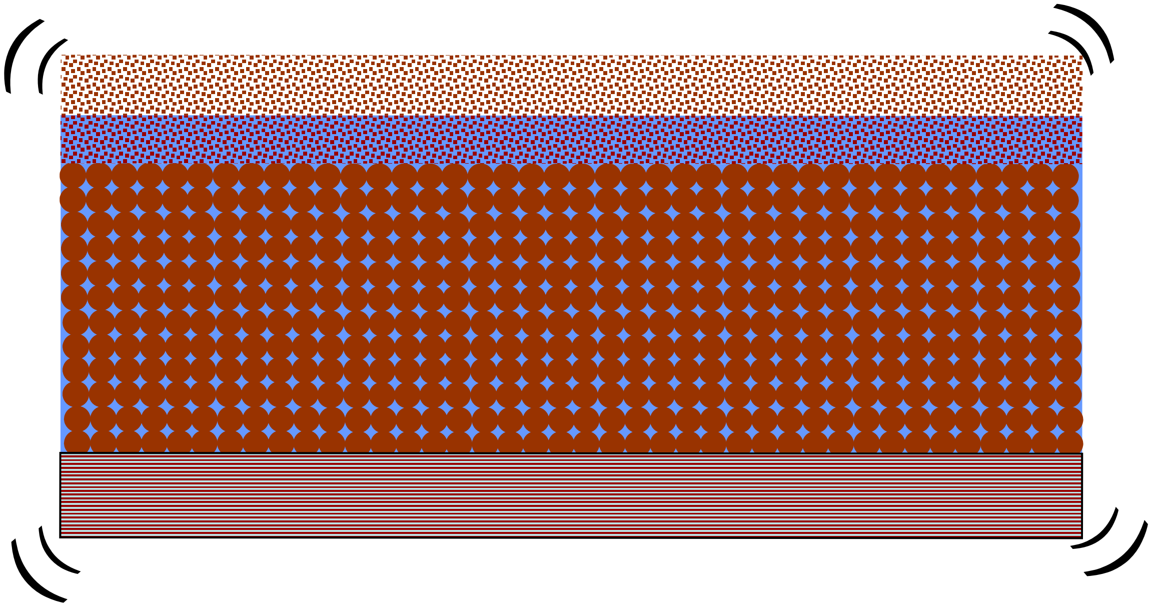
ACADEMIC INSTRUCTIONAL CENTER
WESTERN WASHINGTON UNIVERSITY
BELLINGHAM, WASHINGTON



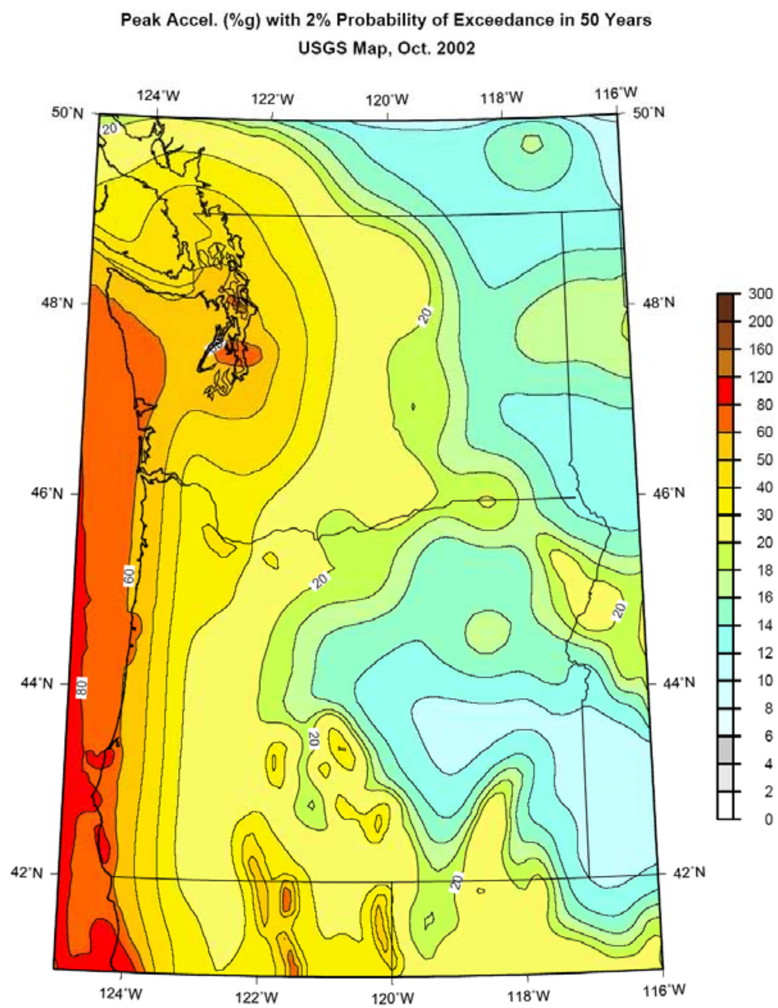
Groundshaking Potential is determined by the

1) earthquake proximity and magnitude

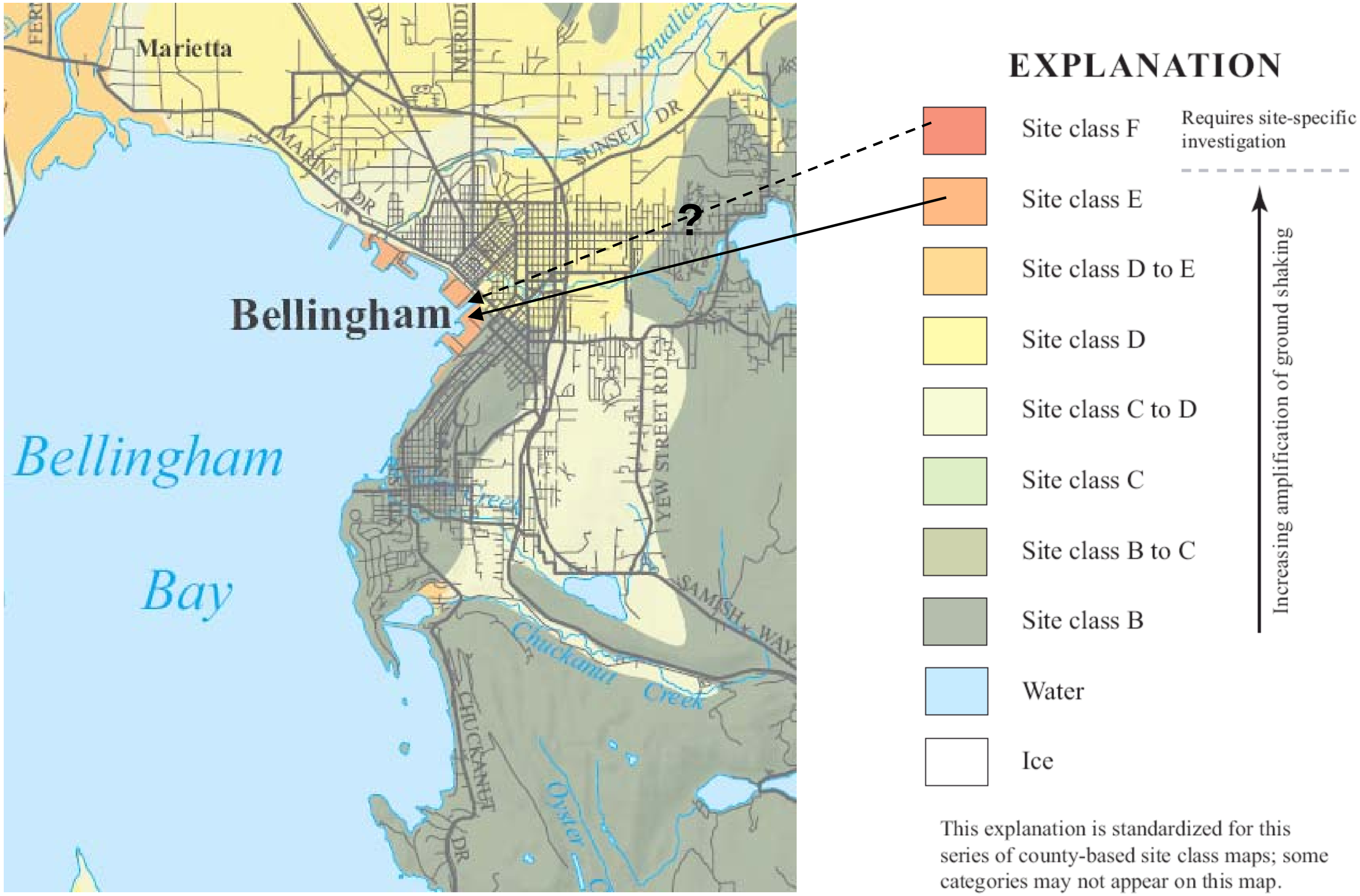
2) degree of wave amplification in soft sediments



Liquefaction is initiated by ground shaking from EQs



http://earthquake.usgs.gov/research/hazmaps/interactive/cmaps/custom2002_2006.php



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