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# Settlement of river dykes and adjacent residences on soft clay deposits after the Tohoku-Pacific Ocean Earthquake in 2011

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# Review of Geotechnical Damage Related to Fine-grained Soils during Past Earthquakes

| Earthquake name | Damage location | Outline of damage related to fine-grained soils | Related reference |
|---|---|---|---|
| Alaska (USA) 1964.9.18 | Anchorage, Alaska | ・Approximately 30 residences on sensitive clays were damaged in Turnagain heights. | Seed & Wilson (1967), Stark and Contreas (1998) |
| Michiocan (Mexico) 1985.9.19 | Mexico City | ・Building structures founded on extremely soft clays (Mexico City Clay) were collapsed. Ground motion amplification was also associated with the collapse of structures. | Mendoza (1987, 1988) |
| Loma Prieta (USA) 1989.10.17 | Oakland, California | ・Numerical analysis indicated that ground motion amplification induced the collapse of structures on soft clays (San Francisco Bay Mud). | Tamura (1991), Boulanger et al. (1998) |
| Hyogo-ken Nanbu (Japan) 1995.1.17 | Awaji Island near Kobe | ・Long-term settlement of artificial island after the earthquake resulted from alluvially-deposited clays. ・Ground motion propagation varied with softness of clays located at the deep position. | Matsuda (1997), Kazama et al. (1998), Ohta et al. (2002) |
| Niigata-chuetsu (Japan) 2007.7.16 | Kashiwazaki, Niigata | ・Settlement of clay (over 20 m deep) in the Kashiwazaki plain continued over 8 yr after the earthquake.<br>・Differential settlement was observed in structures supported by piles. | Isobe and Ohtsuka (2011) |
| Off-Pacific Tohoku (Japan) 2011.3.11 | Urayasu, Chiba | ・Settlements of alluvial clays with 10--40 m deep after the earthquake are differ depending on the mode of reclamation and cases with and without improvement before the earthquake. | Nigorikawa & Asaka (2012) |
| | Iwaki, Fukushima | ・Building structures on soft clays consisting of marine silt and highly organic soil have sustained long-term settlement after the earthquake. Differential settlement has been considerable, but it started before the earthquake. | Sento et al. (unpublished) |
| | Tokai, Ibaraki | ・Countermeasures against settlement of residences on soft clay have been successful. | Yasuhara and Kazama (2015) |
| Kumamoto (Japan) 2016, 4.14 & 4.16 | Mashiki, Kumamoto | ・Both embankment and foundation from volcanic-cohesive soils beneath residences were devastated. | Yasuhara et al (2016), Goto et al. (2017) |

# This paper presents a case study of

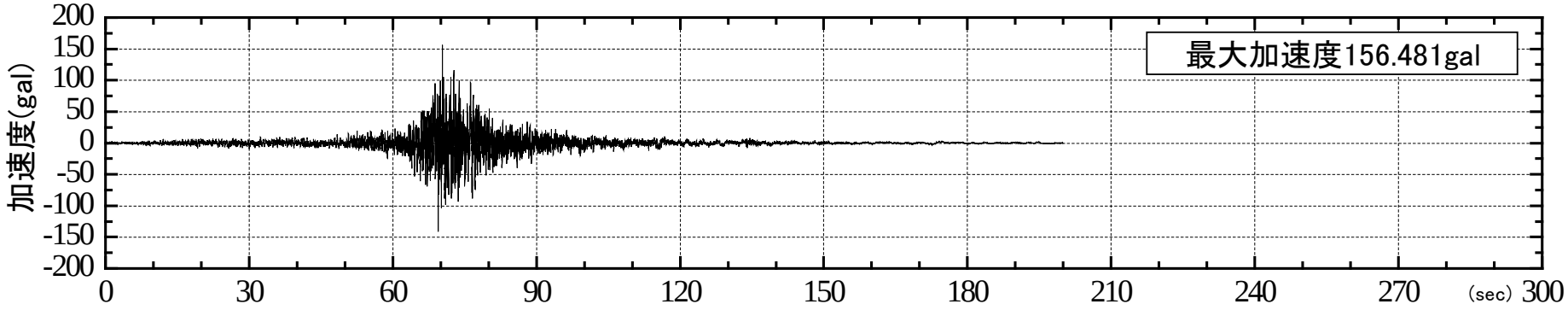
- post-earthquake settlement and deformation of clay deposits underlying the river dykes and their adjacent residences in Ibaraki during and after the Tohoku earthquake in 2011,

- including the effects of countermeasures taken immediately after the earthquake.

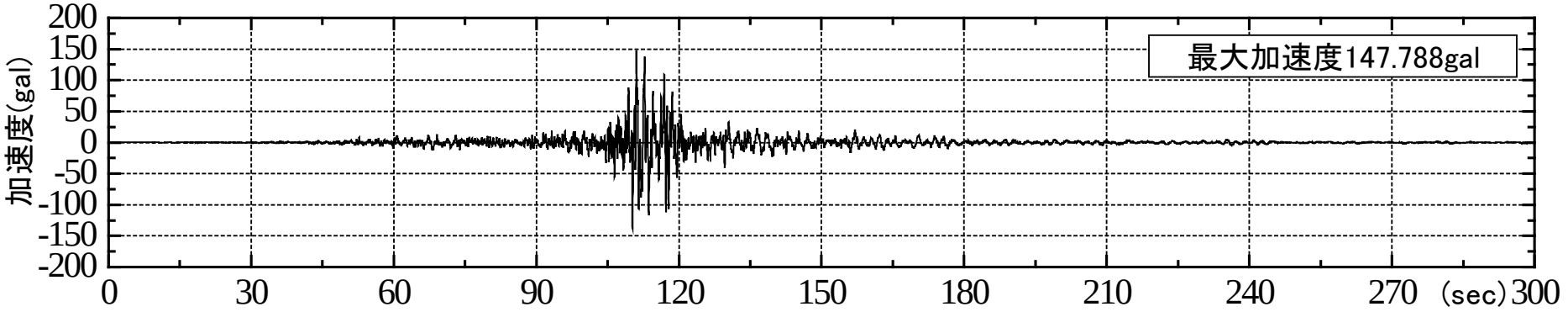
# Content of Presentation

- Description of a case history of post-earthquake settlement of clay deposits underlying river dykes and their adjacent residences during the Off-pacific Tohoku Earthquake in 2011
- Introduction of reactive countermeasures for mitigating damage from settlement and deformation
- Reproduction of the behavior of dykes and their adjacent residences continuously from before to after the earthquake from 2D FE numerical analysis

# Strong Motion Records Measured near River Dykes

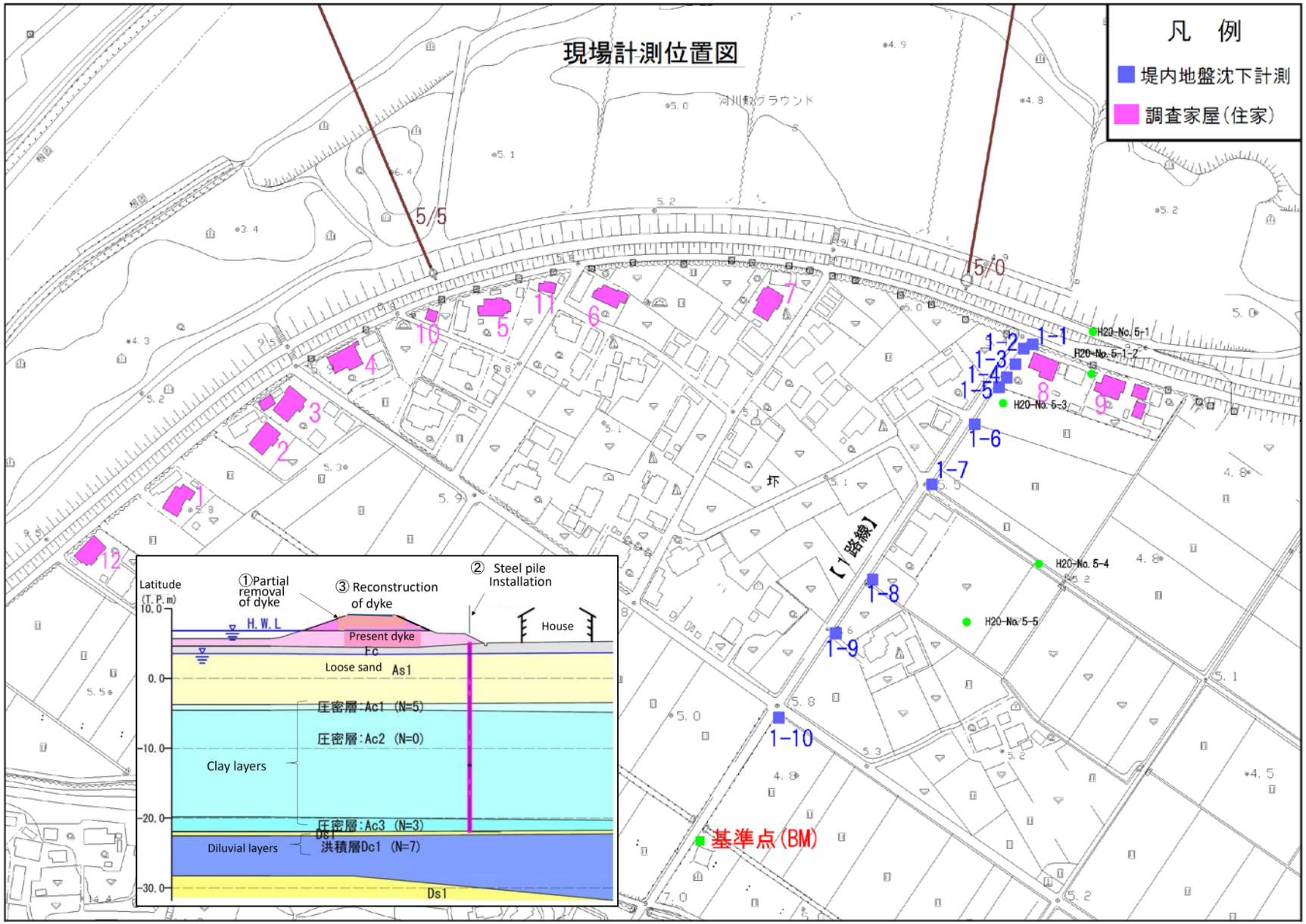



(a) Acceleration record measured near River dykes

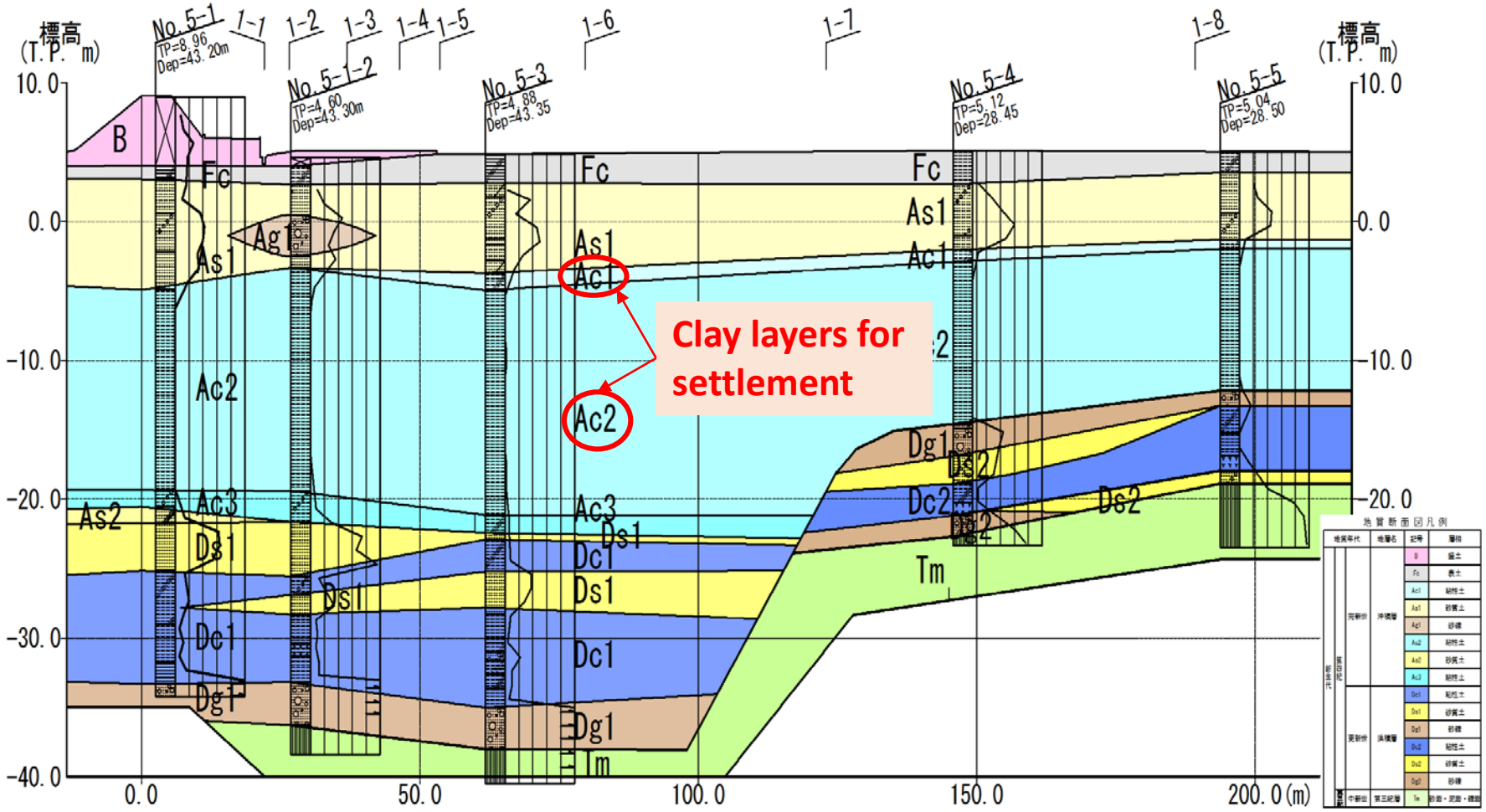



(b) Acceleration record at river dykes estimated from measured records

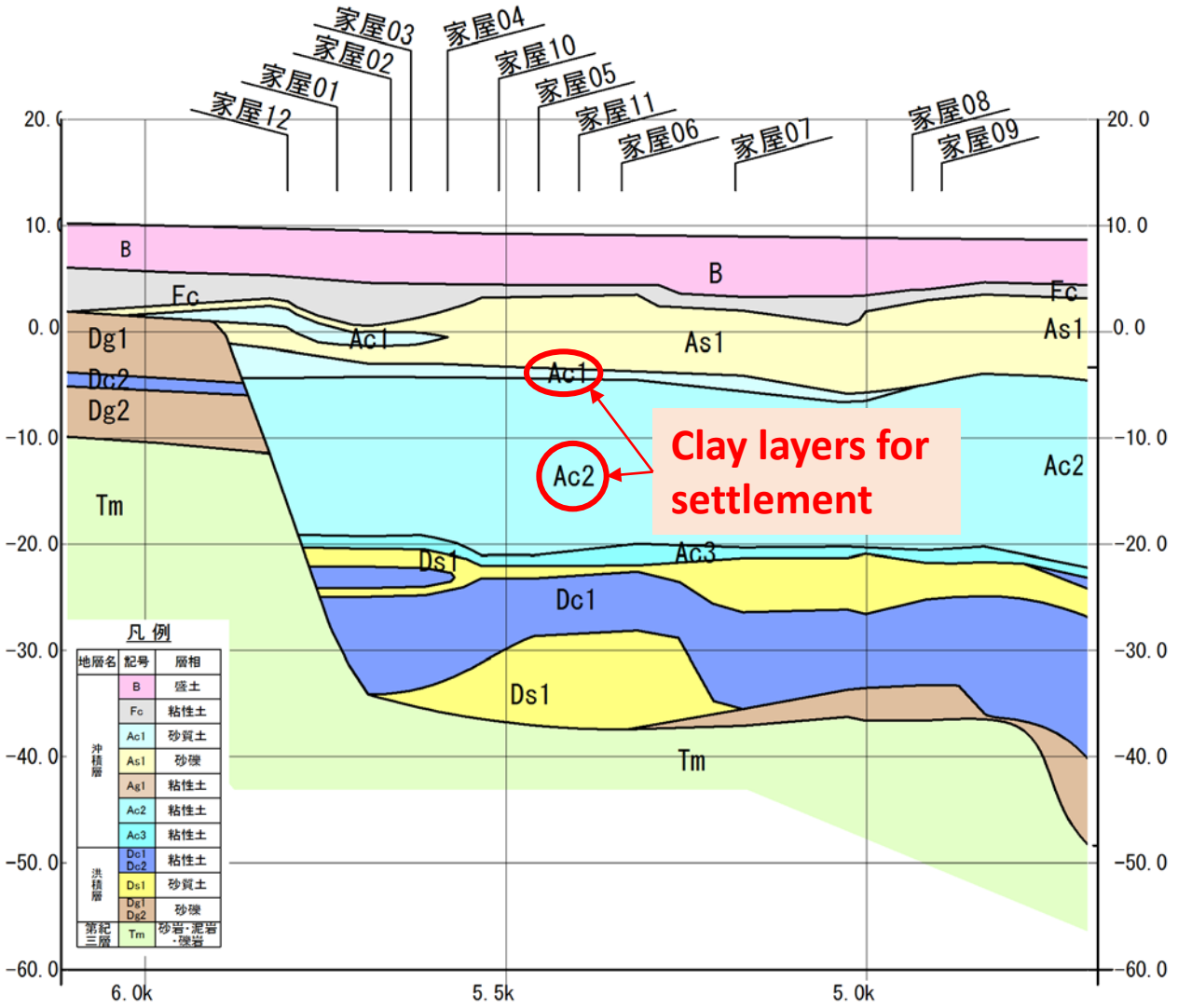
# Locations of Settlement Measurement



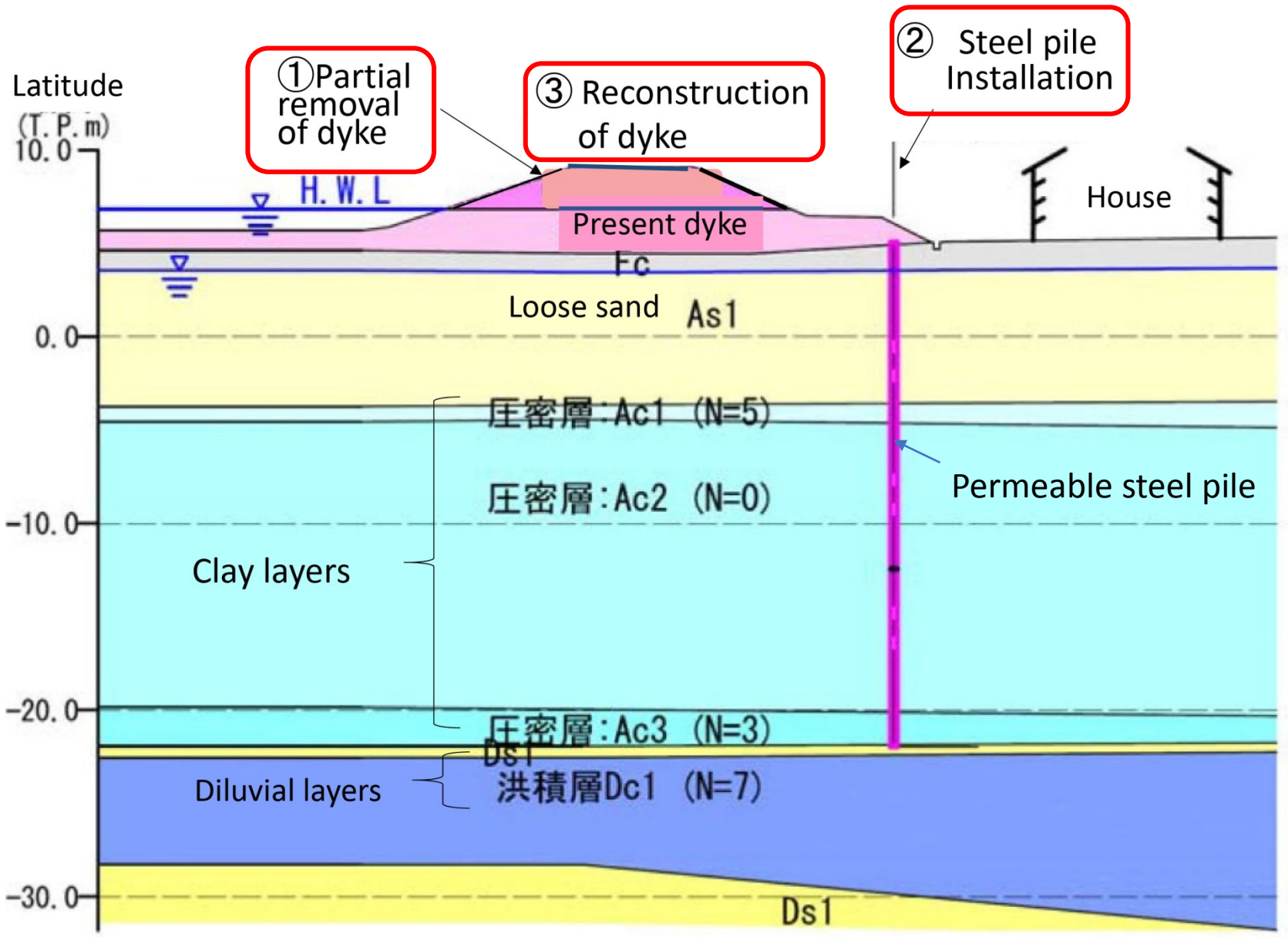
# Locations of Settlement Measurement (Inside Dykes)



# Locations of Measurement of Settlement (Outside Dykes at Residences)



# Procedure for Reactive Countermeasures

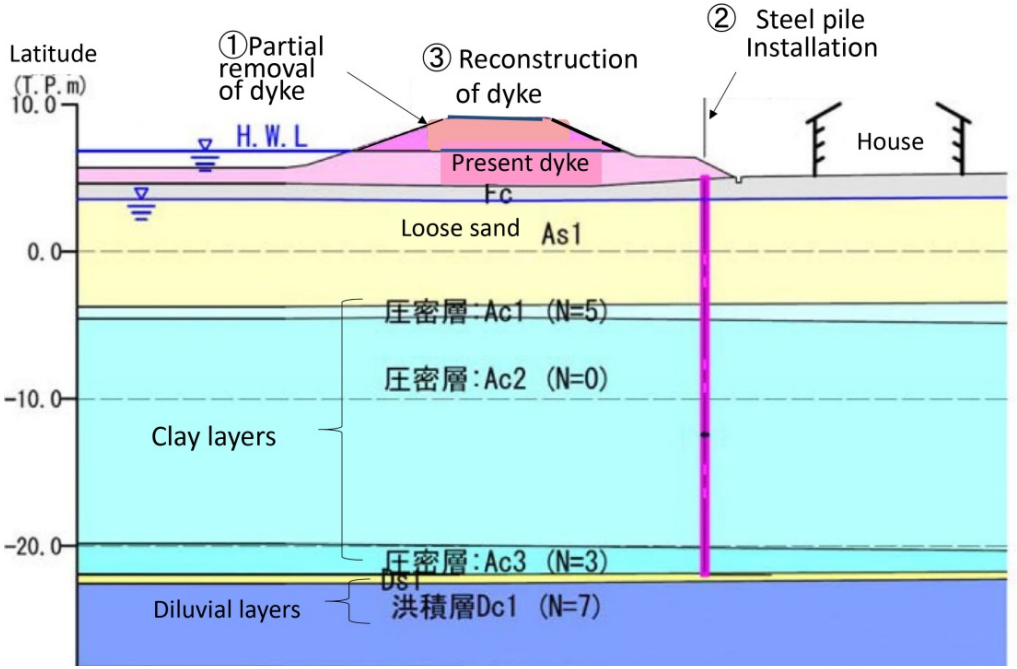


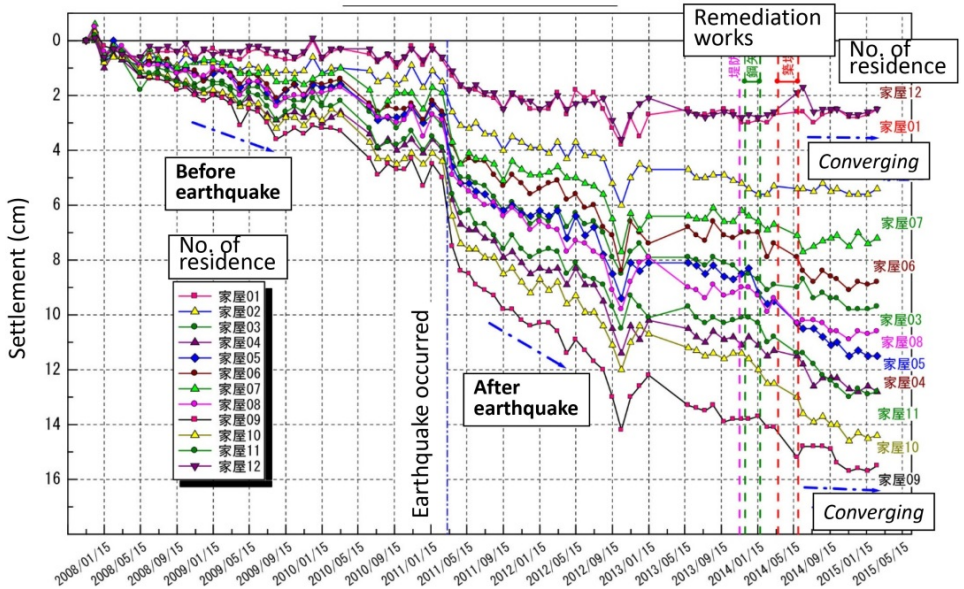
# Procedure of Countermeasures against Subsidence

1. remove 2.2 m of dykes to reduce the dyke weight

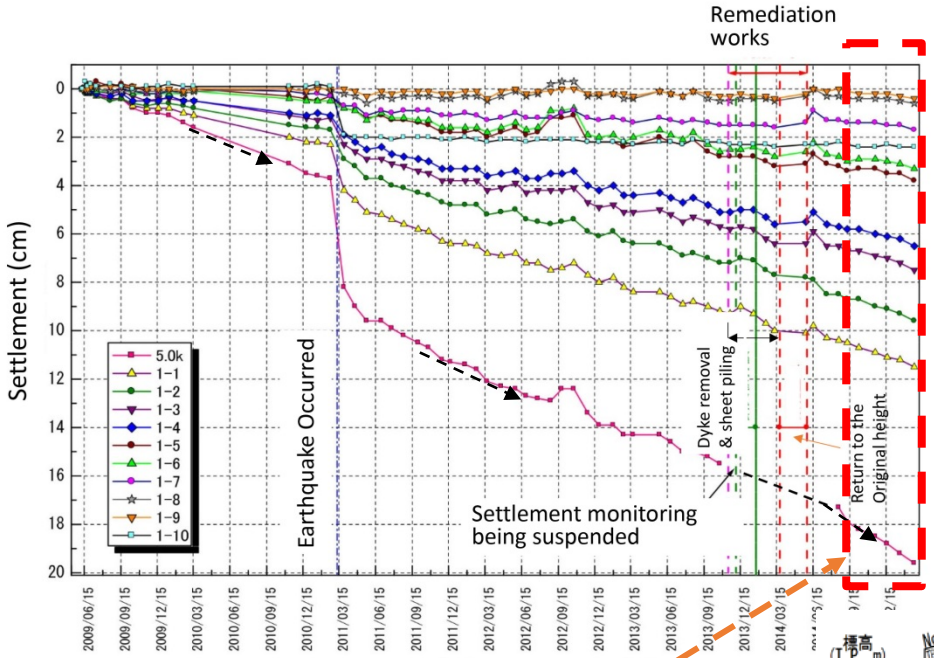
2. then install the sheet piles aside from the river dykes into the hard stratus called Ac3 layers to intercept the effects of self-weight of river dykes on residences

3. return the dyke height to its original height with 4.1 m.



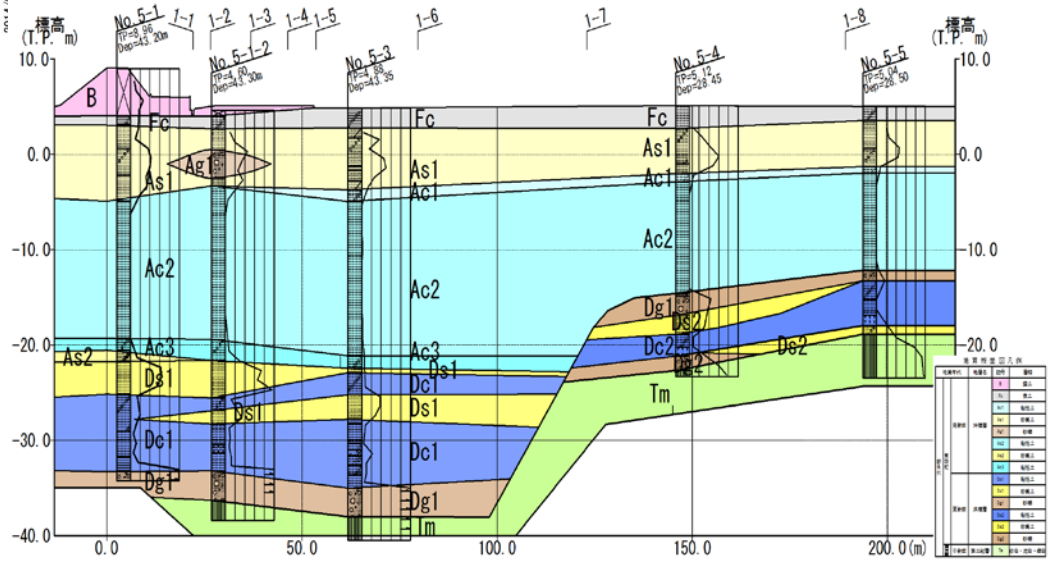



# Variations of Dyke Settlement with Elapsed Time

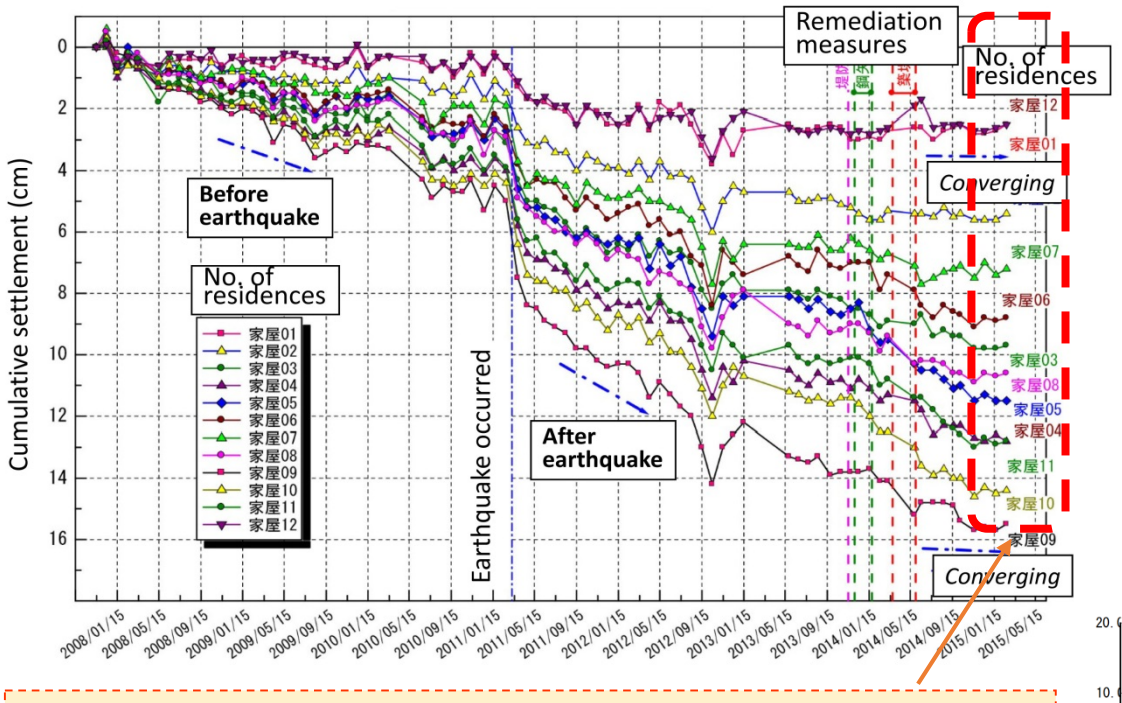



- Dyke construction ended at the end of 2002 and the dyke opened for use.
- Monitoring started from 2009.
- Great earthquake occurred in 2011.

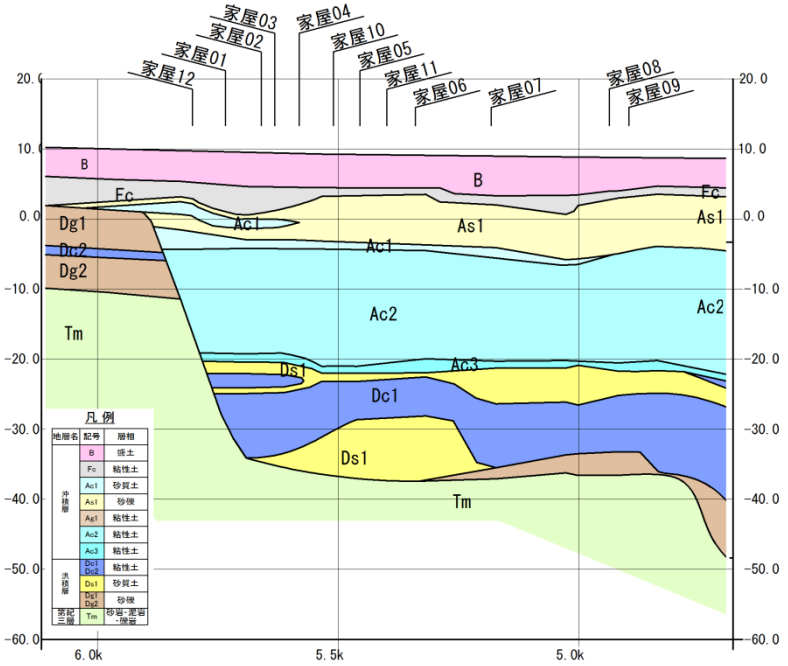
Settlement at some dyke locations continues.



# Residence Settlement Variation with Elapsed Time



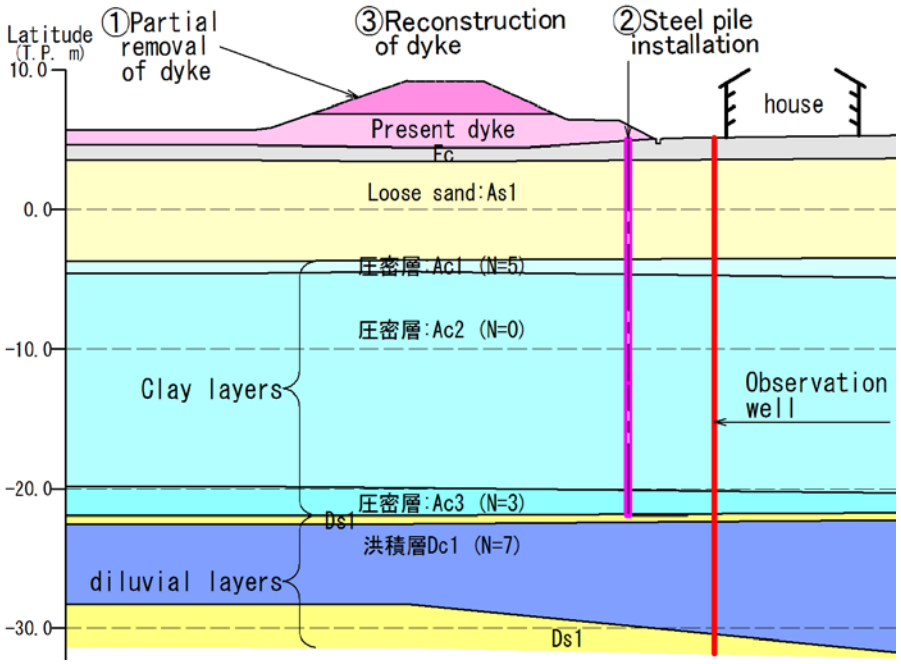

- Dyke construction ended at the end of 2002 and dyke opened for use.
- Monitoring started from 2009.
- Great earthquake occurred in 2011.




Settlement of residences occurred to a considerable degree after earthquake, but instability has risen because of countermeasure installation.

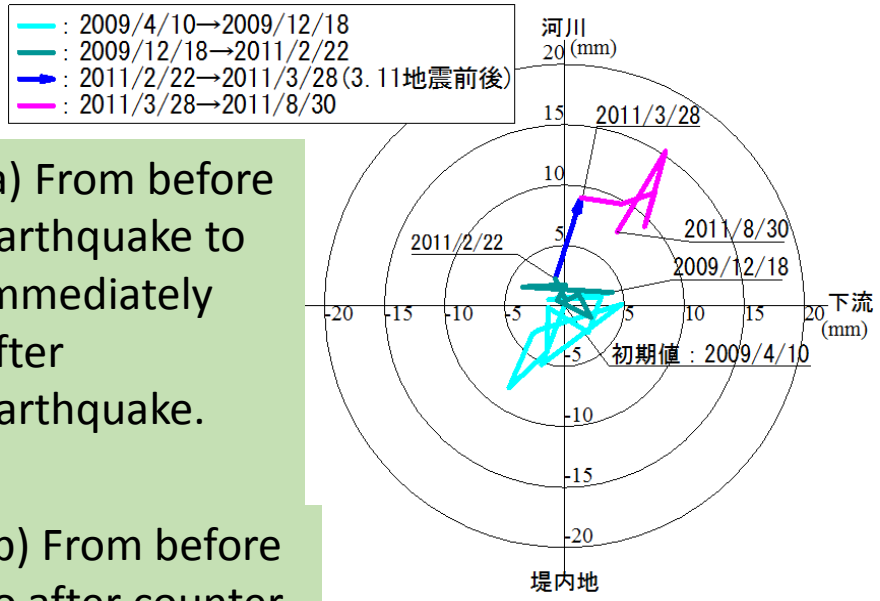
➢ **It is noteworthy that monitoring started before the earthquake.**

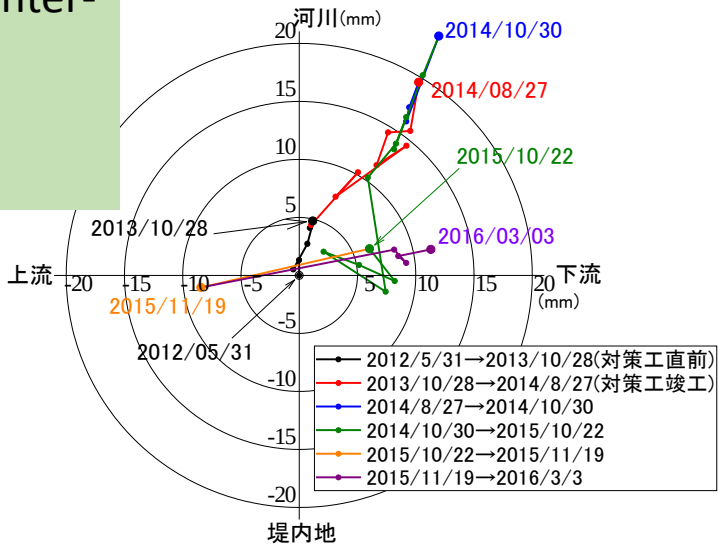
# Borehole Inclinometer Measurements (Adjacent to Residences)




(a) From before earthquake to immediately after earthquake.

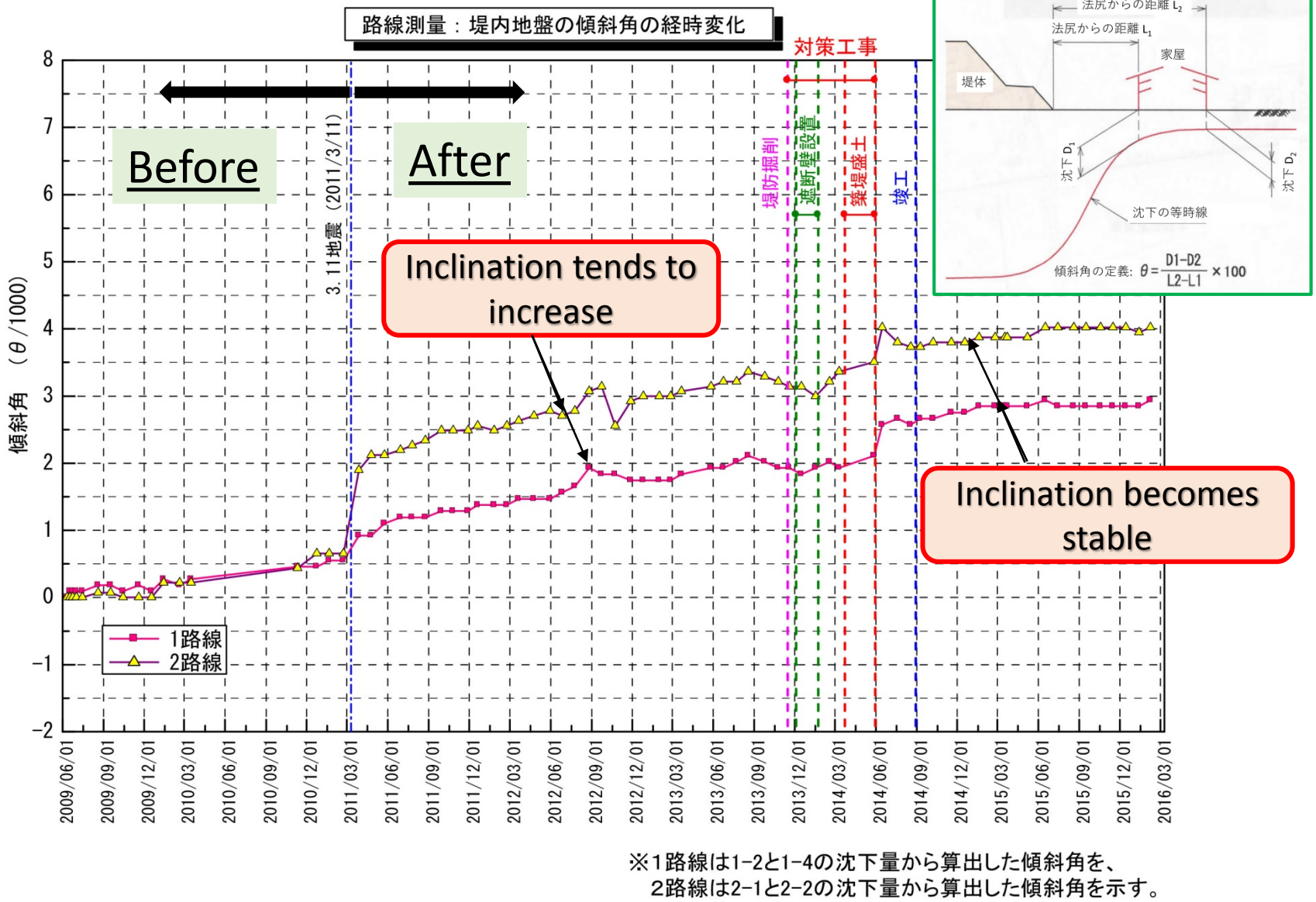
(b) From before to after counter-measure installation



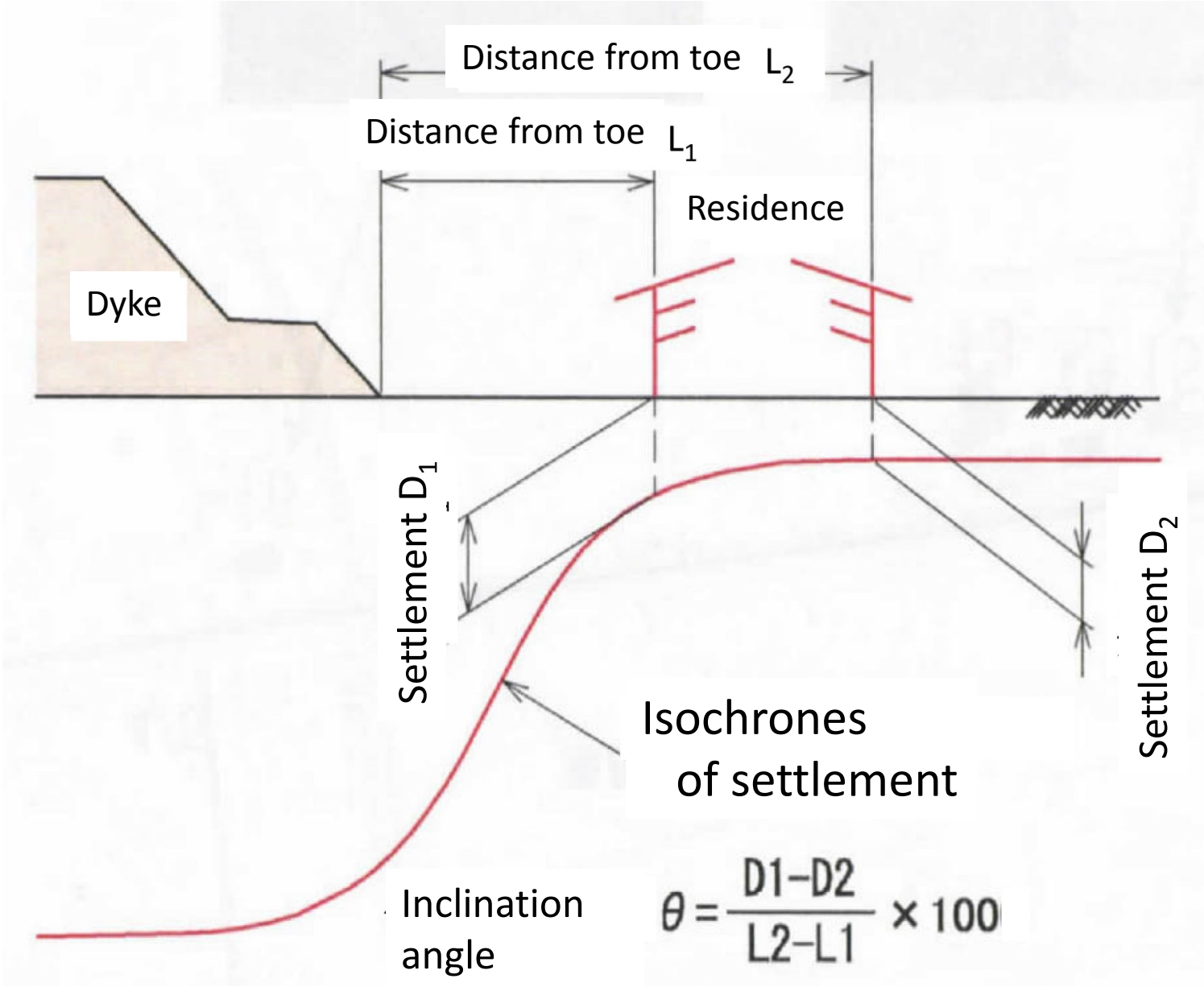

Surface inclination tends to increase toward river dykes, but no measurement data are available for some periods.

# Variation of Surface Inclination Angle Adjacent to Residences




※1路線は1-2と1-4の沈下量から算出した傾斜角を、
2路線は2-1と2-2の沈下量から算出した傾斜角を示す。

# Definition of Inclination Angle

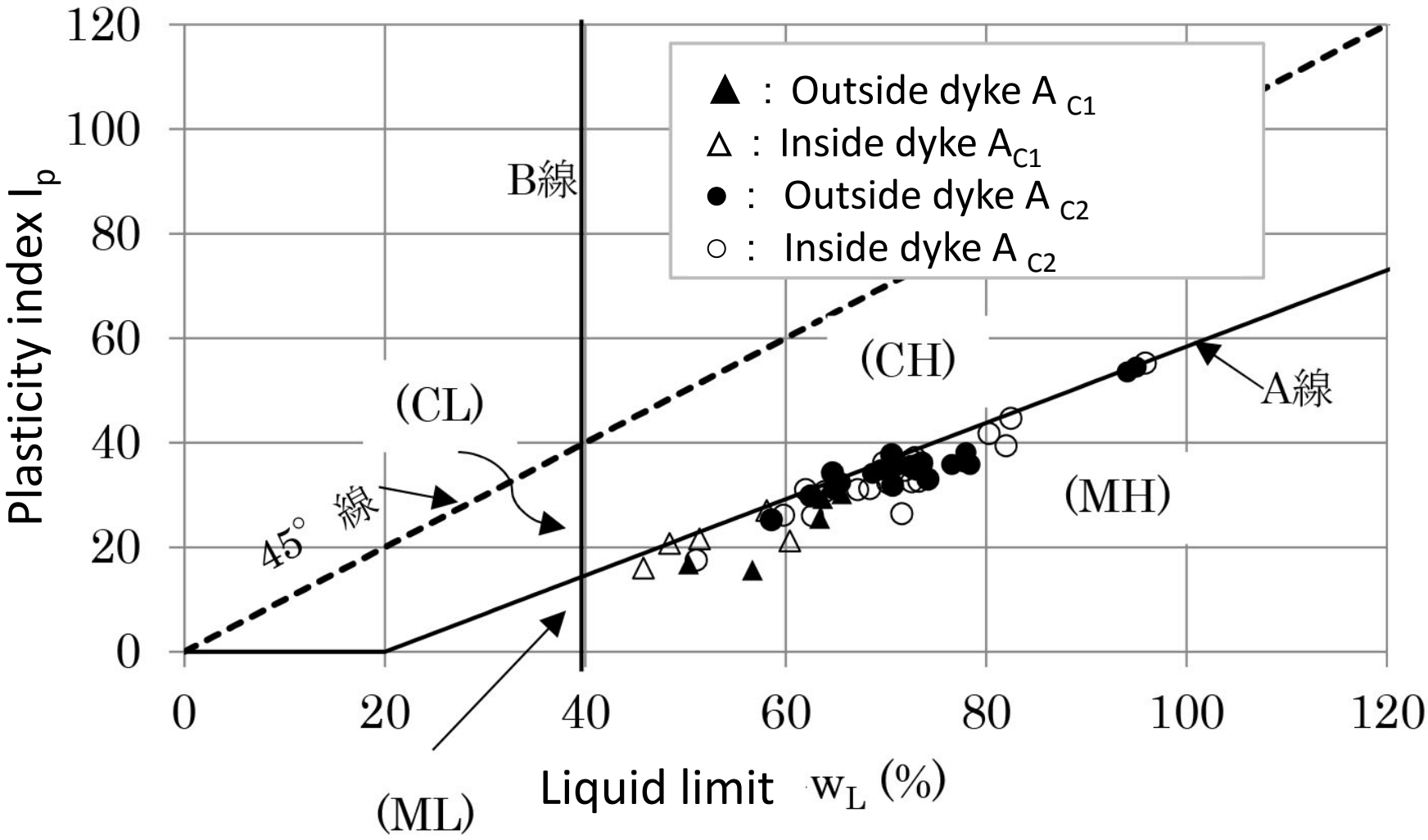


# Representative Index Properties of Clay Layer $A_{c2}$

| Index | Unit | K-clay (under river dyke) | J-clay (under motorway bank) |
|---|---|---|---|
| Void ratio *e* | | 2.17 | 2.40 |
| Particle density $r_s$ | g/cm$^3$ | 2.67 | 2.68 |
| Wet density $r_t$ | g/cm$^3$ | 1.52 | - |
| Initial water content $w_i$ | % | 81.0 | 93.7 |
| Liquid limit $w_L$ | % | 73.0 | 70.7 |
| Plasticity limit $w_L$ | % | 37.0 | 28.8 |
| Plasticity index $I_p$ | - | 36.0 | 41.9 |
| Liquidity index $I_L$ | | 1.20 | 1.20 |
| Sensitivity ratio $S_t$ | | 17.0 | 15.0 |
| Uncon. Compr. Str. $q_u$ | kN/m$^2$ | 90.9 | 70.5 |

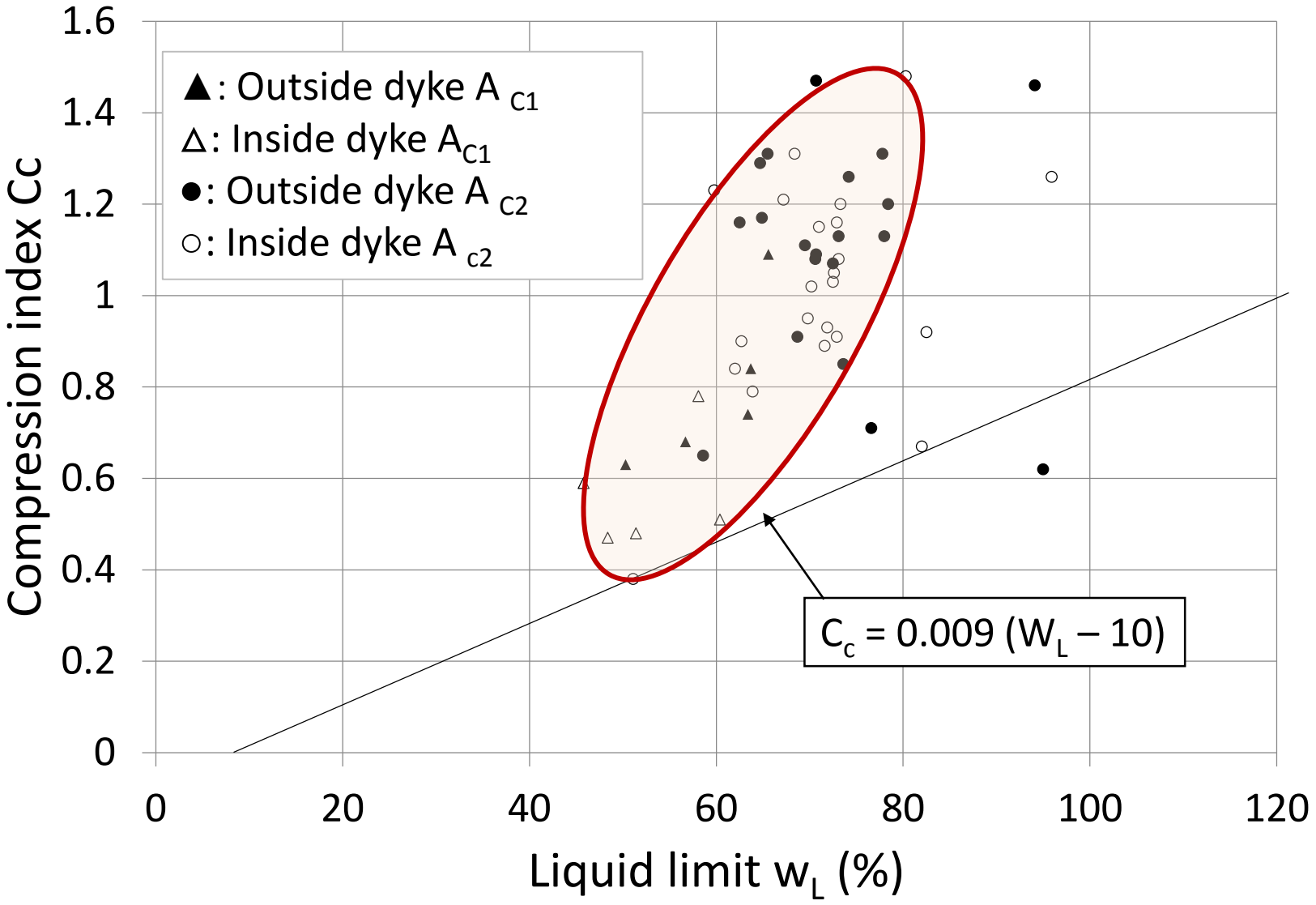
High-sensitivity ratio and high-liquidity index

# Locations of Clay ($A_{c2}$) in the Plastic Chart

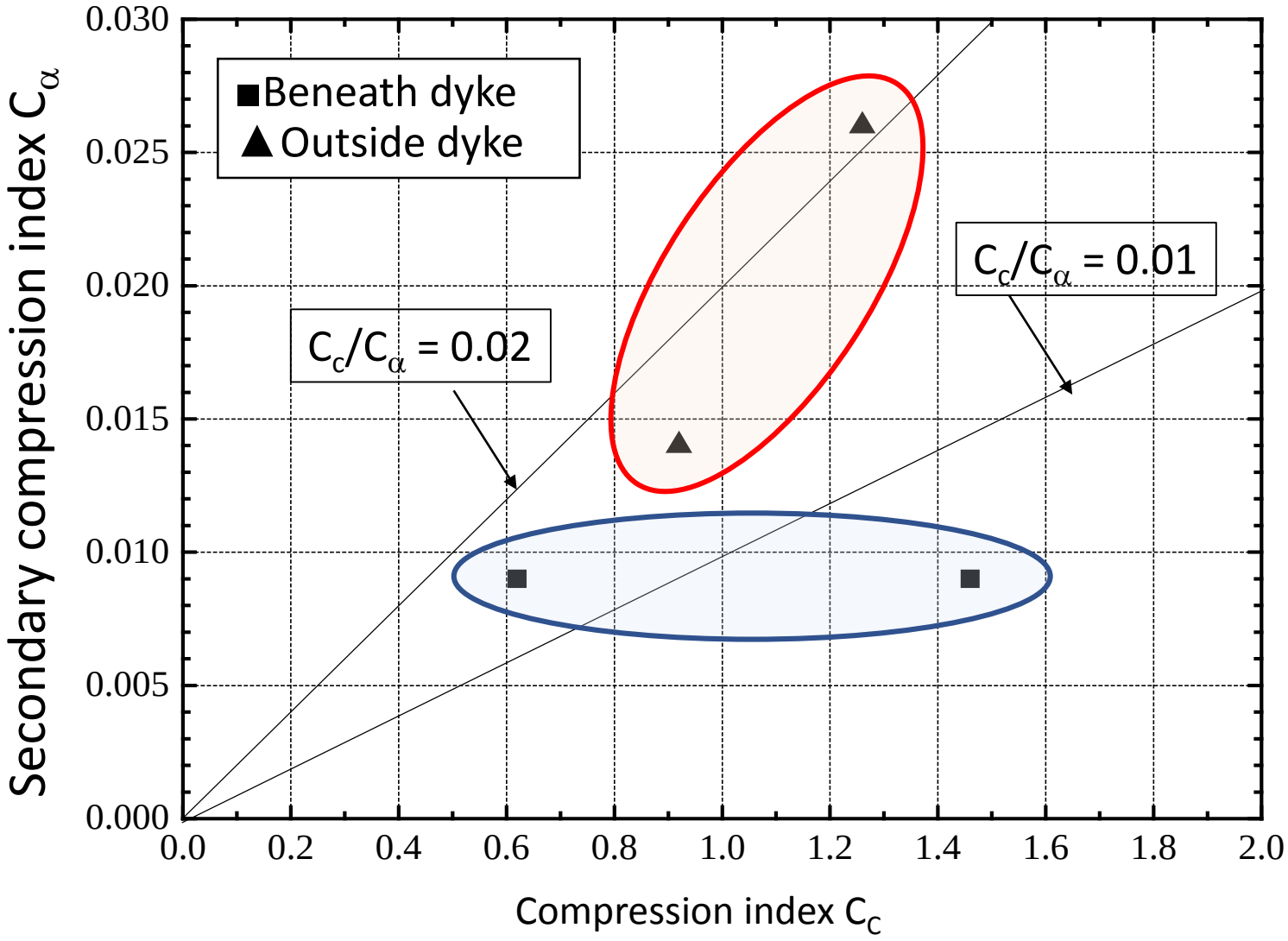



Most clay samples lie just below the A-line. Therefore, they are classified into (MH).

# Compression Index Correlated to Liquid Limit

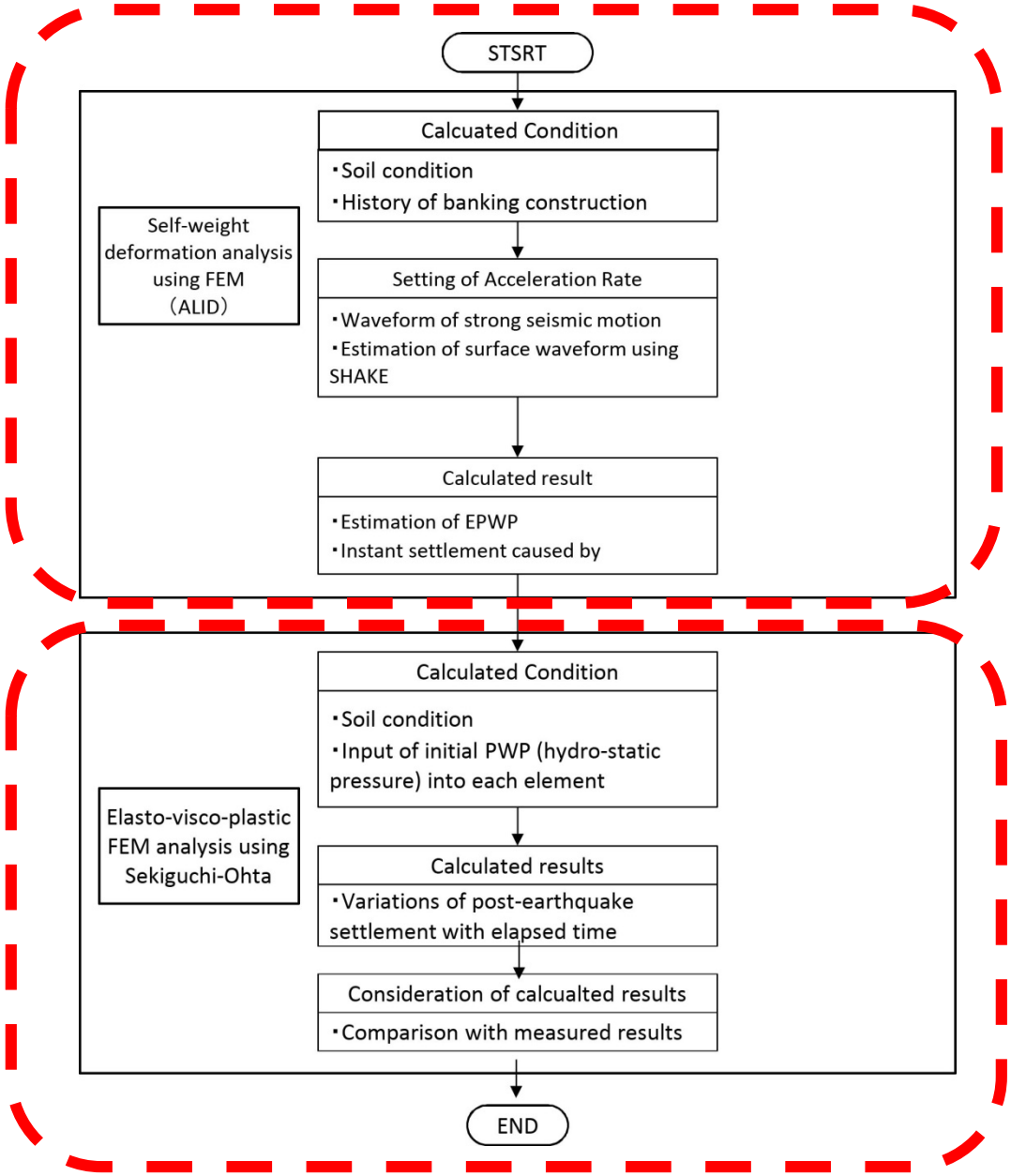


# Correlation between $C_\alpha$ and $C_C$




Secondary compression characteristics are less marked.

# Numerical Analysis Procedures



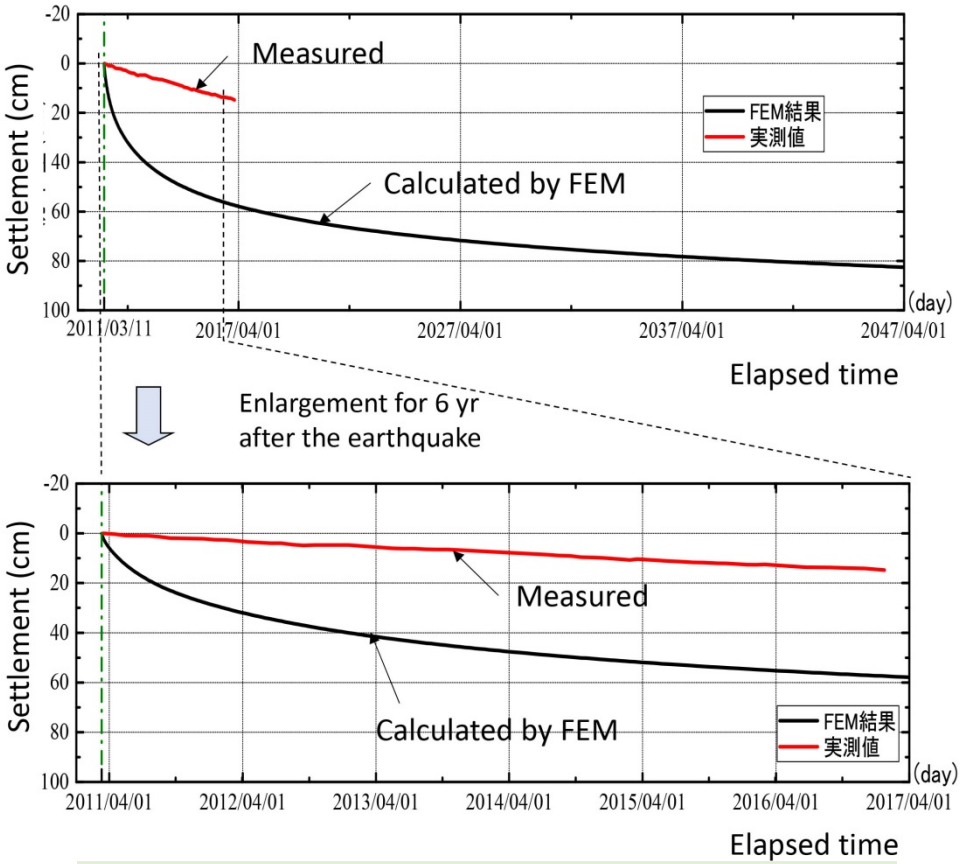

Dynamic Analysis

Static Analysis

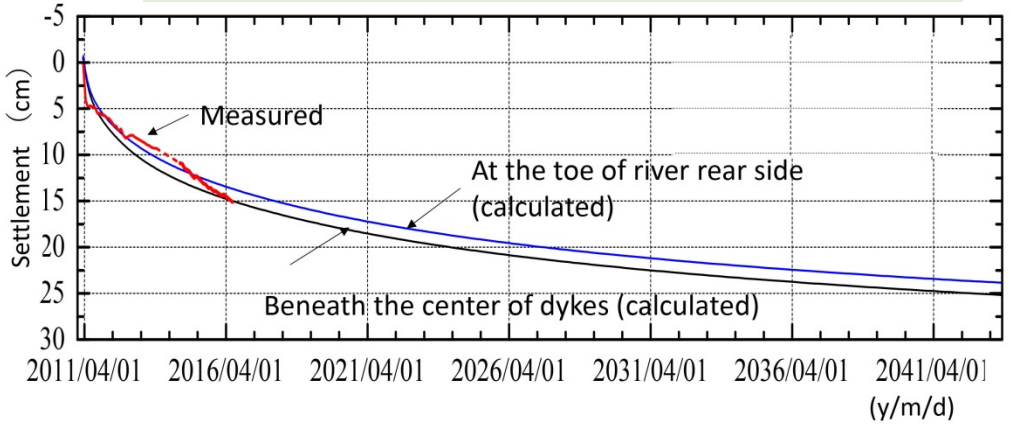
# Comparison of Settlement between Observation and Prediction

| | From Lab test | From BA |
|---|---|---|
| γ (kN/m$^3$) | 14.9 | |
| γ'(kN/m$^3$) | 5.1 | |
| wn (%) | 81.0 | |
| IP | 36.0 | |
| Gs | 2.67 | |
| ei | 2.16 | |
| Cc | 1.04 | |
| λ | 0.451 | 0.120 |
| qu (kN/m$^2$) | 60.6 | |
| OCR | 1.16 | |
| $K_0$ | 0.59 | |
| Ki | 0.63 | |
| ν' | 0.372 | |
| β | 1.03 | |
| Cs | 0.141 | |
| Λ | 0.86 | |
| M | 1.37 | |
| Pc (kN/m$^2$) | 142.9 | |
| cv (m$^2$/day) | 0.046 | |
| mv (m$^2$/kN) | 1.38E-03 | |
| k (m/day) | 6.20E-04 | |
| $\lambda_k$ | 0.137 | |
| e0 | 2.16 | |
| αe | 9.00E-03 | |
| α | 7.45E-03 | 2.53E-03 |
| $v_0$ (1/day) | 8.71E-06 | 2.13E-06 |
| D | 9.02E-02 | 1.57E-02 |
| tc | 855 | |
| σvi' | 148.29 | |
| ϕ'(° ) | 34 | |

(a) Case using parameters from lab tests




(b) Case using parameters from back analysis



# Summary and Conclusion

- i) Combined countermeasures have functioned effectively to reduce settlement and deformation, not only in river dykes but also in adjacent residences founded on clay deposits.
- ii) Numerical analysis using two computer programs suggests that countermeasures are beneficial for reducing dyke and residence settlement and lateral displacement on clay deposits.
- iii) Careful attention must be devoted to the fact that such settlement and deformation are time-dependent. Therefore, monitoring of settlement and EPWP should continue for a long period.

# Acknowledgements


- Our greatest appreciation is extended to the Hitachi River and Road Office, Kanto branch, Ministry of Land, Infrastructure and Transport, which provided important information for this case study.
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# Thank You for Your Kind Attention!