# TWO NEWEST APPLICATIONS OF FEM IN GEOTECHNICAL ENGINEERING

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## ABSTRACT
Two newest applications of FEM are introduced to show that the FEM is a powerful tool in geotechnical engineering. One is about slope stabilization. Drainage wells with sub-horizontal drains drilled from the drainage wells are the most widely used to stabilize landslides in Japan. We propose to use three-dimensional finite element analysis of water flow through variable saturated soils to calculate the water pressure, and then to calculate three-dimensional safety factor of the landslide. The results indicate that the proposed procedure can rationally and economically design the slope stabilization. The other application is about a blind numerical prediction of seismic response of buried pipes in a large shaking table test. We select fully coupled dynamic finite element analysis as the numerical tool for the blind prediction. The numerical results of acceleration, pore water pressure, and floatation of buried pipe compared well with the results of the large shaking table test.

## FE ANALYSIS OF HUGE LANDSLIDE STABILITY
Drainage is often a crucial measure to stabilize landslides because of the important role of pore water pressure in reducing the shear strength. Drainage of surface water and groundwater is the most widely used, and generally the most successful stabilization method, because of its high stabilization efficiency over cost. As a long-term solution it suffers greatly because the drains must be maintained if they are to continue to function. In the case of large and deep landslides, the most effective measure to lower the groundwater is to drill drainage wells and if necessary sub-horizontal drains can be drilled from the drainage wells. The water collected into the drainage wells can be discharged into a drainage tunnel, or directly discharged out the landslide area.
The number and location of the drainage wells is often selected based on the topography and geology of the landslide, and the personal experiences. This paper reports an innovative procedure for the optimization of the number and location of drainage wells, using three-dimensional finite element analysis of water flow through variable saturated soils. As an example, the procedure was applied to a large landslide, the Namasu landslide, about 900m wide, 800m long, and 80m deep, which was observed being moving after a heavy rainstorm in 1985. Additionally, we propose to use the Plan-Do-Check-Act cycle to manage the Namasu landslide because the planned safety factor is lowered down to a value of 1.05 for the normal water level corresponding to a rainstorm with a return period of 30 years and 1.00 for the high water level corresponding to a rainstorm with a return period of 50 years possibly results in the landslide movement during a heavy rainstorm in the future.

A large landslide, the Namasu landslide, 900m wide, 800m long, and 80m deep, was firstly observed being moving after a heavy rainstorm with a total rainfall of 444mm in July, 1985. The movement of the landslide posed heavy damages to roads and building of a junior school located in the landslide area, and a bridge spanned over the Shirasuna river (see Fig. 1). After the first observed movement of the landslide, field surveys and investigation, and laboratory tests were conducted, and surface drainage and subsurface drainage such as waterways, drainage wells, and a drainage tunnel were constructed to stabilize the landslide. Figure 1 shows the plan view of the Namasu landslide.


Figure 1. Plan view of the Namasu landslide

For the Namasu landslide, the finite element mesh as shown in Figure 2 was used for the finite element analysis of water flow through variable saturated soils. The plane elements showed in the upper-right corner of Figure 2 were used to simulate the sub-horizontal drains.

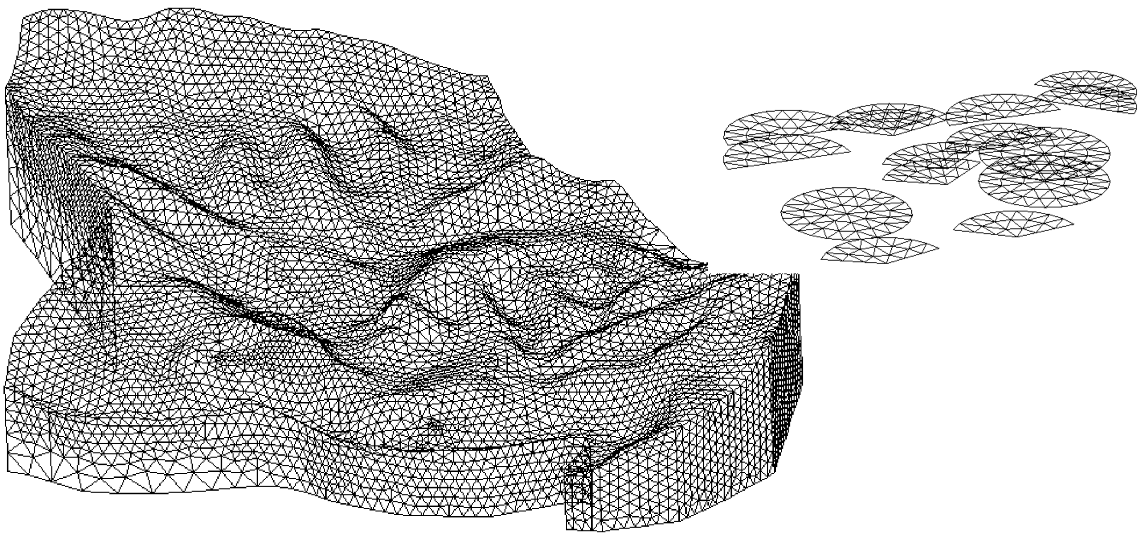

Figure 2. A typical finite element mesh

## BLIND PREDICTION OF THE LIFT-UP OF BURIED PIPES IN A LARGE SHAKING TABLE TEST

The liquefaction-induced lift-up of buried pipes has been widely reported. The infrastructures such as pipelines in Japan have to be upgraded to resist large earthquake after the 1995 Hyogoken-Nambu Earthquake. To select cost-effective countermeasures, it is necessary to clarify the mechanism of the lift-up of buried pipes under seismic loading. Recently, a blind prediction of the lift-up of buried pipes induced by liquefaction in a large shaking table test was conducted. Twenty-one participants including authors have taken part in the blind prediction. In this keynote lecture, we report the results of blind prediction, results of the large shaking table test, and Class B prediction of the lift-up of buried pipes in the large table test. For Class B prediction, the FEM analyses were once again conducted using the recorded input wave.

We used fully coupled dynamic finite element analysis program UWLC to calculate the lift-up of buried pipe induced by liquefaction. First, using the results of static and cyclic triaxial tests that were distributed by the organizers of the blind prediction, we identified the parameters of the elastoplastic constitutive model, the generalized plasticity (P-Z sand model). Figure 3 shows the calculated and measured p-q curve of static triaxial tests and liquefaction strength curve. Second, using the distributed data including the input wave, cross-section of the large shaking table test, characteristics of the buried pipe, we predicted the lift-up of the buried pipe in the large shaking table test.

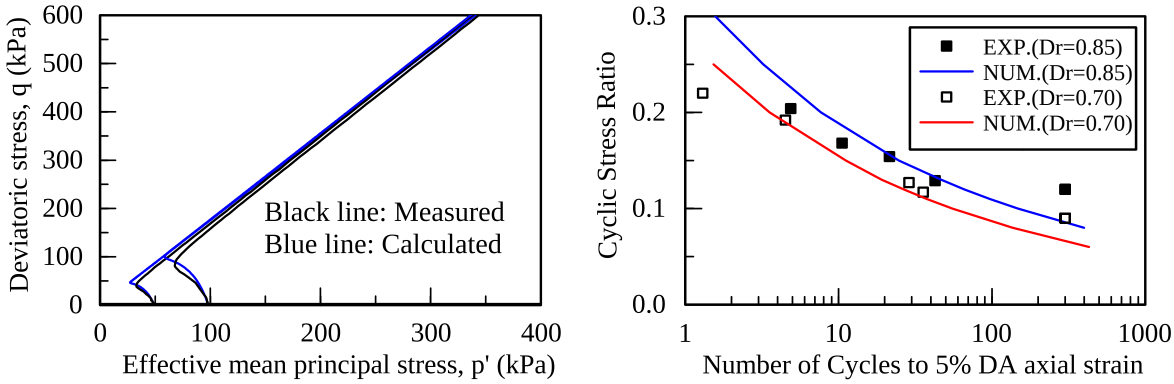


Figure 3. Calculated and measured static (left) and cyclic triaxial test results

Figure 4 shows the cross-sectional view of the large shaking table test for Case 1. The results of blind prediction per participants are listed in Table 1. Generally, the two fully coupled elastoplastic finite element analysis gave good prediction. Because of the recorded input wave of the large shaking table test was some different from the planned, we conducted Class B prediction of the lift-up of buried pipes induced by liquefaction in the large shaking table test, changing the input wave from the planned to the recorded. The results show that the calculated results were generally consistent with the measurements.

The blind prediction reported here indicates that, to satisfactorily predict the lift-up of buried pipes induced by liquefaction, it is essential that the constitutive model used in a numerical code should be able to capture important features of soil behavior under static and cycle loading. Fully coupled elastoplastic finite element analysis usually gives a better prediction than other approaches. It is important to carefully identify parameters of the constitutive model using the static and cyclic element tests.

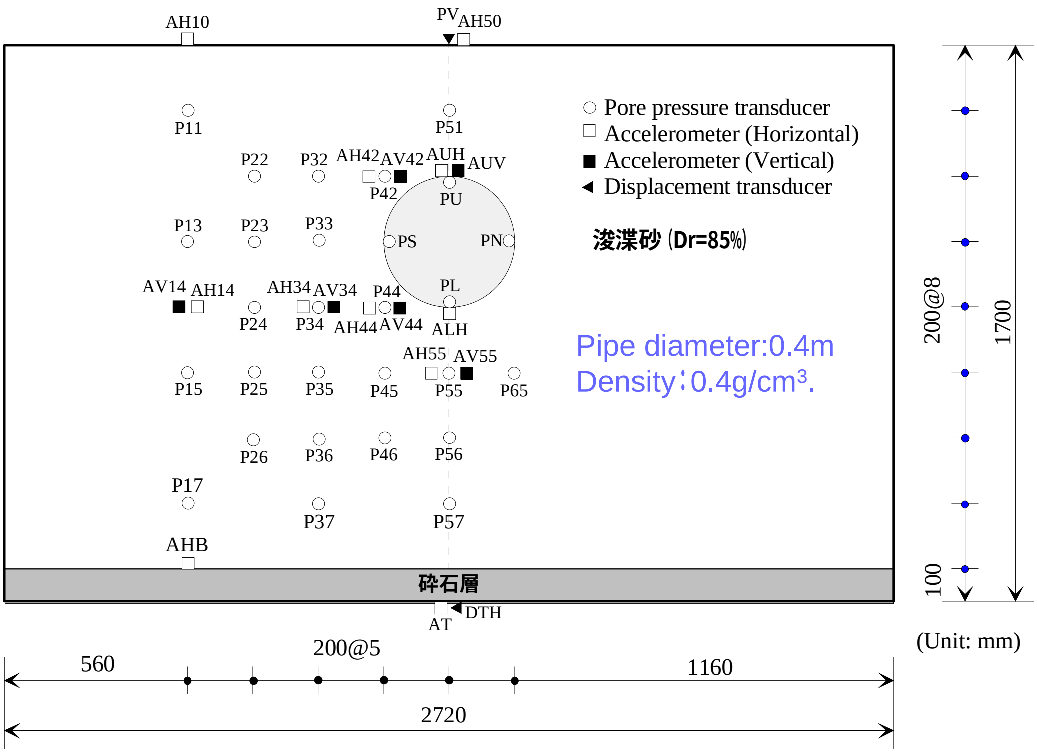


Figure 4. Cross-section for the basic case: Case 1

Table 1. Lift-up of blind prediction for the basic case: Case 1.

| Winner | Participants | Method | Lift-up (cm) |
|---|---|---|---|
| | 1 | Equivalent elastic analysis | 8.0 |
| | 2 | Indirectly coupled nonlinear | 0.5 at 2.5 second |
| | 3 | Fully coupled elastoplastic | 14.3 |
| | 4 | Indirectly coupled nonlinear | 7.2 |
| 3 | 5 | Questionnaire | 13.4 |
| | 6 | Indirectly coupled nonlinear | 3.0 |
| | 7 | Ditto | 7.9 |
| 3 | 8 | Ditto | 9.4 |
| 2 | 9 (Authors) | Fully coupled elastoplastic | 10.0 |
| | 10 | Dynamic elastoplastic | -1.1 |
| | 11 | Intuition | 14.0 |
| | 12 | Viscous fluid | 2.8 |
| | 13 | Indirectly coupled nonlinear | 16.0 |
| | 14 | Equivalent elastic analysis | 41 |
| | 15 | Equivalent elastic analysis | 1.7 |
| | 16 | Viscous fluid | - |
| | 17 | DEM | 25.2 |
| | 18 | Intuition | 1.5 |
| | 19 | Intuition | 21 |
| 1 | 20 | Intuition | 12 |
| | 21 | Intuition | 35 |
| | | Large shaking table test | 11.4 (3.5 at 2.5 second) |

ICCI2004, Beijing, August 15-17

# Keynote Lecture: Two newest applications of FEM in geotechnical engineering

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# FEM-Based Design of Preventive Works for Huge Landslides

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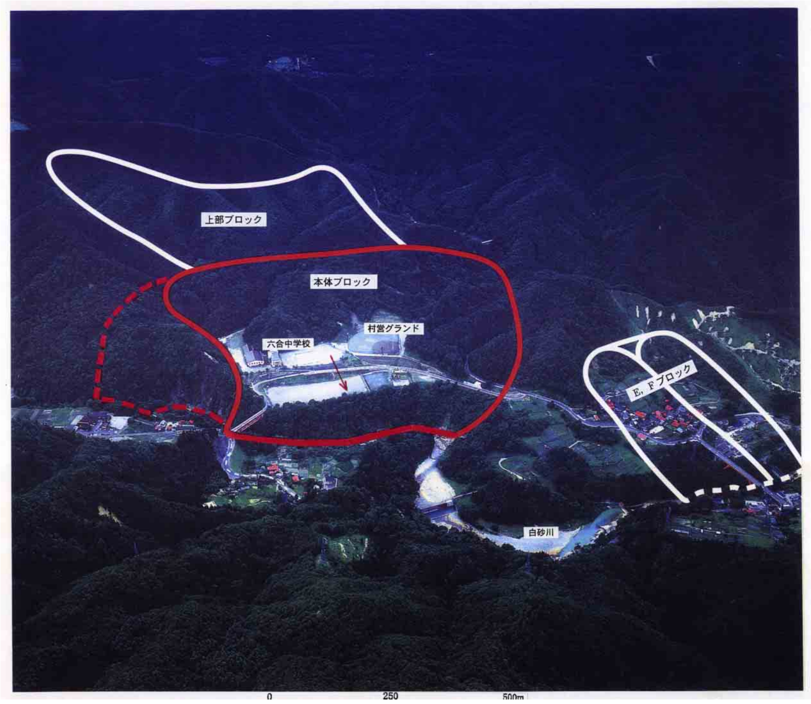


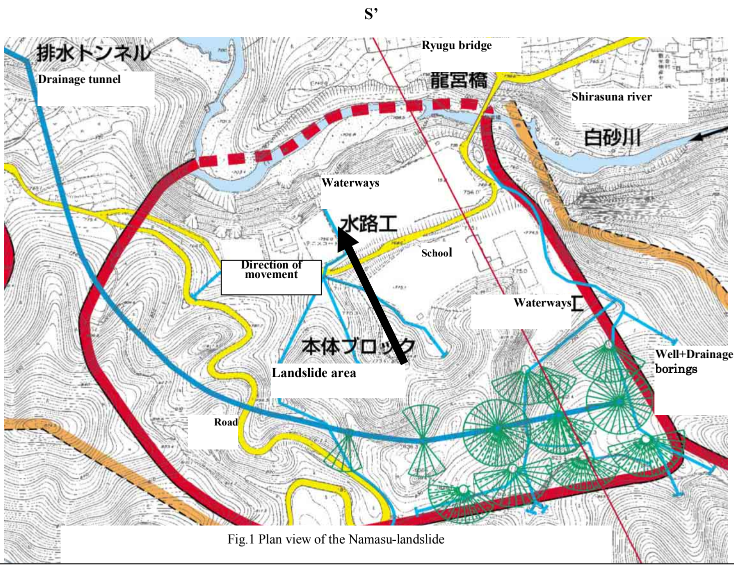




Fig.1 Plan view of the Namasu-landslide

**This figure shows the plan view of the Namasu-landslide whose sliding mass has the size of 900m(width)*800m(length)*80m(depth).**
**The lanslide movement was firstly observed during heavy rainfall with the total amount of 444mm in July, 1985.**
**Due to the movement heavy damages were induced to the roads and the building of the junior high school in the landslide area, and the bridge connecting the lanslide area and a road running on the opposite side across the river which flows along the lower edge of the landslide.**
**After the first landslide movement field investigation, field measurements, and laboratory testing were conducted and a lot of prevention works such as waterways(surface drainage), drainage wells and drainage tunnel were constructed.**

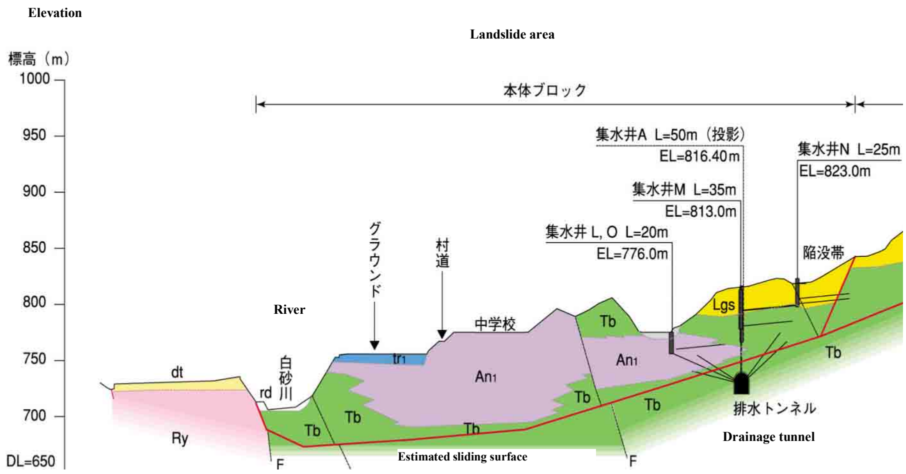
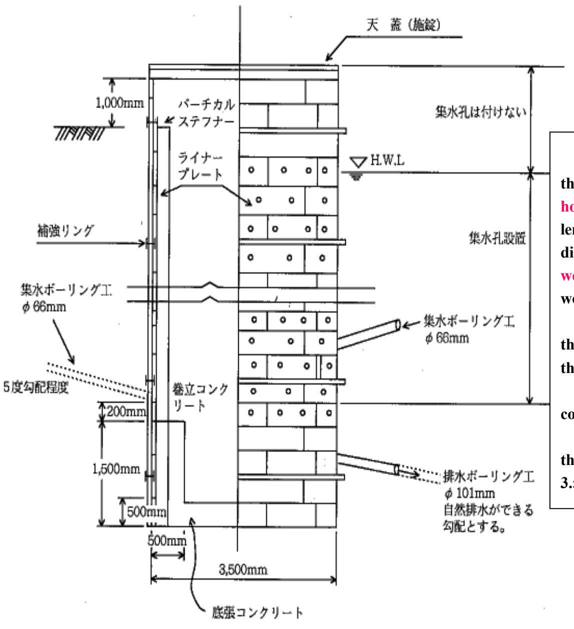



Fig.2 Section S-S' view of the Namasu-landslide (A,L,M,N,O: Well+Drainage borings)
(Geological index: Lgs= Sandy gravel, Tb= Tuff breccia, $An_1$= Andesite)

**This figure shows the section view of the landslide.**

**The cause of the Namasu-landslide are due to two factors, that is, the permeable landslide mass and the weak soil layer along the sliding surface. Around the upper part of the landslide mass there exists a relatively permeable portion, which enables rainfall permeate the soil mass, which results in the increase of water pressure in the weak soil along the sliding surface.**




**In order to collect and drain water from the landslide mass and the outer region, horizontal drainage borings with the typical length of 50m were installed in radial directions from the insides of the drainage wells and tunnel, which are typical preventive works of the Namasu-landslide.**

**These drainage works are used to lower the ground water level and decrease the water pressure along the sliding surface.**

**These drainage measures are very common and familiar in landslides of Japan.**

**The typical drainage wells in the Namasu-landslide has the diameter of 3.5m and the depth of 40-50m.**

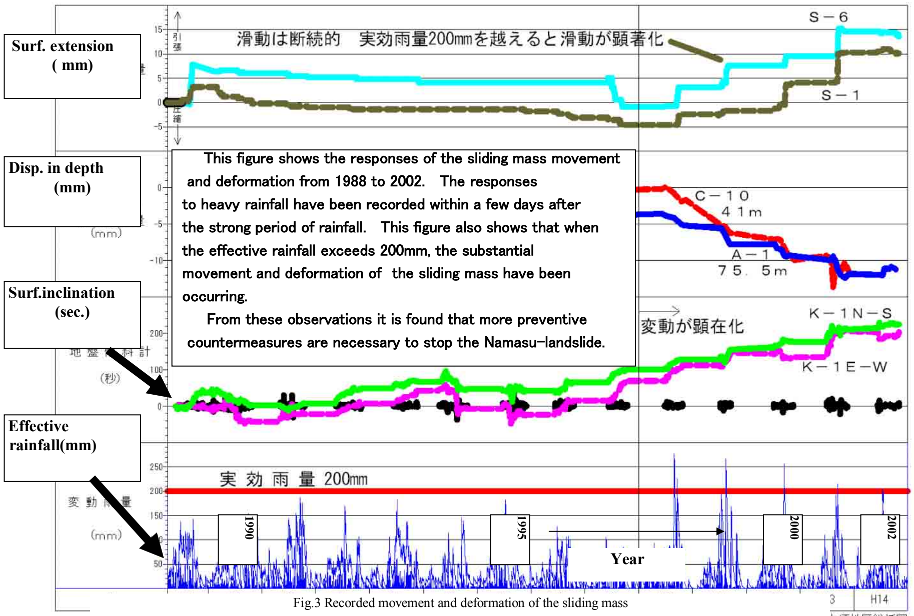



Fig.3 Recorded movement and deformation of the sliding mass

**The second large landslide movement** occurred during heavy rainfall with the **daily amount of 228mm in September, 2000**, which caused damages similar to the first one. This meant that the prevention works constructed up to the moment were not enough to stop the movement during heavy rainfall. The **Namasu-landslide** is so huge that it is very difficult to stop the landslide movement with enough safety factor only by means of drainage systems. If possible, prevention **piles and anchors** are necessary to satisfy the stability conditions. However, piles and anchors cost enormously for huge landslides. Therefore, drainage wells with drainage borings were finally adopted as the successive countermeasures.

The total cost of various prevention measures constructed for the landslide reached **fifteen million US dollars**. It is desirable to reduce further investment on the construction of drainage wells. To this end, **finite element analysis of ground water flow is currently performed in order to plan out an appropriate and cost-effective arrangement of drainage wells.**

## Finite element analysis to search the optimal positions of drainage wells

The optimal arrangement of drainage wells can be found analytically based on the **finite element analysis of water flow through unsaturated-saturated soils**.

It is expected that series of comparative simulation with different arrangement of the wells will clarify the appropriate positioning of wells, which leads to an economical design.

Next figure shows an example of finite element meshes for the ground water flow analysis of **the Namasu-landslide**.

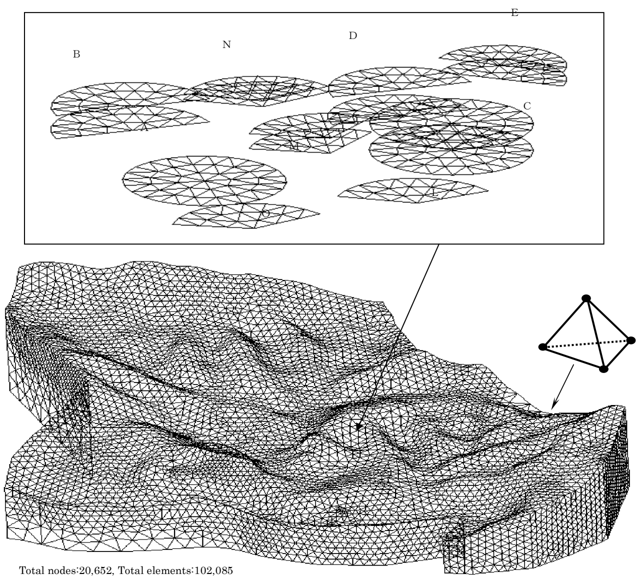



Fig.4 3D FE meshes

## Summaries

The contents of this paper are summarized as follows:

(1) The cause of the Namasu-landslide are due to two factors; the permeable landslide mass and the weak soil layer along the sliding surface.

(2) A number of drainage wells have been set up as the preventive measures for the Namasu-landslide.

(3) In order to decrease the possibility of the landslide movement during heavy rainfall it is found that much more drainage wells must be installed.

(4) The optimal positioning of drainage wells has been performed analytically based on the finite element analysis of water flow through unsaturated-saturated soils, which leads to an economical design of preventive measures for landslides.

## PLAN-DO-CHECK-ACT (PDCA) CYCLE FOR LANDSLIDE MANAGEMENT

**PDCA(Plan, Do, Check, Act) is a cycle of activities designed to drive continuous improvement. Initially implemented in manufacturing, it has broad applicability in business. Firstly developed by Walter Shewhart, it was popularized by Edwards Deming.**

**Here, we use the PDCA cycle for the management of the Namasu landslide including the optimization of the number and location of drainage wells. The steps of the PDCA cycle in detail are as follows:**

**PLAN:**

**1)Specify a planned safety factor of 1.05 for the normal water level and 1.00 for the high water level for the Namasu landslide, which is lower than a conventional value of 1.2.**

**2)Optimize the number and location of drainage wells.**

DO:

1) **Digitize the ground of the landslide using the boring information.**
**2) Back-analyze the groundwater level to determine the permeability of soils using the observed data before any drainage measures were installed.**
**3) Back-analyze the groundwater level to determine the effect of drainage wells using the observed data after some drainage wells were installed.**
**4) Select the construction-possible location of drainage wells, assume some combination of the number and location of drainage wells.**
**5) Calculate the groundwater level if the drainage wells are installed with the assumed number and location using the finite element analysis of water flow through variable saturated soils.**
**6) Use the calculated water pressure to evaluate the safety factor of the landslide.**
**7) Calculate the total cost to install the drainage wells and sub-horizontal drains;**
**8) Select the optimal number and location of drainage wells to satisfy the planned safety factor of the landslide and the lowest cost.**

**CHECK:**

1) Check whether the groundwater level after some other drainage wells installed is lowered down to the calculated value when the number and location of drainage wells were optimized.
2) Check whether the landslide moves after a strong rainstorm with a return period of 30 years and 50 years if possible.

**ACT:**

1) Set up automatical observation systems to record the groundwater level and the possible movement of the landslide for the CHECK step in the PDCA cycle.
2) Establish management system and refuge system because of a low planned safety factor has been used.
3) If the observations showed that desired lowering of the groundwater level is not achieved after some drainage wells are installed, the permeability of soils and the effect of drainage wells and sub-horizontal drains should be necessary to be re-back-analyzed and then restart the PDCA cycle.

## *Thank you*

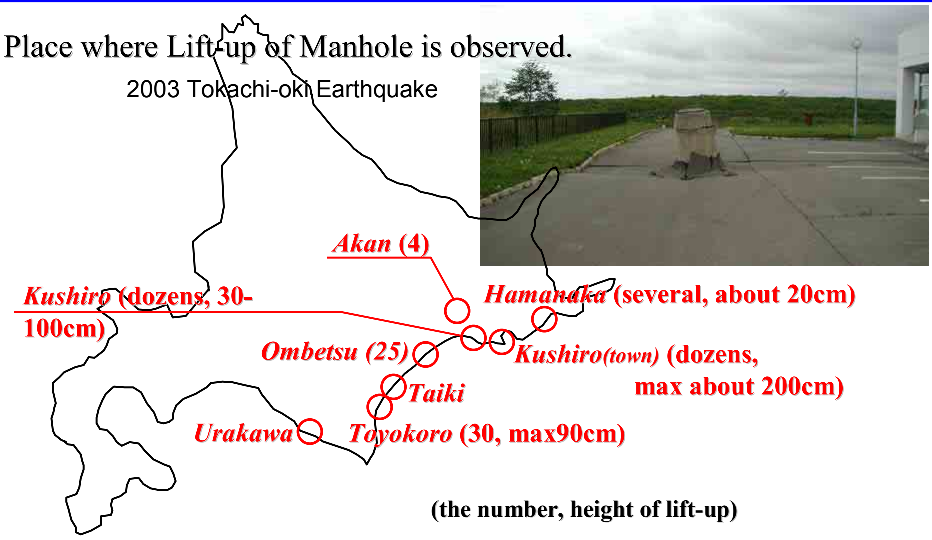
***This project has been done under the support of:***

***Gunma Prefectural Government***
***Nippon Koei Co. Ltd., Japan***

***Also thanks to Forum8 Co.Ltd., Japan***

Contents

## Damage of Sewerage Structures




## Steps of blind prediction

- Recruit participants.
- Distribute static and cyclic triaxial and torsional test results of soils used in large shaking table test and additional data necessary for blind prediction.
- Predict the lift-up of the buried pipes induced by liquefaction, especially for Case 1.

- Present predicted results before the large shaking table test.
- Conduct large shaking table test.
- Compare the lift-up between the prediction and test.
- Announce the winner only based on the results of Case 1.

## Governing equations of *u*-*p* formulation

| | |
|---|---|
| Momentum balance for soil-fluid mixture | $\sigma_{ji,j} - \rho \ddot{u}_i + \rho b_i = 0$ |
| Momentum balance for fluid | $(k_{ij}(-p_{,j} - \rho_f \ddot{u}_j + \rho_f b_j))_{,i} + \alpha \dot{\varepsilon}_{ii} + \frac{\dot{p}}{Q} = 0$ |
| Principle of effective stress | $\sigma_{ij} = \sigma'_{ij} - p\delta_{ij}$ |
| Constitutive law | $\Delta\sigma'_{ij} = D_{ijkl}\Delta\varepsilon_{kl}$ |
| Strain compatibility | $\varepsilon_{ij} = (u_{i,j} + u_{j,i})/2$ |

## Finite element discretization for *u*-*p* formulation in space

Soil-fluid mixture:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} - \mathbf{Q}\mathbf{p} = \mathbf{f}^u$$

Fluid:

$$\mathbf{Q}^{\mathrm{T}}\dot{\mathbf{u}} + \mathbf{H}\mathbf{p} + \mathbf{S}\dot{\mathbf{p}} = \mathbf{f}^p$$

**M** = Mass matrix
**K** = Stiffness matrix
**Q** = Coupling matrix
**H** = Permeability matrix
**S** = Compressibility matrix
**u** = Displacement vector
**p** = Pore pressure vector
**f**$^u$ = Force vector for mixture
**f**$^p$ = Force vector for fluid

Five types of unknown variables:
Acceleration, velocity, displacement
Pore pressure rate, pore pressure

## Finite difference technique for *u-p* formulation: Newmark method

$$\ddot{\mathbf{u}}_{n+1} = \ddot{\mathbf{u}}_n + \Delta\ddot{\mathbf{u}}_n$$
$$\dot{\mathbf{u}}_{n+1} = \dot{\mathbf{u}}_n + (1+\theta_1)\Delta\ddot{\mathbf{u}}_n\Delta t$$
$$\mathbf{u}_{n+1} = \mathbf{u}_n + \Delta\dot{\mathbf{u}}_n\Delta t + \frac{1}{2}(1+\theta_2)\Delta\ddot{\mathbf{u}}_n\Delta t^2$$
$$\dot{\mathbf{p}}_{n+1} = \dot{\mathbf{p}}_n + \Delta\dot{\mathbf{p}}_n$$
$$\mathbf{p}_{n+1} = \mathbf{p}_n + \left(1+\overline{\theta}_1\right)\Delta\dot{\mathbf{p}}_n\Delta t$$

The scheme is unconditionally stable if taking

$\theta_2 \geq \theta_1 \geq 1/2 \qquad \overline{\theta}_1 \geq 1/2$

## Discretized *u-p* formulation

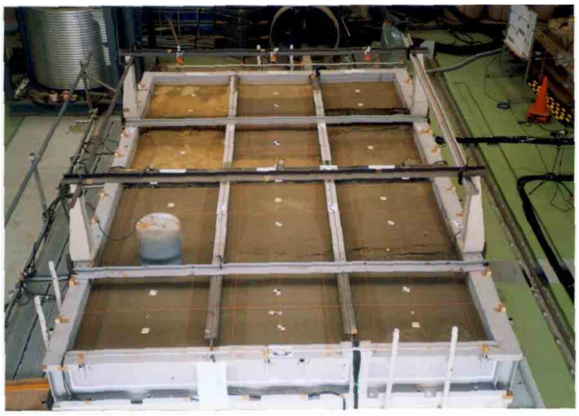
$$\begin{bmatrix} \mathbf{M} + \frac{1}{2}\theta_2\Delta t^2\mathbf{K} & -\overline{\theta}_1\Delta t\mathbf{Q} \\ -\overline{\theta}_1\Delta t\mathbf{Q}^{\mathrm{T}} & -\overline{\theta}_1/\theta_1\left(\overline{\theta}_1\Delta t\mathbf{H} + \mathbf{S}\right) \end{bmatrix} \begin{Bmatrix} \Delta\ddot{\mathbf{u}}_n \\ \Delta\dot{\mathbf{p}}_n \end{Bmatrix} = -\begin{Bmatrix} \boldsymbol{\psi}^u_{n+1} \\ -\overline{\theta}_1/\theta_1\,\boldsymbol{\psi}^p_{n+1} \end{Bmatrix}$$

$$\boldsymbol{\psi}^u_{n+1} = \mathbf{M}_{n+1}\ddot{\mathbf{u}}_{n+1} + \int_\Omega \mathbf{B}^{\mathrm{T}}_{n+1}\boldsymbol{\sigma}' d\Omega - \mathbf{Q}_{n+1}\mathbf{p}_{n+1} - \mathbf{f}^u_{n+1}$$

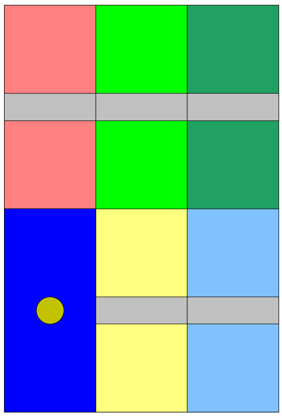
$$\boldsymbol{\psi}^p_{n+1} = \mathbf{Q}_{n+1}\dot{\mathbf{u}}_{n+1} + \mathbf{H}_{n+1}\mathbf{p}_{n+1} + \mathbf{S}_{n+1}\dot{\mathbf{p}}_{n+1} - \mathbf{f}^p_{n+1}$$

Iteration is necessary!

# Lift-up of buried pipes induced by liquefaction

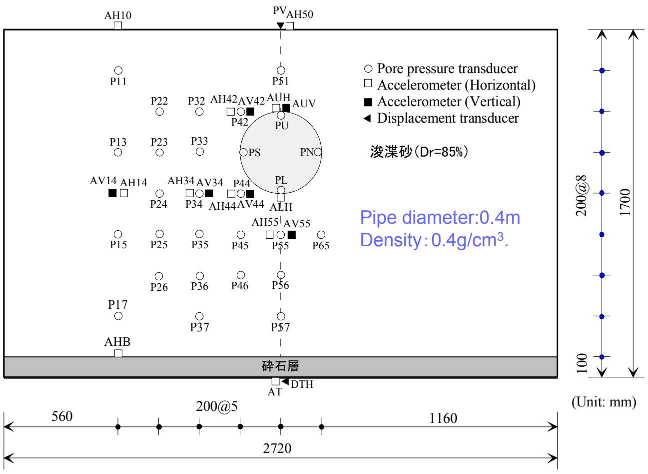


Large shaking table test



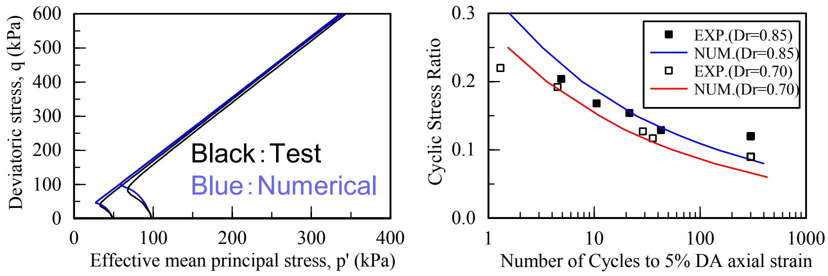

# Lift-up of buried pipes induced by liquefaction

Basic Case: Case 1



# Parameters of generalized plasticity

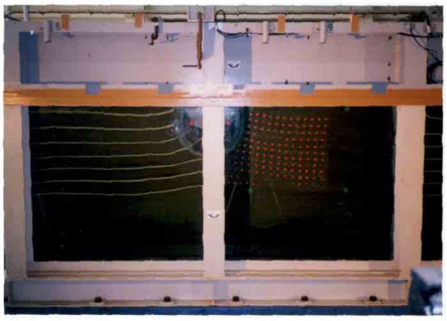
## Static and cyclic triaxial tests




# Results of blind prediction

| | Participant | Method | Lift-up (cm) |
|---|---|---|---|
| | 1 | Equivalent elastic analysis | 8.0 |
| | 2 | Indirectly coupled nonlinear analysis | 0.8 at 2.5 second |
| | 3 | Fully coupled elastoplastic analysis | 14.3 |
| | 4 | Indirectly coupled nonlinear analysis | 7.2 |
| 3 | 5 | Questionnaire | 13.4 |
| | 6 | Indirectly coupled nonlinear analysis | 3.0 |
| | 7 | Ditto | 7.9 |
| 3 | 8 | Ditto | 9.4 |
| **2** | **9** | **Fully coupled elastoplastic analysis** | **10.0** |
| | 10 | Dynamic elastoplastic analysis | -1.1 |
| | 11 | Intuition | 14.0 |
| | 12 | Viscous fluid | 2.8 |
| | 13 | Indirectly coupled nonlinear analysis | 16.0 |
| | 14 | Equivalent elastic analysis | 41 |
| | 15 | Equivalent elastic analysis | 1.7 |
| | 16 | Viscous fluid | - |
| | 17 | DEM | 25.2 |
| | 18 | Intuition | 1.5 |
| | 19 | Intuition | 21 |
| 1 | 20 | Intuition | 12 |
| | 21 | Intuition | 35 |
| | | **Large shaking table test** | **11.4 (3.5 at 2.5 second)** |

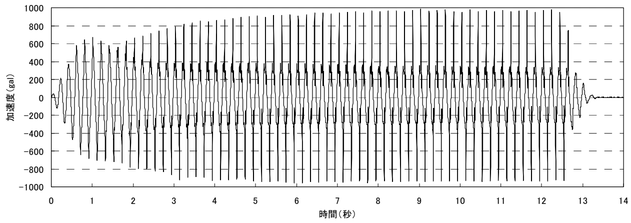
# Large shaking table test

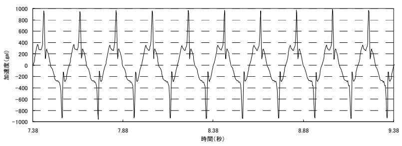


Cross-sectional view

Top plan view

# Recorded Input Wave



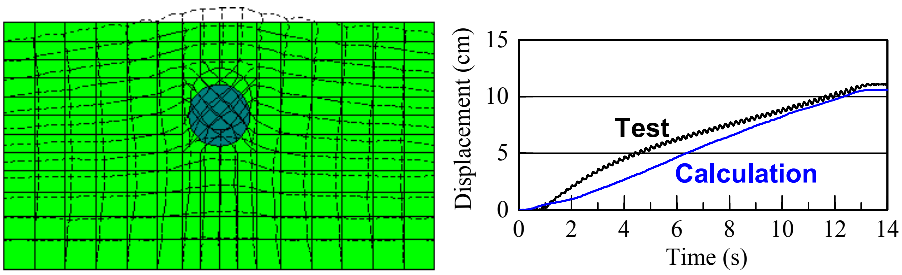




Input wave

Planned Input wave: sine wave of 600 gal

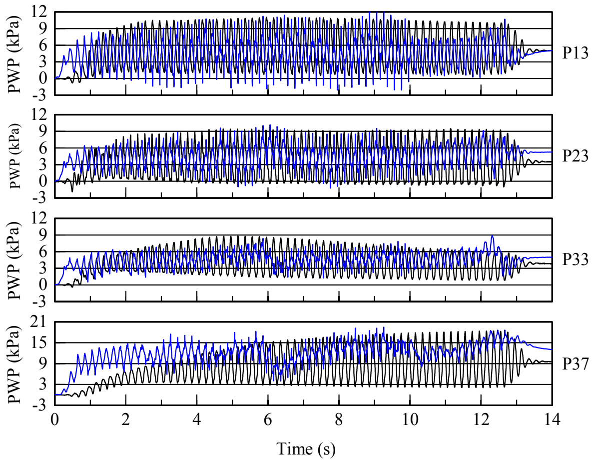
## Results of Class-B prediction

Only input wave is changed



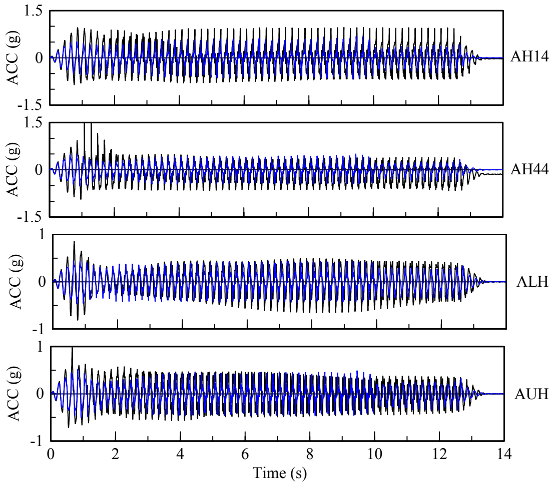

## Results of Class-B prediction

Excess pore pressure（Black line: Test, Blue line：Prediction）



# Results of Class-B prediction

Acceleration (Black line : Test, Blue line : Prediction)




# Results of Class-B prediction

| Case | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Prediction | 10.61 | 22.35 | 20.17 | 8.90 | 5.13 |
| Test | 11.08 | 28.48 | 25.36 | 9.81 | 6.06 |

# Results of Class-B prediction


| Case 2 | Floatation |
|---|---|
| Prediction | 22.35 |
| Test | 28.48 |

# Results of Class-B prediction


| Case 3 | Floatation |
|---|---|
| Prediction | 20.17 |
| Test | 25.36 |

# Conclusions

- To satisfactorily predict the lift-up of buried pipes induced by liquefaction, it is essential that the constitutive model used in a numerical code should be able to capture important features of soil behavior under static and cycle loading.
- Fully coupled dynamic finite element analysis usually gives a better prediction than other approaches.
- It is important to carefully identify parameters of the constitutive model using the static and cyclic element tests.