Challenges in ground improvement for soft soils: Japan's experiences in coastal development

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Organização

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Ground Improvement

Technologies to strengthen the ground

Purposes

1. **Increasing shear strength**
   in stability problem
2. **Reducing compressibility**
   in settlement/consolidation problem

(1 and 2: Almost common)

3. **Lightening and strengthening**
   in stability problem
4. **Increasing liquefaction resistance**
   in seismic problem

Purpose 1: **Increasing shear strength** in stability problem

Principles for ground improvement:

- **Densification** for clay
  - **Vertical drains** to promote consolidation
    - (→ **SD**: Sand Drains, **PVD**: Prefabricated Vertical Drains)
- **Replacement with good material**
  - **Displacement method**
    - (→ Ground displacement, **SCP**: Sand Compaction Piles)
- **Solidification**
  - **DMM**: Deep Mixing Method (CDM: Cement Deep Mixing Method)
  - **Shallow Mixing Method**
  - **Cement Treated Soil** (as premix)

Purpose 2: **Reducing compressibility** in settlement/consolidation problem

Principles for ground improvement:

- **Densification** for clay

  Vertical drains to promote consolidation with preloading

  (→ **SD**: Sand Drains, **PVD**: Prefabricated Vertical Drains)

  + Preloading (surcharge by sandfill/vacuum)

- **Solidification**

  Cement Treated Soils

  Lightness with shear strength

Most of these technologies are common with that for Purpose 1: Increasing shear strength

Purpose 3: **Lightening and strengthening** in stability problem

Principles for ground improvement:

- **Solidification (+ Lightning)**

  Cement **Treated Soils** (as premix)

  Mixture of **Dredged clay + Cement**

  Mixture of **Dredged clay + Cement + Air-foam**

Purpose 4: **Increasing liquefaction resistance** in seismic problem

Principles for ground improvement:

- **Densification** for sand
  Compaction
  (**SCP**: Sand Compaction Piles, **CPG**: Compaction Grouting, Vibro-floatation)
- Rapid dissipation of excess pore water pressure
  Drainage (**Gravel Drains**)
- **Replacement of pore fluid**
  Chemical grouting
  (→ by **injection**, **permeation**, cement/chemical **grouting**)
- Measures to prevent liquefaction other than ground improvement
  Enclosing diaphragm wall/sheet pile, Lowering ground water level (Deep well)

Purpose 1: **Increasing shear strength** in stability problem

- **Densification**
  Vertical drains for clay to promote consolidation
  (→ **SD**: sand drains, **PVD**: Prefabricated Vertical Drains)

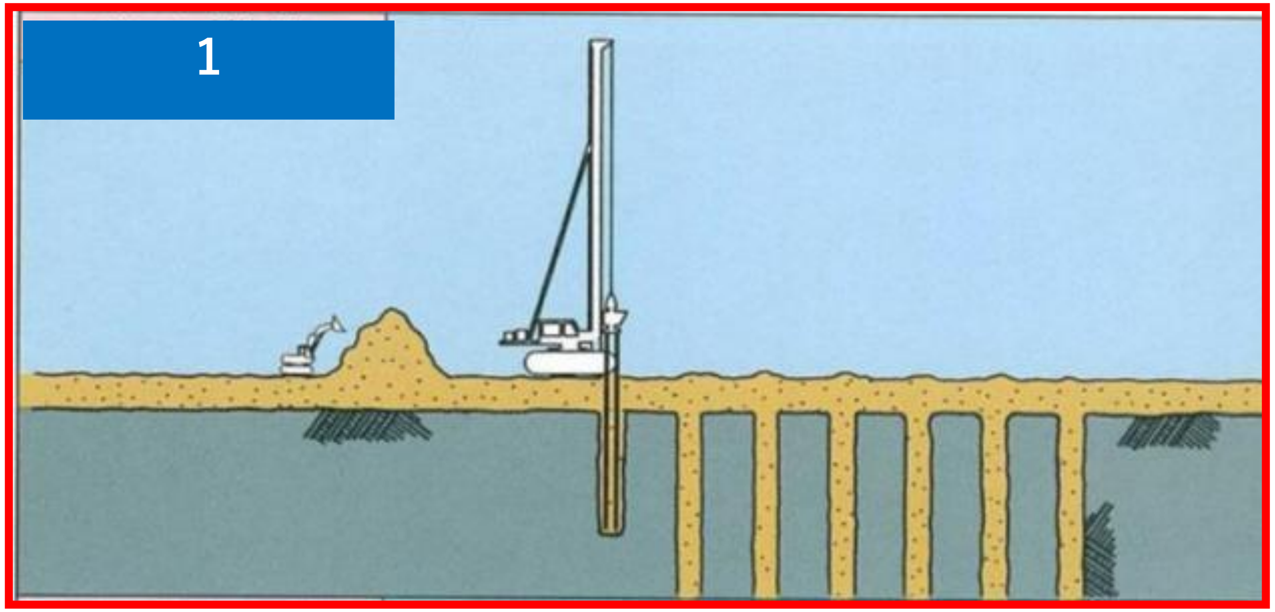
Purpose 2: **Reducing compressibility** in settlement/consolidation problem

- **Densification** for clay by
  Vertical drains to promote consolidation with preloading
  (→ **SD**: Sand Drains, **PVD**: Prefabricated Vertical Drains)
  + **Preloading** (surcharge by sandfill/vacuum)

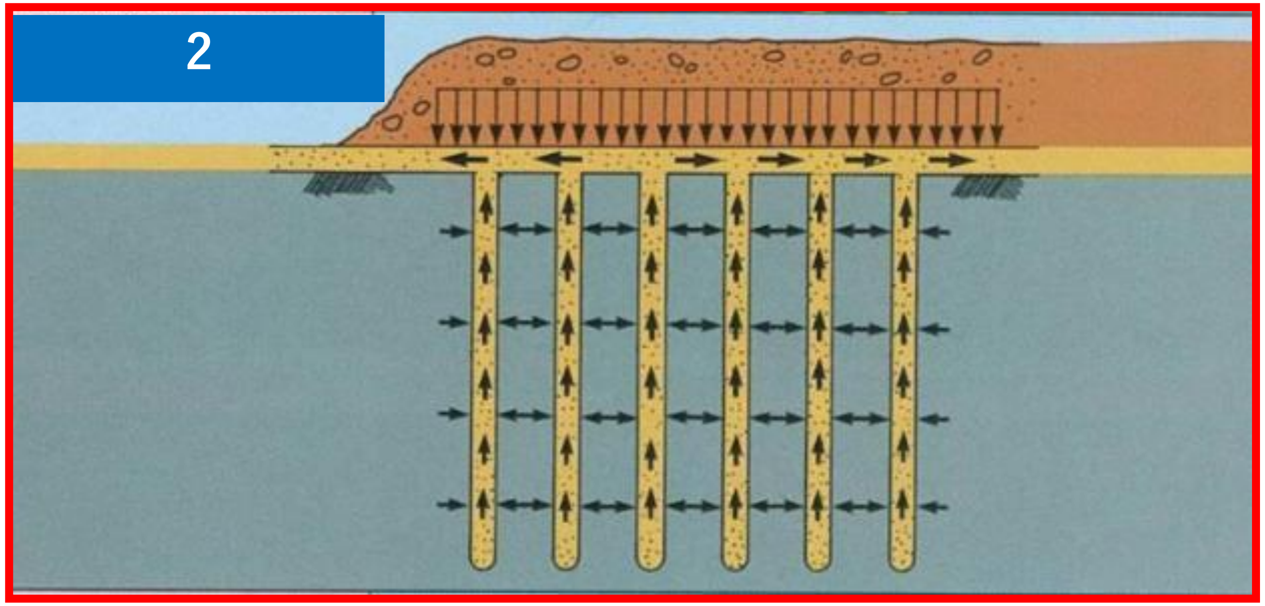
Almost common

Vertical drains + Preloading

Illustration by Kanto Regional Development Bureau, MLIT



Installation of sand drains **SD**



Earth filling = **Preloading**
→ Consolidation under a preload

Sand Drain method (SD)

Permeable sand is installed as **drain columns**

-The most popular and proven technology in coastal engineering in Japan
-To **accelerate/promote** the consolidation settlement in a wide area
-High installation ability
-High drainage capacity

Prefabricated Vertical Drain method (PVD)

-PVD is used instead of SD
-Continuity is ensured

Installation of Sand Drains (SD)

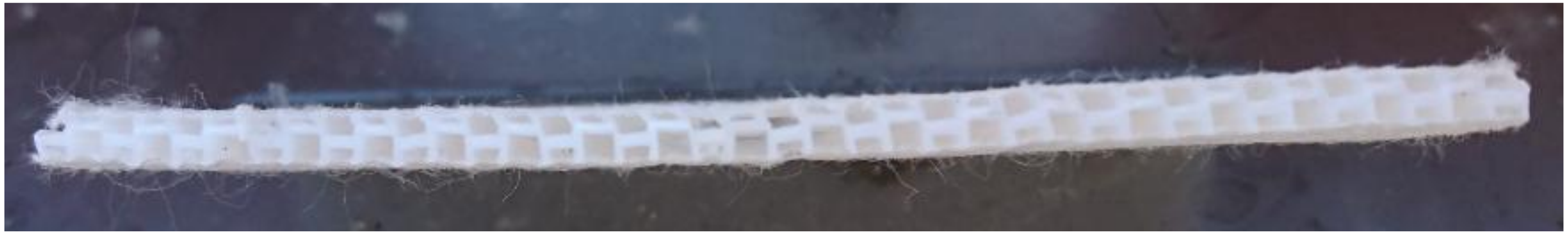
Offshore construction

Land (onshore) construction

Prefabricated Vertical Drains (PVD)

Permeable **prefabricated vertical drains (PVDs)** are installed into soft deposit/ultra-soft soil deposit

- -The most popular and proven technology in coastal engineering in the world
- -To **accelerate/promote** the consolidation settlement in a wide area
- -**Continuity** of vertical drainage is ensured even in a dredged clay deposit
- -Small disturbance of the ground during the installation
- -Uniform drain performance in the longitudinal direction



Purpose 1: **Increasing shear strength** in stability problem (cont'd)

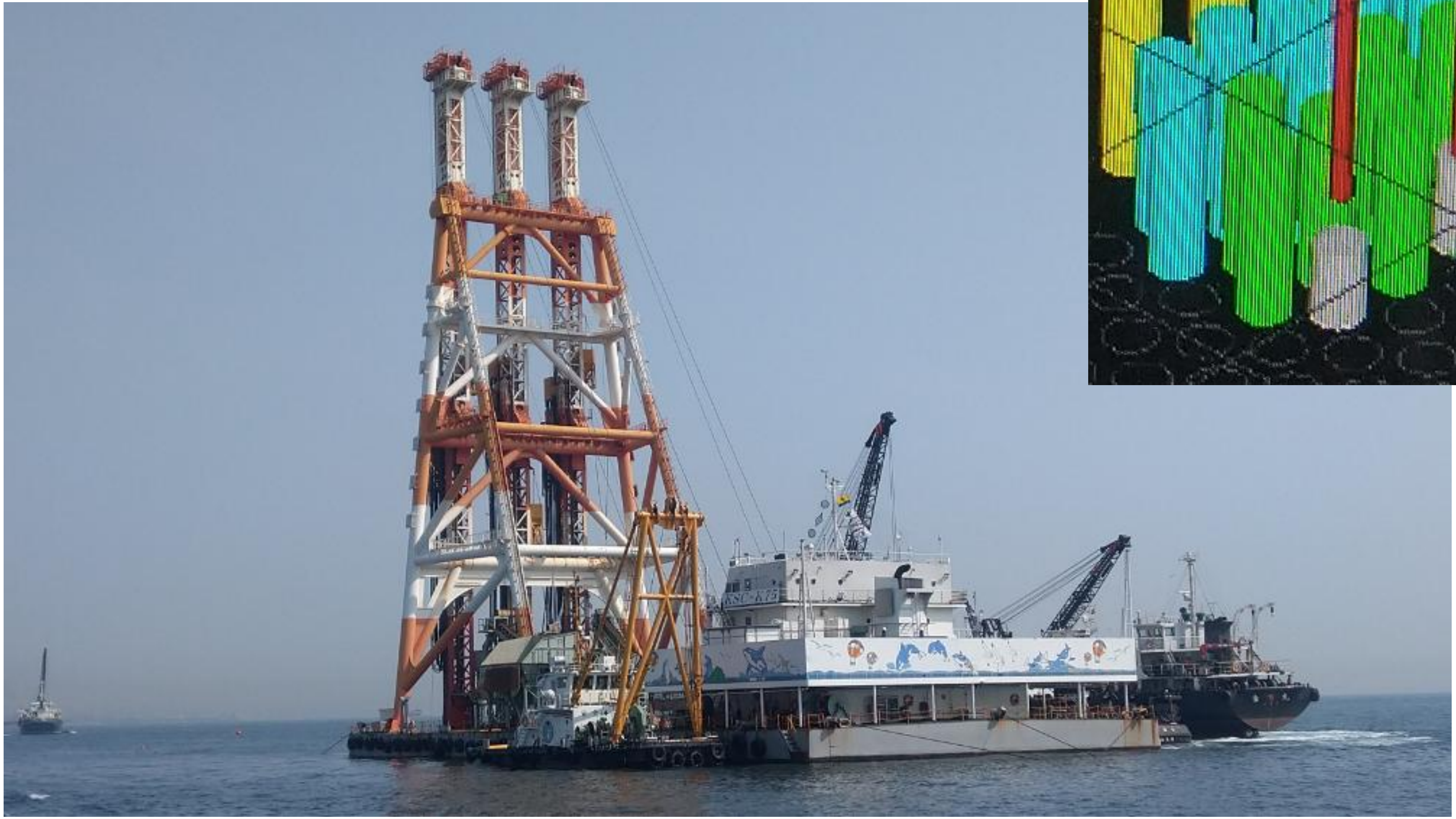
Principles for ground improvement:

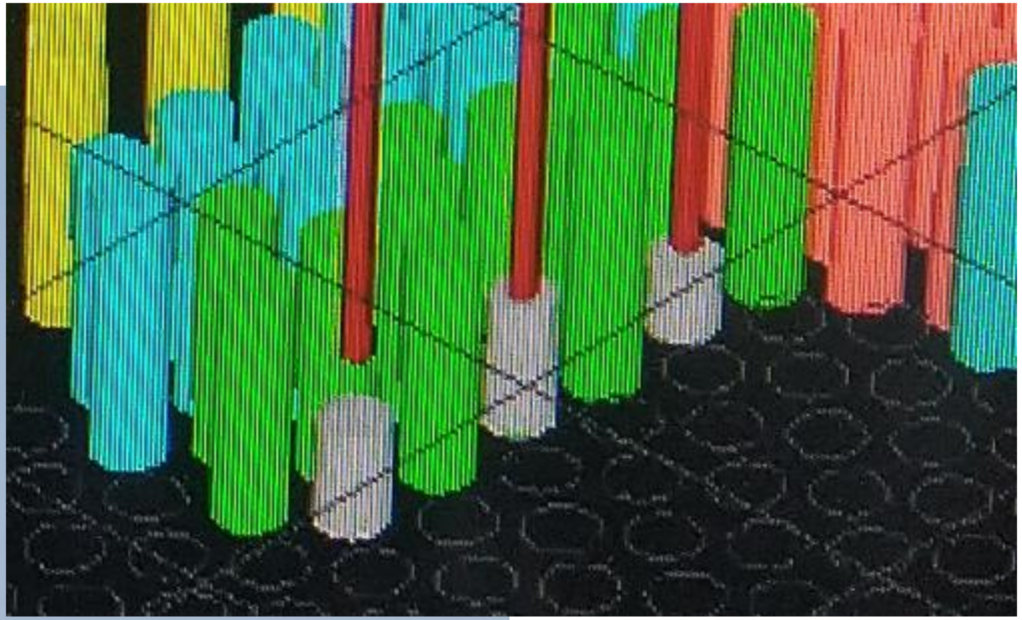
- **Replacement with good material**

  Displacement method

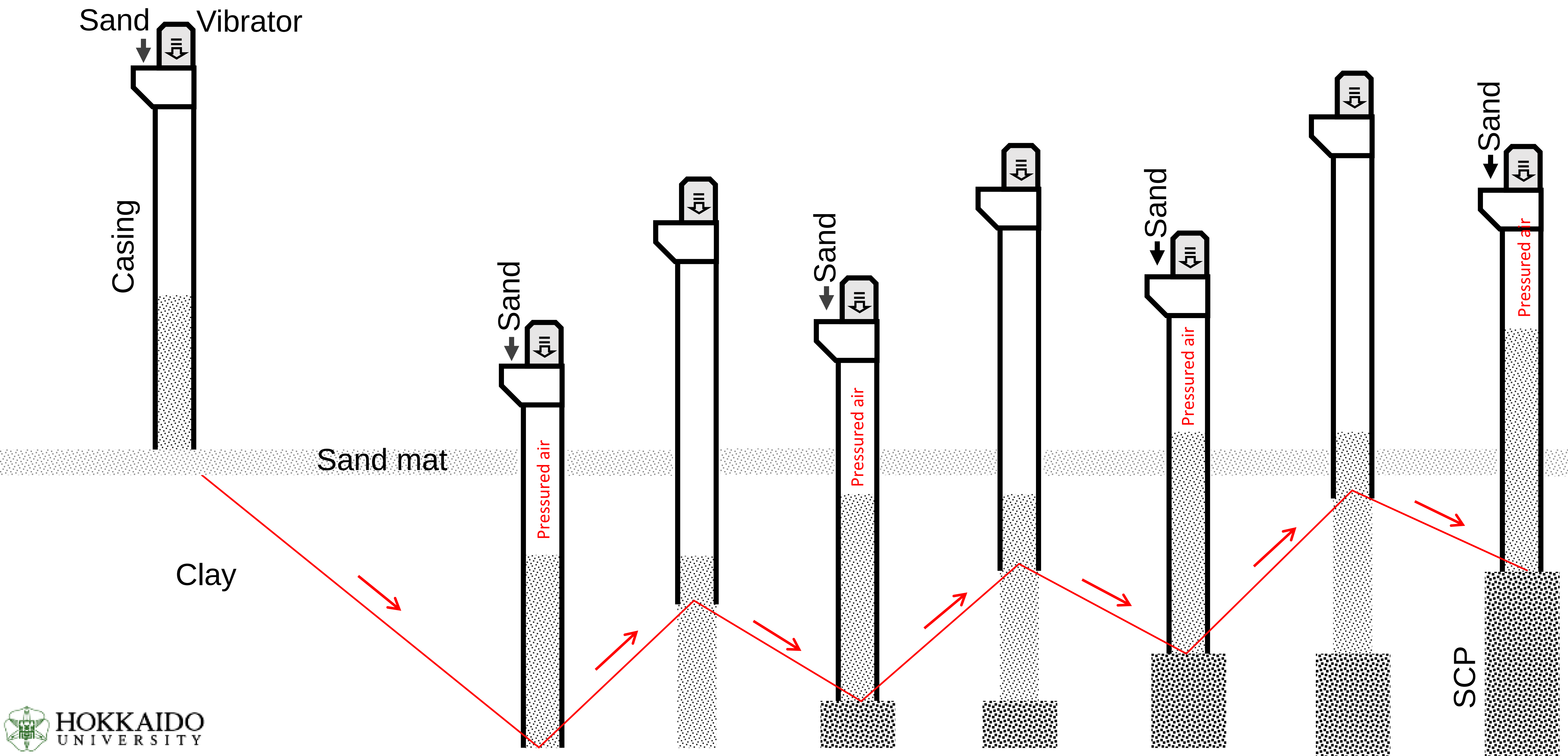
  (→ Ground displacement, **SCP**: Sand Compaction Piles)

Sand Compaction Piles (SCP)

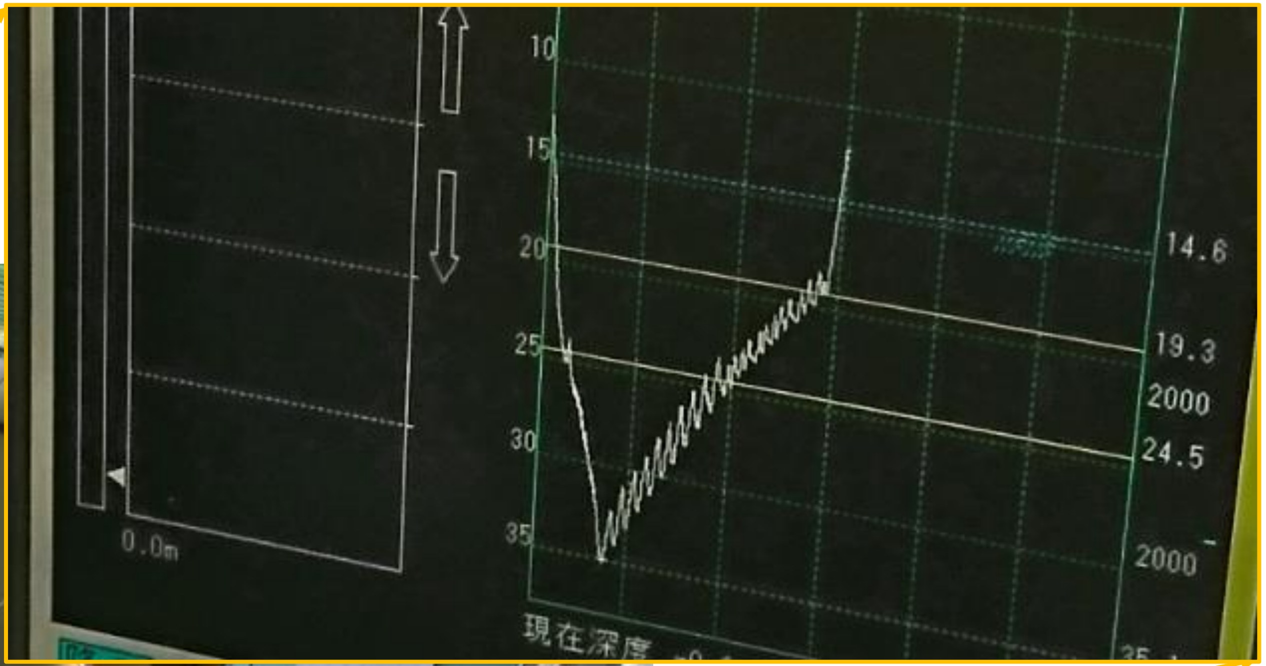




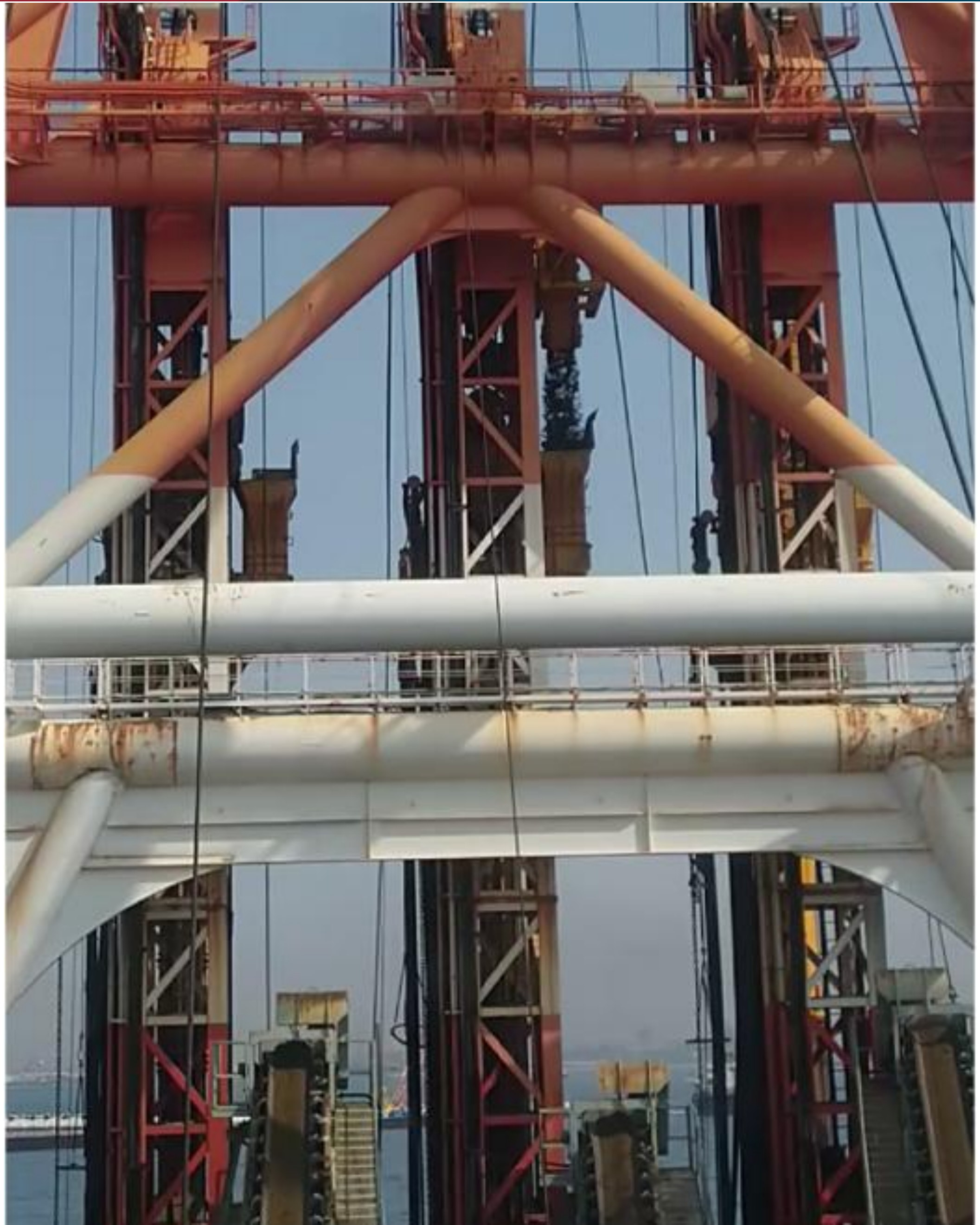
Sand Compaction Piles (SCP)



Sand Compaction Piles (SCP)

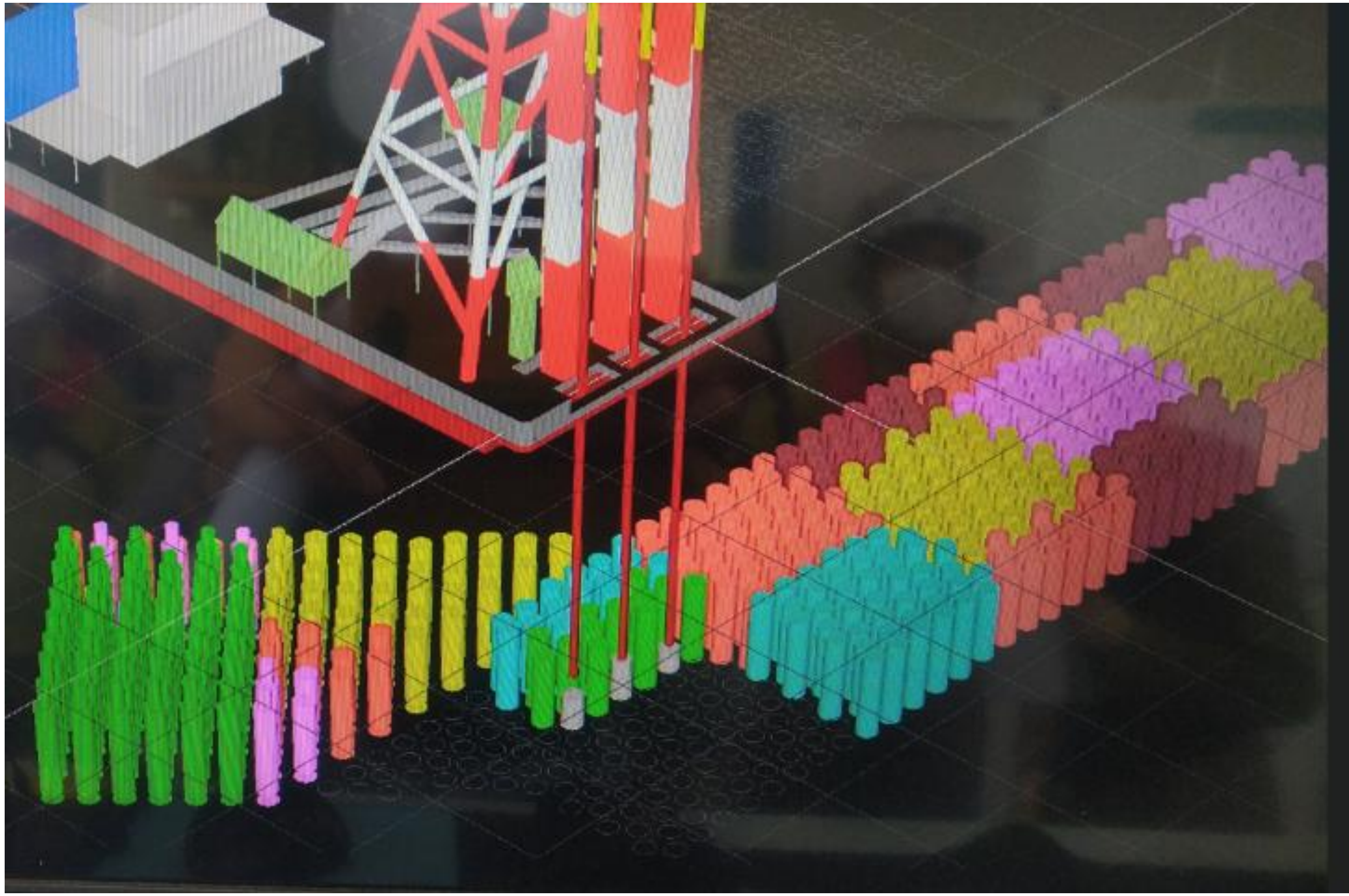


Operation room of SCP vessel



Sand Compaction Piles (SCP)

Installation of SCPs



Sand Compaction Piles (SCP)

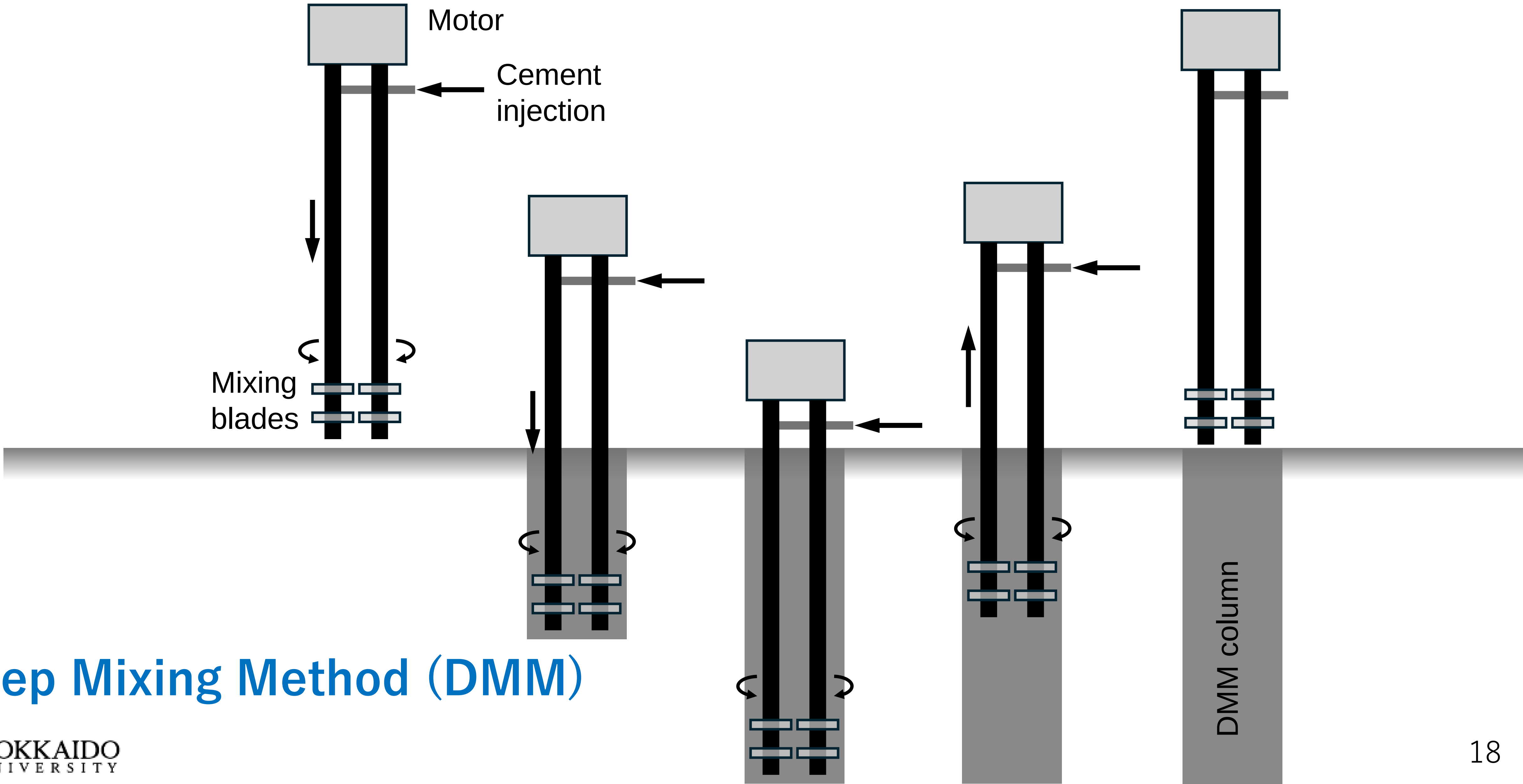
Offshore construction

Land (onshore) construction

Purpose 1: **Increasing shear strength** in stability problem (cont'd)

Principles for ground improvement:

- **Solidification**
  - **DMM**: Deep Mixing Method (CDM: Cement Deep Mixing Method)
  - Shallow Mixing Method
- **Solidification (+ Lightning)**
  - **Cement Treated Soil**



Deep Mixing Method (DMM)

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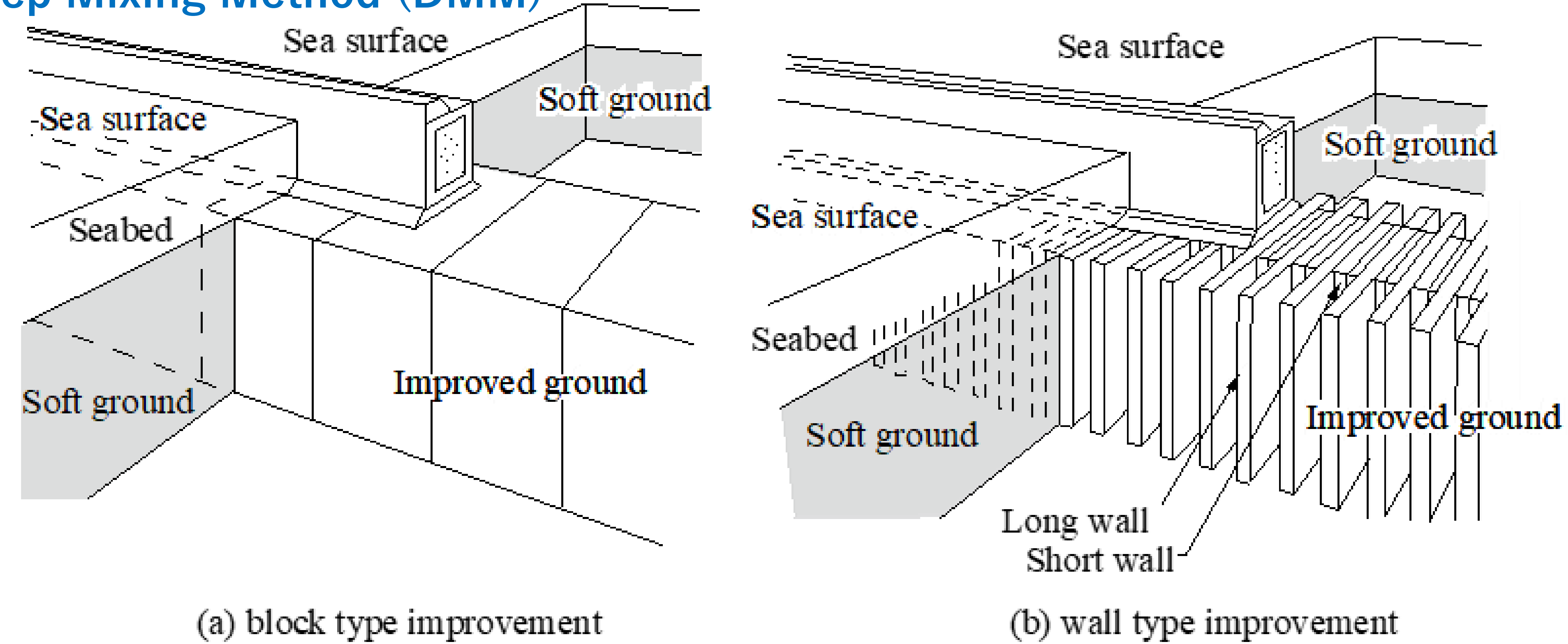
Deep Mixing Method (DMM)



Typical Improvement Patterns in the Deep Mixing Method
DMM improvements are designed as a solid structure in the ground

PIANC Report of MarCom WG205

Shallow Mixing Method

Preparation for ground improvement
→ Lime/cement-mixing for trafficability (surface treatment)

Ground improvement with Prefabricated Vertical Drains PVD

Kanto Regional Development Bureau, MLIT

Purpose 1: **Lightening and strengthening** in stability problem (cont'd)

Principles for ground improvement:

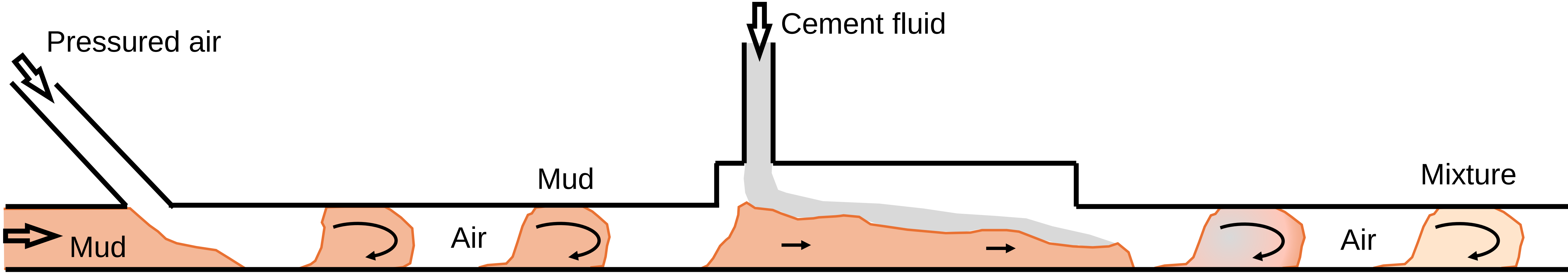
- **Solidification (+ Lightning)**

  Cement Treated Soils

  Mixture of **dredged clay + cement**
  Mixture of **dredged clay + cement + air-foam**

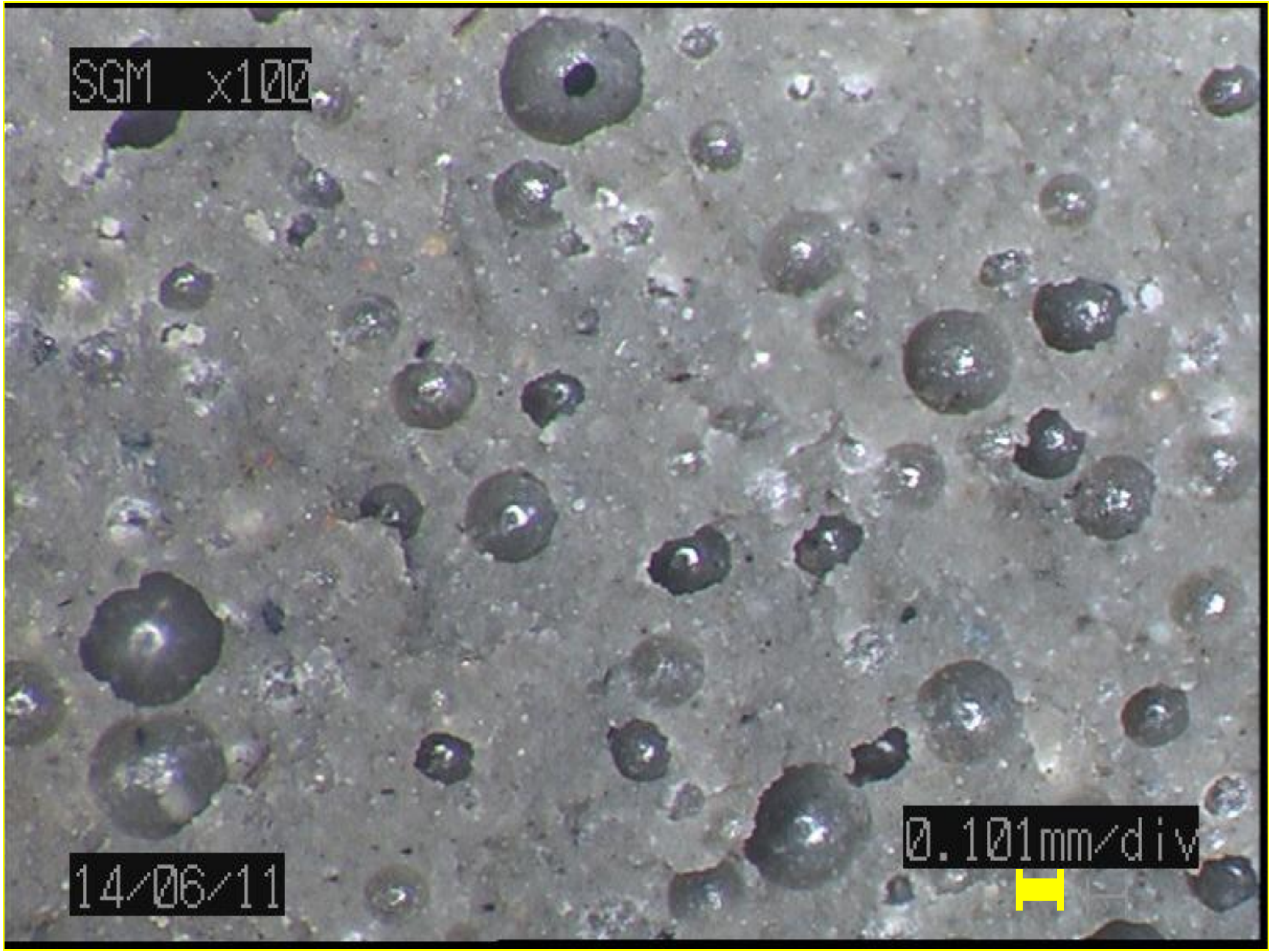
Cement Treated Soils (Premix with cement)

Pneumatic Flow Mixing Method



Cement Treated Soils (Premix with cement)

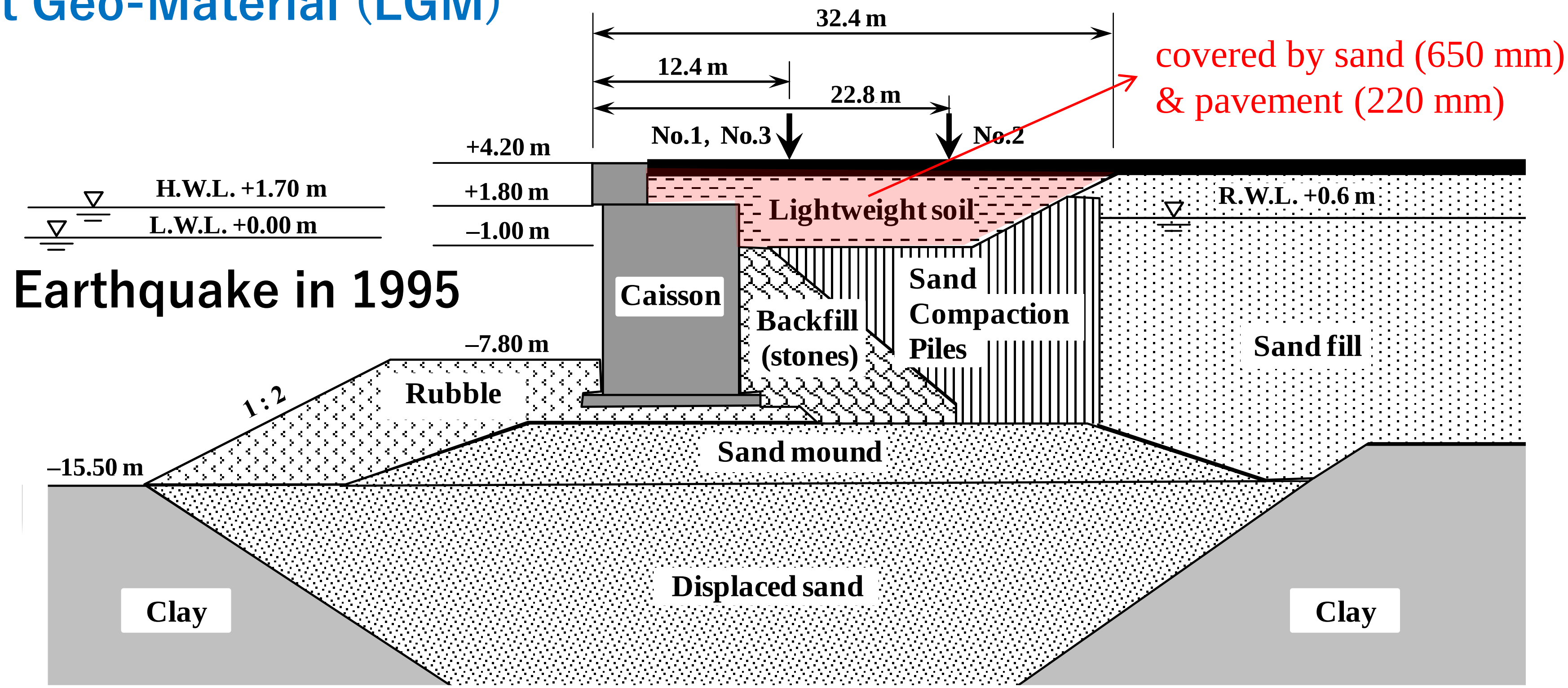
Air-foam treated Lightweight Geo-Material (LGM)



Air-foam treated Light weight Geo-Material (LGM)

Air-foam treated Lightweight Geo-Material (LGM) in Kobe Port Island

Restoration work after Kobe Earthquake in 1995



Physical properties of the material soil

Natural water content w (%)	Soil particle density ρ_s (g/cm^3)	Grain size fraction Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Liquid limit w_L (%)	Plastic limit w_p (%)
122.0	2.71	3.0	14.0	54.0	28.0	97.0	41.0

Mix proportion (per 1 m^3) of the air-foam-treated lightweight soil

	Slurry (kg)	Cement (kg)	Airfoam (m^3)	Density in design (g/cm^3)	Unconfined compression strength in design (kPa)
Above water level	849	140	0.279	1.0 (Mg/m^3)	196
Below water level	952	140	0.196	1.2	196

Purpose 4: **Increasing liquefaction resistance** in seismic problem

Principles for ground improvement:

- **Densification** for sand
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  (**SCP**: Sand Compaction Piles, **CPG**: Compaction Grouting, Vibro-floatation)
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  (→ by **injection**, **permeation**, cement/chemical **grouting**)
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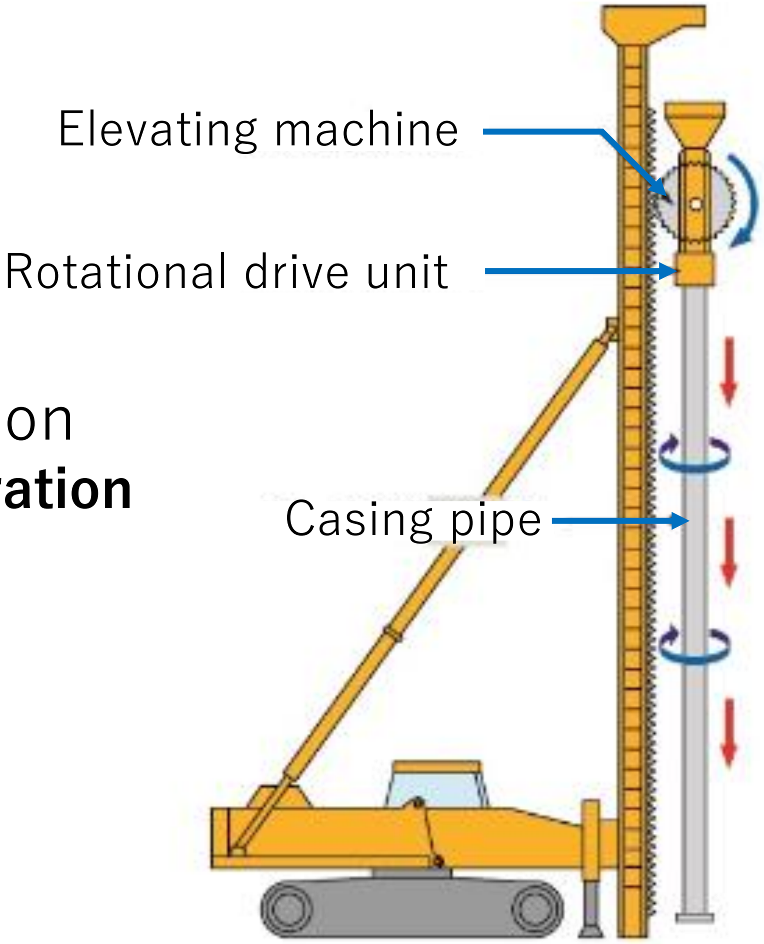
  Enclosing diaphragm wall/sheet pile, Lowering ground water level (Deep well)

Sand Compaction Piles (SCP)

Non-vibratory SCP

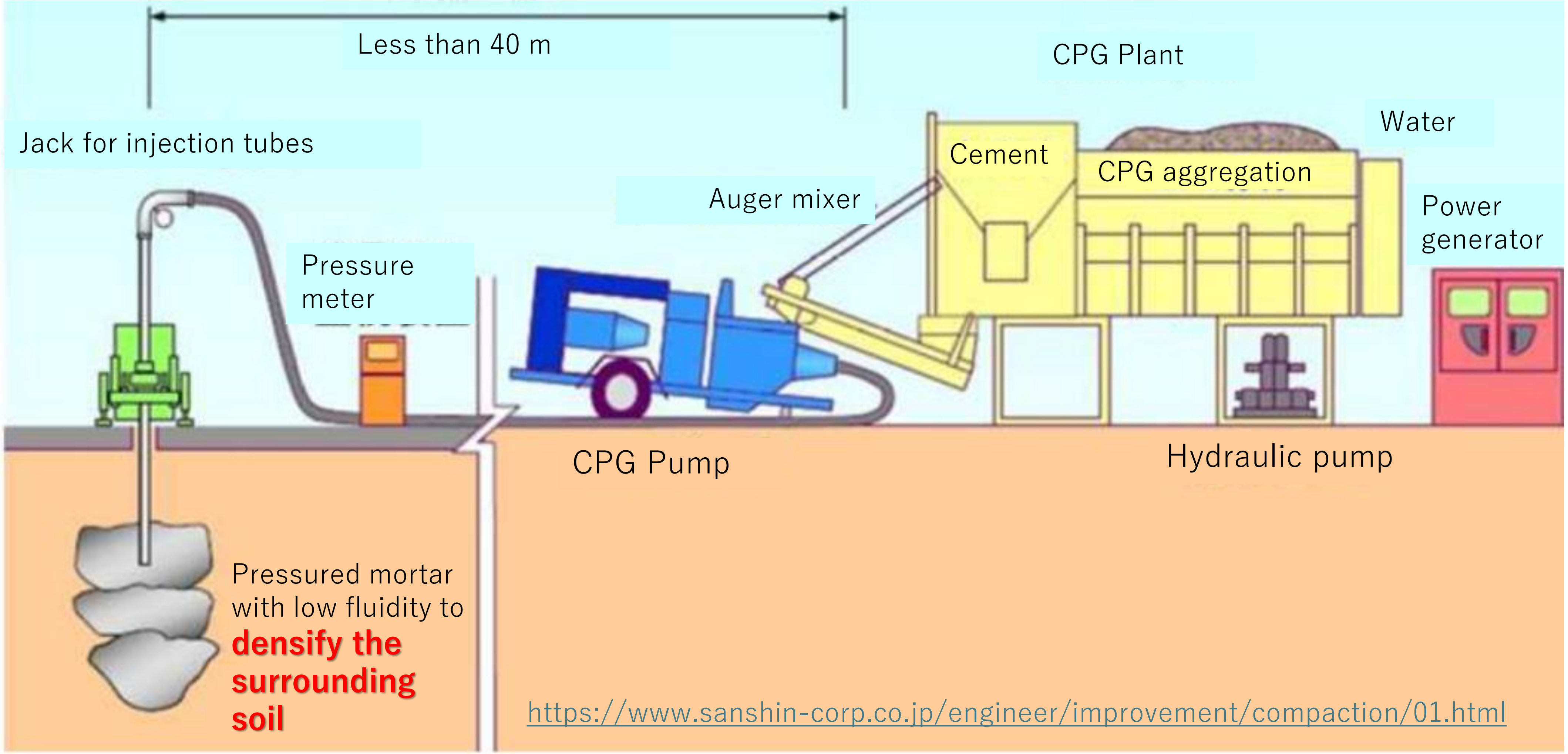
mainly in inland/onshore construction

SCP method **with rotation instead of vibration**



https://www.fudotetra.co.jp/solution/soil/save_composer/

Compaction Grouting Method (CPG)

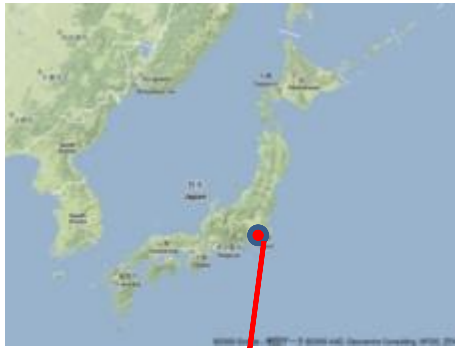


A case study: Tokyo International Airport (Haneda Airport)

The development of the airport is an offshore expansion history by land reclamation since 1931.

The offshore expansion project, in which the airport was constructed on an ultra-soft clay deposit, was carried out from 1984 to 2004.

The further expansion project "D-runway" was constructed from 2007 to 2010. The new runway is a hybrid island consisting of piled-pier and land reclamation.



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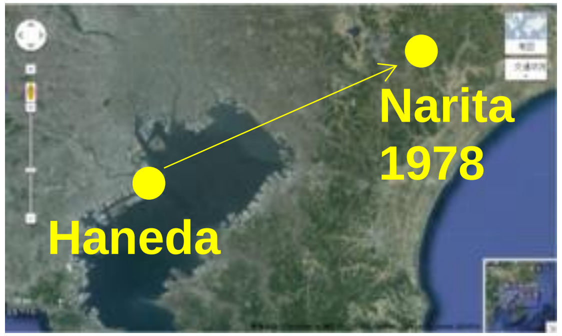
After moving international flights from Haneda to Narita in 1978, the development was temporally suspended.
Since then, Haneda Airport had been operated for domestic flights only.



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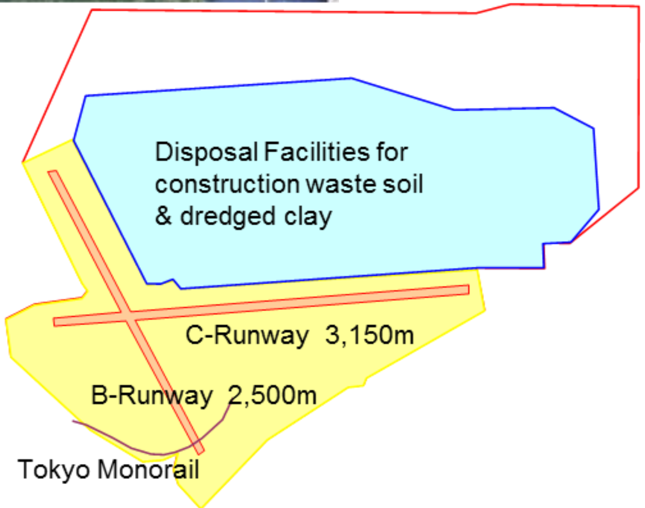
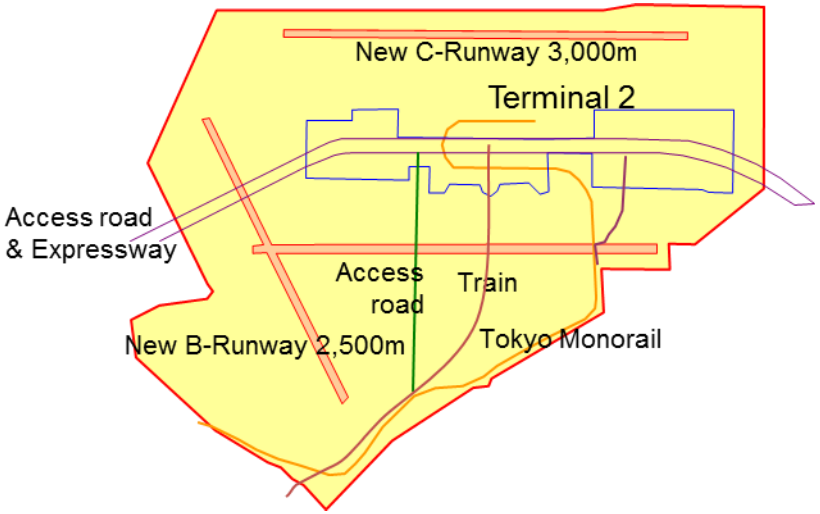


Offshore expansion project

1988 Completion of 1st phase
New A-runway with 3000 m

1993 Completion of 2nd phase
New terminal building → T1

1997 New C-runway with 3000 m



Further expansion project (D-runway: 2007-2010)

The offshore expansion project from 1984 to 2004

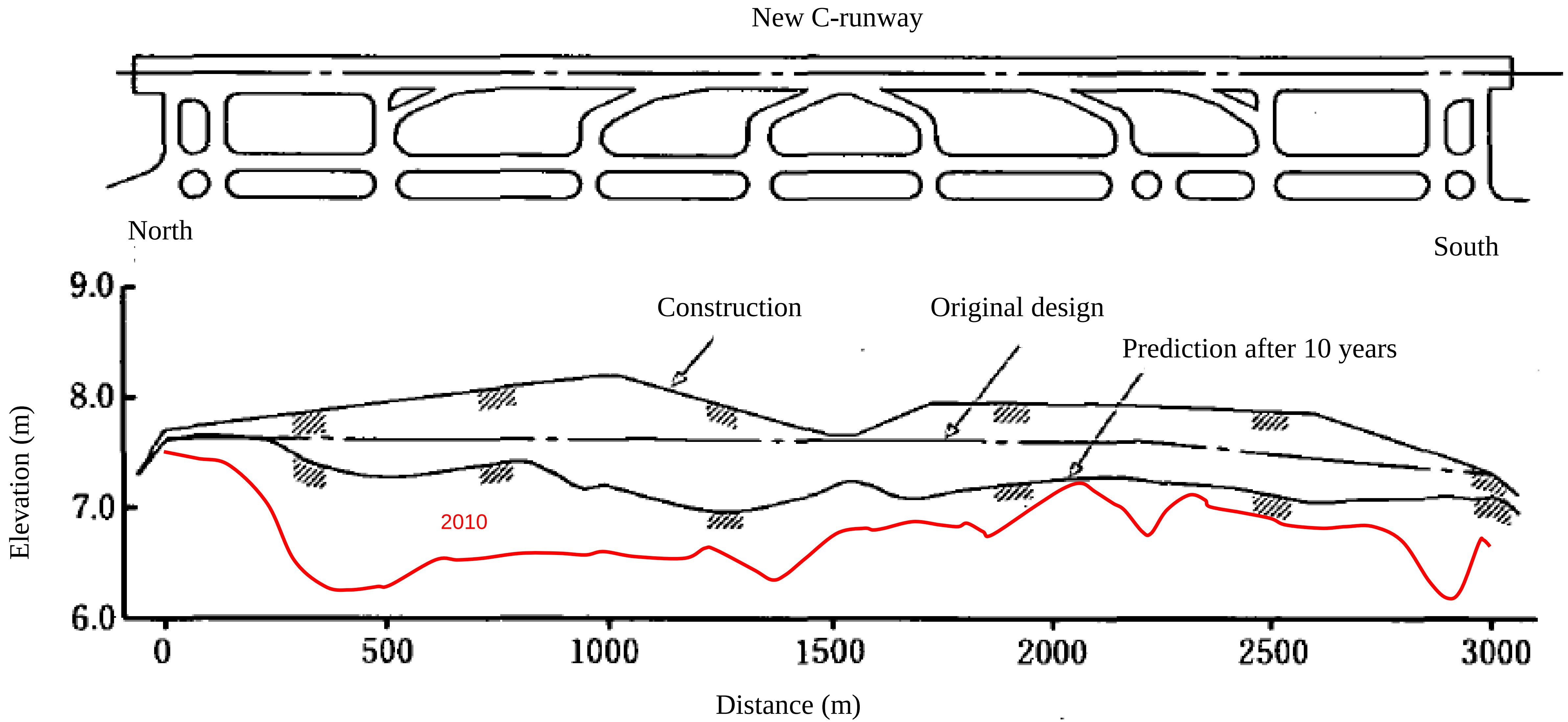
Waste reclamation facility for dredged clay was transformed into an airport facility

Vertical drains + Preloading

Preparation for ground improvement
→ Lime/cement-mixing for trafficability
(surface treatment)

Ultra-soft state of dredged clay in the waste reclamation facilities
(Photo by Dr. M. Katagiri at Kita-kyushu Airport)

Vertical drains + Preloading



Significant differential settlement

Kanto Regional Development Bureau, MLIT

Differential settlements cause a trouble particularly at an interface between different foundation types

Countermeasures for differential settlement

Apron of the Tokyo International Airport

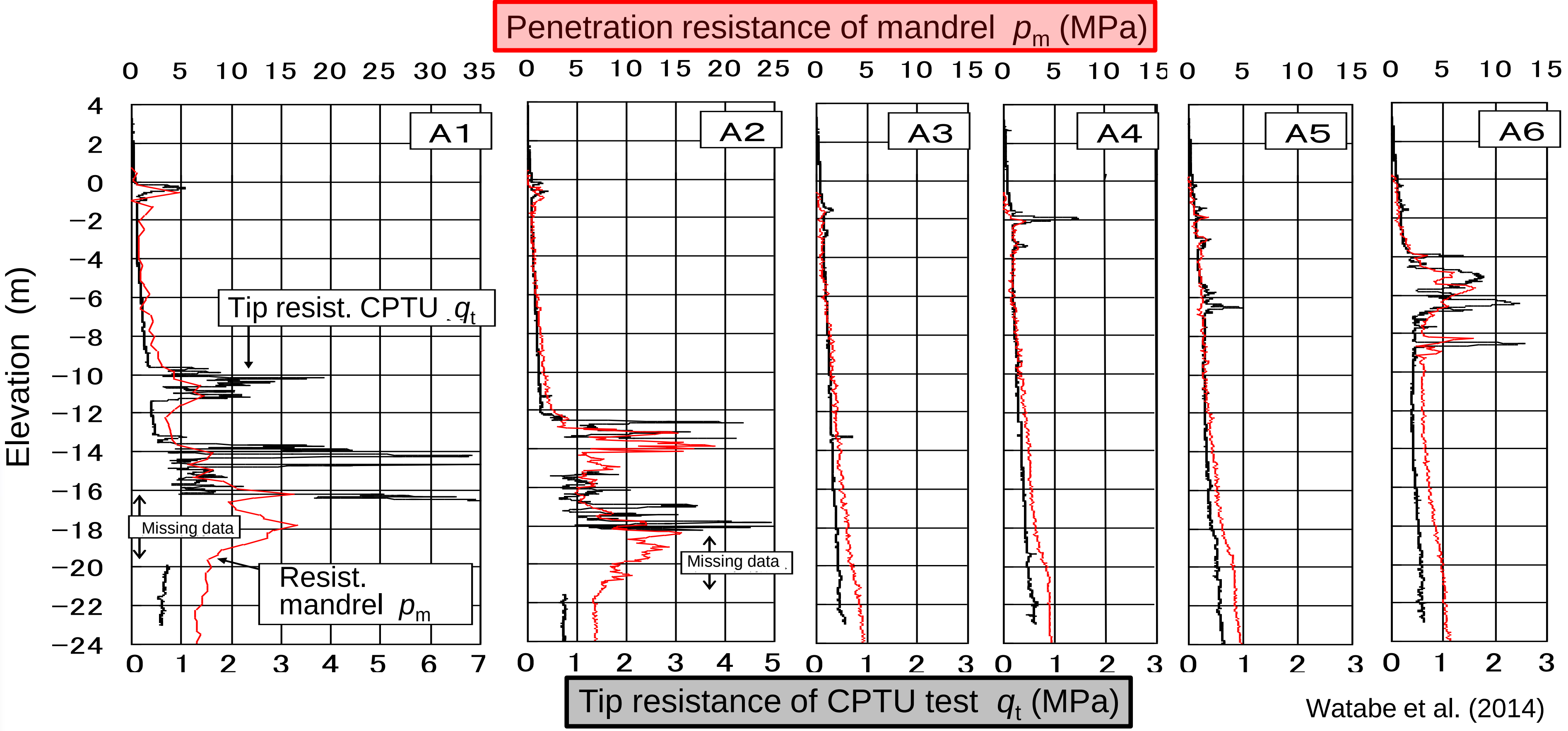
Lift-up method:

To adjust the differential settlement, which causes unacceptable slopes, the prestressed concrete (PC) slab is jacked up and the clearance gap is grouted.

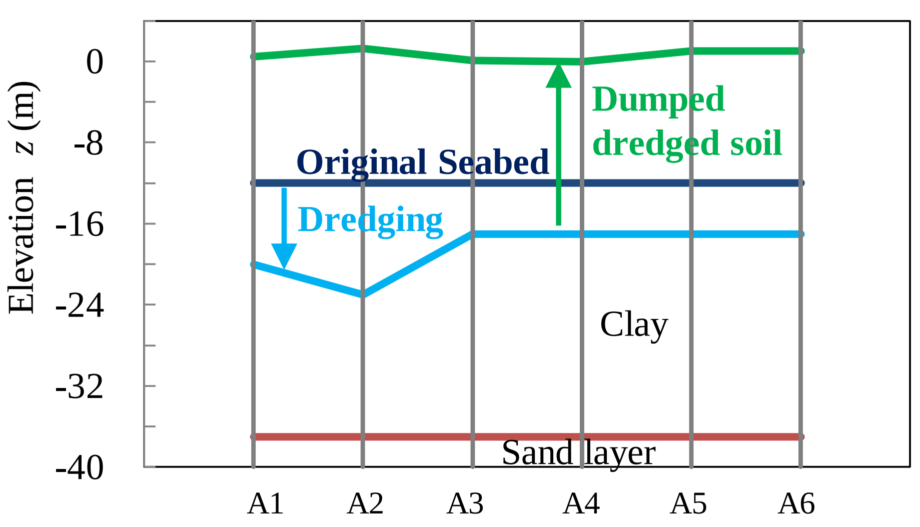
Kanto Regional Development Bureau, MLIT

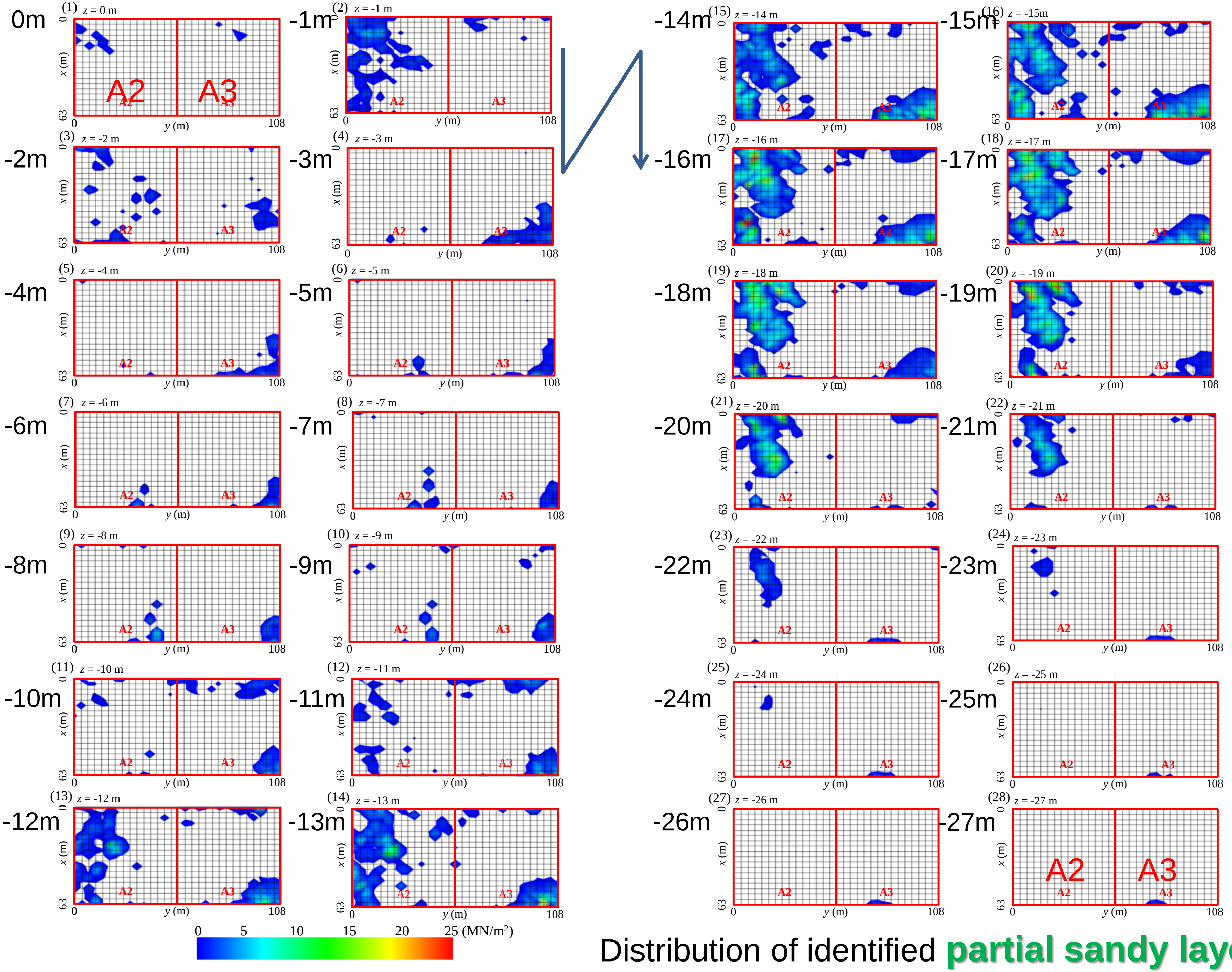
Prediction of differential settlement

(this is not the case of Tokyo Haneda Airport)



Watabe et al. (2014)

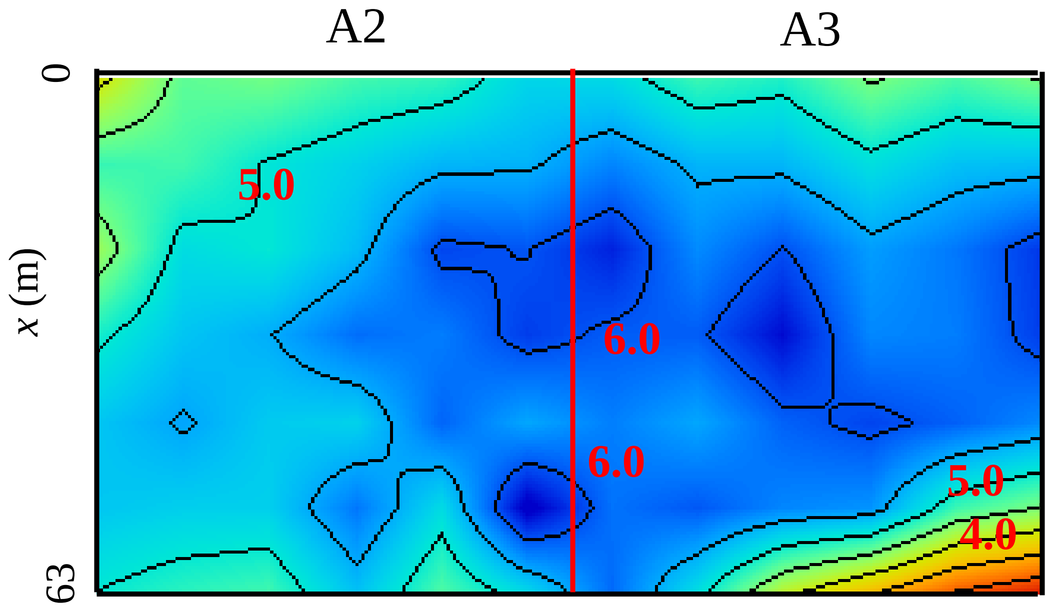




Watabe et al. (2014)

Distribution of identified **partial sandy layers**

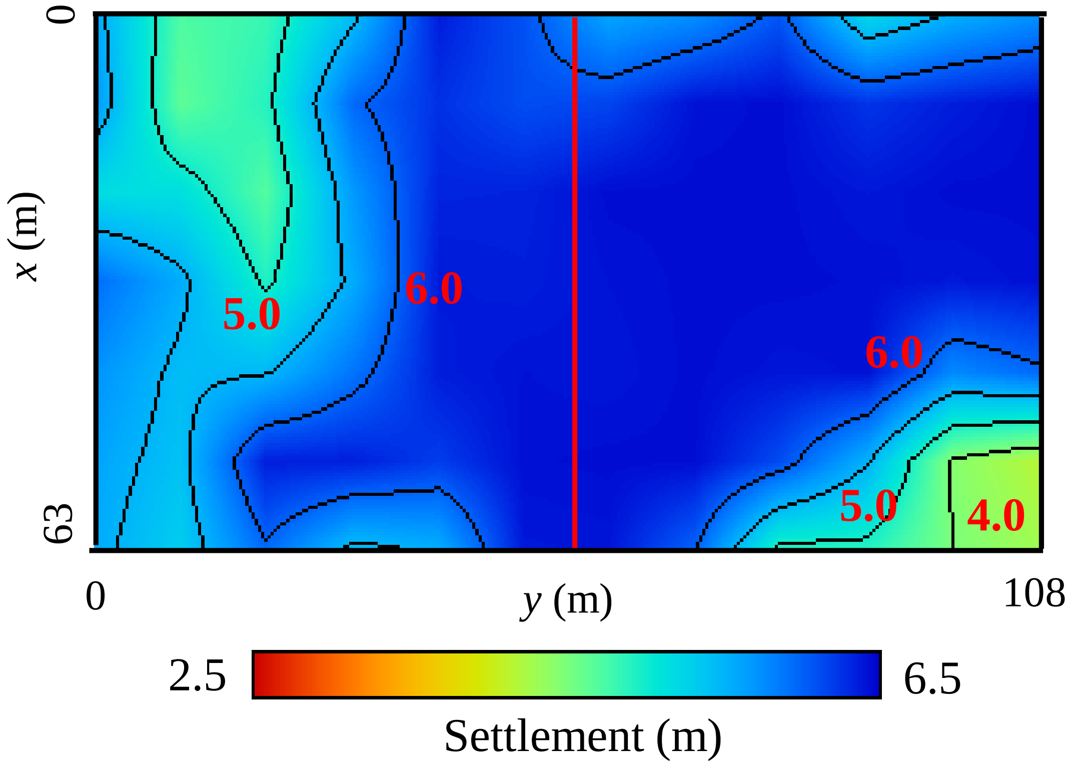
Measured by bathymetry
(differential before and after) →



Calculated
based on PVD installation →

Differential settlement is predictable!

calculated
every 3.6 m

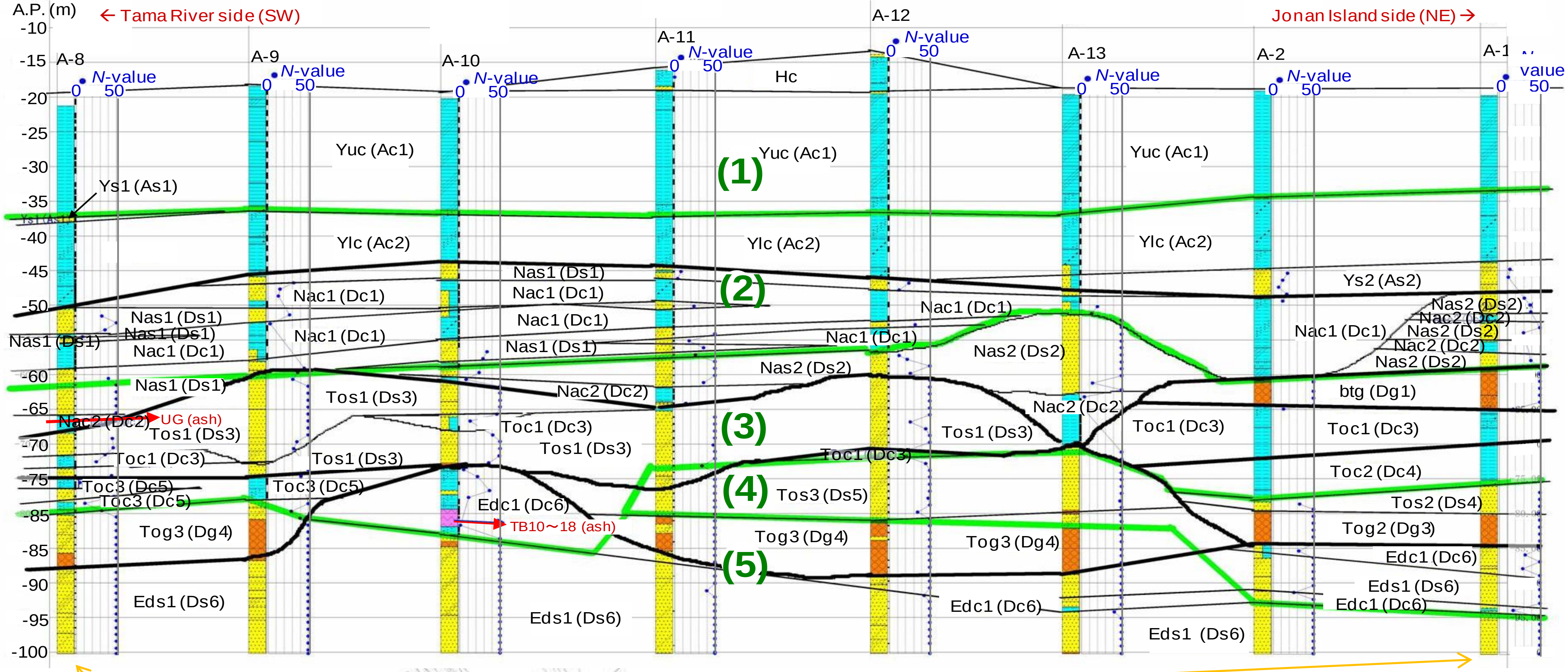


calculated
every 10.8 m

Watabe et al. (2014)

Outline of the D-runway

- -D-runway → Hybrid structure of “reclamation” & “piled pier”
- -River mouth of the Tama river → Piled pier structure to ensure the flow rate
- -Runway length 2500 m
- -Water depth A.P. –12 to –20 m

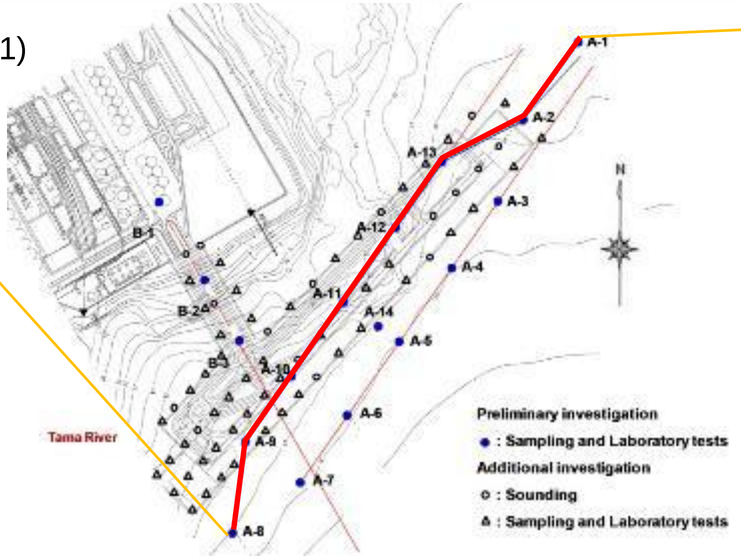


Ground improvement → Technology can overcome the problems

Too deep to be improved → Prediction is important (following a natural law)

Bearing layer for piled foundations

Watabe and Noguchi (2011)



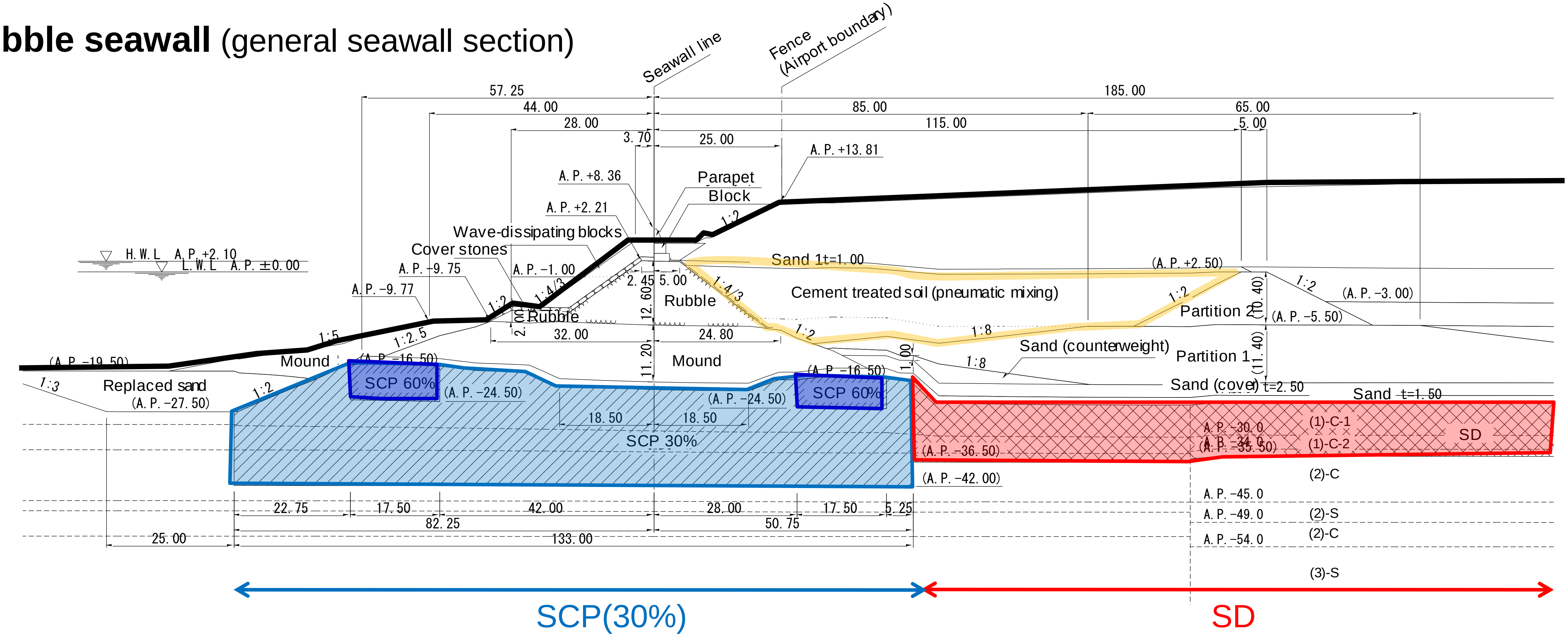
Integration of ground improvement technologies

Technologies used for a manmade island at Tokyo Haneda Airport (D-Runway):

1. **Consolidated with vertical drains** (acceleration/promotion of consolidation)
2. **Replaced by good material** (clay → sand)
3. **Strengthened** (cement treatment)

- Soft clay deposit **inside the reclamation section** → improved by **1** (**SD**=Sand Drains)
- Under the **rubble seawall** → improved by **1** and **2** (**SCP** with low replacement area ratio)
- Under the **important seawalls** → improved by **3** (**DMM**, **CDM**=Cement Deep Mixing)

Rubble seawall (general seawall section)



Watabe and Noguchi (2011)

1. **Consolidated with vertical drains**
   (acceleration of consolidation)
2. **Replaced by good material** (clay → sand)
3. **Strengthened by solidification** (cement treatment)
4. **Lightened and solidified**

Cross section of the rubble seawall

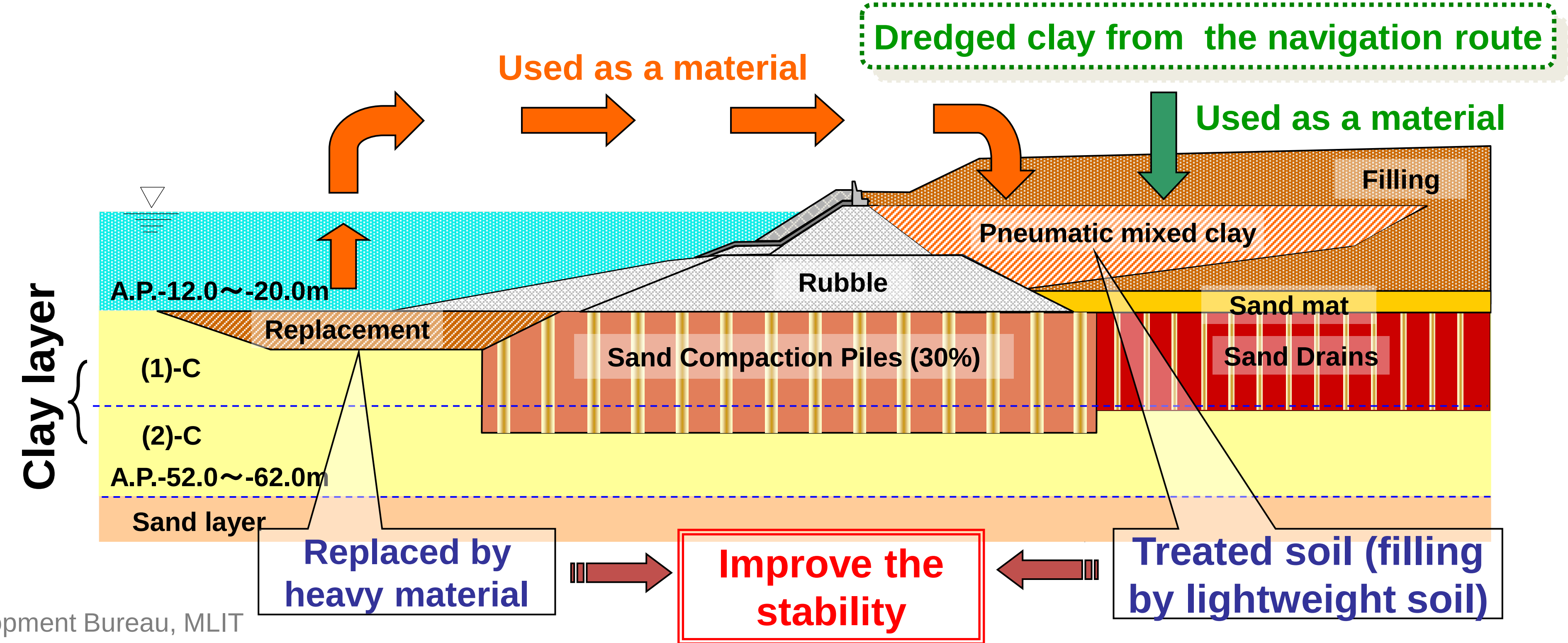
Deformability for the settlement and lateral soil movement

→ **Rubble seawall (mild slope)**

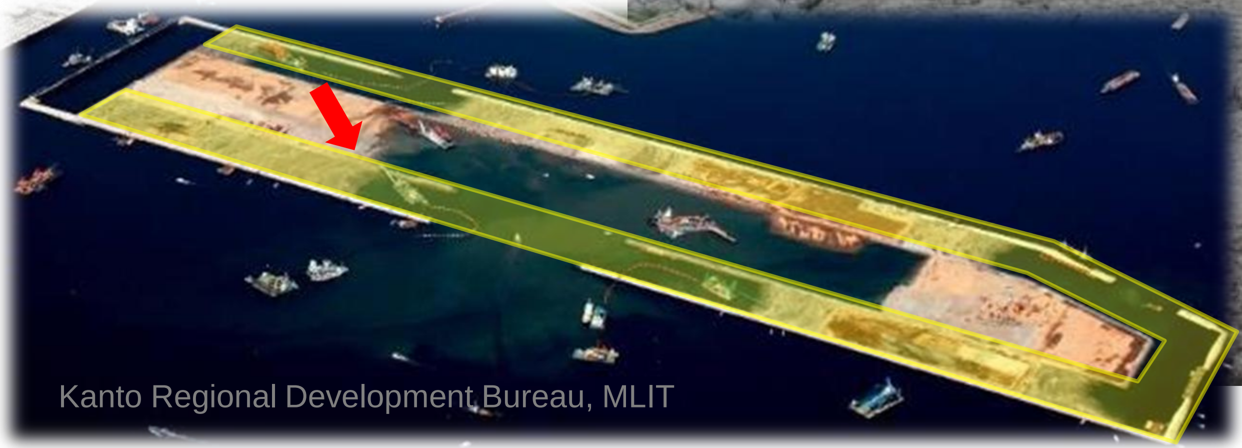
- -Thick soft clay deposit and large water depth
- -Very high embankment in a short construction period (35 month)

(1) **Sand Compaction Piles** with a low replacement ratio (30%)
→ to improve the stability and promote the consolidation

(2) **Light weight soil** (Air-foam treated soil & pneumatic mixing treated soil)
→ to ensure the stability of the seawall



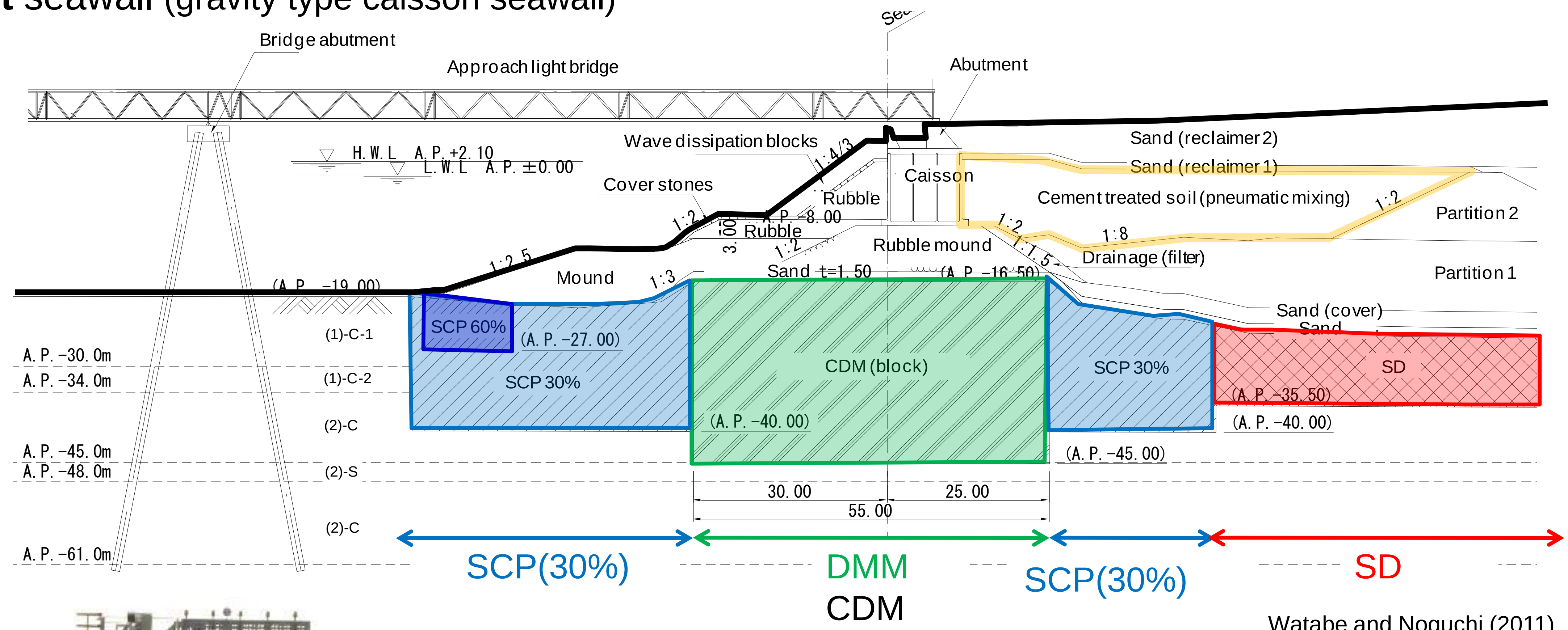
Kanto Regional Development Bureau, MLIT



Watabe and Noguchi (2011)

A placement scene of the **pneumatic mixing cement treated soil**
inset: aerial photo showing the placement scene between the seawall and partition

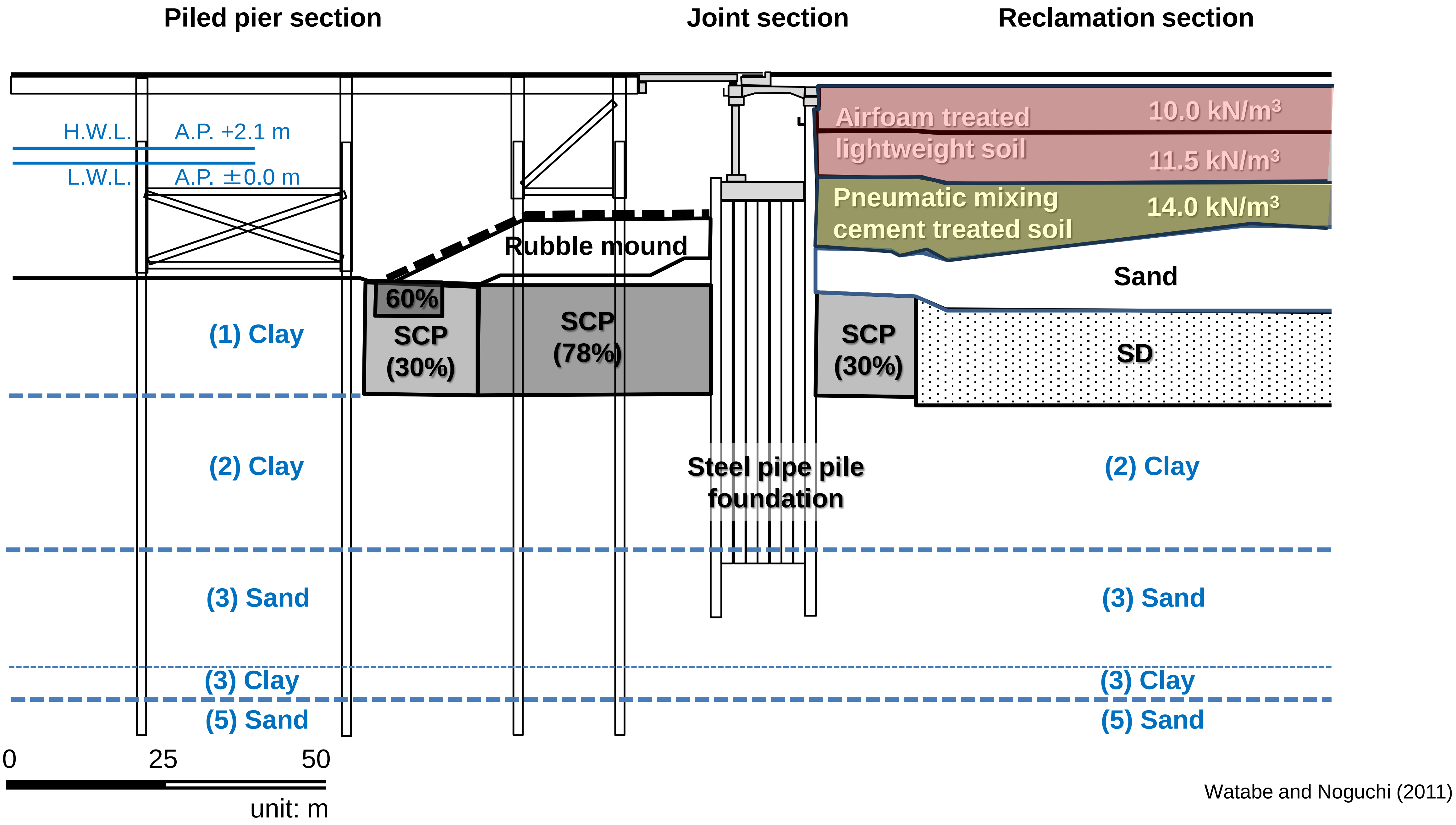
Approach light seawall (gravity type caisson seawall)



Watabe and Noguchi (2011)

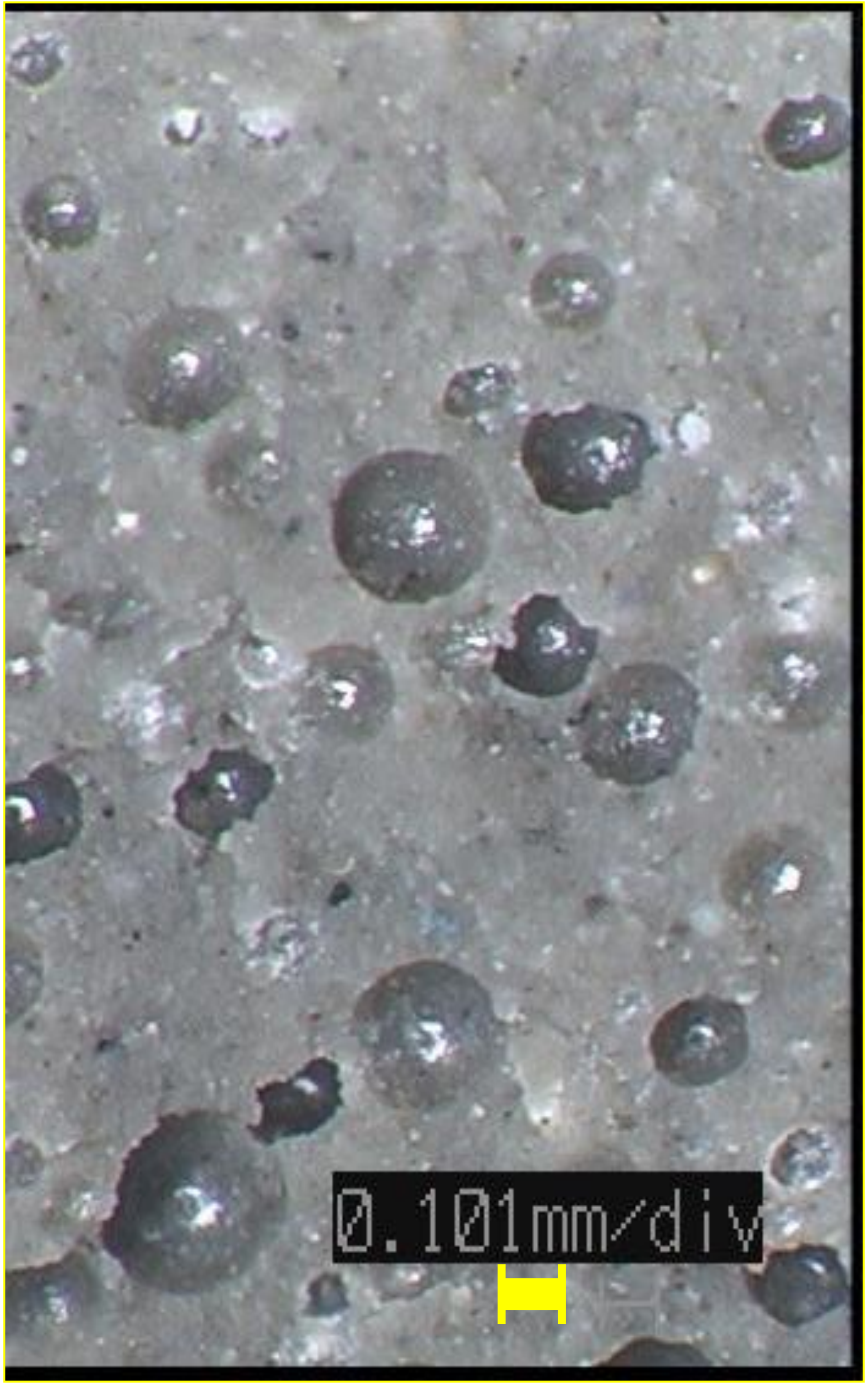
1. **Consolidated with vertical drains** (acceleration of consolidation)
2. **Replaced by good material** (clay → sand)
3. **Strengthened by solidification** (cement treatment)
4. **Lightened and solidified**

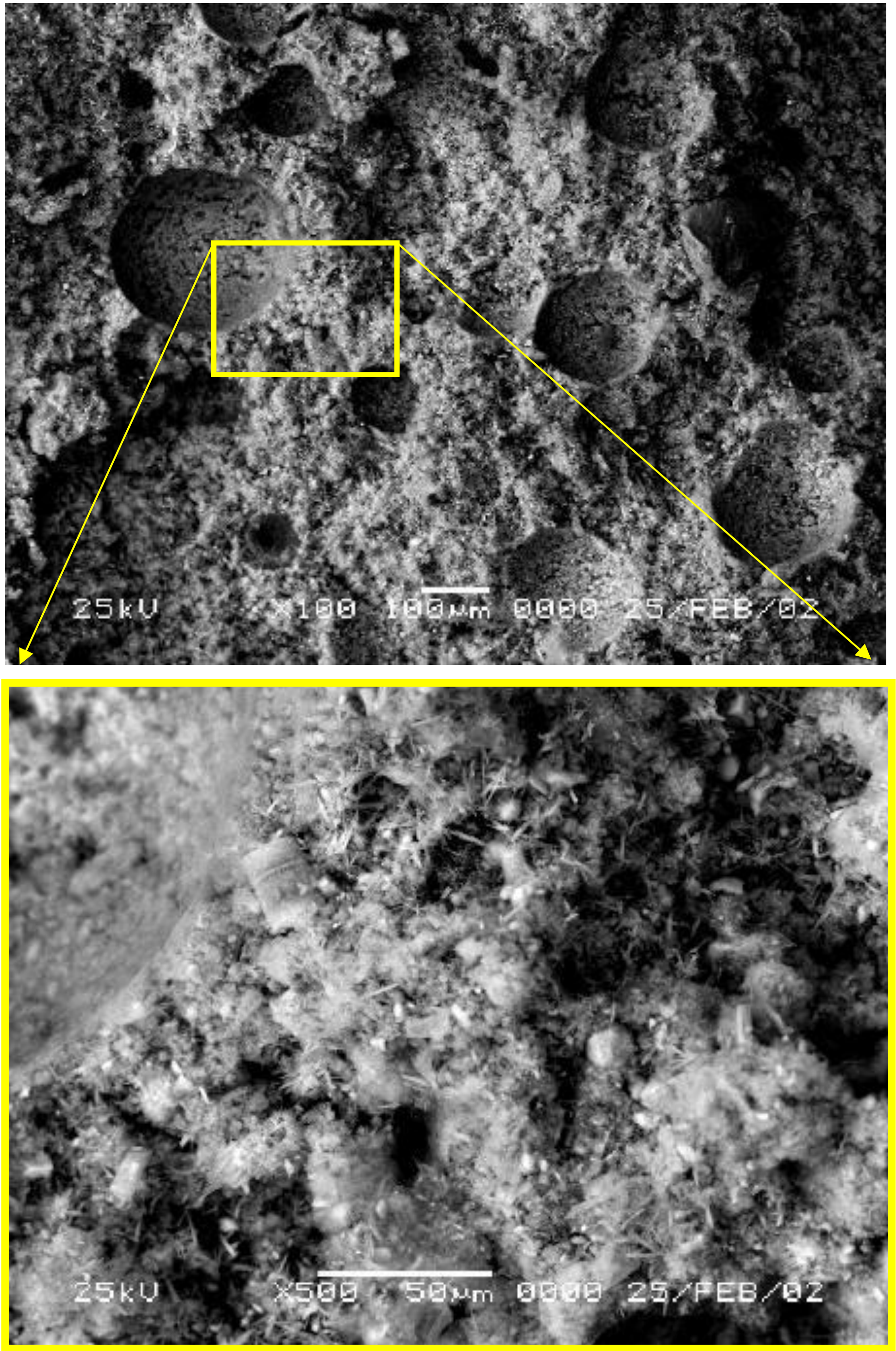
The right ground improvement method is applied in the right place.

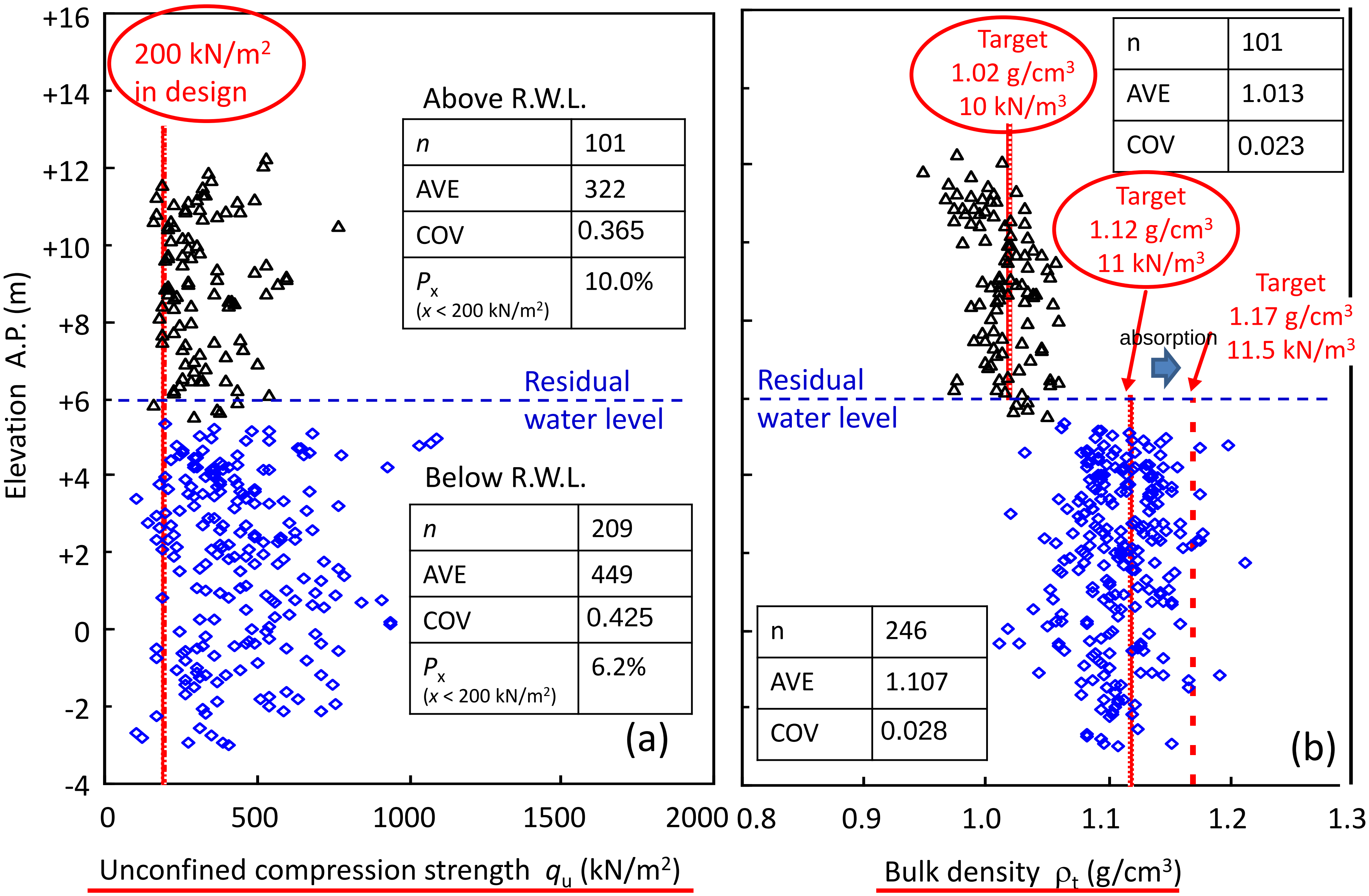


Cross-section of the joint structure between the reclamation and pier sections

Air foam treated Lightweight Geo-Material (LGM)



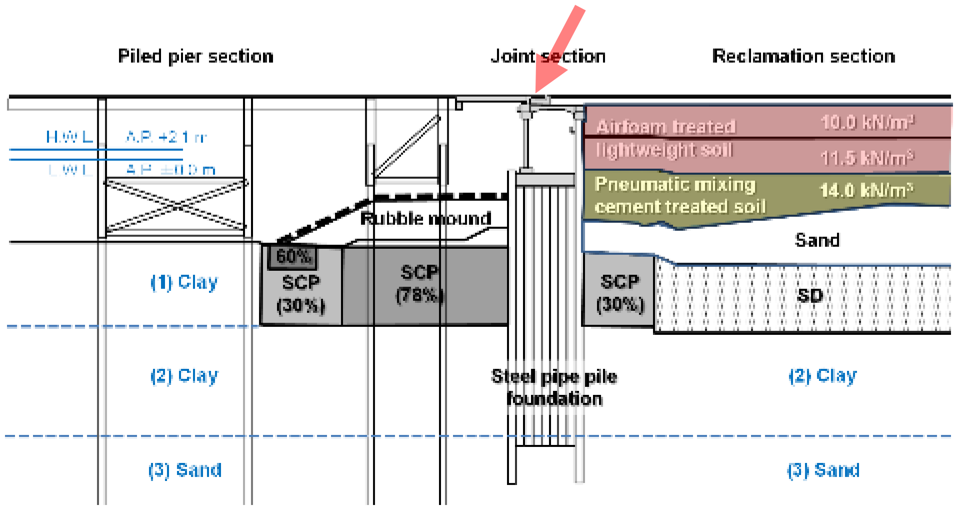


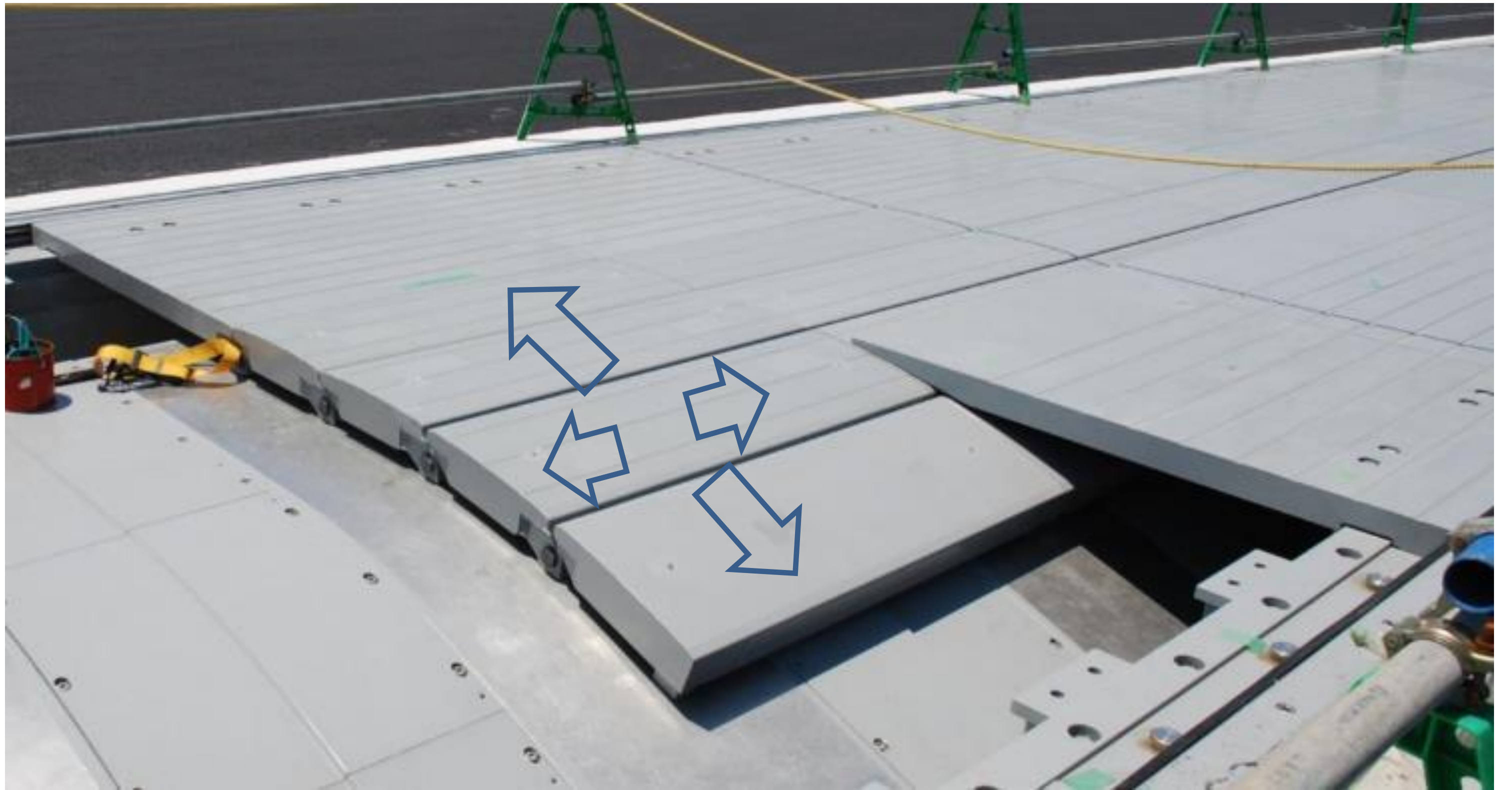


Depth profiles by confirmatory boring for air-foam treated lightweight soil (at 91 days): (a) unconfined compressive strength; (b) bulk density

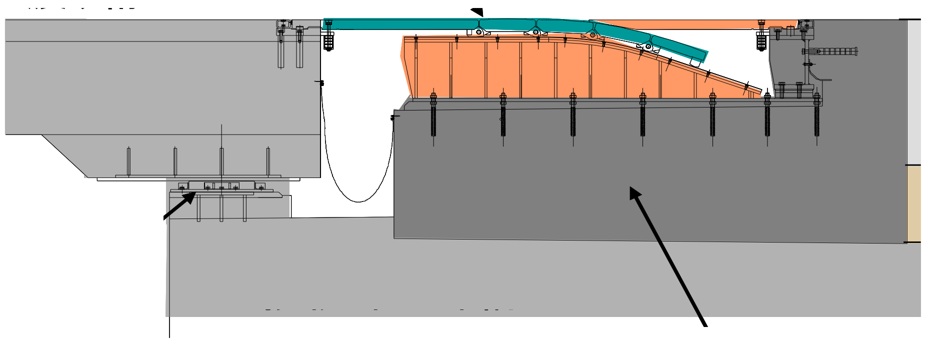
Watabe and Noguchi (2011)

Buffer structure —Expansion joint—

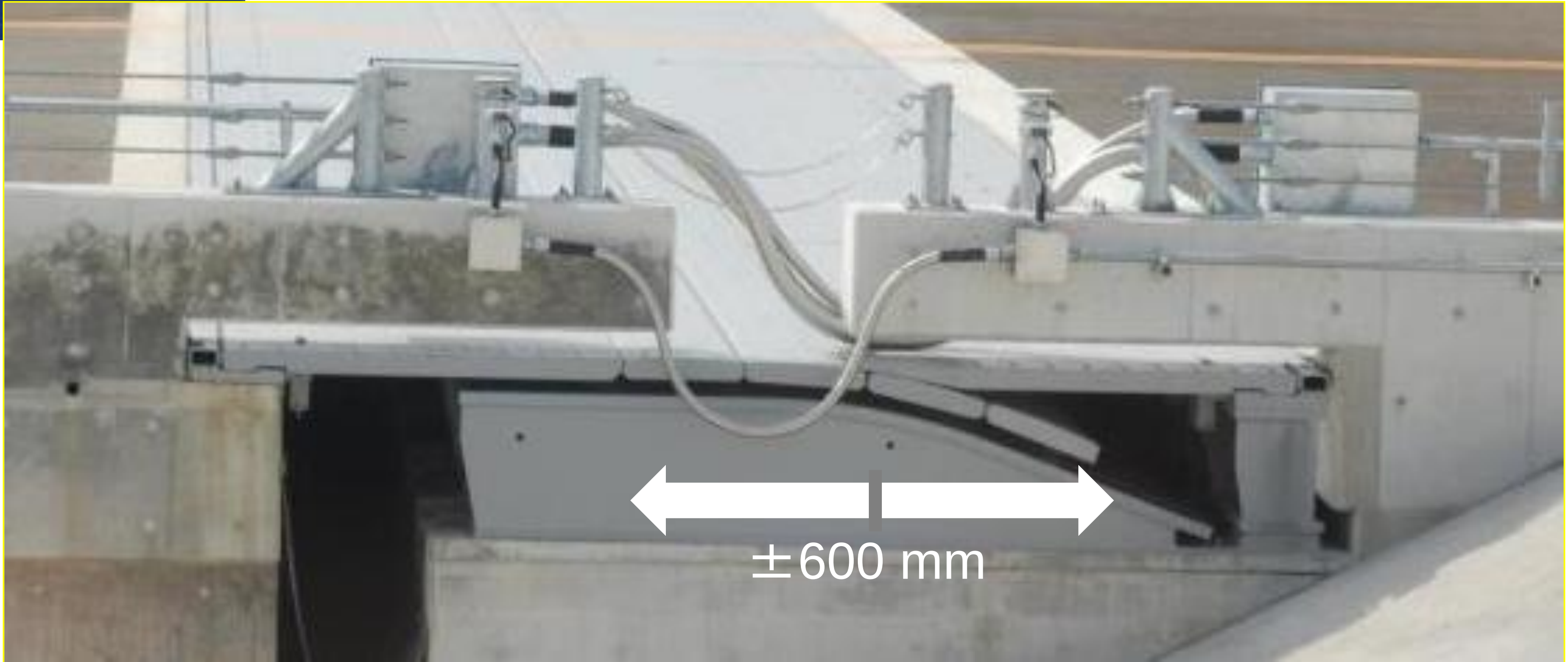




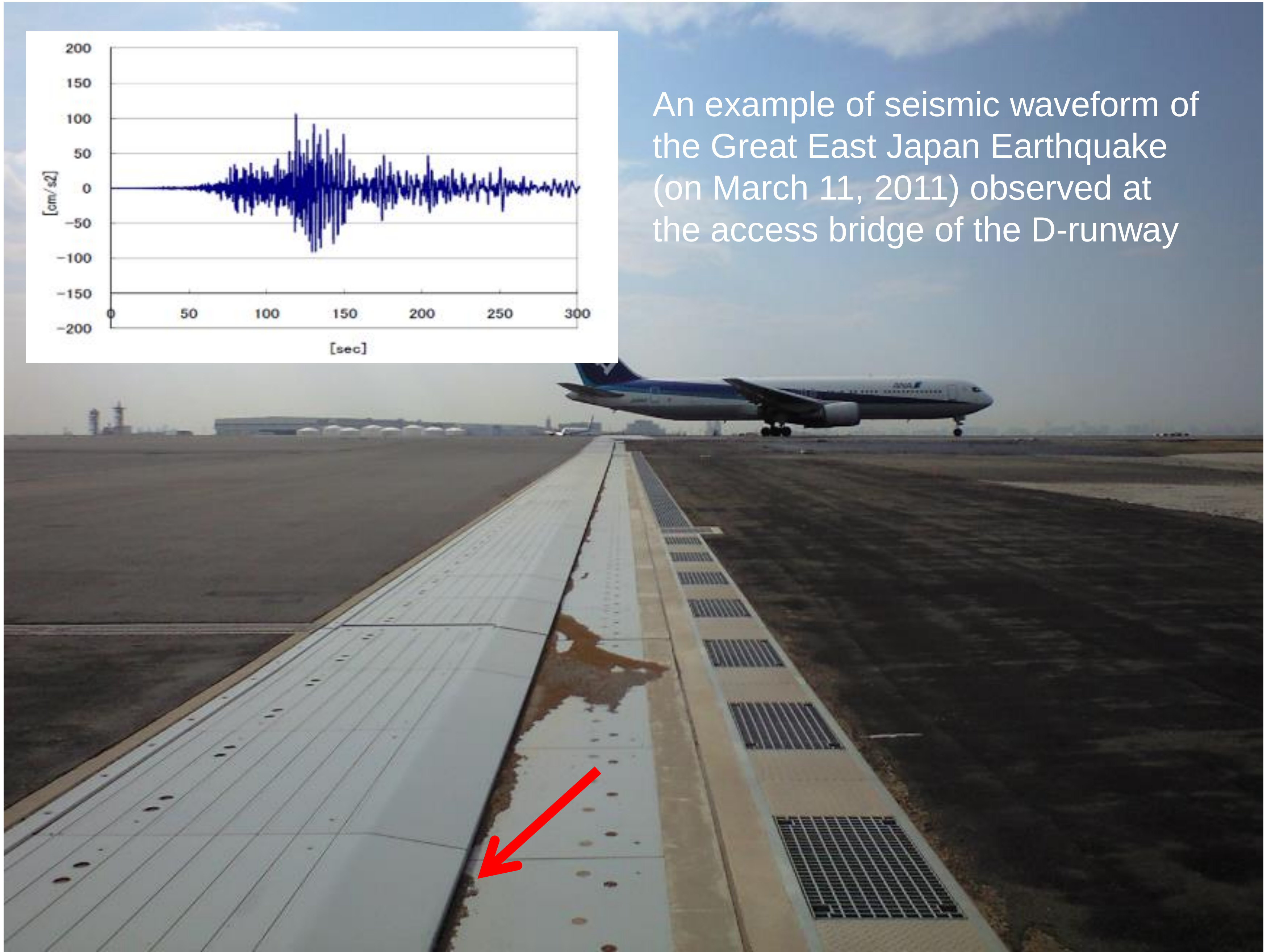
±600 mm



Concrete
(Knock off structure)


±600 mm


Direction of the Runway



An example of seismic waveform of the Great East Japan Earthquake (on March 11, 2011) observed at the access bridge of the D-runway

Summary

- Conventional reclamation method
  → Vertical Drains (SD/PVD) + Preloading: Consolidation
  Sand Compaction Piles (SCP): Replacement
  Deep Mixing Method (DMM): Solidification
- Prediction of differential settlement
  → Use of construction management data (penetration resistance of PVD)
- Rapid construction
  → Cement treatment (pneumatic flow mixing): Solidification as premix
- Additional lightness
  → Air-foam treated lightweight soil: Solidification as premix

References

1) **Watabe, Y.** and Noguchi, T.: Site-investigation and geotechnical design of D-runway construction in Tokyo Haneda Airport, *Soils and Foundations*, Vol.51, No.6, pp.1003-1018, 2011. http://dx.doi.org/10.3208/sandf.51.1003
2) **Watabe, Y.**, Noguchi, T. and Mitarai, Y.: Use of cement-treated lightweight soils made from dredged clay, *Journal of ASTM International*, Paper ID: JAI104219, 2012. http://dx.doi.org/10.1520/JAI104219
3) **Watabe, Y.**, Shinsha, H., Yoneya, H. and Ko, C.: Description of partial sandy layers of dredged clay deposit using penetration resistance in installation of prefabricated vertical drains, *Soils and Foundations*, Vol.54, No.5, pp.1006-1017, 2014. http://dx.doi.org/10.1016/j.sandf.2014.09.006
4) **Watabe, Y.**, Shinsha, H., Yoneya, H. and Ko, C. Description of partial sandy layers of dredged clay deposit using penetration resistance in installation of prefabricated vertical drains, Soils and Foundations, 54(5), 1006–1017, 2014. http://dx.doi.org/10.1016/j.sandf.2014.09.006

Thank you
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