Damages Caused by Liquefaction

- due to stiffness and strength loss in soil materials
  - **rise of buried structure**, **subsidence of structures**, **sway of retaining structures**
- due to slide and flow of soil materials
  - lateral flow, **flow failure of fill**, **slump of fill**
- due to change in vibration properties
  - **increase in natural period**

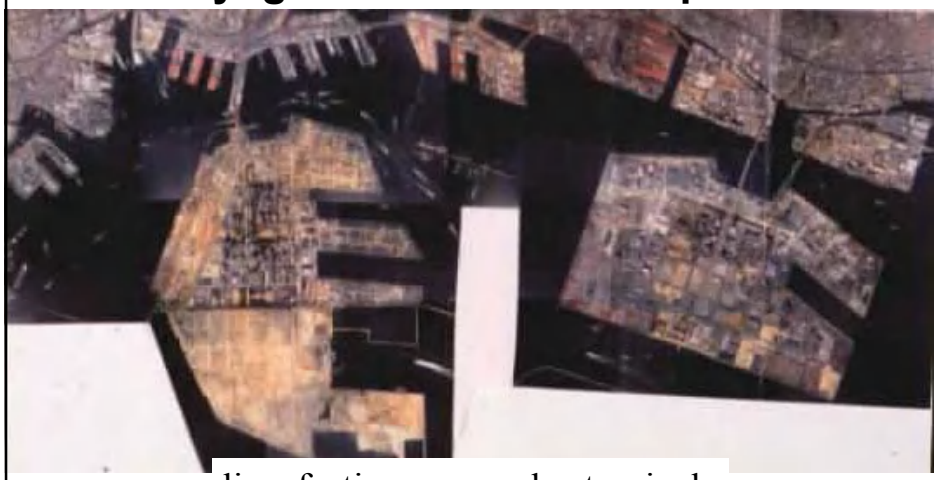
(positive and negative effects)

(some more explanation: L-2-1)

Estimated Damage Hanshin-Awaji EQ.,1995

Items	Estimated value (billion yen)
1. Structure (building)	5800.0
2. Railway	343.9
3. Expressway	550.0
4. Public facilities	296.1
5. Harbor	1000.0
6. Reclaimed land area	6.4
7. Facilities for education	335.2
8. Facilities for agriculture, forestry and fisheries	118.1
9. Facilities for health, medical and welfare	173.3
10 Facilities for waste and sewage disposal	4.4
11. Facilities for water supply	54.1
12. Facilities for gas and electricity	420.0
13. Facilities for communication and broadcasting	120.2
14. Facilities of commerce and industry	630.0
15. Other public facilities	75.1
Total	9926.8 billion yen

Water Front in Kobe City after 1995 Hyogoken Nambu Earthquake

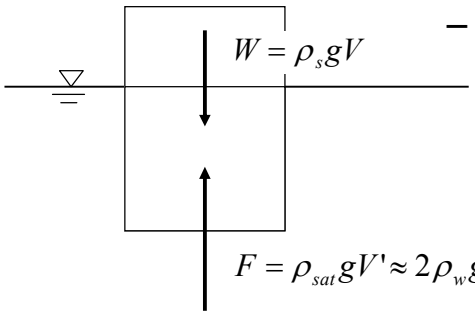


liquefaction occurred extensively

Port Island in Kobe City

grand is covered with boiled sand

Rise of buried structures



– in liquefied ground buried structures are subjected to buoyancy force greater than that in water

V; total volume, V'; volume of under ground part
ρ_s*; average density of structure,*
ρ_{sat}*; density of saturated soil*

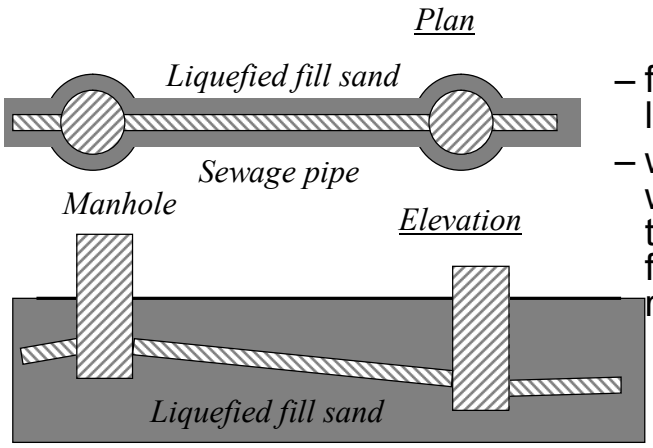
Damaged water tank

buried water tank floated up in Niigata Port, during 1964 Niigata Earthquake

Damaged sewage system

a manhole was lifted by 1.4m due to liquefaction of fill sand during 1993 Kushiro-oki Earthquake

Raise of sewage system

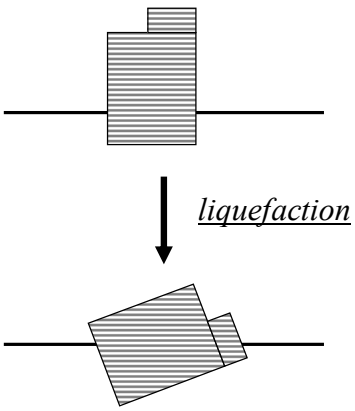


- fill sand was liquefied
- whole system was subjected to buoyancy force and raised.

Damaged chemical storage tank

Empty tank floated up
in 1993 Hokkaido Nansei-oki Earthquake

Subsidence of structures

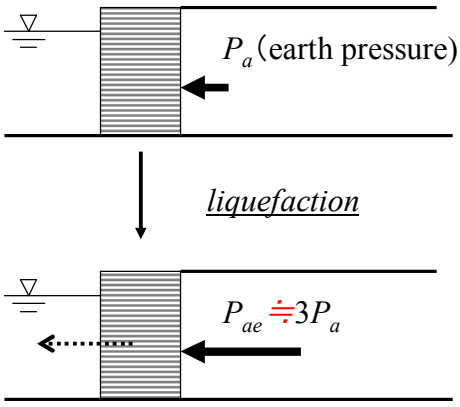


- liquefied ground looses bearing capacity
- structures subside with tilting esp. for asymmetric structures

Damaged buildings

some buildings were tilted and subsided in 1964 Niigata Earthquake

Sway of retaining structures

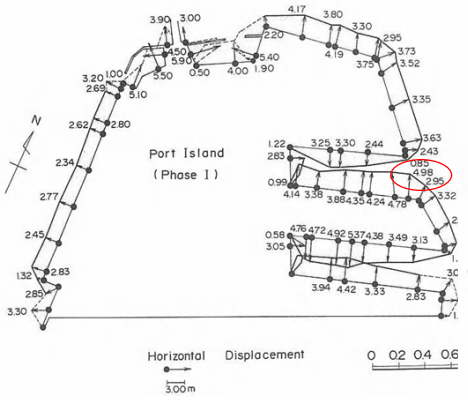


- in water front resultant force increases by the factor of three
- sliding and/or subsidence occur

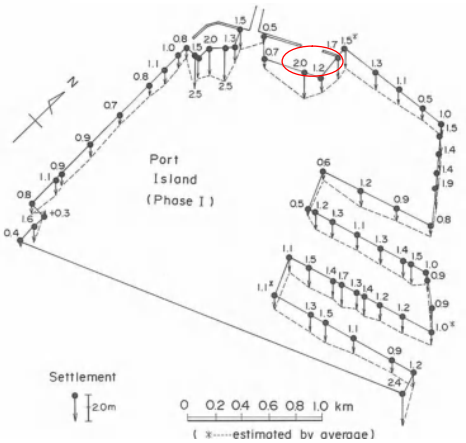
Zone of liquefied area in Rokko Island at 1995 Hoguken-Nanbu Eq.

Displacement of quay wall by Kobe Eq. (Port Island)

S&F special issue (1996)



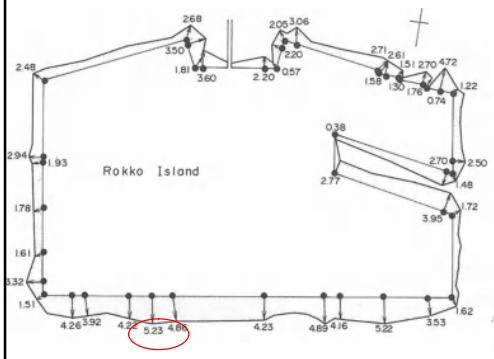
Horizontal displacement



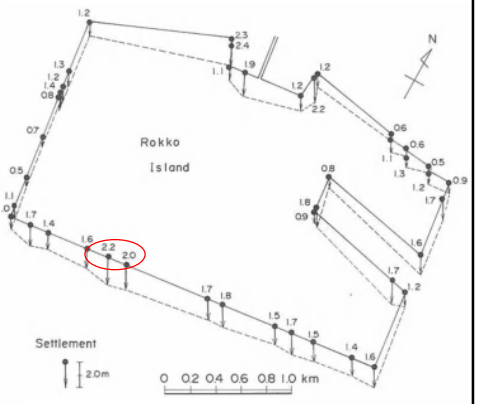
Vertical displacement

Displacement of quay wall by Kobe Eq. (Rokko Island)

S&F special issue (1996)



Horizontal displacement



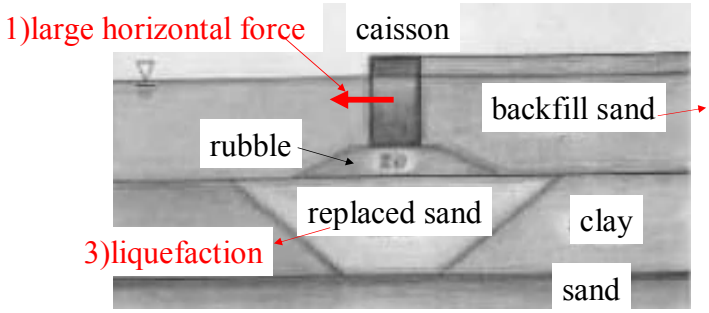
Vertical displacement

Damaged quay wall

S&F paper L-4-4

many quay walls were damaged due to liquefaction of backfill in1995 Hyogoken-Nambu Earthquake

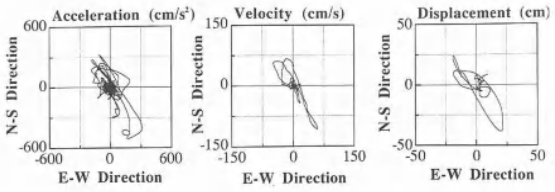
Typical section of quay wall in Kobe Port

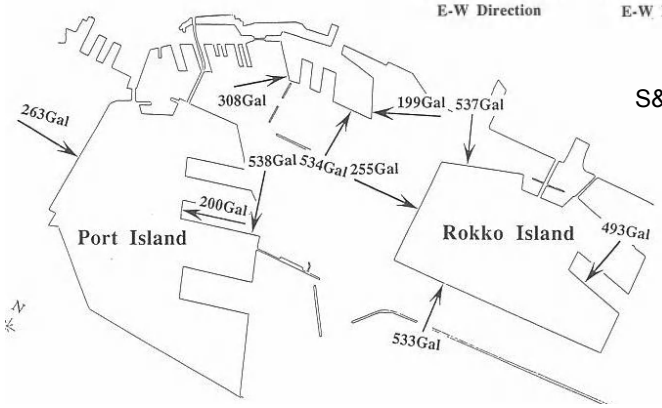


These three conditions caused **5m** lateral displacement.

S&F paper L-4-4

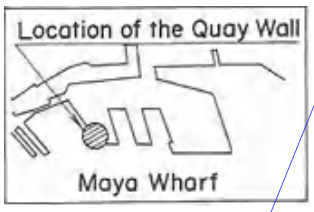
Observed ground motions and accelerations at Kobe Port





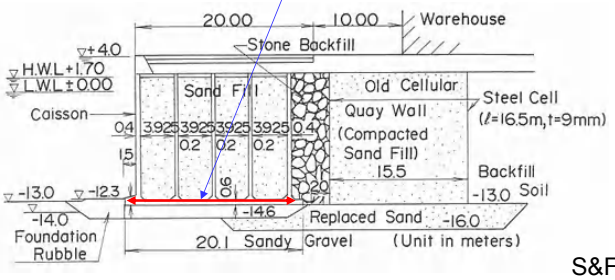
S&F special issue (1996)

High seismic resistant quay walls at Maya Warf



Seismicity:0.25

No liquefiable sand beneath and behind quay wall



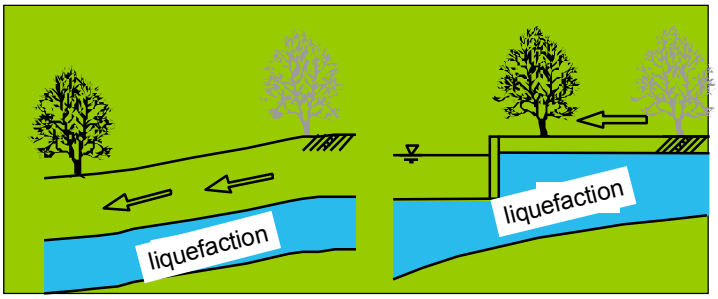
HSRQW performed very well against strong motion.

S&F special issue (1996)

Due to slide and flow of soil materials

- Lateral flow
  - pipelines, pile foundations
- Flow failure of fill
  - fill embankments on slope (housing lots, road, rail road), dams
- Slump of fill
  - fill embankments (road, railroad, housing lots), river dike

Lateral flow



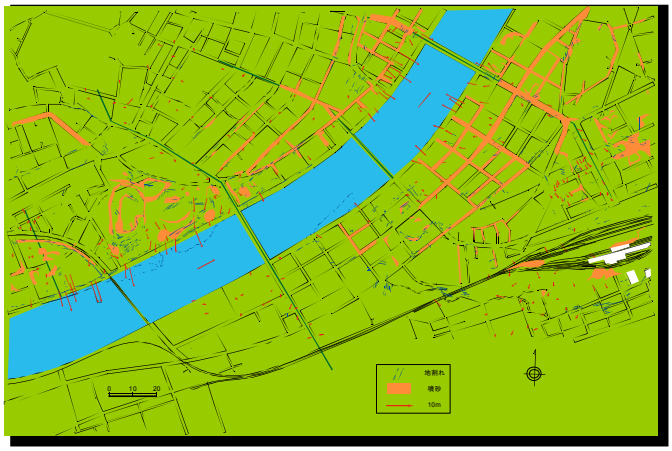
- Sloped ground Ground with laterally free

Liquefaction in flat area

Ground subsided by 30cm with sand boiling,
in port island during 1995 Hyogoken-nambu Rarthquake

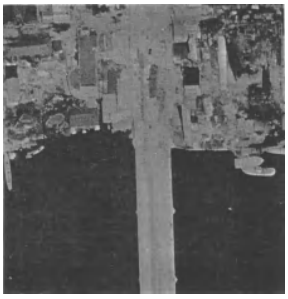
Lateral flow in Niigata city

Extensive lateral flow occurred around Shinano River, during 1964 Niigata Earthquake



Lateral flow around Bandai Bridge

1962



1964 (after hrs.)

1971

river side slid toward river in 1964 Niigata Earthquake

Lateral flow of river side

river sides slid toward river with many parallel cracks, in 1964 Niigata Earthquake

Collapse of Showa-ohhashi Bridge

in 1964 Niigata Earthquake

Bridge piers were distorted by lateral movement of foundation ground and girders fell down.

Damaged pile foundation

in 1964 Niigata Earthquake

pile foundation for a building at river side
was distorted by lateral flow of liquefied ground

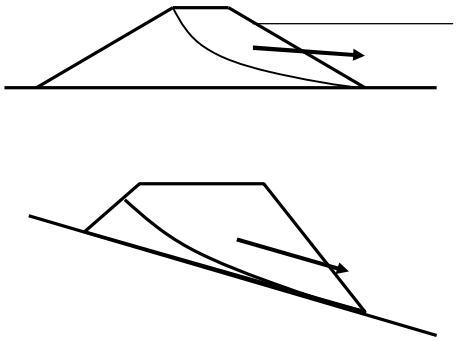
Lateral movement of ground

in 1995 Hyogoke-Nambeu Earthquak S&F paper L-4-2

Entire ground surface moved 1-3m towards north, resulting severe damage of not quay walls but also concrete piles and buried piles

Change the design code of of highway bridge foundation, considering force due to lateral M.

Flow failure of fill

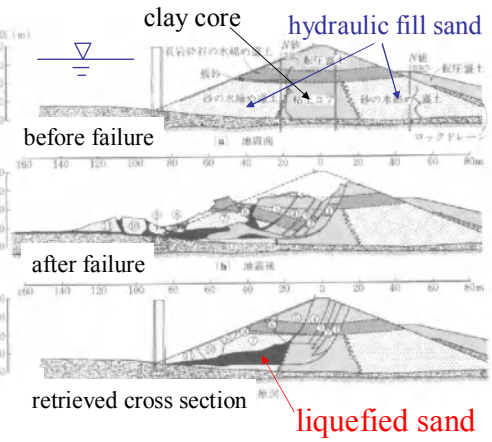


reduction of shear strength due to liquefaction leads to slide failure of embankments or dams.

Flow failure of earth dam

San Fernando Dam: Hydraulic fill dam constructed in 1930.

Slide in the Lower San Fernando Dam during 1971 San Francisco Earthquake



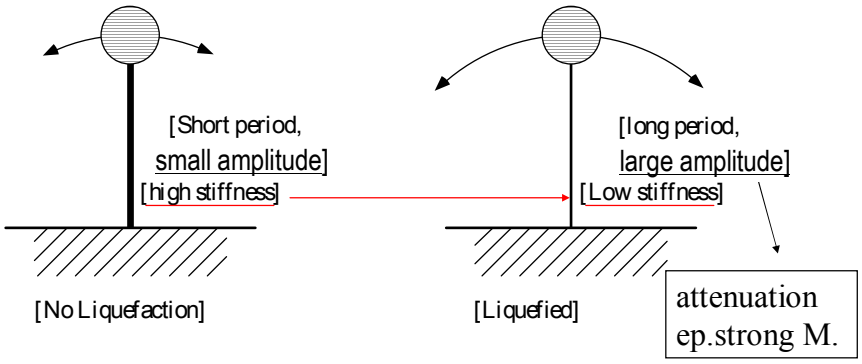
Collapsed road fill embankment

a part of road embankment constructed curved slope was slid away, in 1993 Kushiro-oki Earthquake.

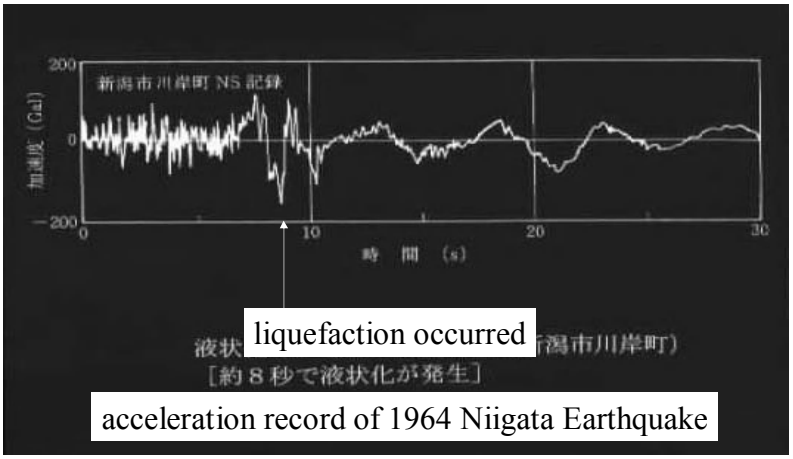
Slumped embankments in 1993 Kushiro-oki Earthquake

Due to change in vibration properties

- Increase in natural period



change of vibration properties due to liquefaction



Damaged cement storage tank due to resonance with liquefied ground

Countermeasures against Liquefaction
-preventing the required condition for liquefaction-

- Cyclic shear deformation
- Uniformly graded sand ground
  - silt or clay exhibits no dilatancy behavior
  - liquefaction is not sustainable in gravel (high permeability prevents the accumulation of Δu)
- Loose ground
  - loose grounds show large volume reduction
- High ground water table
  - liquefaction is not sustainable in dry condition
  - ground water keeps liquefaction

Remedial Methods against Liquefaction

- Improvement of the properties of ground and soil structure
  - replacement, strengthen, densification
- Enhancement of drainage
  - lowering ground water table, control of pore water pressure increase
- Reinforcement of ground-structure system
  - reinforcement of ground and soil structures, reinforcement of structural foundations

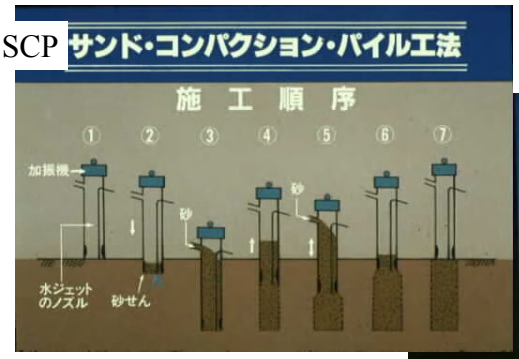
(further details: L-2-2)

Improvement of properties of ground and soil structure

- Replacement
  - clean sand is replaced with silty sand or gravel
- Strengthen
  - use some kinds of chemical binder
  - deep mixing method (DMM)
- **Densification (*most common and economical*)**
  - sand compaction pile method (SCP)
  - dynamic consolidation method (DC)

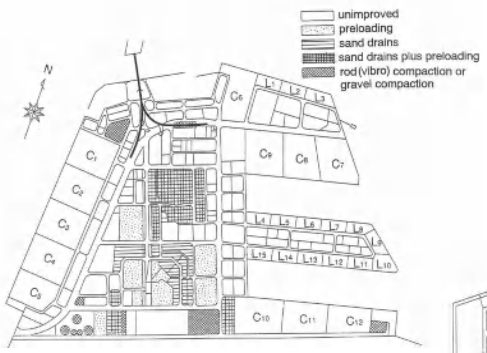
Sand compaction method (SCP) and dynamic consolidation method (DC)

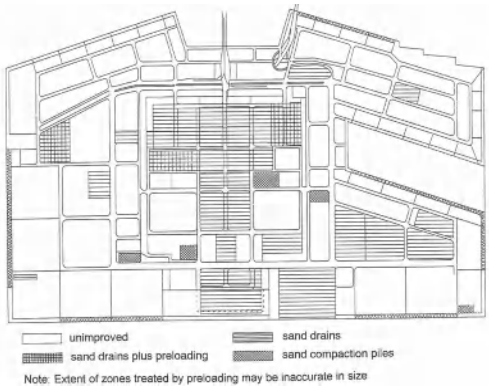
SCP



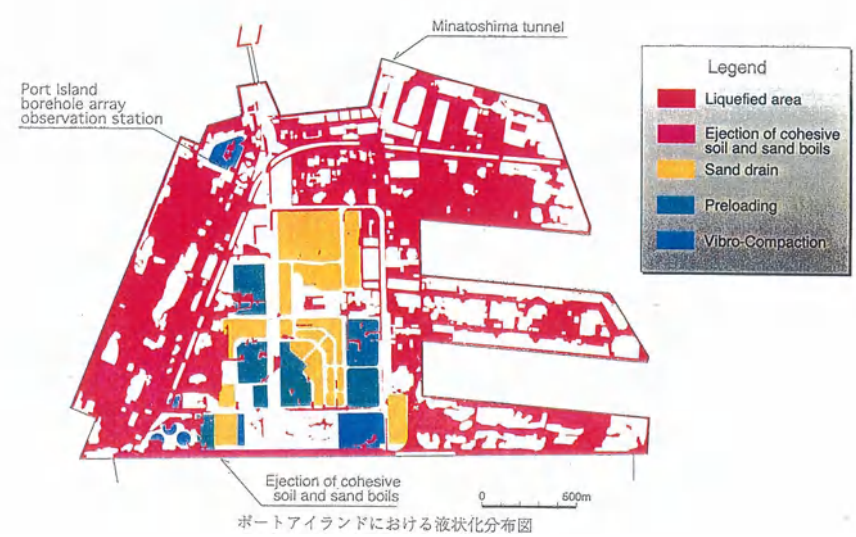
DC

Ground improvement used in Port and Rokko islands

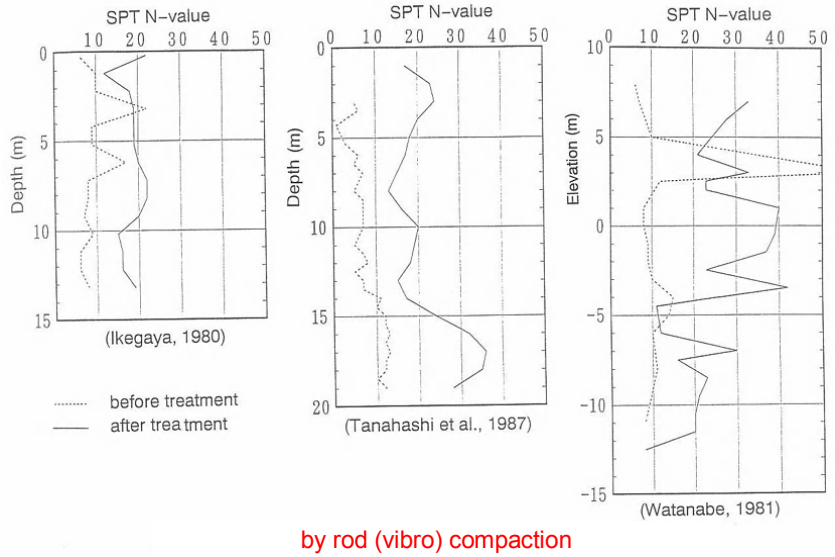




Zone of liquefied area in Port Island at 1995 Hoguken-Nanbu Eq.

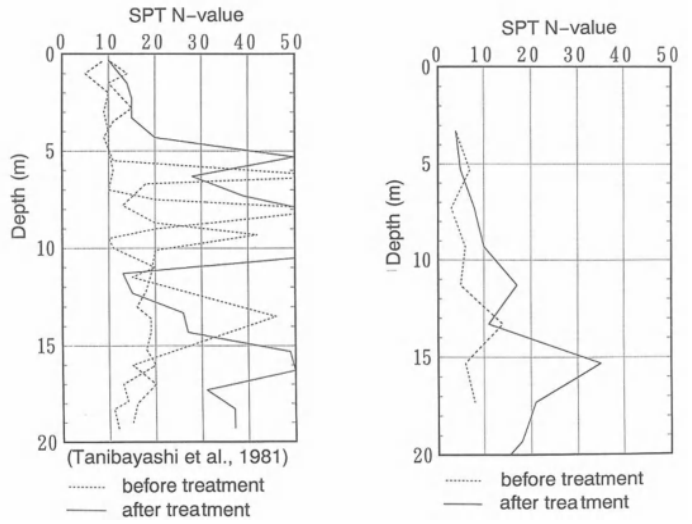


Increase in N-value due to treatment



by rod (vibro) compaction

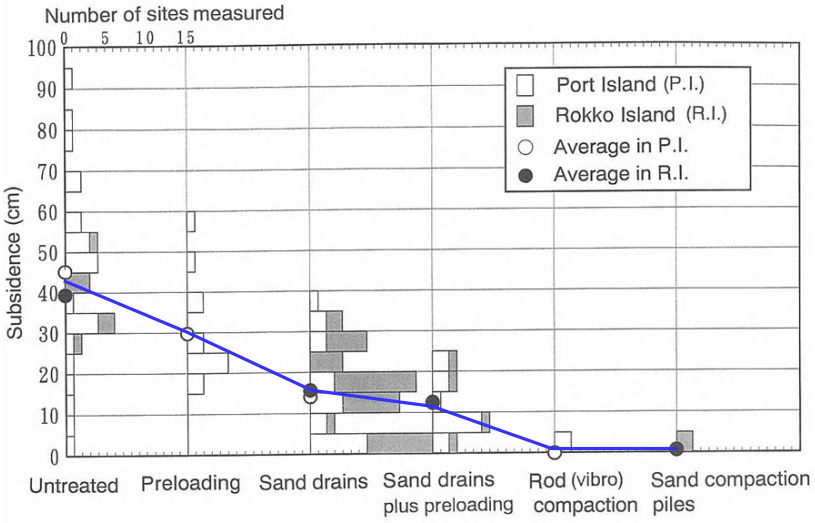
Increase in N-value due to treatment



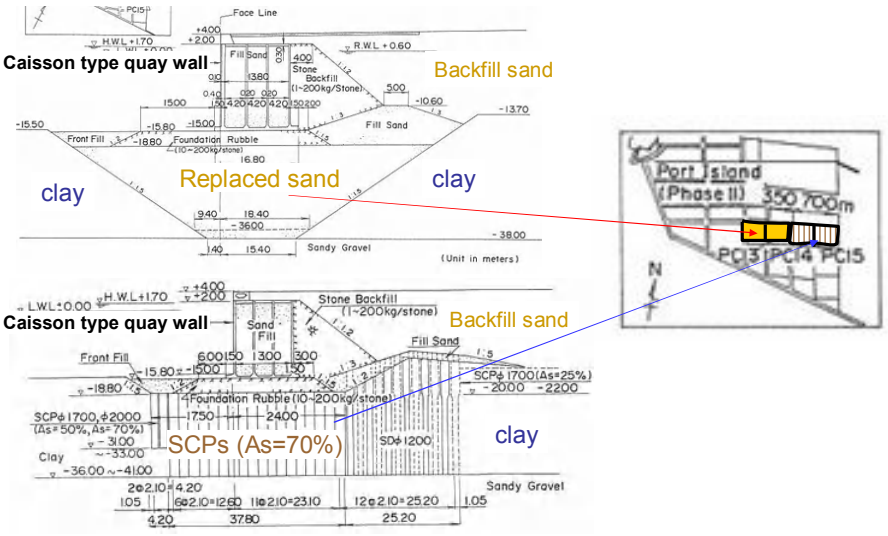
by sand drain + preloading

by sand drain

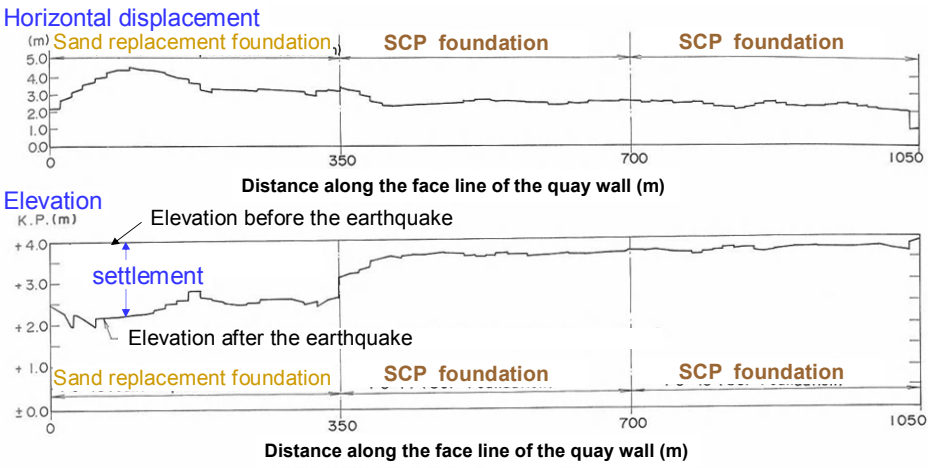
Comparison of ground subsidence in zones treated by different methods



Two types of ground improvement for the foundation of quay walls at Port Island phase II



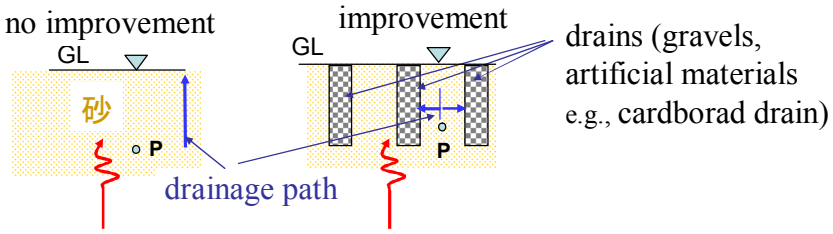
Displacements of quay wall founded on replaced sand and SCPs



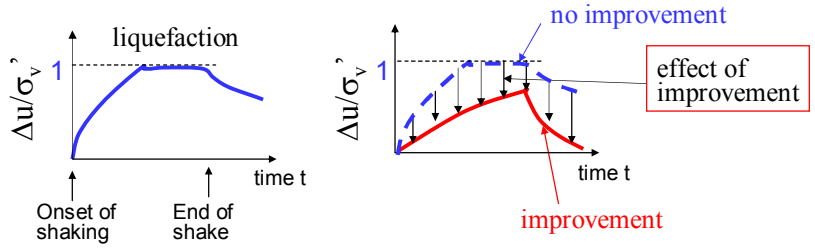
Enhancement of drainage

- control of pore water pressure increase
  - gravel drain method
  - steel members with drainage function
- lowering ground water table
  - deep well method
  - drainage method

Enhancement of drainage (I)
- vertical drains -

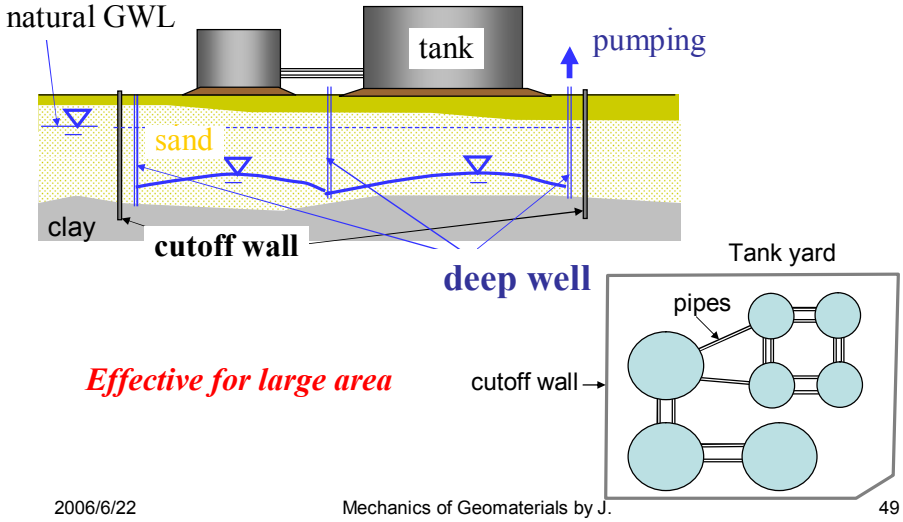


Generation of excess pore water pressure at P



Enhancement of drainage (I)

- Grand water table lowering method with deep wells -



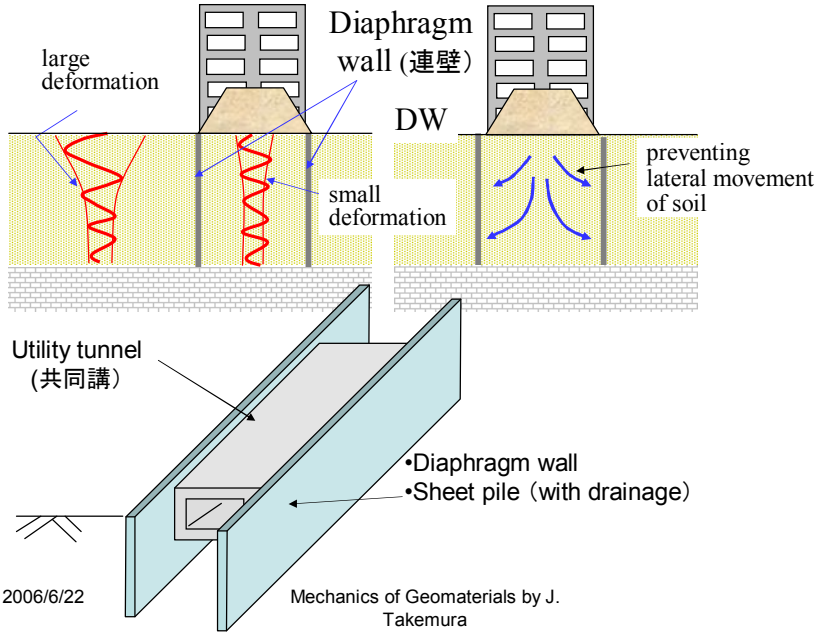
Effective for large area

Reinforcement of ground-structure system

- reinforcement of ground and soil structures

  preventing shear deformation of soil
  - continuous wall method
  - sheet pile method
- reinforcement of structural foundations
  - increase the capacity of piles
  - reinforcement of spread footing
  - introduction of flexible joints

Reinforcement of ground with diaphragm walls



Modification of seismic design considering liquefaction

EX)

•Quay wall design
(L-3-2)

•Bridge foundations (pile foundations)
(L-3-1)

Key words: liquefaction, level 2 motion, lateral movement