Advanced technology and Case histories of liquefaction mitigation in Japan

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   -Japan
   -U.S.
   -New Zealand

Mitigation Liquefaction

Principle	Typical method
Densification	Dynamic Compaction Vibro-Stone Colume Sand Compaction Pile MVT Tamper Grouting (sand)
Solidification	Deep Soil Mixing
Dewatering	Vertical Drain Gravel Drain

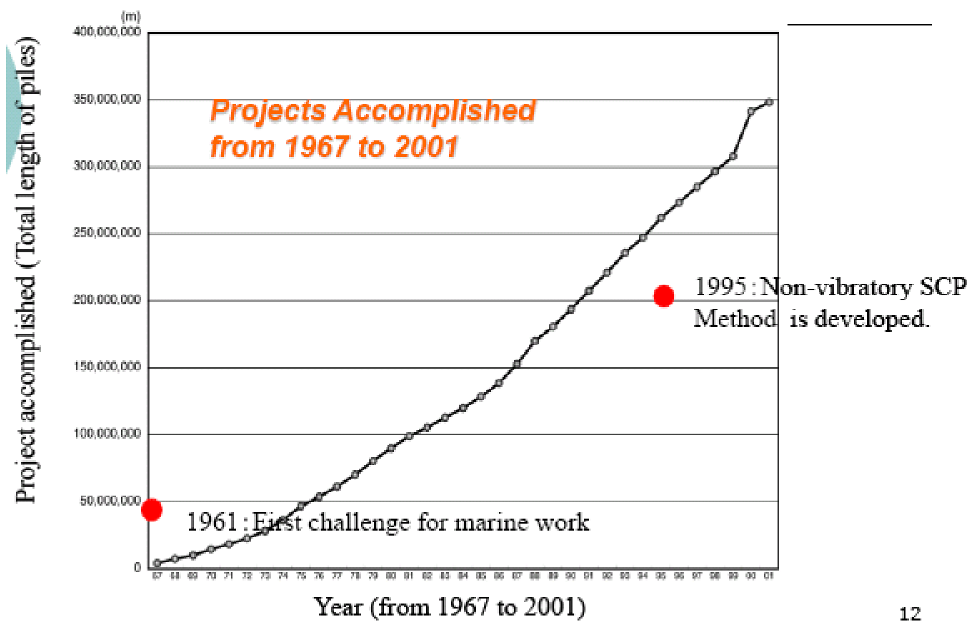
Liquefaction

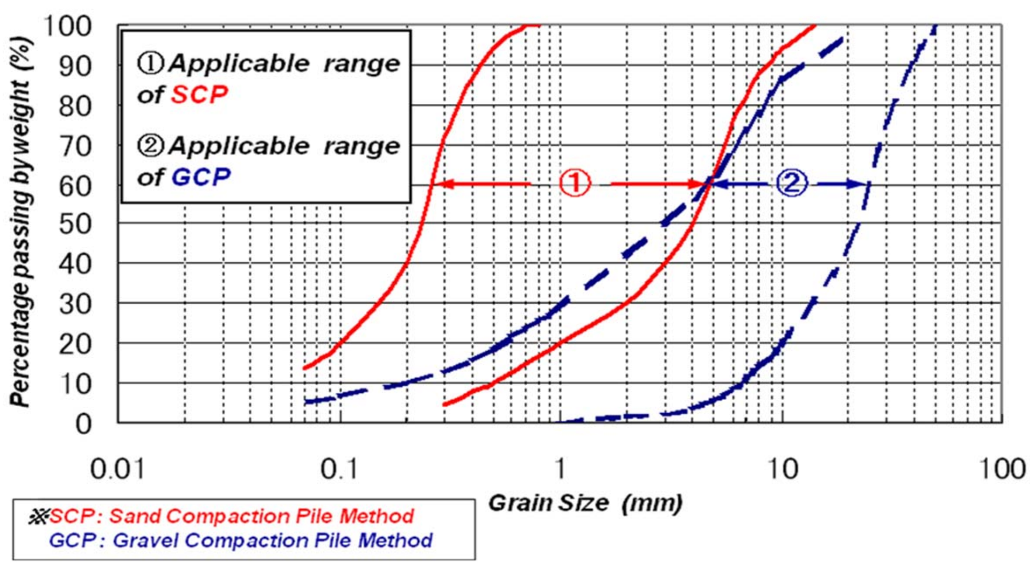
新潟市川岸町[直接基礎]
(1964年新潟地震)

神戸六甲アイランド
(1995年兵庫県南部地震)

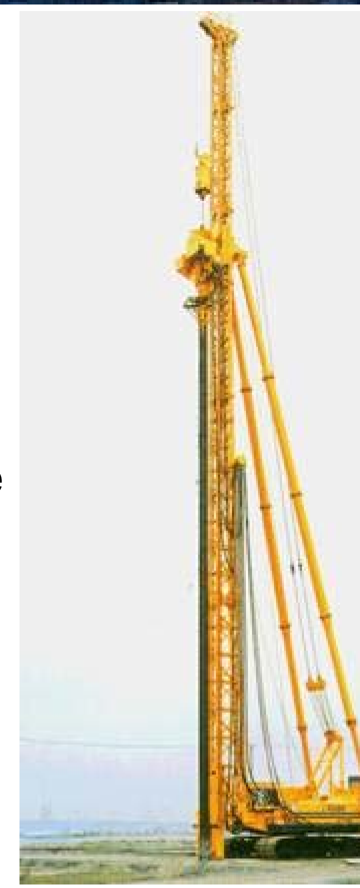
愛知県木曽川堤防
(1891年濃尾地震)

[1]SCP (Sand Compaction Pile)

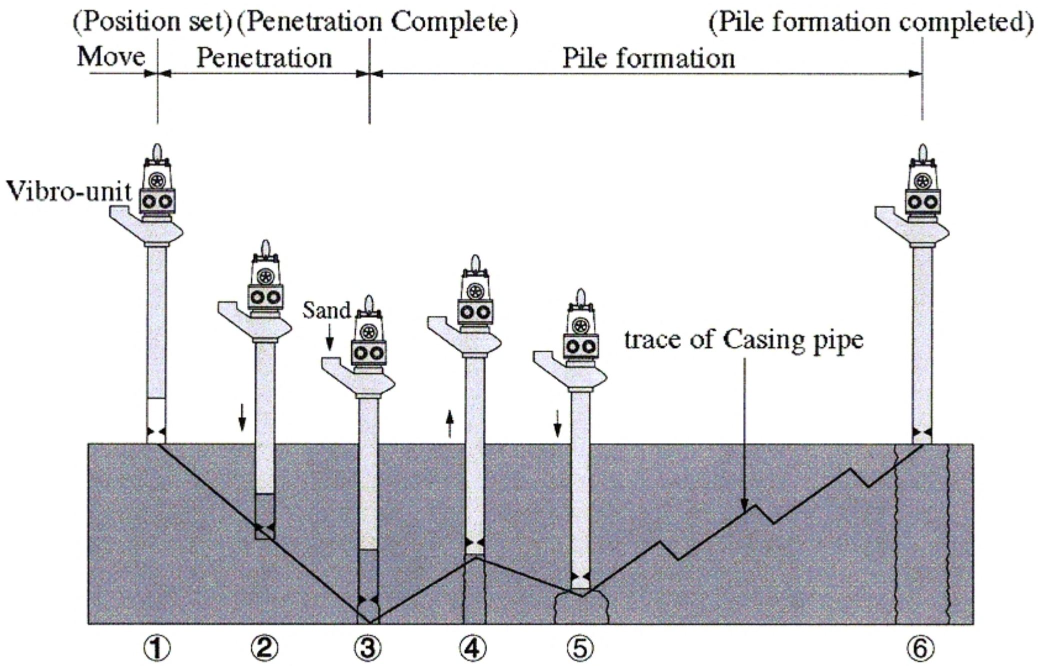


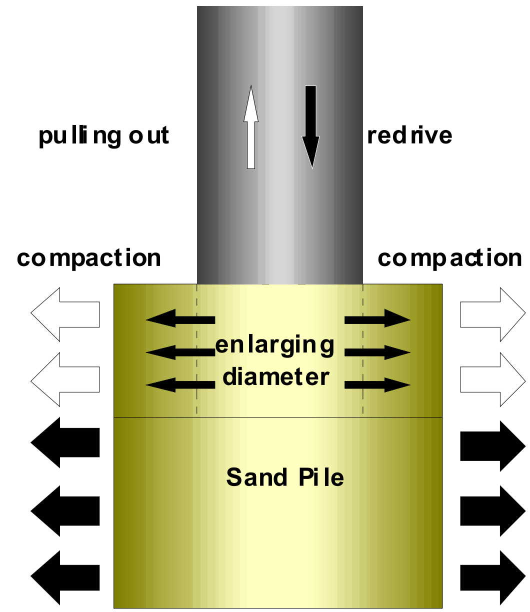


In this technology, both sand and stone are available to be used.



Work sequence





(1) Casing pipe is correctly positioned.

(2) Casing pipe is driven into the ground using a vibro-hammer.

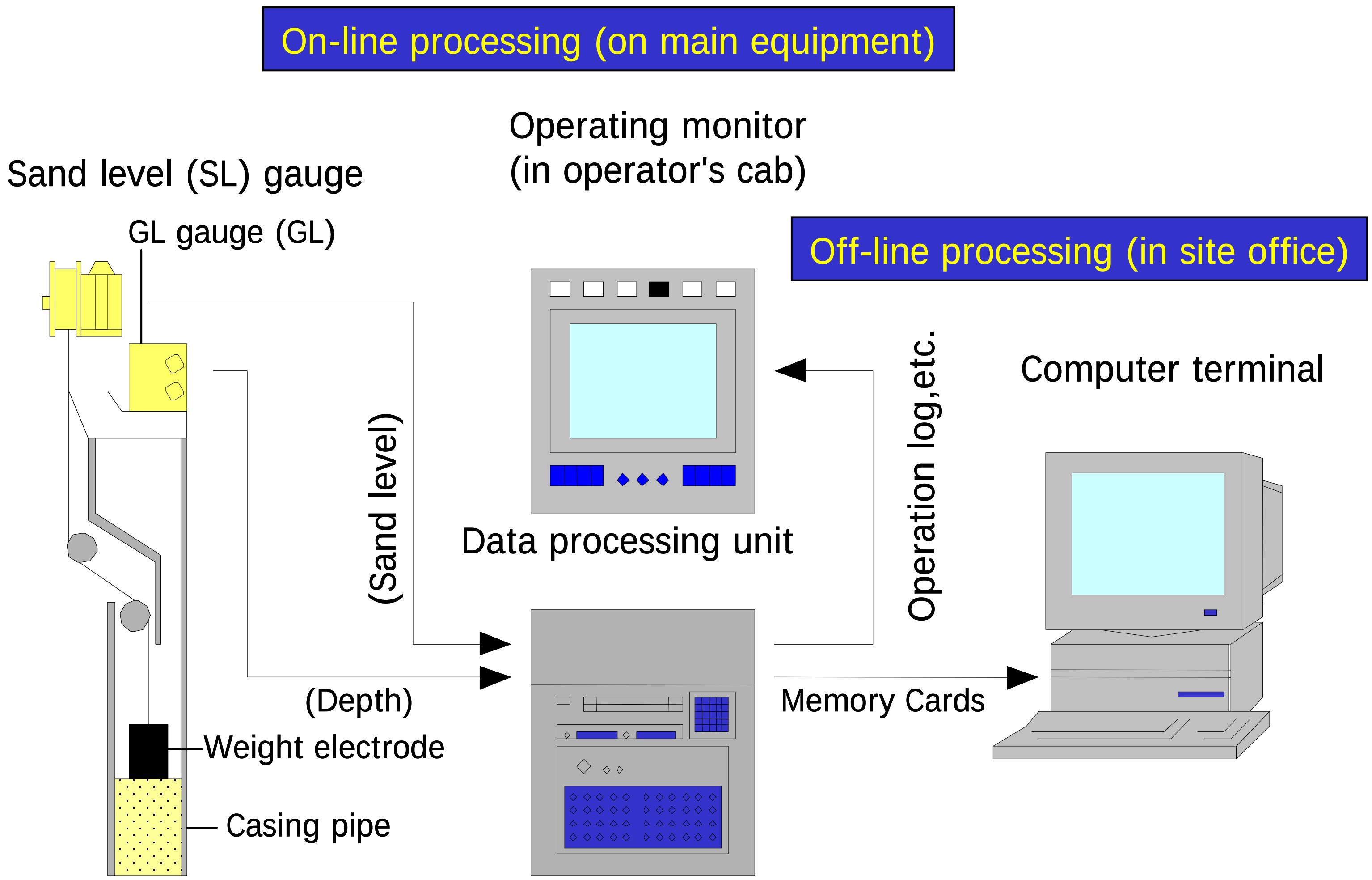
(3) When it reaches the required depth, the casing pipe is charged with a specified volume of sand/gravel.

(4) As the casing pipe is raised by a specified margin, the sand/gravel is discharged into the ground using compressed air.

(5) The sand/gravel pile is compacted and enlarged by driving the pipe back down.

(6) The pipe-raising, sand/gravel discharge and re-driving procedure is repeated, forming a complete compacted sand/gravel pile.

Quality Control



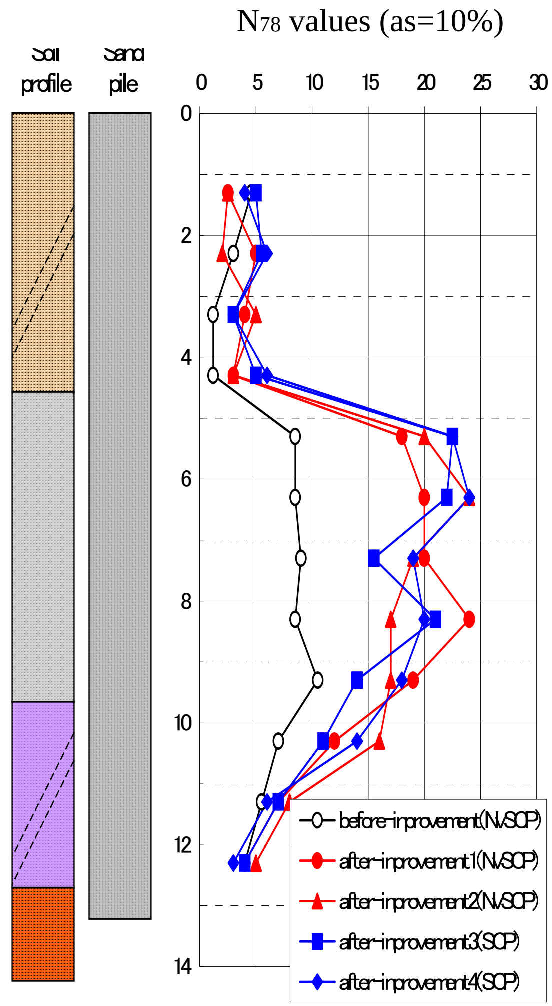
To secure the diameter of SAND/GCP pile, the following On-line processing system is used. In this system, weight electrode detects the sand/gravel surface inside of casing pipe and consequently the operator is able to measure the discharged sand/gravel volume to secure consistent column diameter.

SAVE COMPOZER

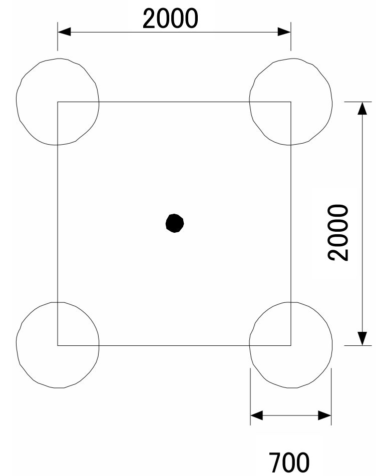
1.3×N78(JP)=N60(US)

(No Vibration system by forced Rack & Pinion)

N values (Improvement ratio, as=10%)



NSCP:Non-vibratory SCP method



According to the FEM analysis, large amount of volume strain is occurred around the sand pile. Dilatancy effect due to expansion of pile diameter is dominant in case of reclaimed land densification with inclusion of some amount of fine content.

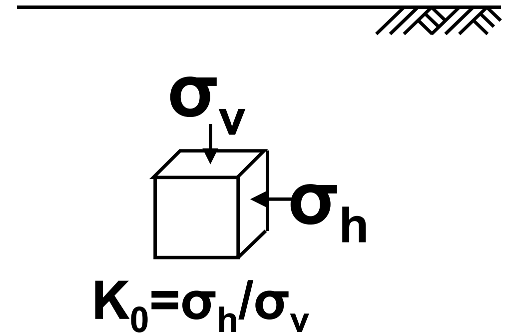
Advantages of Sand Compaction Pile

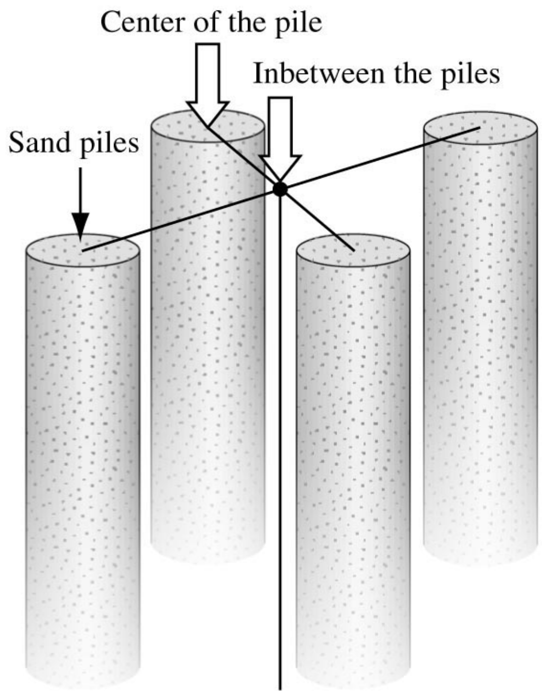
Except of Large density increase…

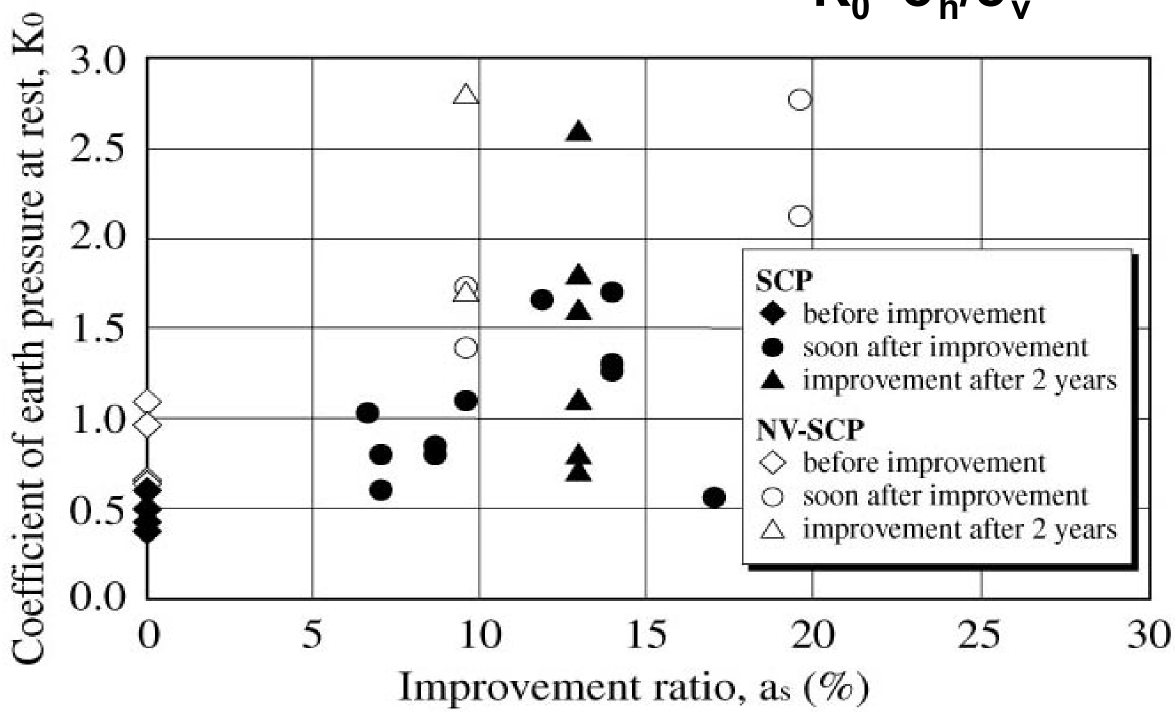
(1) Increase of lateral stress (Increase of Ko)

(2) Decrease of saturation degree due to air injection for discharging in-filling sand

(1) Increase of K_0 Value after Installation







Relationship between the improvement ratio and K_0 measured before and after improvement

Increase of K_0 has close relationship with increase of qc, fs and liquefaction strength (Harada 2000).

(2) Air injection effect into the ground

Reduction of saturation degree has been observed in many past SCP improved areas. Air pressure charged in casing pipe for the purpose of discharging the sand causes the air leakage into the surrounding sandy ground.

Prof. Okamura (2002) presented that the decrease of saturation degree has been maintained for even more than 25 years by using accurate frozen samplings.

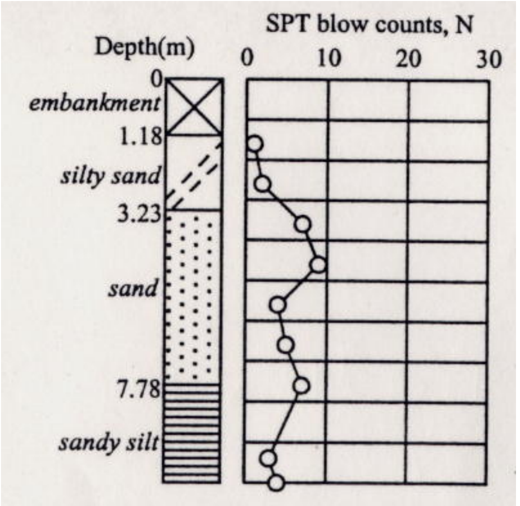
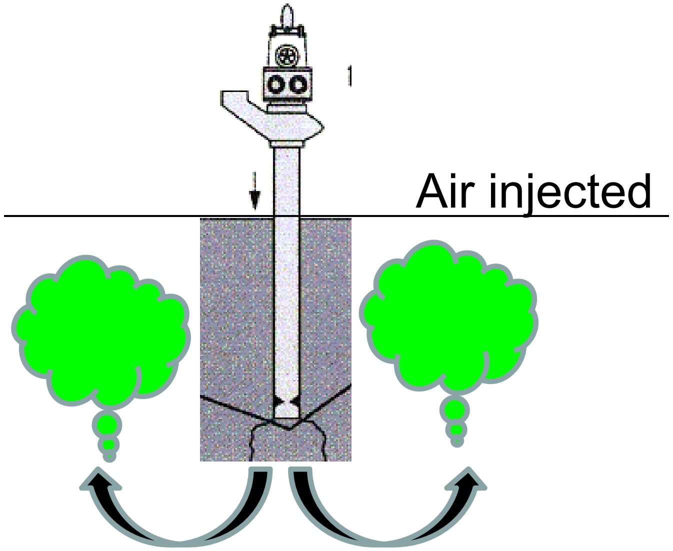
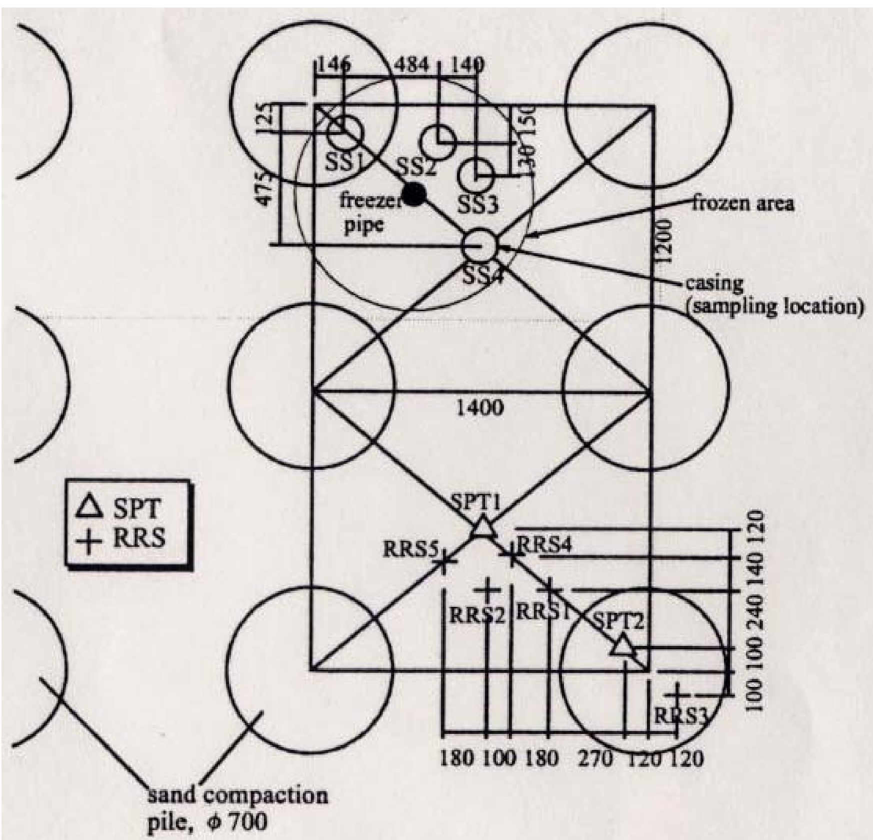


図 1　地盤改良前の柱状図と N 値



Location of Frozen sampling and results of measured degree of saturation, Niigata

(Okamura et.al , Liquefaction resistance of sand deposited improved with sand compaction piles, Soils and Foundations, 2003)



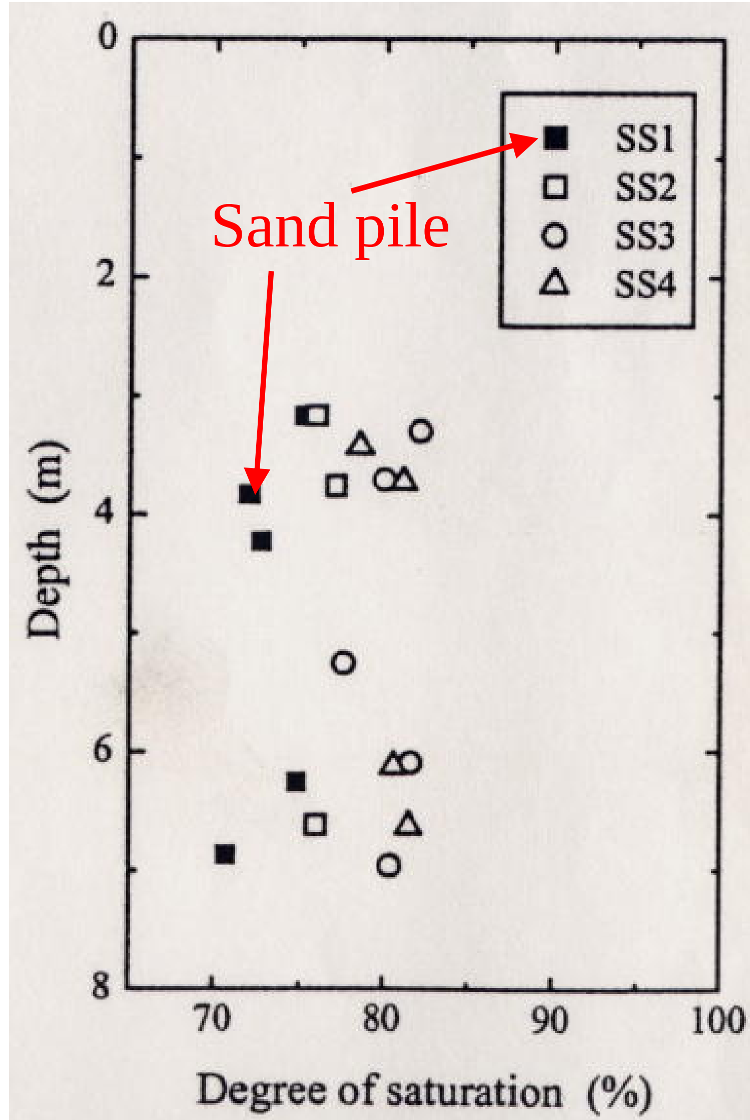
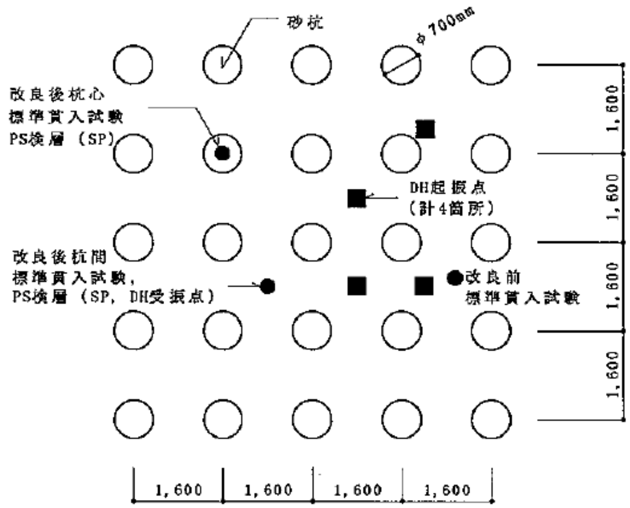
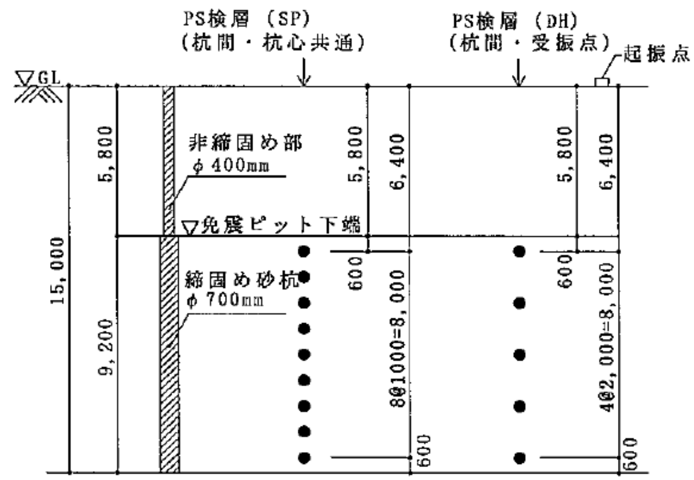


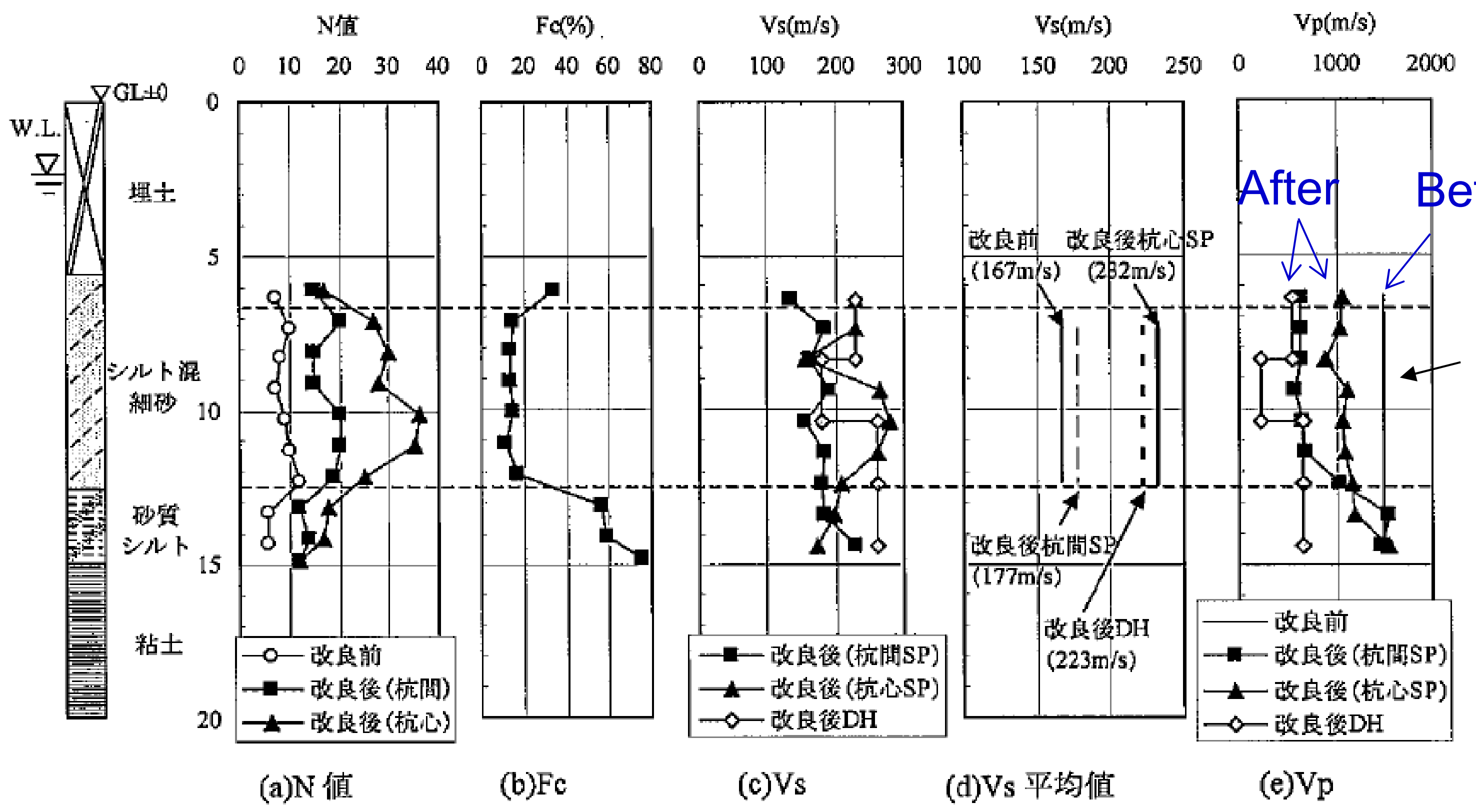
図 8　凍結試料の飽和度の深度分布

In-situ Test in Tokushima (Akiyama et al 2002)

Cross-Hole, Down-Hole Test at 3 weeks later of GCP installation







Significant reduction of P-wave Velocity

High accuracy surface wave investigation system by Seismographs (Aochi, et al)

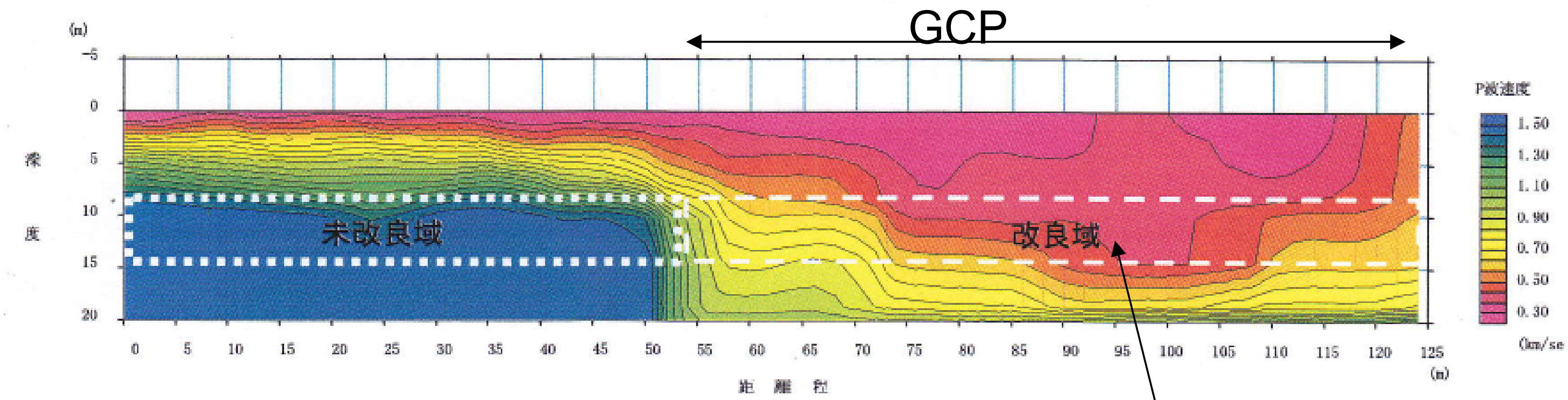


図 5　P 波速度断面

P-wave velocity reduction in GCP area

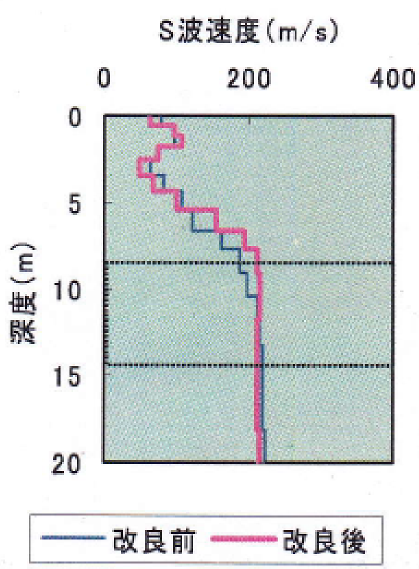


図 6　平均 1D- Vs モデル

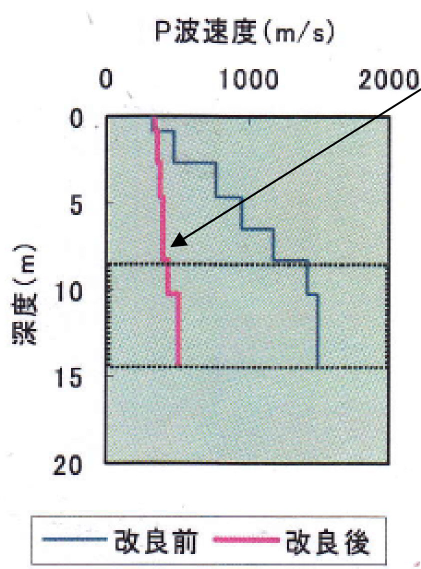


図 7　平均 1D- Vp モデル

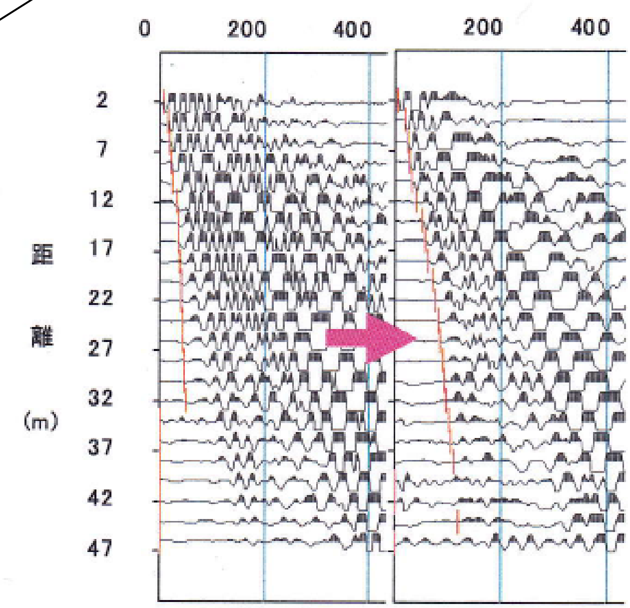


図 8　改良前後の初動到達時刻の変化

The liquefaction mitigation effect of Pneumatic Caisson due to air leakage effect (S. Shiraishi, 1997)

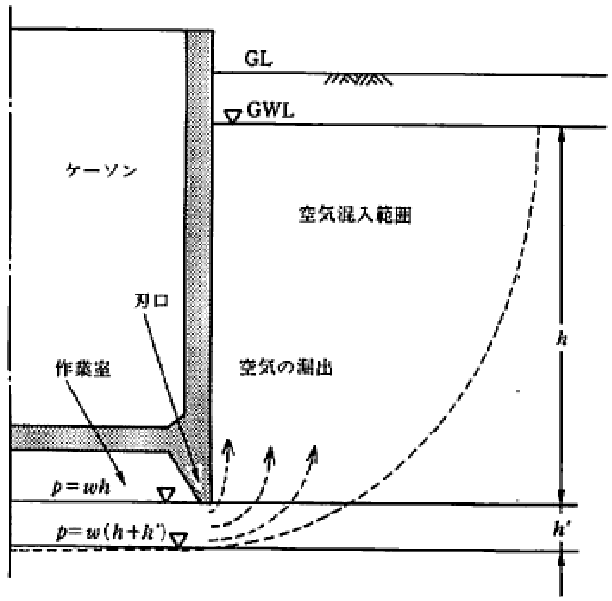


図-1 ニューマチックケーソンからの漏気

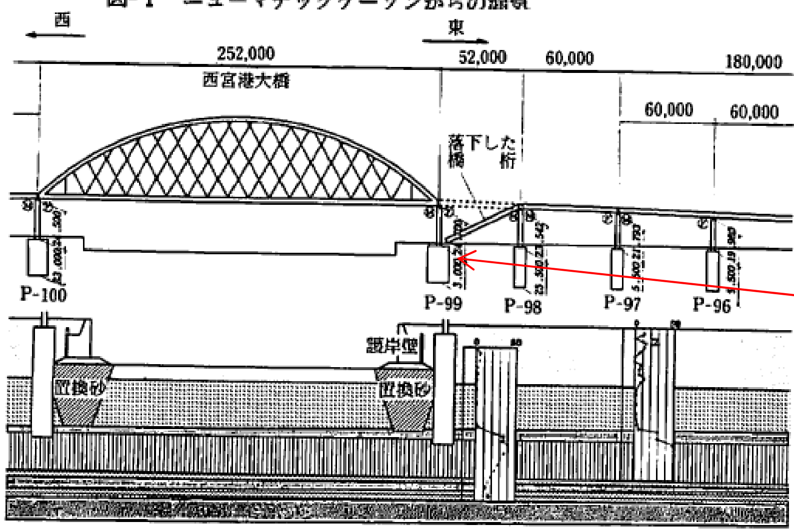


図-4 西宮港大橋の東端側径間橋桁の落橋

BANDAI bridge (1929) is the first case of pneumatic caisson in Japan, there was no significant damage at Niigata earthquake (1964), whereas neighbor Showa bridge girders have fallen.

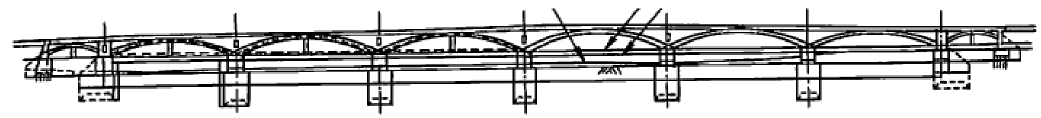


図-3 萬代橋の縦断面図

Fallen Showa bridge

Pneumatic caisson pier

Nishinomiya-Minato bridge was safe at Kobe earthquake (1995).

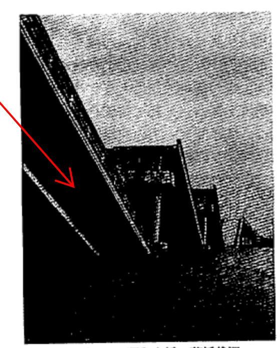
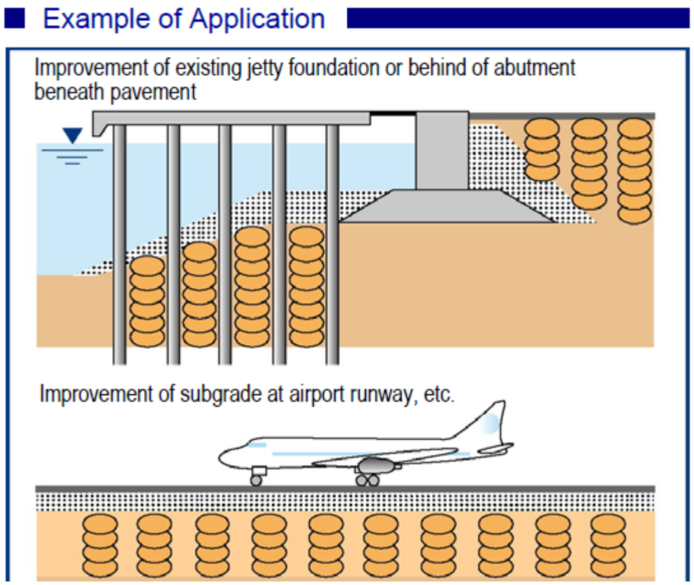


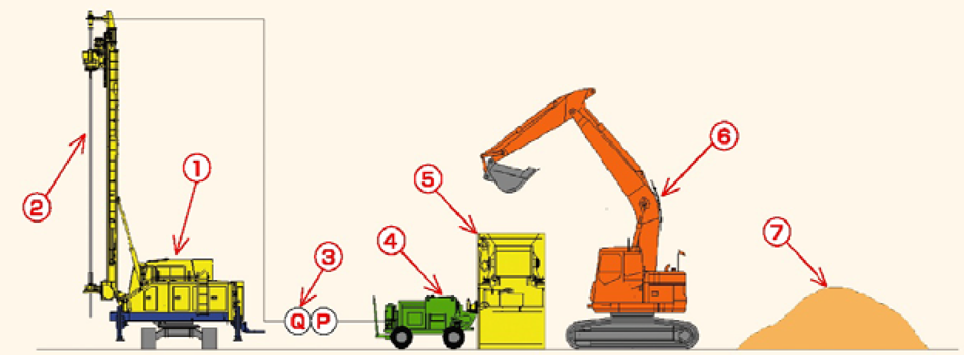
写真-1 昭和大橋の落橋状況

[2] SAVE-SP (Densification by Sand Press in with compact size machines)

Fluidized sand by added fluidizer are used to be injected into the loose sandy ground and later the sand is back to the solid condition by added plasticizer.



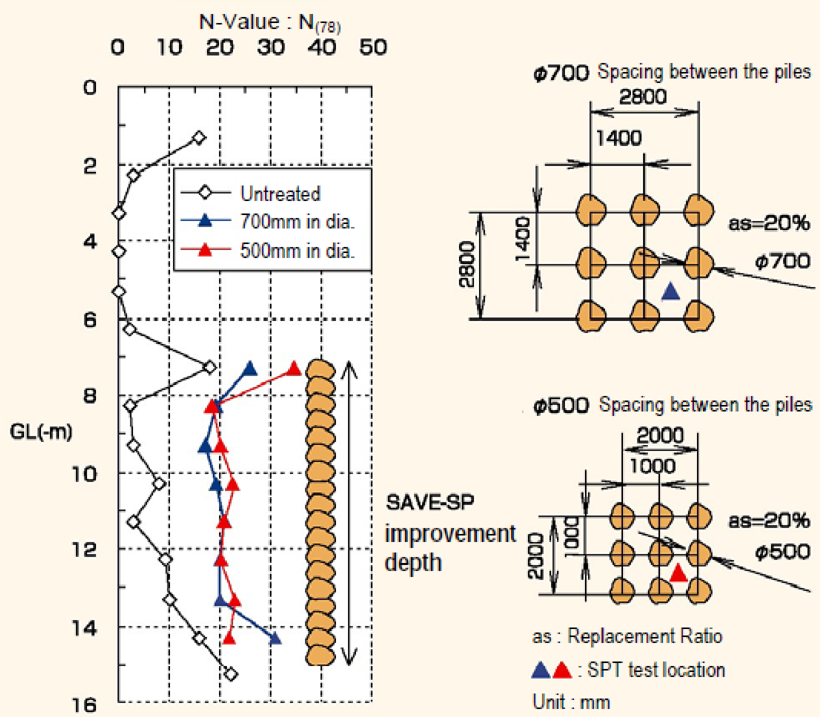
Construction Systems

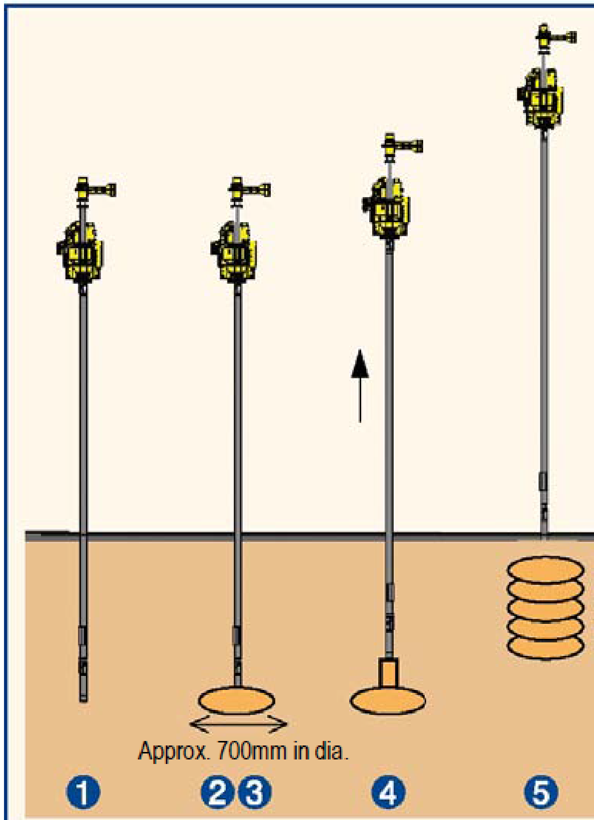


No.	Item
①	Base machine
②	Boring rod
③	Flow meter & pressure gauge
④	Pump for injecting fluidized sand
⑤	Fluidized sand mixing plant
⑥	Backhoe
⑦	Sand stockpile

Construction Sequence of SAVE-SP

Increase of N-Value between the Piles





Case Study (1): Muya, Tokushima

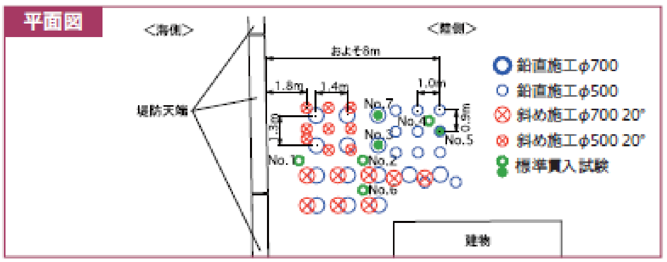
施工概要

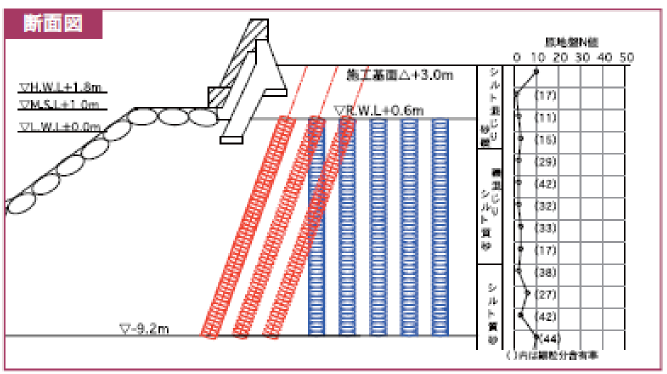
工　期	2009年3月～4月
施工場所	徳島県鳴門市撫養町
改良仕様	φ700mm□1.4m (as=20%) φ500mm□1.0m (as=20%) 改良深度：GL-12.2～-2.4m
施工数量	φ700mm：22本,193m　φ500mm：20本,147m
改良目的	堤防背面の狭隘地の締固め
特記事項	地盤の細粒分20%程度　盛上りほとんどなし

出来型

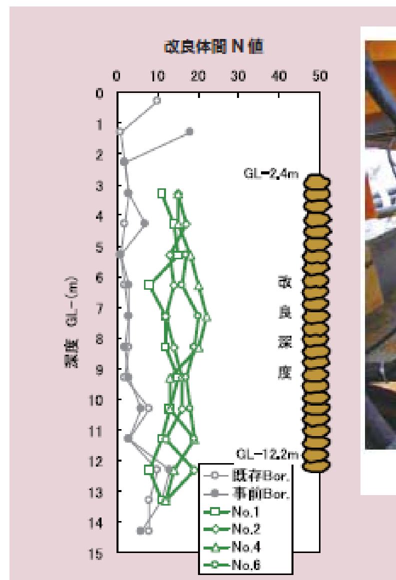
φ500mm 仕様での出来型

施工仕様





改良効果

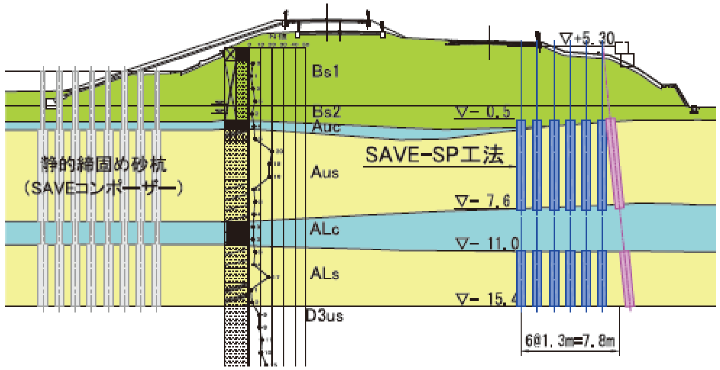


●N値3程度が15程度に増加。

写真−1　流動化砂

This is new application in Japan under the existing structure (sea wall). Sufficient densification effect was obtained without any lateral deformation and damage to neighbor structures.

Case Study (2): Shonai River, Aichi

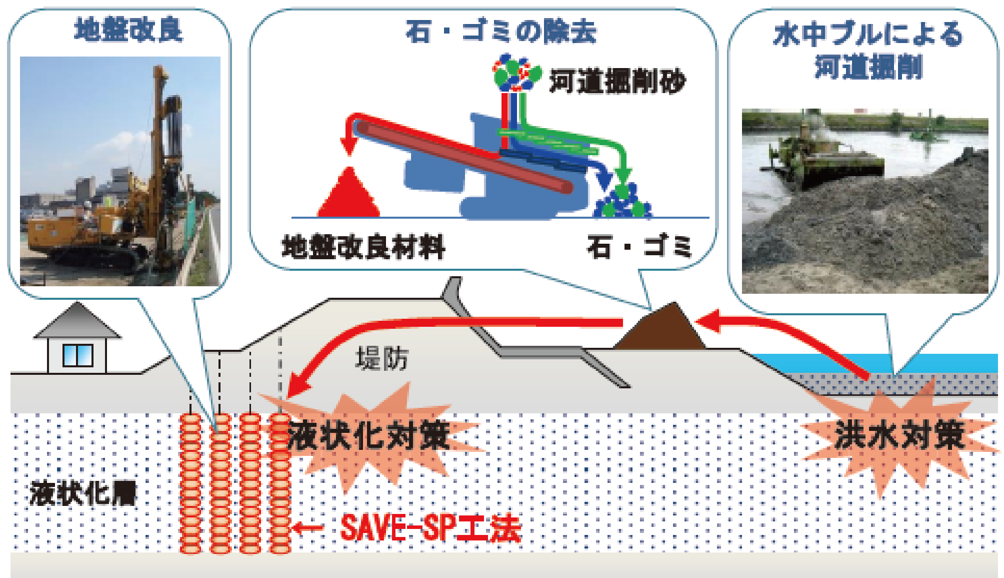


図–6　改良断面の一例

写真–3　庄内川での施工箇所の一例

写真–4　施工状況

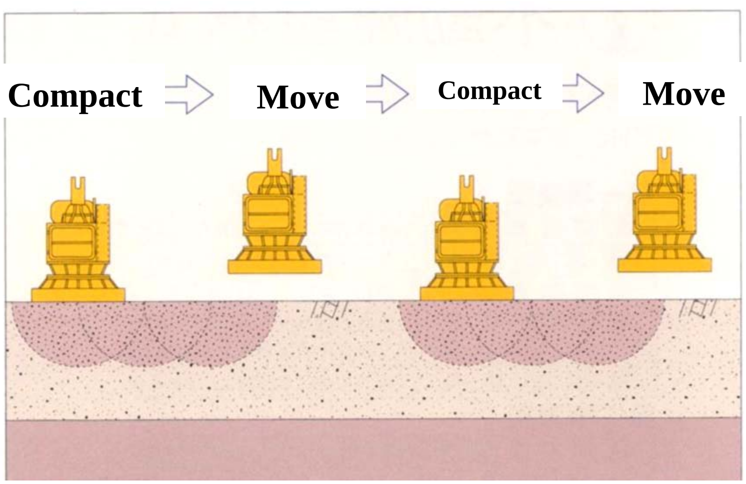
In Shonai-River, the dredged sandy soil were able to be used for the material of SAVE-SP.
In Japan, it is not permitted to use the cement grouting and cement mixing inside the river dike due to disturbance risk of water flow.

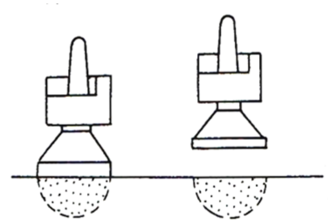


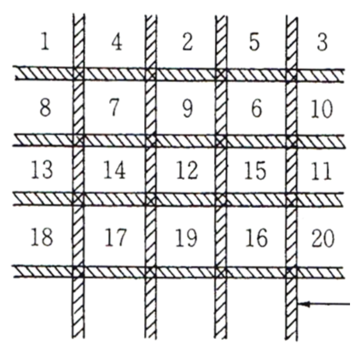
図–10　河道掘削砂の利用方法

[3] Mammoth Vibro-Tamping (MVT)

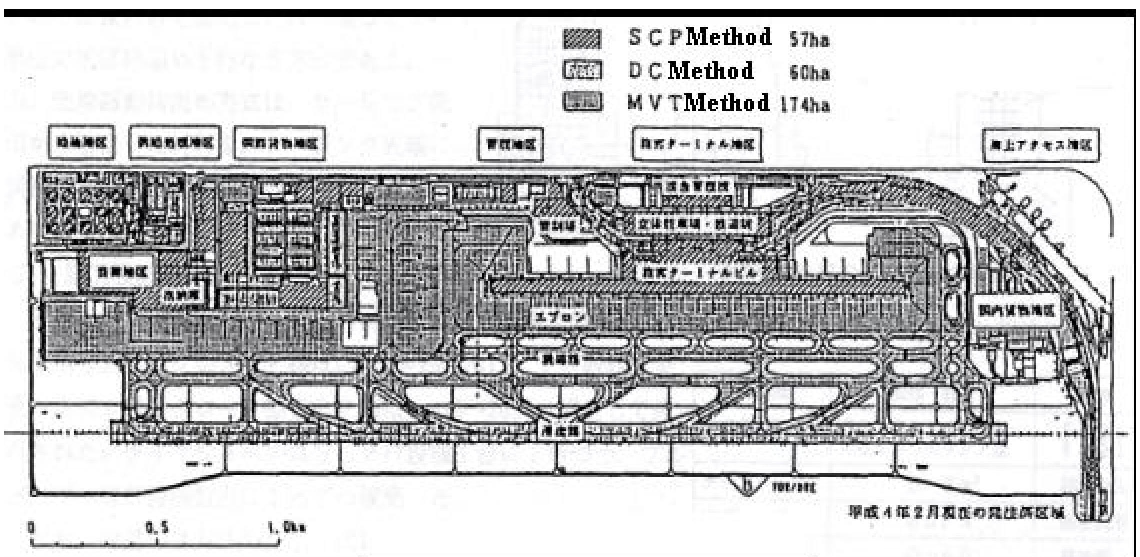
MVT Method is to compact the surface area (15-17ft) of sandy ground using a strong vibratory motor on top of large-scale steel tamper plate (10’ x 10’) and specified duration.





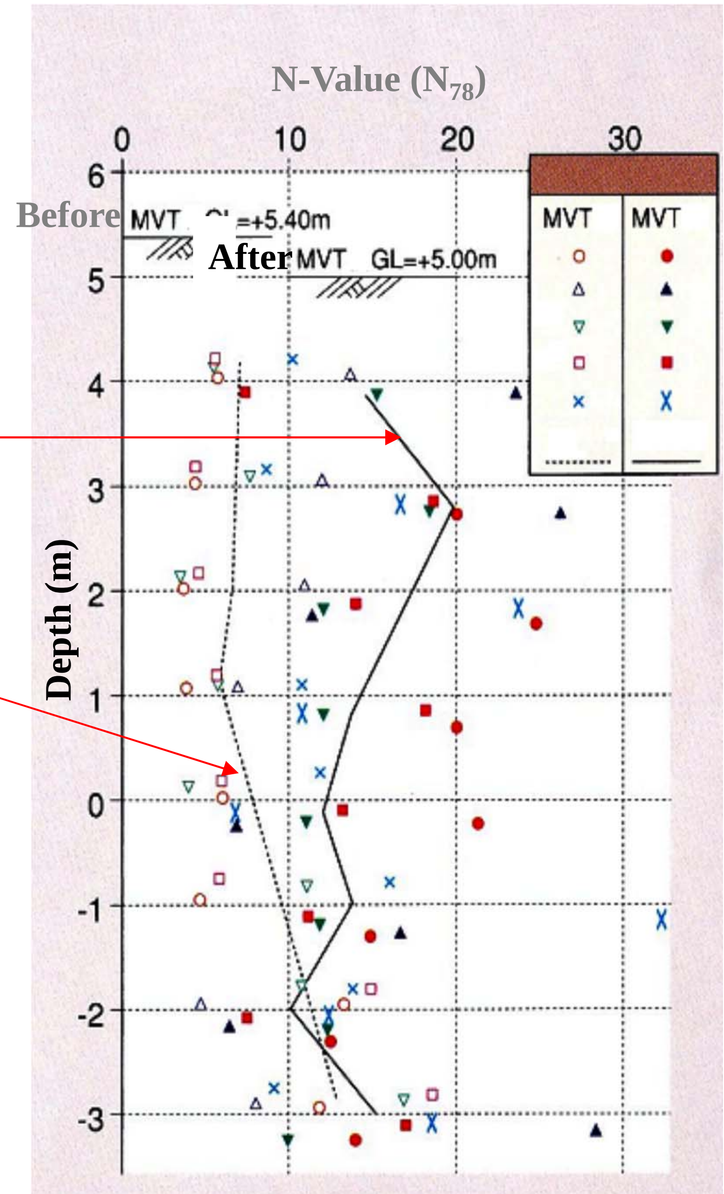


Work Experience of Kansai International Airport, Japan 1998



After

Before

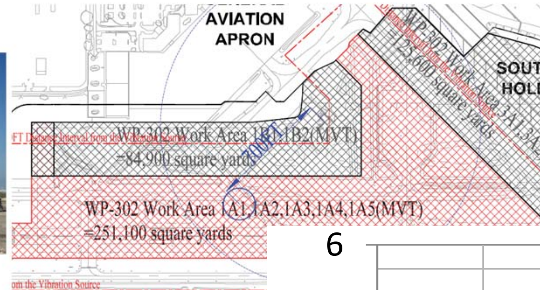


Effect of liquefaction mitigation at Miho Airport, Tottori, Tottori-ken Seibu earthquake 2003, M=7.3

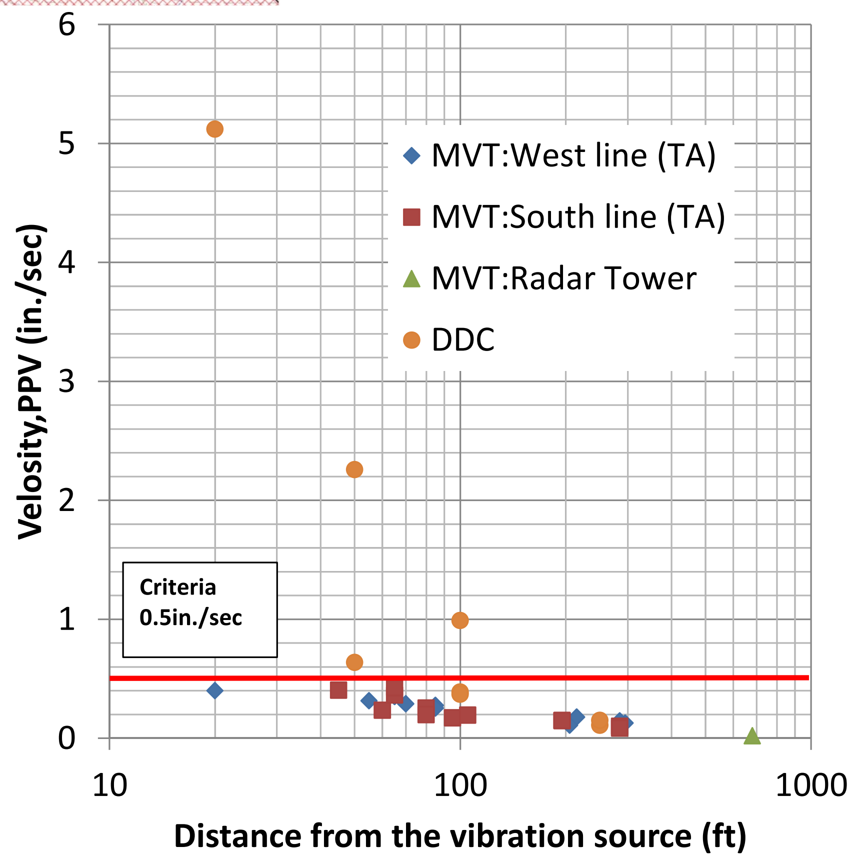
MVT has been applied at the runway expansion area in 1994 and there was no liquefaction observed in 2003.

U.S. Fort-Lauderdale Airport (Florida) Runway Compaction work by MVT (2012.10-2014.2)

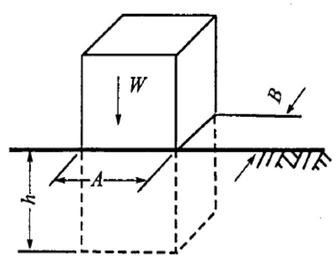
空港のレーダー塔
距離約200m



Seismograph

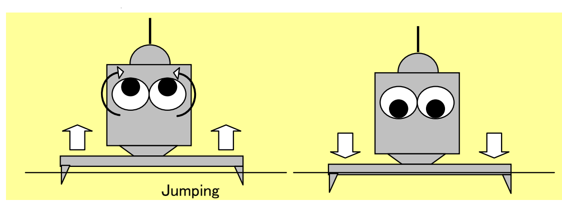


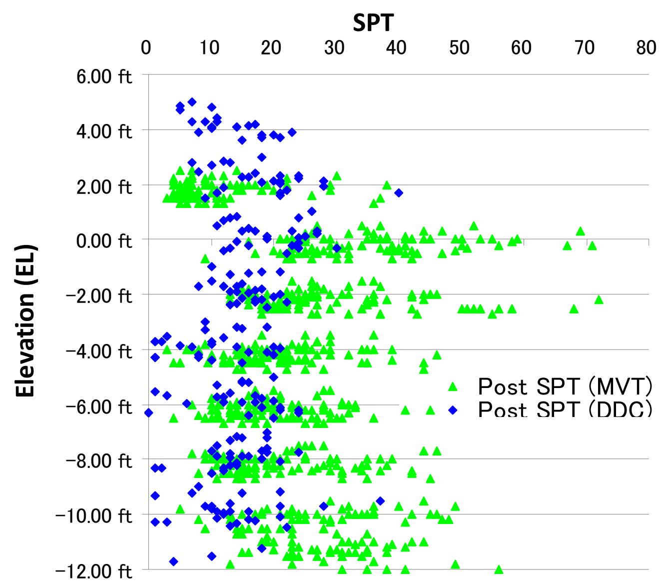
Mammoth Vibro Tamper Type-1 (Large MVT)	Mammoth Vibro Tamper Type-2 (Regular MVT)	Specified Dynamic Compaction (weight dropping)
E = E0 x n x t x 60 / (A x B x h) E0 = 2 x a x (W + F / 2) x (f / 60) Where E0: Compaction Energy to ground per unit time n: Number of Compaction = 1 t: Duration (min) = 1.67 A, B: Effective width (cm) = 300 h: Thickness of layer (cm) = 305 a: Vibration amplitude (cm) = 2.63 W: Weight (tf) = 25.0 F: Vibration force (tf) = 80 f: Frequency (rpm) = 560 E0 = 3191.067 tf cm/sec E = 0.011648 tf cm/cm3 = 116.48 tf m/m3 E = 355.27 tf m/m2 --- per unit area = 108.29 tf ft/sf --- per unit area	E = E0 x n x t x 60 / (A x B x h) E0 = 2 x a x (W + F / 2) x (f / 60) Where E0: Compaction Energy to ground per unit time n: Number of Compaction = 1 t: Duration (min) = 1.67 A, B: Effective width (cm) = 200 h: Thickness of layer (cm) = 305 a: Vibration amplitude (cm) = 2.63 W: Weight (tf) = 11.7 F: Vibration force (tf) = 60 f: Frequency (rpm) = 558 E0 = 2,039.881 tf cm/sec E = 0.016754 tf cm/cm3 = 167.54 tf m/m3 E = 510.99 tf m/m2 --- per unit area = 155.75 tf ft/sf --- per unit area	E = W x H x N / (A x B) tf ft/sf Where W: Weight = 25 tons H: Height = 110 ft N: Time of drop = 3 drops A, B Effective width = 12 ft E = 57.29 tf ft/sf --- per unit area
* Kiichi Tanimoto, "Fundamental study for compaction by means of surface vibration", doctor's thesis at Kyoto University, 1958.		
*** Compaction energy by both MVT Type-1 and Type-2 are larger than the compaction energy by the specified Dynamic Compaction.**		



a : Amplitude (cm)	1.1	*B* : Effective width (cm)	310
W : Weight (tf)	21.5	*n* : Number of applications (No.)	2~4
F : Oscillatory force (tf)	87.7	*t* : Time of application (min)	
f: Frequency (cpm)	560	*h* : Thickness of improvement (cm)	400
A: Effective width (cm)	310		

Figure 5.59. Calculation of vibratory compaction energy.





2. Effect of Mitigation Liquefaction

-Japan, US, New Zealand

Case Histories on Effectiveness of SCP

Tokachi-oki Earthquake (Sep.'03;M=8.0)
Effectiveness confirmed of SCP improvement for Tokachi port etc.

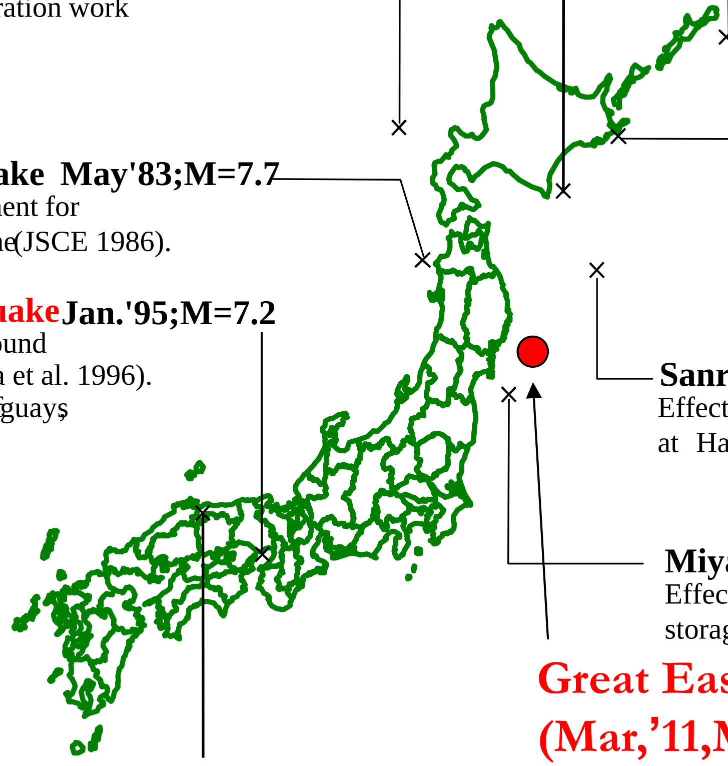
Hokkaido Nansei-oki Earthquake July'93;M=7.8
Effectiveness of SCP improvement for storage tank site at Hakodate confirmed.
SCP used in embankment restoration work of Goshiribetsu River.

Hokkaido Toho-oki Earthquake (Oct.'94;M=8.1)
Effectiveness confirmed of SCP method at site where it was adopted for restoration work after '93 Kushiro-oki earthquake (Nishikawa et al. 1995)

Kushiro-oki Earthquake (Jan'93;M=7.8)
Effectiveness confirmed of SCP and gravel drain method used for Kushiro's West Harber (Iai et al. 1993).
SCP used in restoration work of Kushiro and Tokachi Rivers (Sasaki et al. 1995).

Nihonkai-Chubu Earthquake May'83;M=7.7
Effectiveness of SCP improvement for Okitate storage tank site confirmed (JSCE 1986).

Hyogo-ken Nambu Earthquake Jan.'95;M=7.2
Earthquake-resistant effect of ground improvement confirmed (Yasuda et al. 1996).
SCP used for restoration work of quays, Breakwaters,etc.



Sanriku-Haruka-oki Earthquake (Des.'94;M=7.5)
Effectiveness of SCP improvement confirmed at Hachinohe storage tank site (JGS 1994).

Miyagi-ken-oki Earthquake (Jun.'78;M=7.4)
Effectiveness of SCP improvement confirmed at storage tank site near Ishinomori fising port (Ishihara et al. 1980)

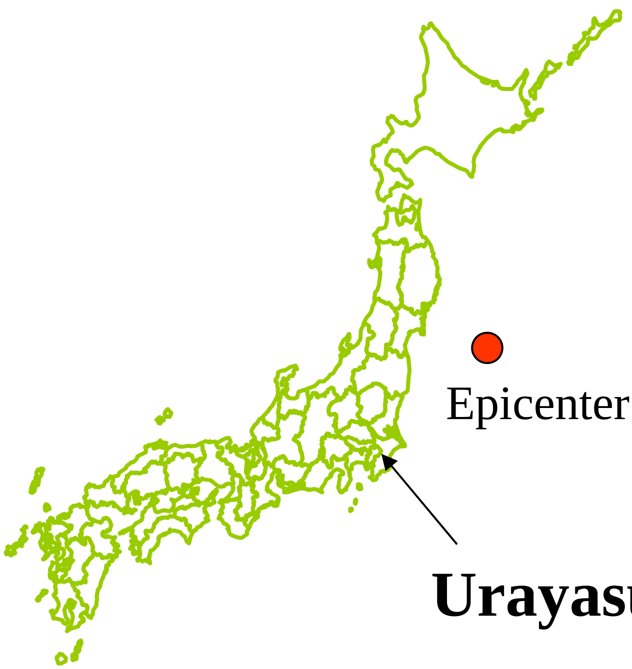
Great East-Japan earthquake (Mar,'11,M=9.0)

Tottoriken Seibu Earthquake (Oct.'00;M=7.3)
Effectiveness confirmed of SCP improvement for Sakaiminato port etc.

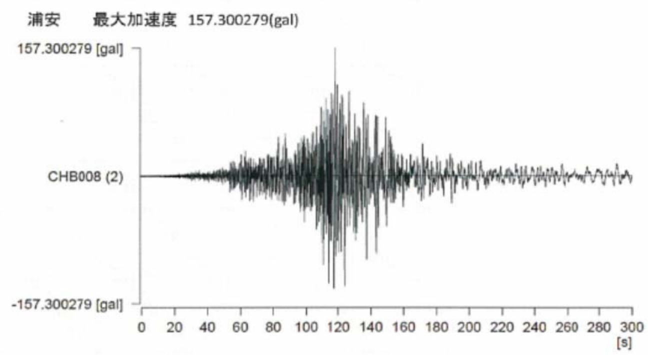
Improvement effectiveness at Urayasu
(The 2011 Great East Japan Earthquake)

Outline of the Earthquake

- Occurrence time:2011.3.11
- Magnitude : M=9.0
- Depth : 8km



Unimproved Area



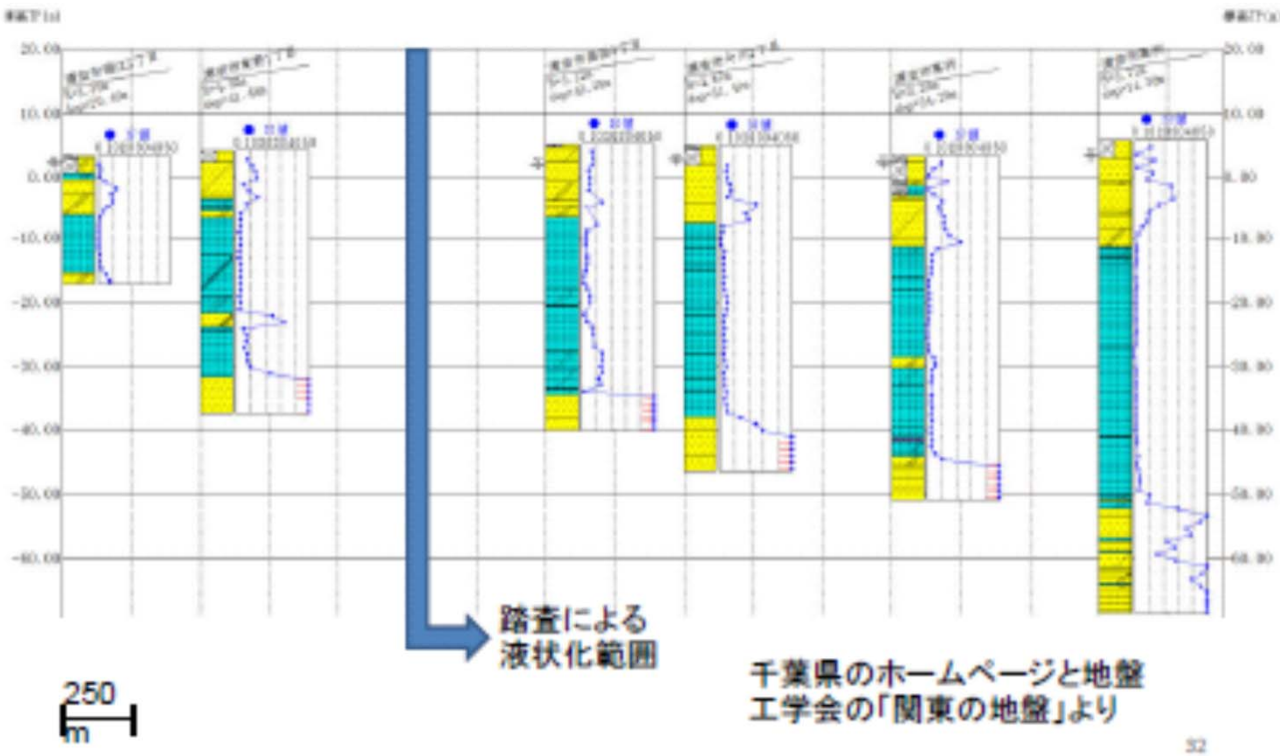
図ー2　浦安の K-NET2)で観測された地表面の加速度波形

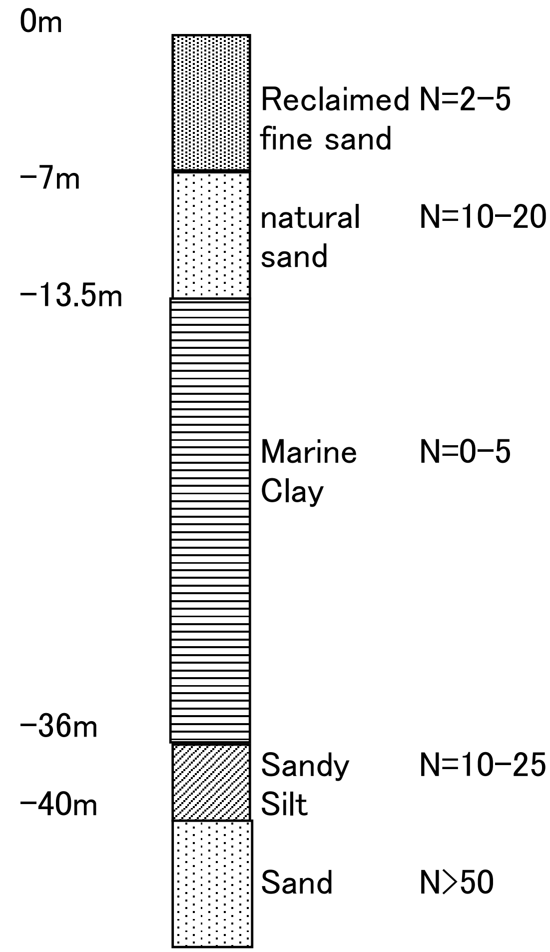
(東京電機大・安田進教授らの調査による)

Area where liquefaction damage were observed near Tokyo

Soil Condition in Urayasu area

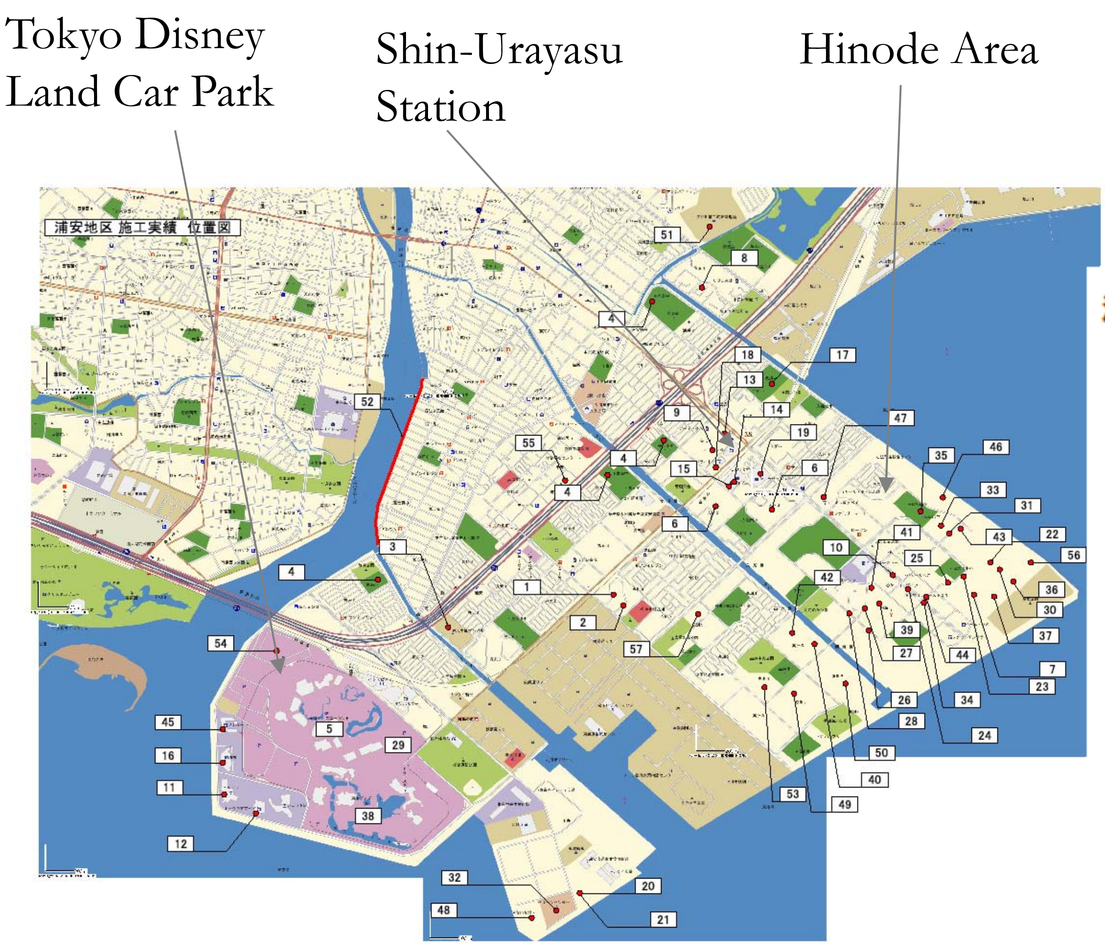
In this area, very thick (25-40m) soft marine clay layer has been deposited.



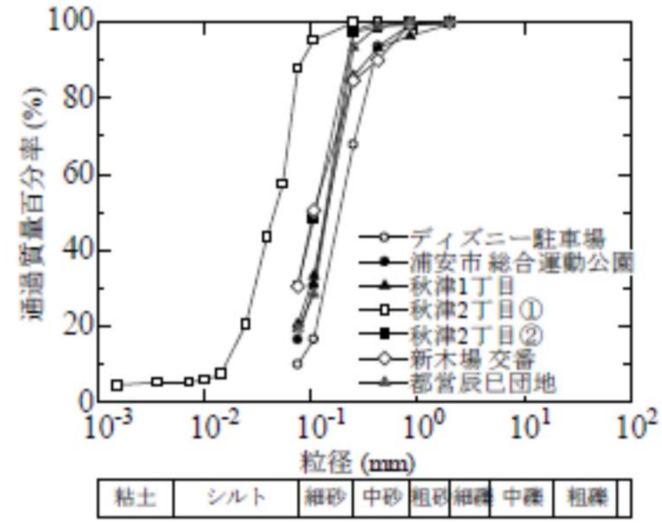


Tomioka area

Location of Urayasu ground improvement area



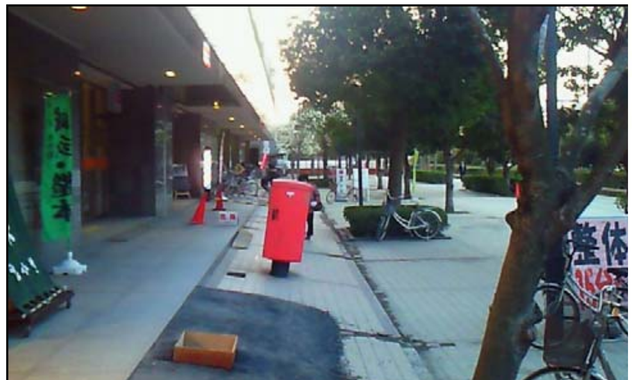
Location of liquefaction mitigation sites by Fudo



Liquefied sand grading

Reclamation history in Urayasu

Liquefaction damage at Shin Urayasu Station



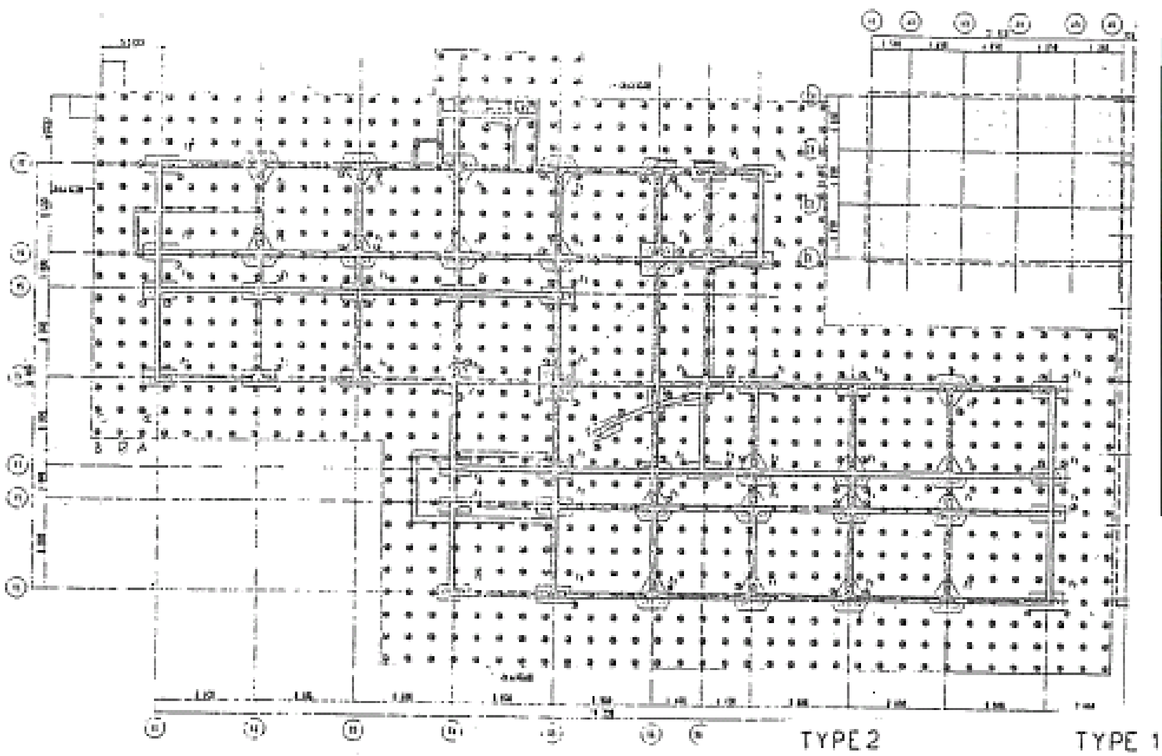
Liquefaction damage, Lateral flow & sliding failure

Liquefaction damage, Settlement at Sakai-river wall

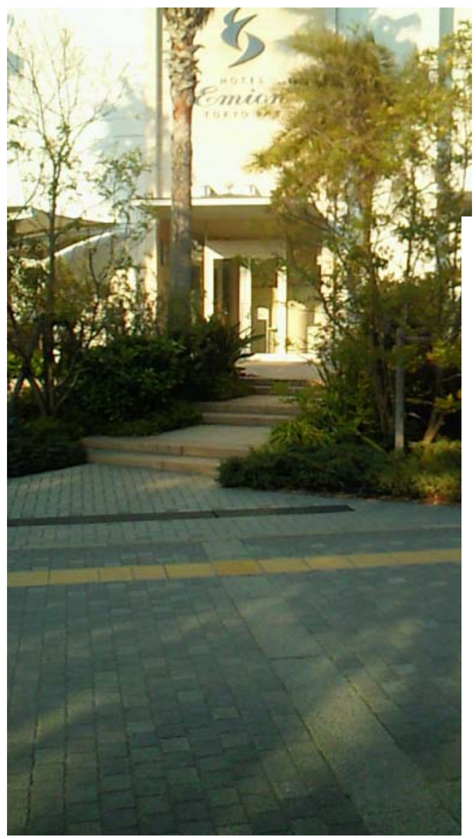
Large settlement around 3ft due to liquefaction

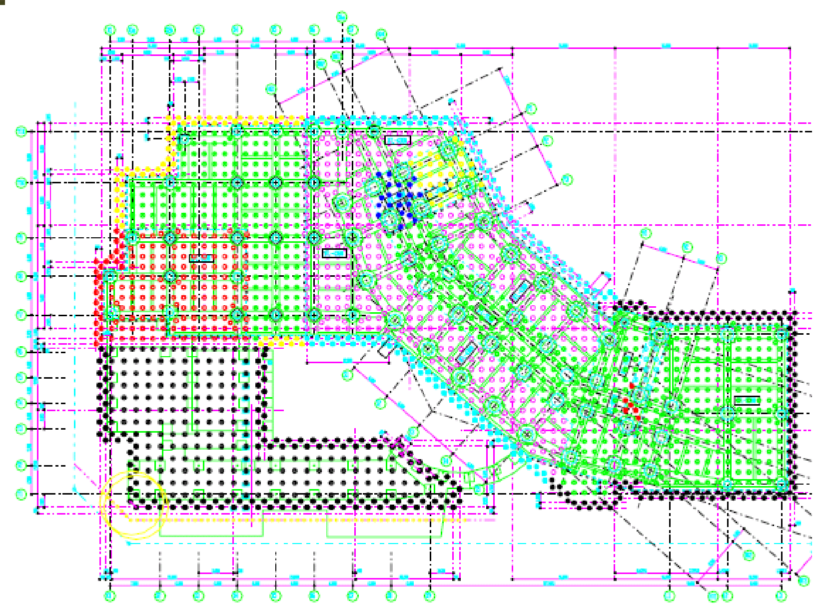
Liquefaction mitigation effect

Project	H junior high school Soil Improvement
Method	GCP
Diameter	50cm
Spacing	2m
Length	12.2m
Total	10989m 935pcs
Remarks	Single particle diameter stone was used to keep high permeability.
Date	1993



Project	E Hotel
Method	SAVE (no-vibration method)
Diameter	70cm
Spacing	1.6-1.9m
Length	5.5-12m
Total	19,032m　1886pcs
Remarks	
Date	2003





Tokyo Disney Land

Many types of columns like SCP, GD were installed at under structures.

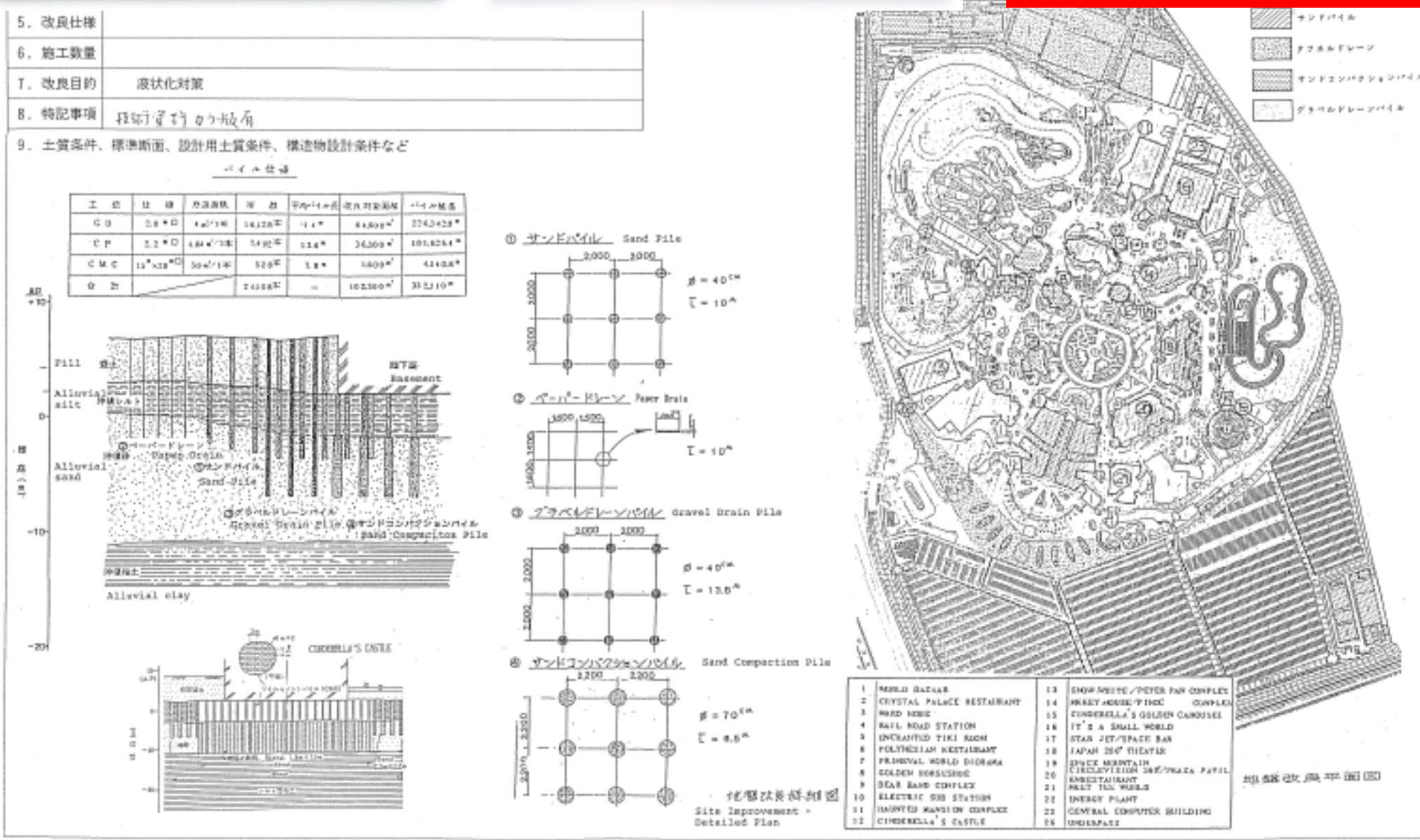


Figure 5. Sidewalk settles relative to a building on piles (left), whereas a three-story building settles more than the adjacent sidewalk surface (right) in Urayasu (N35.6485, E139.9178).

Figure 6. Closeup of settled three-story building in Figure 5 (N35.6485, E139.9178).

appeared to be primarily fill materials or young alluvium.

Liquefaction caused extensive damage to light residential and light commercial structures in many of the areas visited, with the magnitudes of the settlements and tilts larger than often observed for such light structures. Tilts of up to 2 or 3 degrees were observed in many cases (Figure 3). Many of these structures were founded on mat-type foundations with deep grade beams (Figure 4) that limited damage to the superstructures despite the large settlements and tilts. Figures 5 and 6 illustrate a case in Urayasu where the sidewalk and street settled approximately 30 cm relative to a building on piles, while an adjacent three-story building on a mat settled 40 cm more than the adjacent ground surface (that is, 70 cm relative to the pile-supported building), and tilted noticeably without observable damage to the superstructure.

Liquefaction-induced ground surface and building settlements were often observed to vary significantly over short distances. Differences in settlements at some of these locations (Urayasu) may be related to the differences in the dates of fill placement and ground improvement (Tokimatsu et al., 2011). The boil materials did not appear to differ substantially in characteristics across some of these locations. These data may allow examination of whether the effects of age and differences in fill source materials are adequately reflected in the results of in-situ tests and accounted for in existing engineering procedures. Moreover, the large dataset on settlement patterns and rotations for buildings on shallow foundations (Figures 3, 5, and 6) at these sites provides a similarly unique opportunity for testing engineering procedures for predicting foundation performance in the presence of liquefaction.

Liquefaction-induced damage to utilities caused widespread disruptions for homeowners and businesses, described later in the section on lifelines.

Areas known to have been improved by sand compaction piles and other techniques were observed to have performed well, in that ground surface displacements were not observed.

The detailed studies of liquefaction effects underway in areas such as Urayasu can be expected to produce significant findings in the near future.

Future GEER efforts will include Spectral Analysis of Surface Waves (SASW) and Cone Penetration Test (CPT) testing at select sites in coordination with Japanese researchers.

Levees

Hundreds of kilometers of levees border several rivers in the Tohoku and Kanto regions in northeastern Japan. Data on levee damage resulting from the earthquake and tsunami, documented immediately following by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), were graciously shared with the GEER team. Our field efforts were largely limited to the eastern parts of Miyagi and Ibaraki prefectures.

Most levee reaches performed well, with little or no damage or distress. This generally good performance may be partly attributed to the fact that river levels were relatively low at the time of the earthquake, and thus the majority of levee embankments were not saturated. In many areas, settlements of nondistressed levees appeared to be about 7-15 cm relative to structures such as bridge piers or buried water conveyance structures.

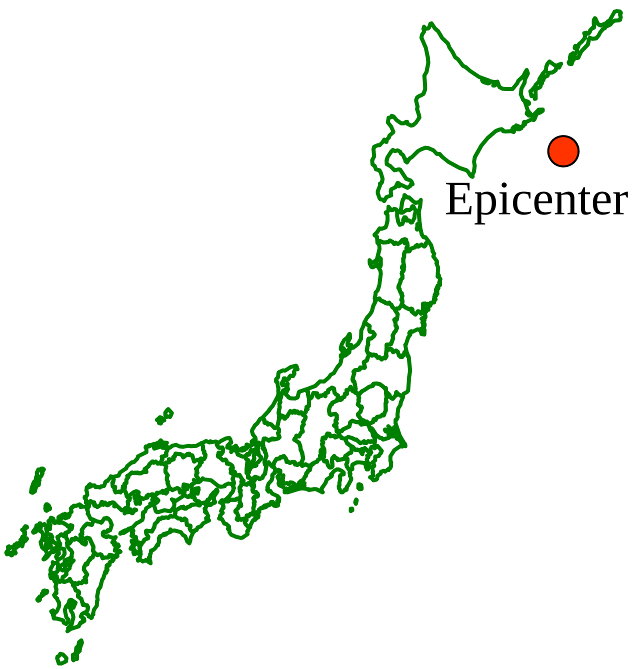
EERI（Earthquake Engineering research Institute, U.S.) Special report (Sep.,2011)

There is no significant settlement damage and well organized in Improved area by SCP.

Improvement effectiveness at quay wall
(The 1993 Kushiro-oki Earthquake)

Outline of the Earthquake

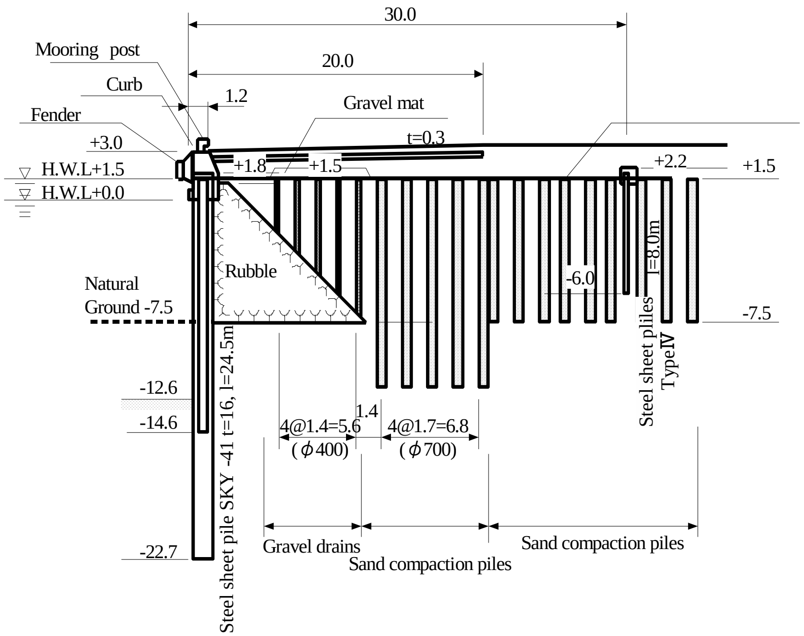
- Occurrence time:1993.1.15
- Magnitude : M=7.8
- Depth : 107km



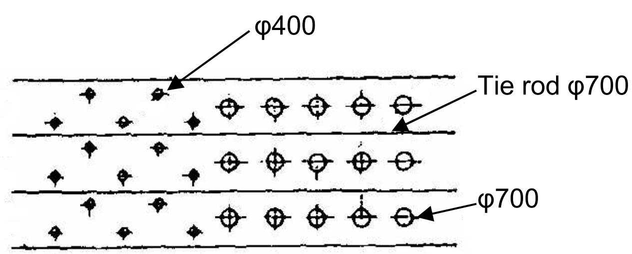
Unimproved Area

Large cracks appeared.

Quay walls could not be used.



Cross Section



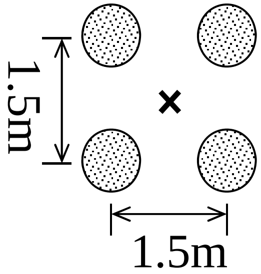
Plane figure

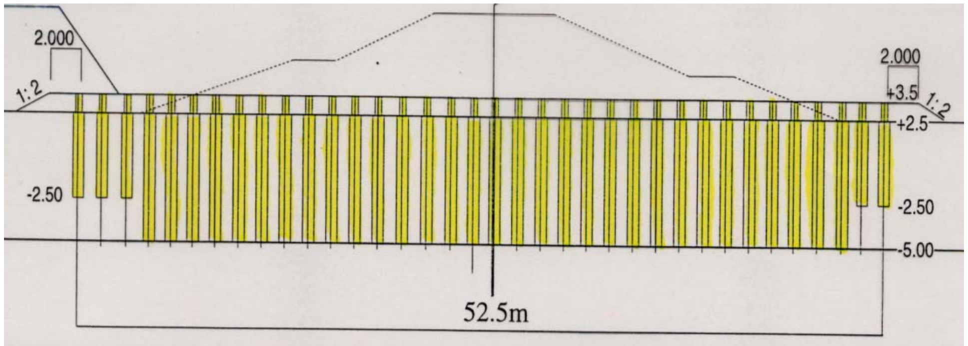
Improved Area

No damage was observed.

Port activities were resumed on the following days.

Remedial works by SCP at Levee was safe after next earthquake

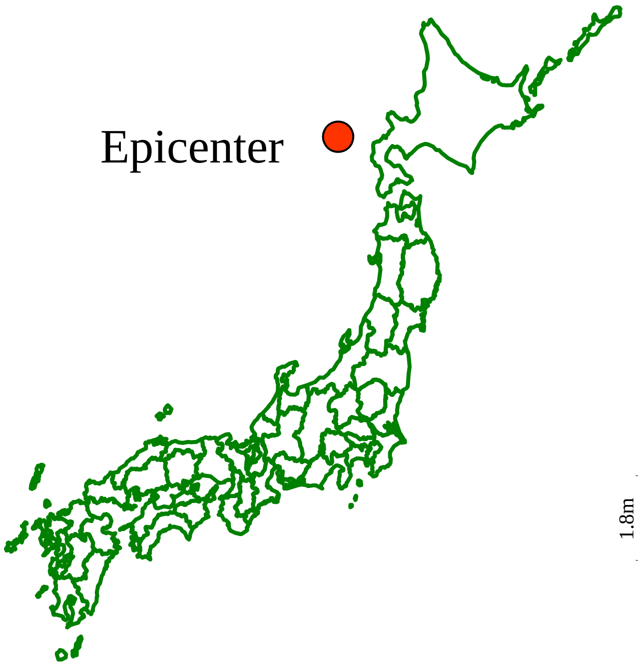


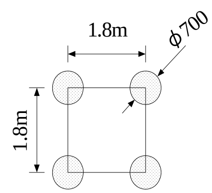


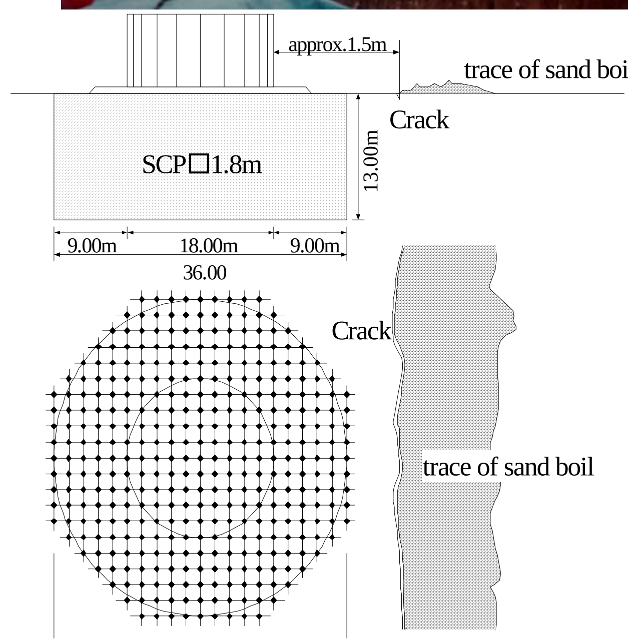
No Damage was observed at 1994 Hokkaido-Tohooki earthquake at treated area.

Improvement effectiveness at Oil Tank
(The 1993 Hokkaido Nansei-oki Earthquake)

Outline of the Earthquake
- Occurrence time:1993.6.28
- Magnitude : M=7.8
- Depth :34km





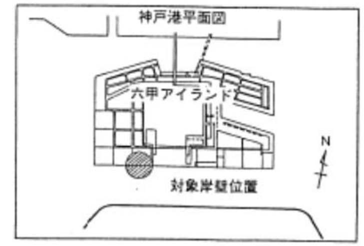


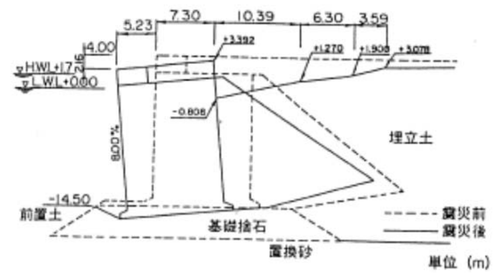
Improvement effectiveness
(The 1995 Hyogo-Ken Nambu Earthquake)

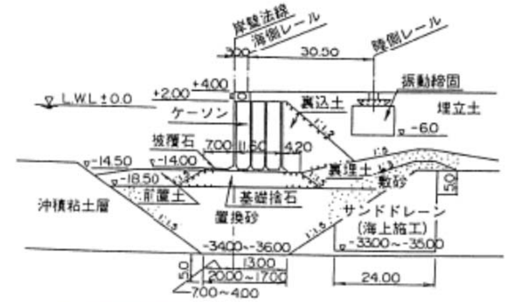
Outline of the Earthquake

- Occurrence time:1995.1.17
- Magnitude　　: M=7.2
- Depth　　　　: About 20km

Large Differential Settlement was observed.

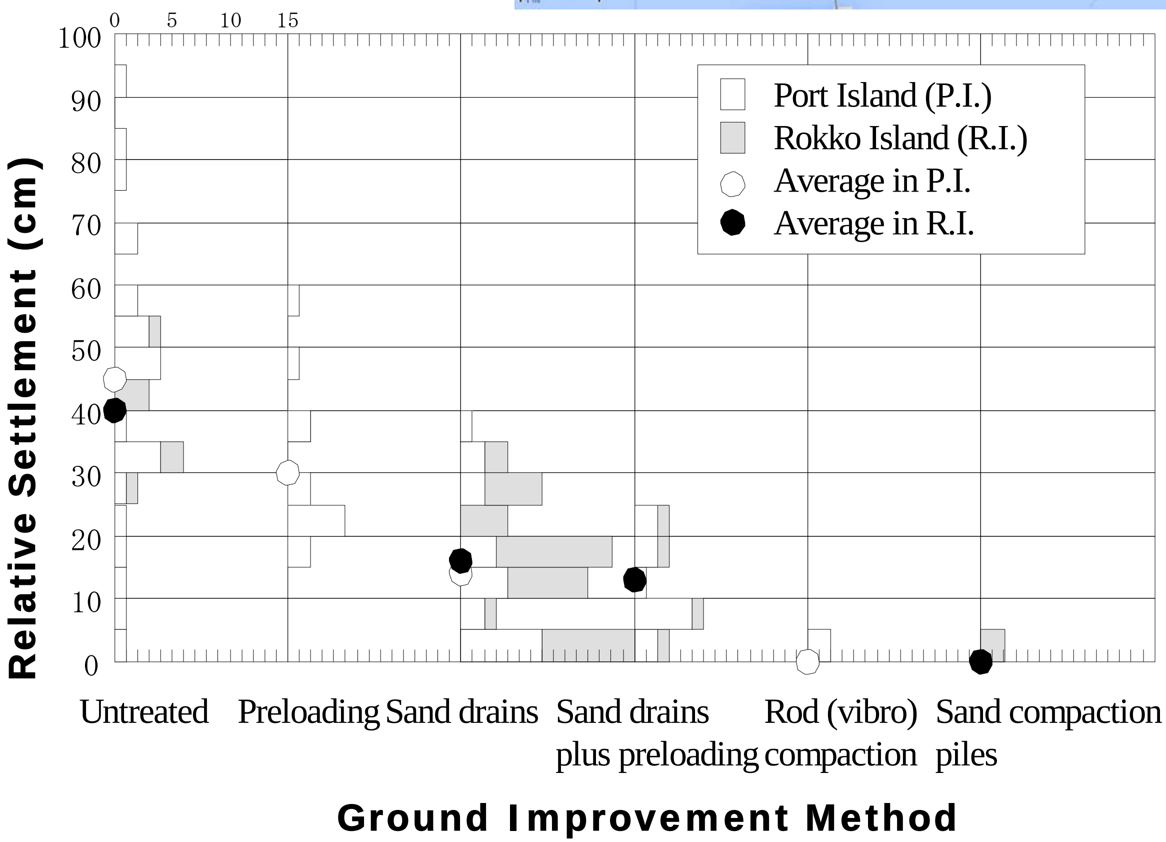




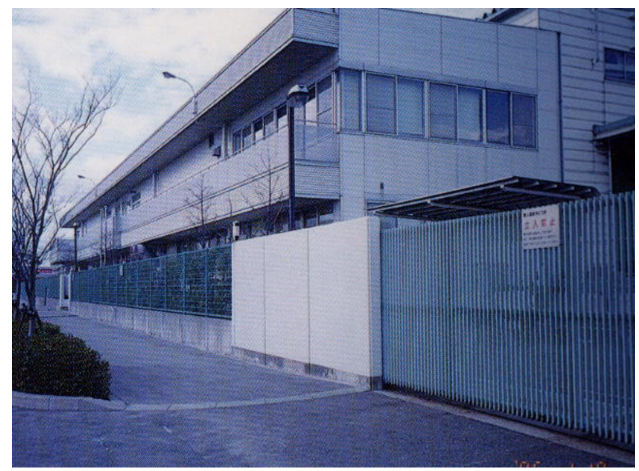


Unimproved Area

Relation between Relative Settlement and Ground Improvement Method



Unimproved Area



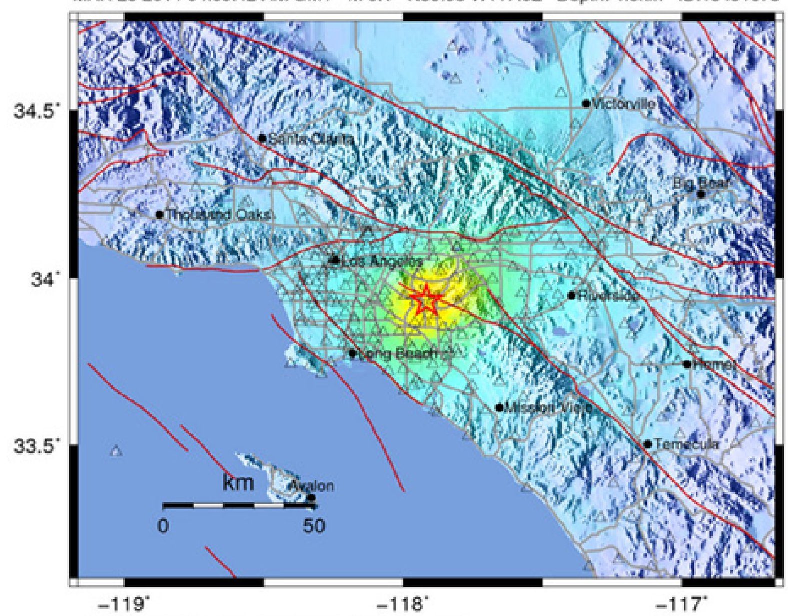
Improved Area

UPS Cerritos, in LA (Apr. 3, 2014)

Approximately two miles south from the epicenter
It has been improved by SCP and SAVE.
There was no sand boiling and anomalous induced settlement after the earthquake.

Magnitude	Mw 5.1
Region	GREATER LOS ANGELES AREA, CALIF.
Date time	2014-03-29 04:09:42.0 UTC
Location	33.93 N ; 117.94 W
Depth	10 km

CISN/sc ShakeMap : 2.4 km (1.5 mi) NW of Brea, CA
MAR 29 2014 04:09:42 AM GMT M 5.1 N33.93 W117.92 Depth: 4.8km ID:15481673



Map Version 9 Processed Thu Apr 17, 2014 07:58:31 PM GMT

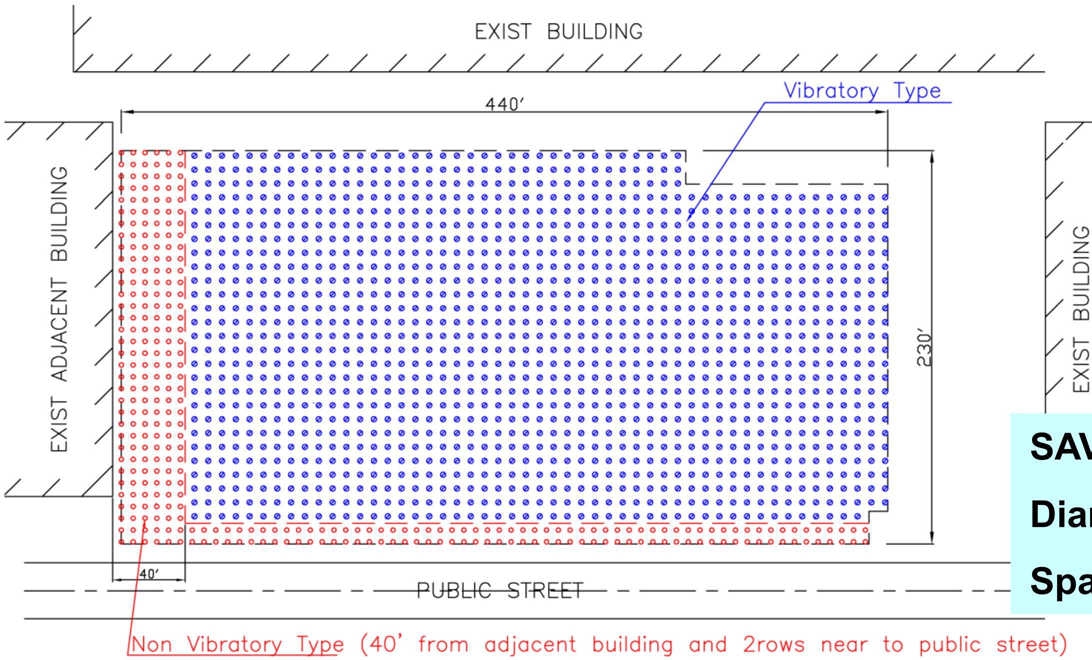
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

SCP

Diameter;3.0ft

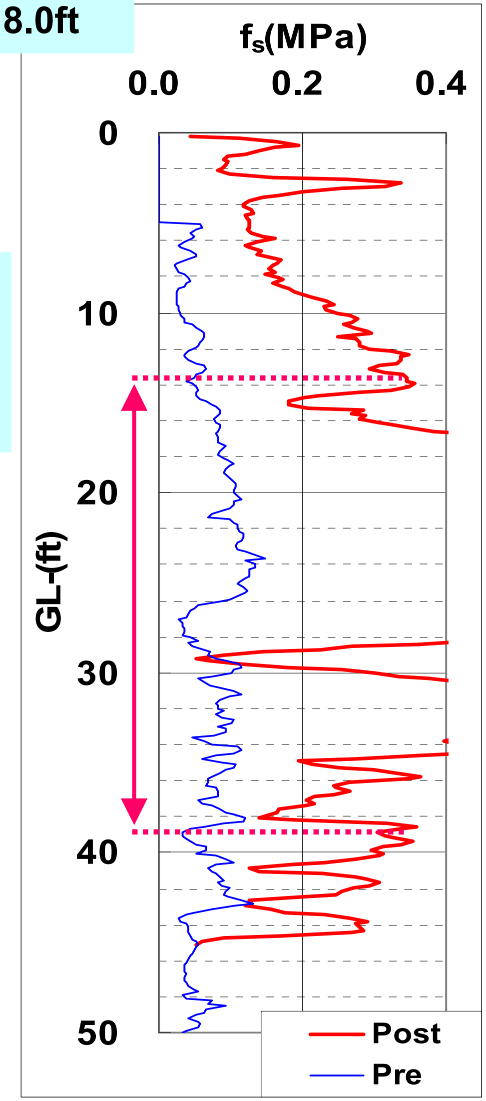
Spacing;8.0ft

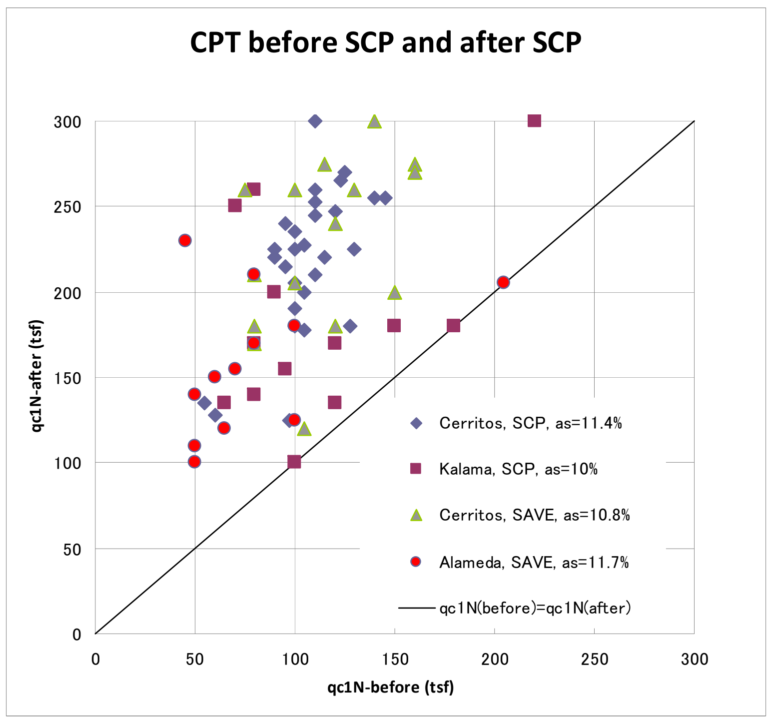


SAVE

Diameter;2.5ft

Spacing; 6.75ft

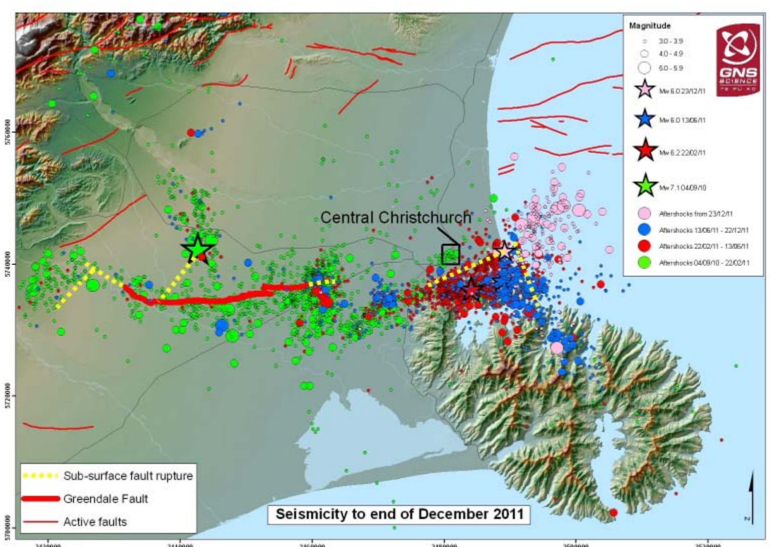




AMI Stadium, Christchurch.
（Misko Cubrinovski, 2012）

Stone Column（Length 8-9m）have been installed, but 40cm of settlement was occurred due to Liquefaction.

Figure 33: (a) Aerial photo of AMI Stadium indicating liquefaction damage; and (b) Liquefaction damage to the stadium field.

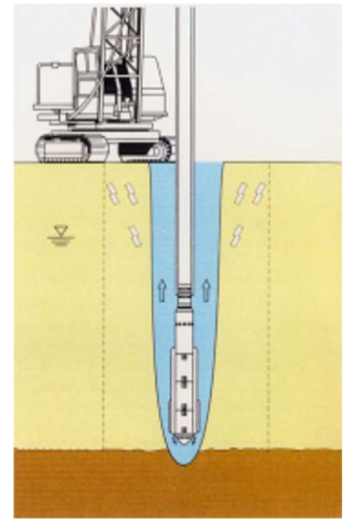


STONE COLUMN METHOD …

Pre-drilling rig

Top-feed type

Bottom-feed type



In case of Stone Column, sometime pre-drilling holes need to be made due to less penetration power. Accordingly, ground may be disturbed and the compressed air might be easy to be out from the ground.

Thank you for your kind attention.