Unconfined Compressive Strength (UCS) of Grout

Material	Compressive Strength, kPa, of Material After Grouting
Very loose granular material saturated with a silicate grout, cured dry	4,000-7,000
Very loose granular materials saturated with a silicate grout, cured at 80-100% relative humidity	2,800-3,500
Very loose granular materials saturated with a silicate grout, cured underwater	700-2,800
Average field conditions with one injection (incomplete saturation)	700-2,800
Compact, medium-grain granular materials saturated with a silicate grout, wet subsurface	200-4,000

EM1110-1-3500 (1995)

Cost of Grout:

Formulation	Relative Cost of Materials
Cement–bentonite	
w/c = 3, 5% bentonite by weight of water	1.0
w/c = 2, 3% bentonite by weight of water	1.3
w/c = 1, 1% bentonite by weight of water	2.3
Cement	
(w/c = 0.5)	3.4
Silicate–bentonite	
20% bentonite, 7% silicate (by weight of water)	1.3
Silicate–chloride (Joosten)	4.0
Silicate–ester	
37% silicate, 4.4% ester (by volume)	5.0
47% silicate, 5.6% ester (by volume)	6.5
Silicate–aluminate	
46% silicate, 1.4% aluminate (by weight)	5.0
Phenol–formaldehyde	
13% (by volume)	10.5
19% (by volume)	15.3
Acrylate	
10% (by weight)	18.5
Resorcinol–formaldehyde	
21% (by volume)	23.0
28% (by volume)	31.0
Polyacrylamide	
5% (by volume)	20.0
10% (by volume)	40.0

Littlejohn (1985)

Cost of Permeation Grouting

- A cost of $0.65 per liter in place for a project using more than 200,000 liters of sodium silicate grout
- $10,000 -$50,000 for a mobilization/demobilization rate
- Starting at $65 per linear meter for providing & installing the sleeve port grout pipes

FHWA NHI-04-001

Compaction Grouting – Concept

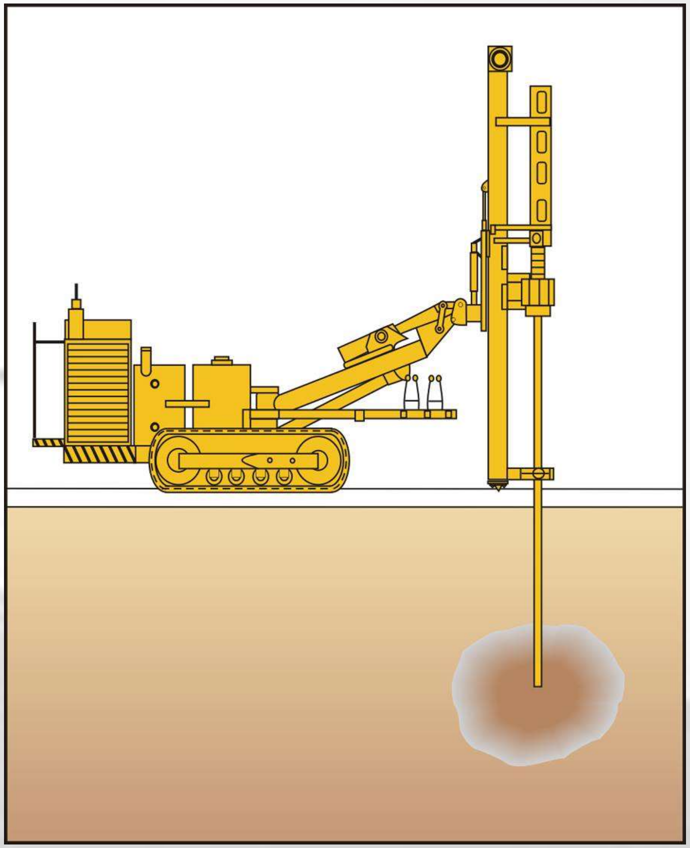
- Improve bearing capacity & density of soil by injecting stiff mortar to form a bulb around the injection tube
- Displace and compact weak soil by the formation of the bulb
- The mortar should be a coherent mass not to enter pores or fractures

http://www.youtube.com/watch?v=NBJgahvJQ-w&feature=related

Compaction Grouting

Compaction Grouting uses displacement to improve ground conditions. A very viscous (low-mobility), aggregate grout is pumped in stages, forming grout bulbs, which displace and density the surrounding soils.

Significant improvement can be achieved by sequencing the grouting work from primary to secondary to tertiary locations.



Compaction Grouting – History

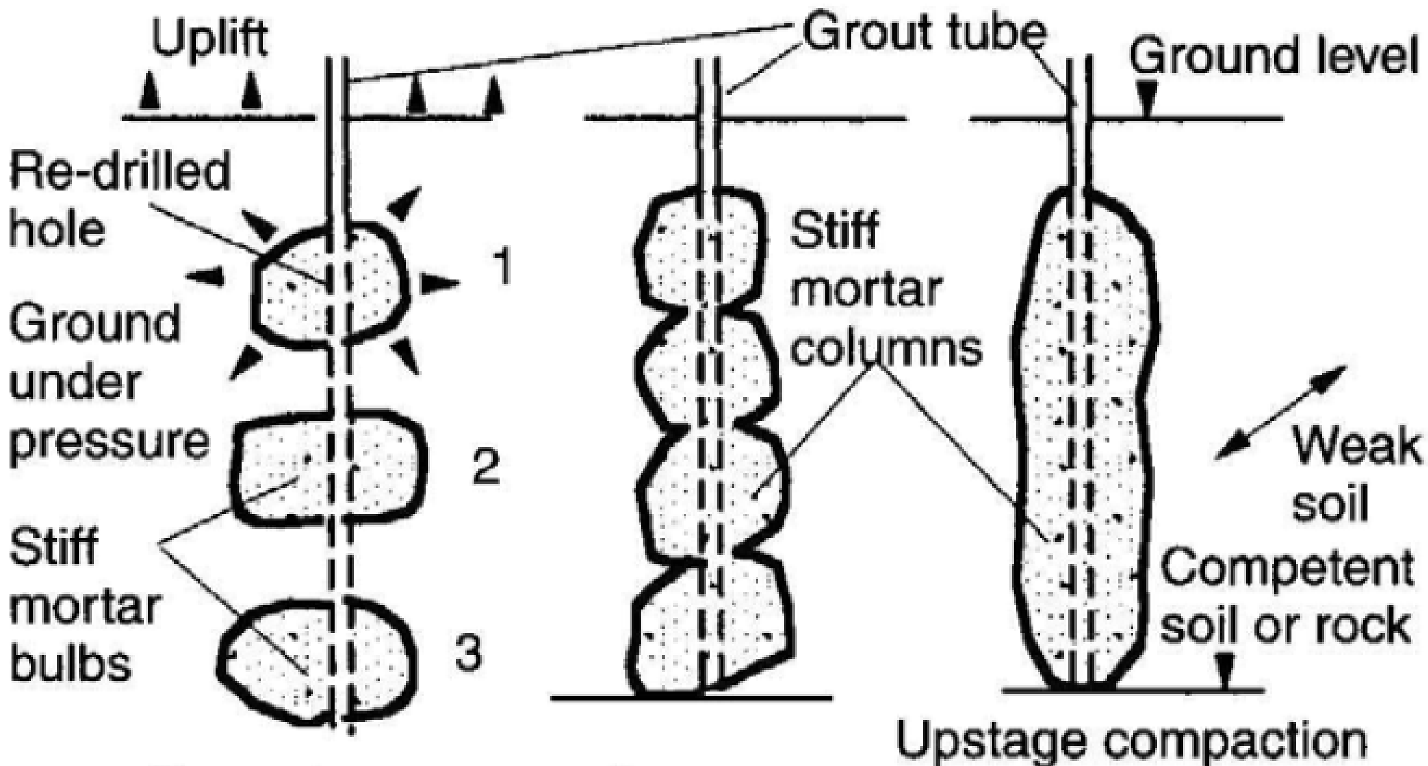
- First used in the early 1950s on the west coast of the United States

- For the first 30 years it was used exclusively as a remedial technique

- In the late 1970s it gained acceptance in other parts of the United States

- In 1990, this technology was exported to Japan

Construction Method

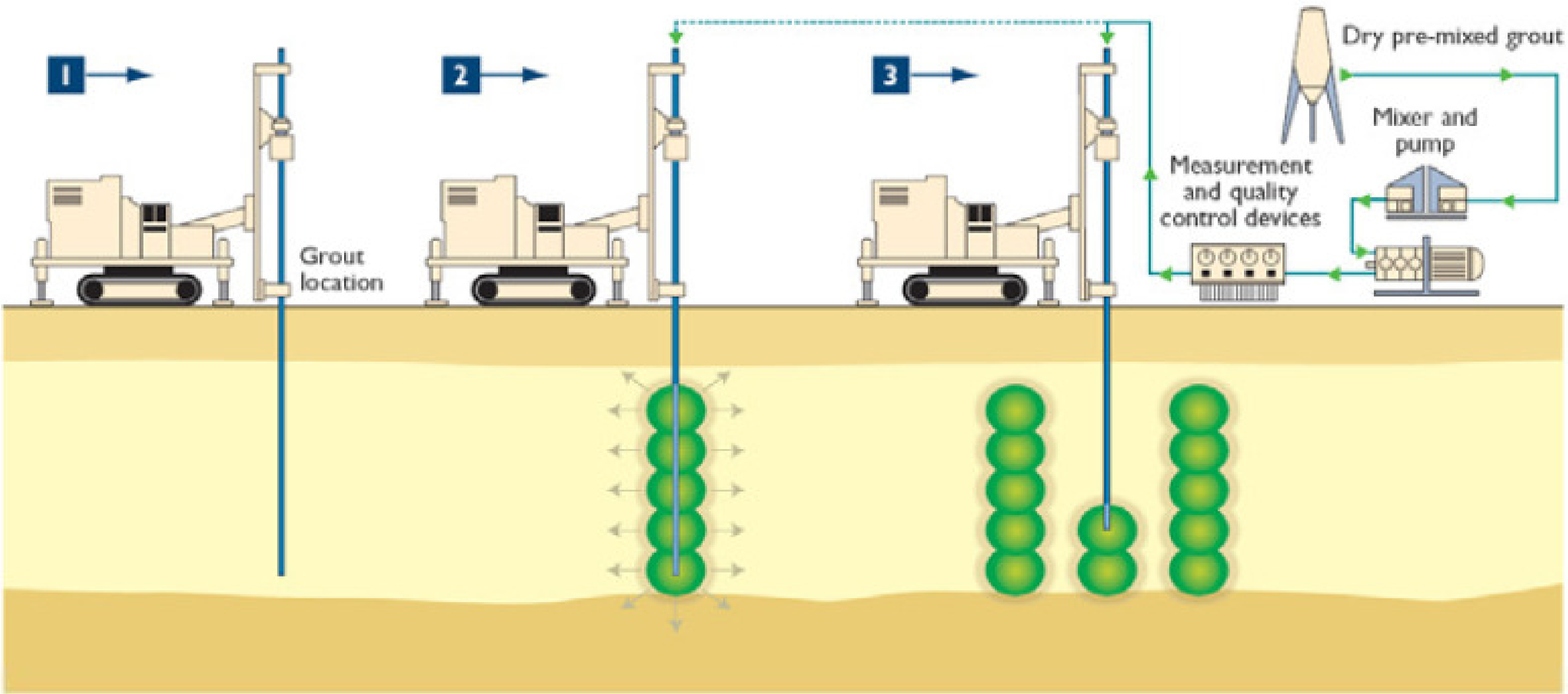


Grout injected at specific zones to displace and compact soil. Re-drilling of each grouted bulb.

Hole drilled to competent bearing layer and grout injected as grout tube withdrawn.

Woodward (2005)

Construction Method



1 Installation of the Grout Pipe
The grout pipe is either installed by means of a drill rig or a vibro hammer, depending on the soil and on the treatment requirements.

2 Compaction Grouting
The grout paste is prepared in the mixing plant and pressed into the soil by means of a custom-built grout pump.
While gradually pulling or penetrating the grout pipes, individual intersecting grout bulbs are consecutively formed, thus creating column shaped structural elements.

3 Staged Compaction
In order to achieve a uniform compaction of the soil, the injections are at first executed in a large primary grid, and may be compacted further by means of a secondary grid.

Keller

Downstage versus Upstage

- Downstage
  - Suitable for shallow injection (< 15ft)
  - Each injected stage provides additional restraint and containment for those that follow

- Upstage
  - Suitable for deep injection
  - Fast and economical

Woodward (2005)

Applications

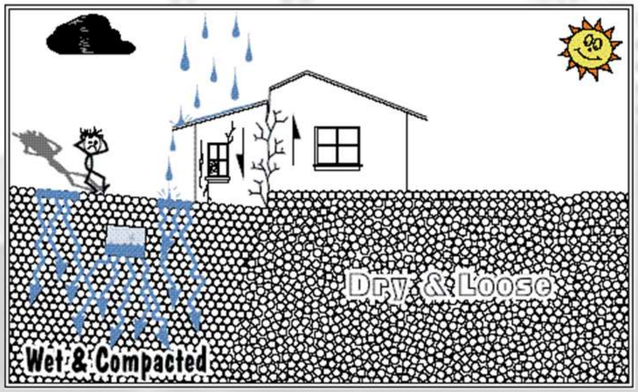
- Primary application: densification of soils
  - Loose, granular soils above or below the groundwater table
  - Loose, non-saturated fine-grained soils
  - Collapsible soils
  - Soil voids caused by adjacent excavation activity, sinkhole activity, improper dewatering, broken utility lines

- Secondary application: re-level settled structures

Compaction Grouting Applications

- Poorly Placed Fill
- Loosened Soil: Pre-Treatment
- Loosened Soil: Post-Treatment
- Liquefiable Soils

- Collapsible Soils



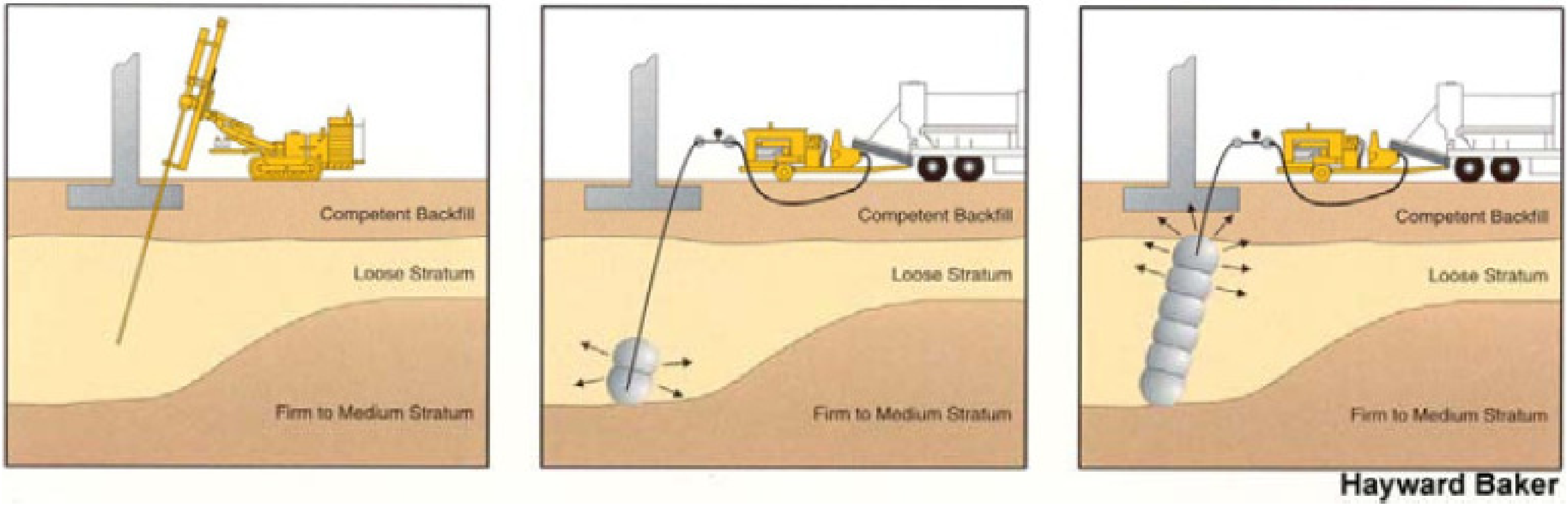
- To compensate for ground loss during tunneling

Slump Test

Low slump but pumpable

Keller

Installation Procedure



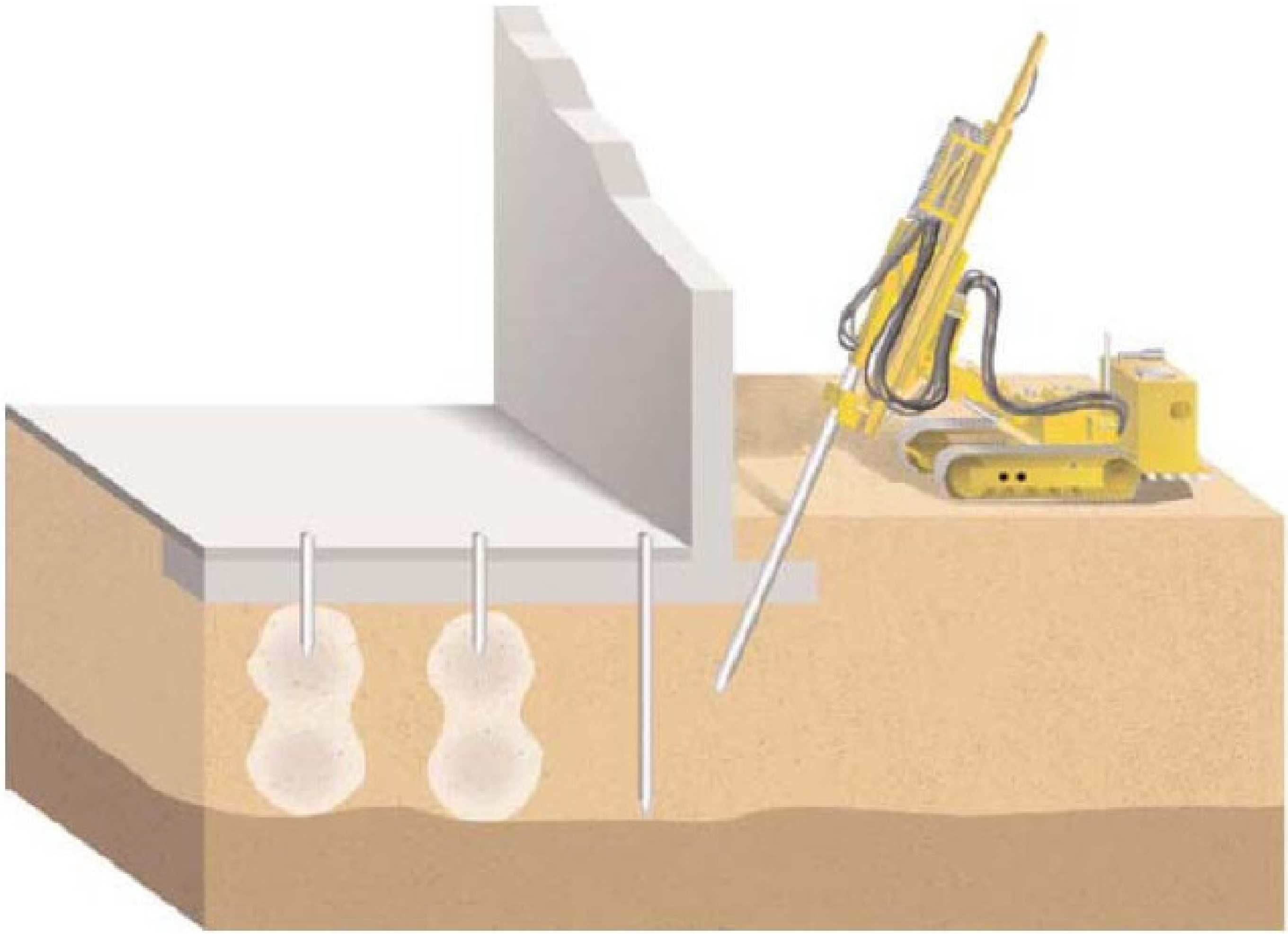
Step 1: Install grout pipes using drilling or driving techniques.

Step 2: The mortar-like grout, injected through the pipes, displaces the surrounding soil. The grout pipe is then lifted some distance (0.3 to 1.5 m), and the injection process is repeated.

Step 3: Injection in "stages" continues until the target layer has been treated.

Hayward Baker

Installation Procedure



Hayward Baker

Field Installation

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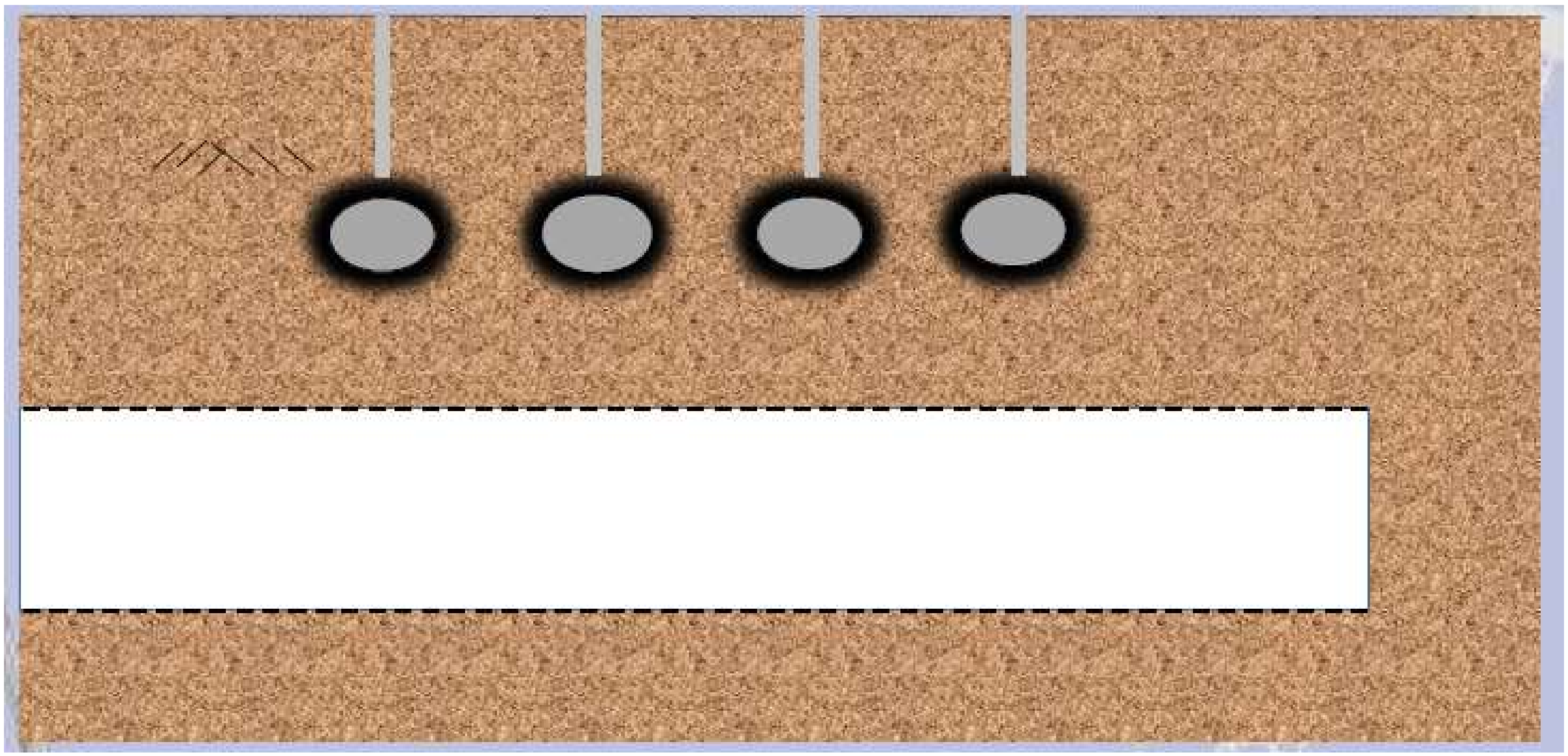
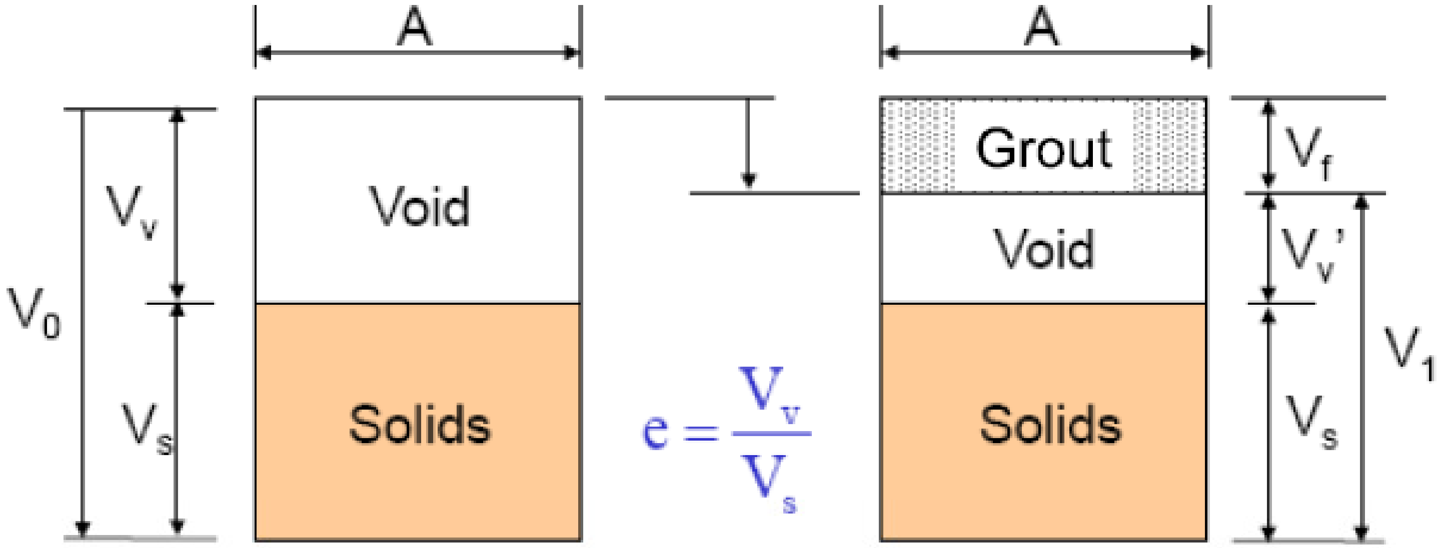
Compaction Grouting Process

Compaction Grouting to Mitigate Tunnel Induced Settlement



Assume full displacement



$$e = \frac{V_v}{V_s}$$

$$V_0 = V_s(1+e_0) \qquad V_1 = V_s(1+e_1)$$

$$V_f = V_0 - V_1 = V_s(1+e_0) - V_s(1+e_1) = V_s(e_0 - e_1) = \frac{V_v}{e_0}(e_0 - e_1)$$

$$V_v = e_0 V_s = \frac{e_0}{1+e_0} V_0 \qquad V_f = \frac{e_0 - e_1}{1+e_0} V_0 \qquad a_s = \frac{V_f}{V_0} = \frac{e_0 - e_1}{1+e_0} V_0$$

Required Spacing of Grouting

Volume of grout

$$V_f = \frac{e_0 - e_1}{1 + e_0} V_0$$

Considering ground heave, δ_h

$$V_f = \frac{e_0 - e_1}{1 + e_0} V_0 + \delta_h s^2 = \frac{e_0 - e_1}{1 + e_0} s^2 L + \delta_h s^2$$

L= thickness of treated ground

Spacing for square pattern

$$s = \sqrt{\frac{(1 + e_0) V_f}{(e_0 - e_1) L + (1 + e_0) \delta_h}} = \sqrt{\frac{\pi (1 + e_0) d^2 L}{4 (e_0 - e_1) L + 4 (1 + e_0) \delta_h}}$$

Spacing for triangular pattern

$$s =$$

Design of CG for Bearing Capacity

Step 1: Determine the required friction angle of cohesionless soil

Step 2: Estimate the corresponding SPT N value & relative density

Step 3: Calculate the required void ratio after treatment

Step 4: Assume the size of grout bulbs, d, and the limiting heave, δh

Step 5: Determine the grouting spacing using the related equation

Other Design Guidelines

- Typically greater than 1,500 psf overburden stress is required to maximize densification
- Limited densification can be achieved with less overburden
- Overburden stress comes from overburden soil, surcharge loads, and/or foundation loads
- Treated spacing ≤ 6 to 10 ft
- Replacement ratio = (Compaction grout volume) /(Treated volume) = 5 to 15%

Hayward Baker

Heave

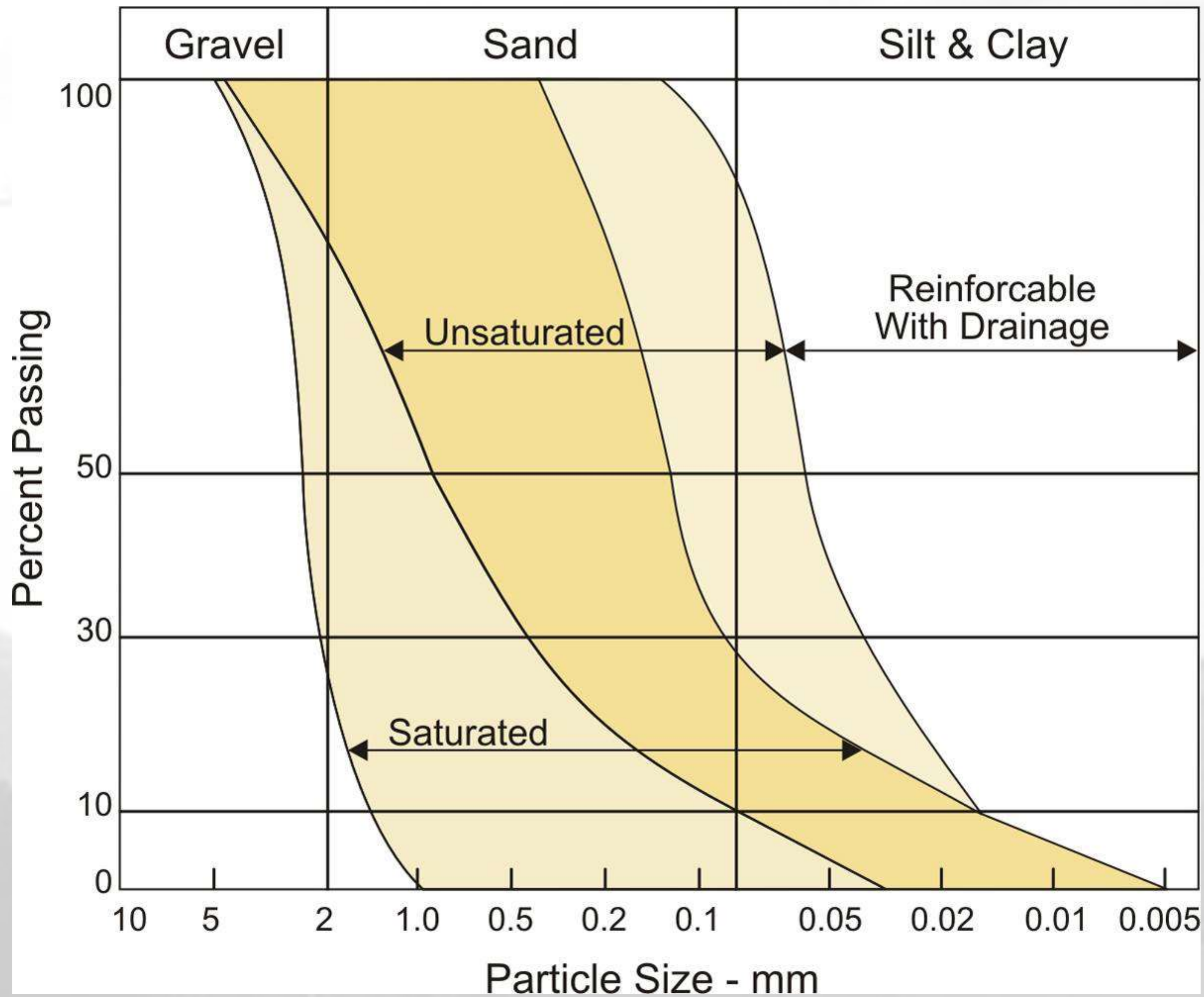
- Surface and/or structural heave is the most common limiting factor
- Heave indicates that compaction stresses have exceeded the confining stresses and fracturing develops
- Typically limit the total heave less than 0.5 in. except for re-leveling projects

Moseley & Kirsch (2004)

Compaction Grouting
Geotechnical Considerations

- Soils that lose strength during remolding (saturated, fine-grained soils; sensitive clays) should be avoided.
- Greater displacement will occur in weaker soil strata. Exhumed grout bulbs confirm that compaction grouting focuses improvement where it is most needed
- Collapsible soils can usually be treated effectively with the addition of water during drilling prior to compaction grout injection

Compaction Grouting Range of Improvable Soils



Compaction Grouting
Advantages

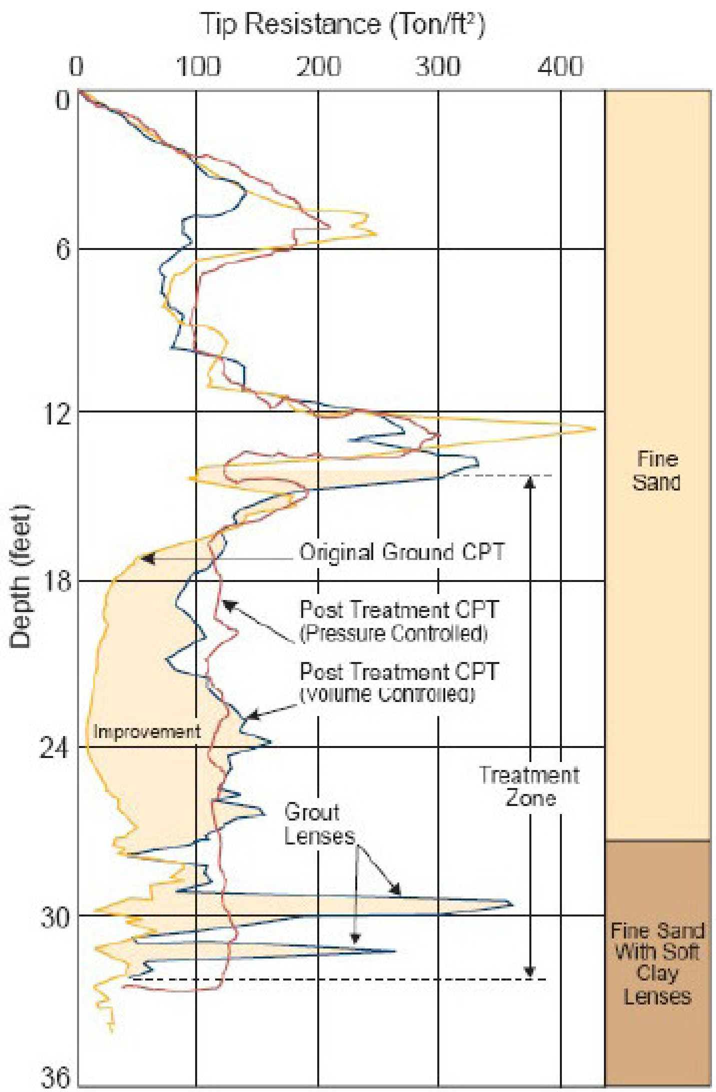
- Pinpoint treatment
- Speed of installation
- Wide applications range
- Effective in a variety of soil conditions
- Can be performed in very tight access and low headroom conditions
- Non-hazardous
- No waste spoil disposal
- No need to connect to footing or column

More…

Compaction Grouting
Advantages

- Non-destructive and adaptable to existing foundations
- Economic alternative to removal and replacement or piling
- Able to reach depths unattainable by other methods
- Enhanced control and effectiveness of in situ treatment with Denver System^{tm}
- Minimal impact to surface environment

Improvement of Soil Properties



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Cost of Compaction Grouting

- Typical cost range from $5 -$50 per cubic meter of soil treated plus mobilization and pipe installation cost
- The cost of the grout alone is in the range of $60 – $120 per cubic meter

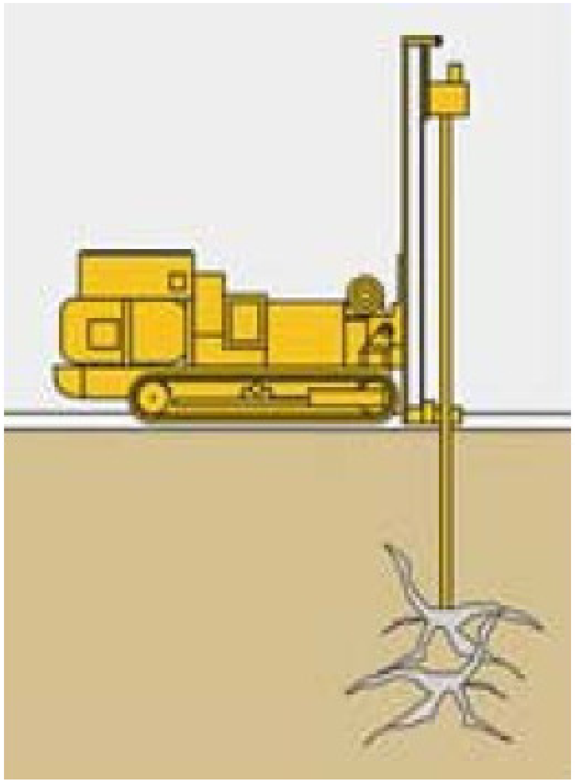
Hydro-Fracture Grouting – Principles

- To open up existing fissures or create fissures by controlled injection of grout under pressure and thereby provide lenses of material to compact and strengthen soil or reduce permeability

http://www.youtube.com/watch?v=Gi6LUsJVxyY&feature=related

Woodward (2005)

Installation Method



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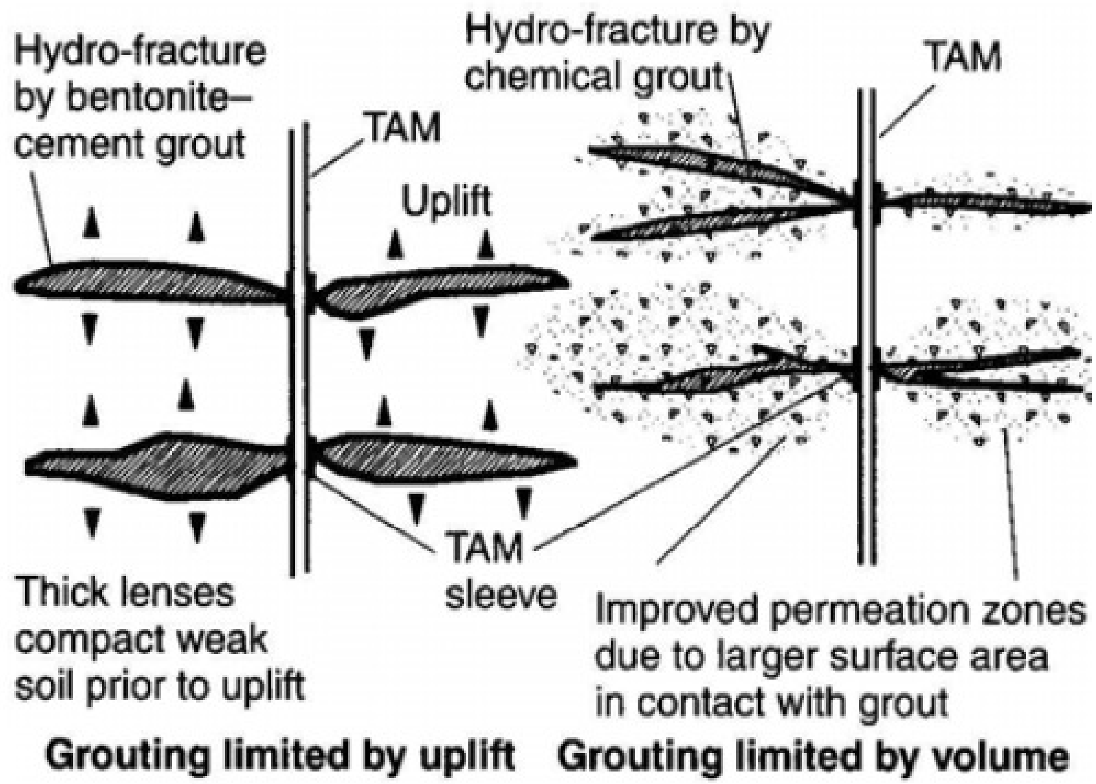
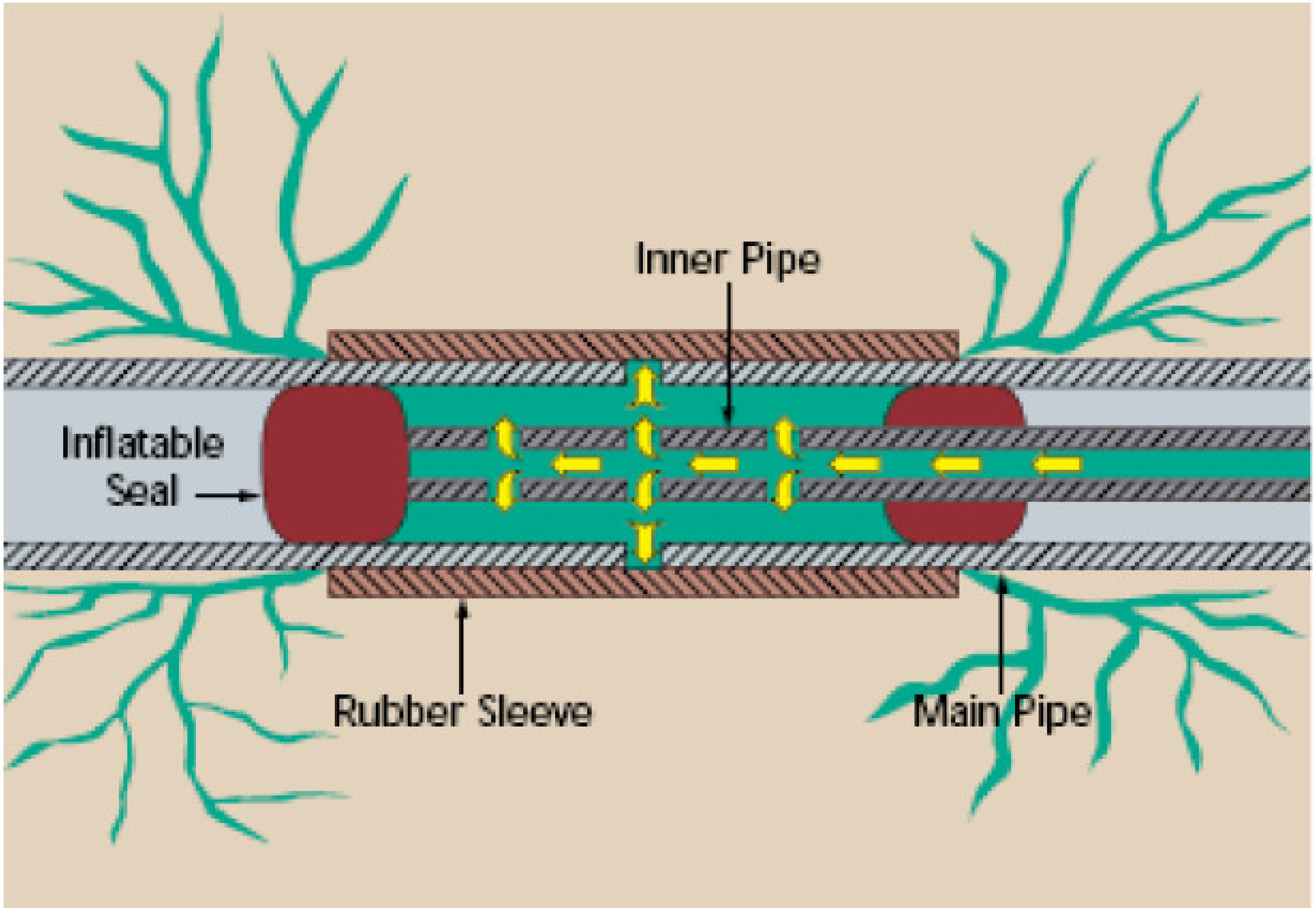


TAM = Tube-a-Manchette

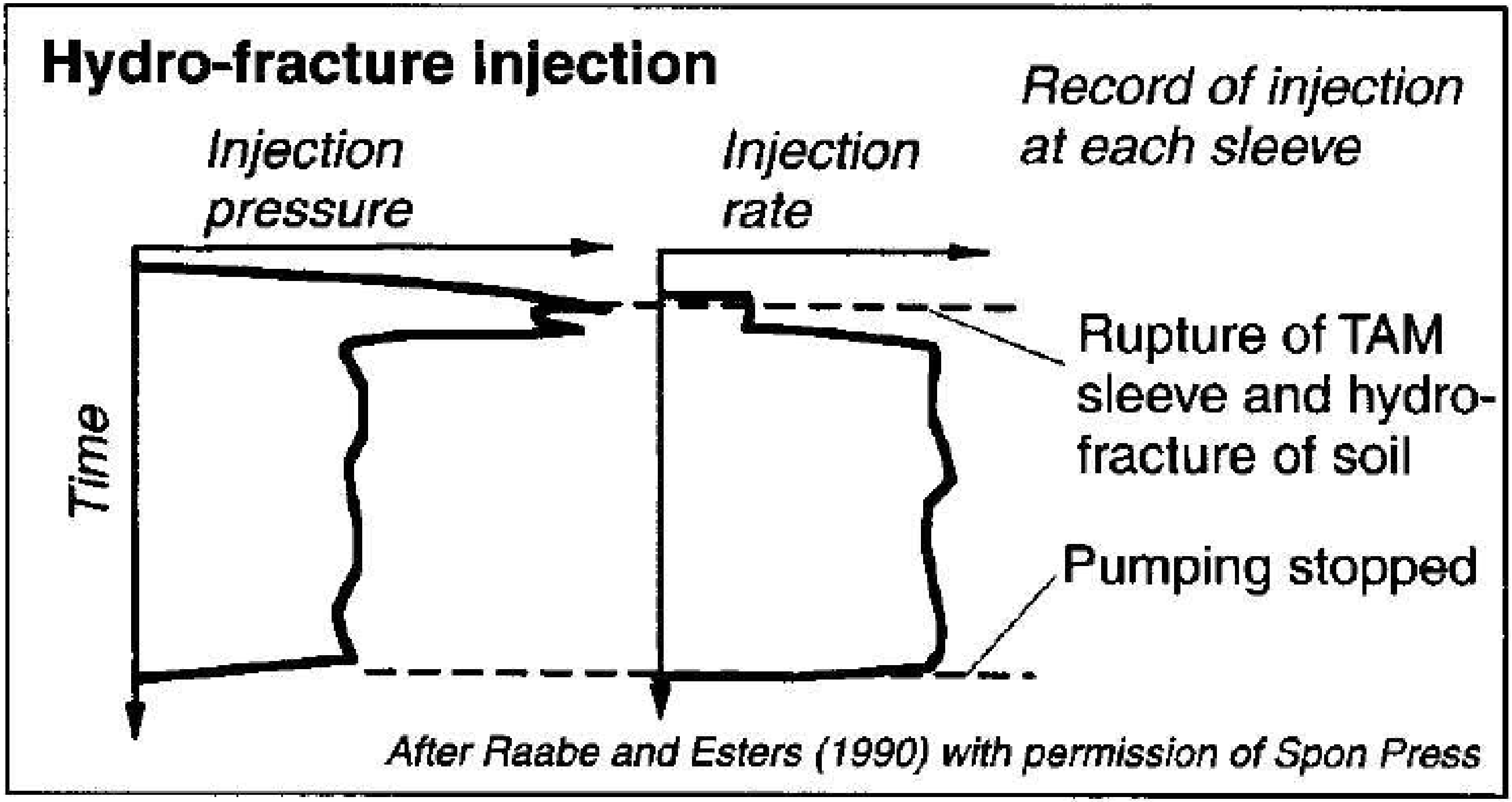
Woodward (2005)

TAM Grout Injection Tube



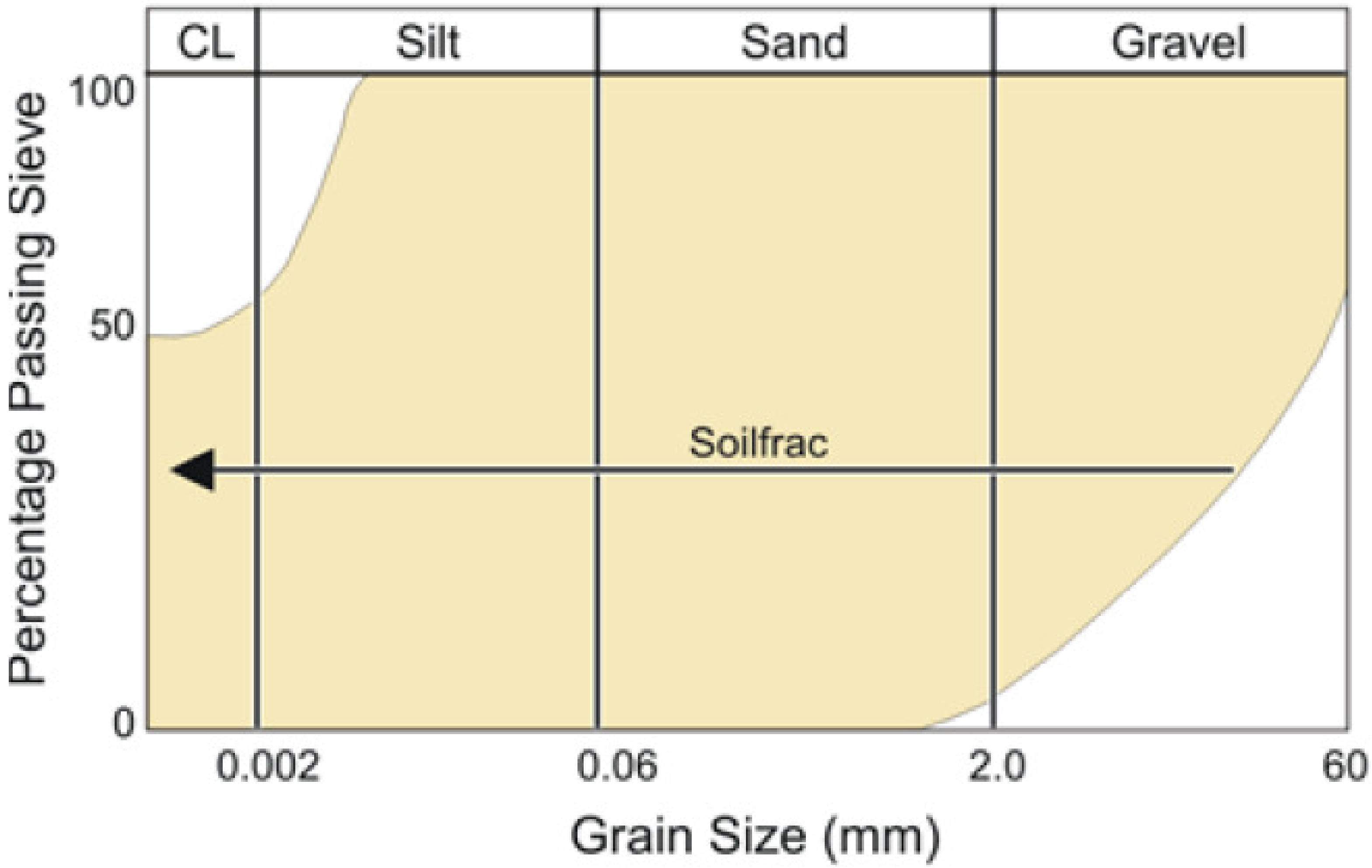
Keller

Variation of Injection Pressure and Rate



Woodward (2005)

Suitability of Hydro-Fracture Grouting



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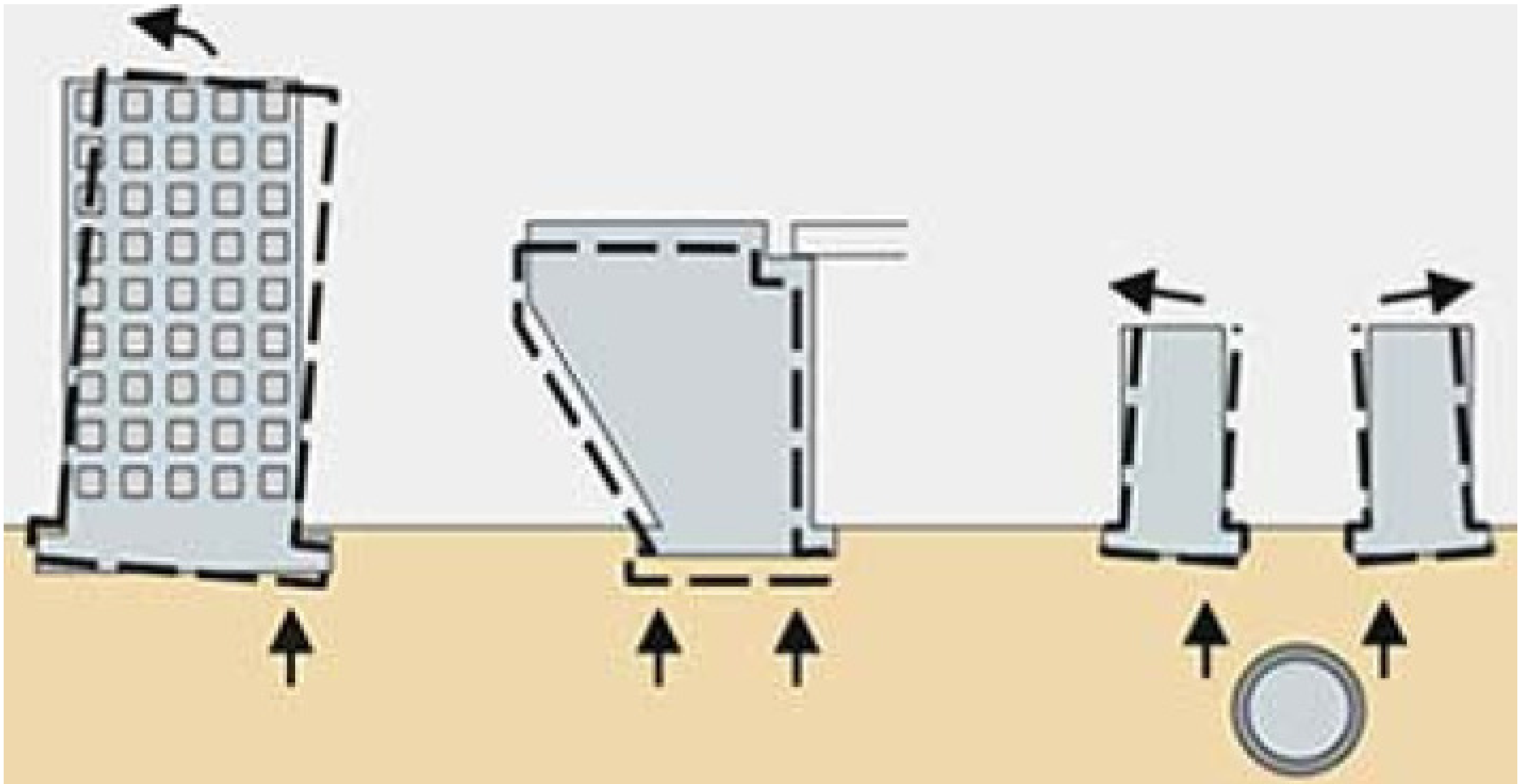
Applications of Hydro-Fracture Grouting



Hayward Baker