14 Aug 2008, 4:30pm - 6:00pm

Case History and Numerical Analysis of Trench Collapse in Japan

Sahaphol Timpong
National Institute of Occupational Safety and Health, Tokyo, Japan

Kazuya Itoh
National Institute of Occupational Safety and Health, Tokyo, Japan

Yasuo Toyosawa
National Institute of Occupational Safety and Health, Tokyo, Japan 2040024

6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

CASE HISTORY AND NUMERICAL ANALYSIS OF TRENCH COLLAPSE IN JAPAN

Timpong Sahaphol
National Institute of Occupational Safety and Health
Tokyo, Japan 2040024

Itoh Kazuya
National Institute of Occupational Safety and Health
Tokyo, Japan 2040024

Toyosawa Yasuo
National Institute of Occupational Safety and Health
Tokyo, Japan 2040024

ABSTRACT

This paper presents a case history of trench collapse occurred during trench excavation in soft ground. The development of settlement and horizontal displacement, the generation of pore water pressure during the construction and mechanism of trench collapse are investigated by means of centrifuge modeling and numerical analysis. It is found that the combination of centrifuge modeling and in-flight sand hopper can provide dramatic result for simulation of the trench collapse. Based on the results, it is verified that the occurrence of trench collapse is mainly caused by the excessive surcharge load of excavated material stockpiled on top of the trench.

INTRODUCTION

Trench excavations in soft grounds often encounter difficulties in design and construction due to high compressibility and low shear strength of the soft grounds. In Japan, trench collapses have caused a number of casualties of construction workers for example during the period of 1989 to 2004 about 30 workers were killed every year due to the trench collapse incidents. According to the case history of trench collapse presented in this paper, three workers lost their lives as a result of trench cave in during trench excavation for burying water pipelines for agriculture area in the northern part of Japan. The trench was excavated up to approximately 4m depth with a trench wall slope of 60 degree. Based on the site investigation and eyewitness interview, one of possible causes of the trench collapse is due to the excessive surcharge load from excavated materials that stockpiled on the trench wall slope without sufficient side clearance as presented in Fig. 1. To provide an insight into the mechanism of trench collapse, the centrifuge model test was conducted using the NIIS Mark-II centrifuge (beam-type centrifuge with a 2.3 m effective radius and maximum acceleration of 100g) at the National Institute of Occupational Safety and Health. This centrifuge has two platforms, which is capable of simulating static and dynamic geotechnical problems (Horii *et al.* 2006).

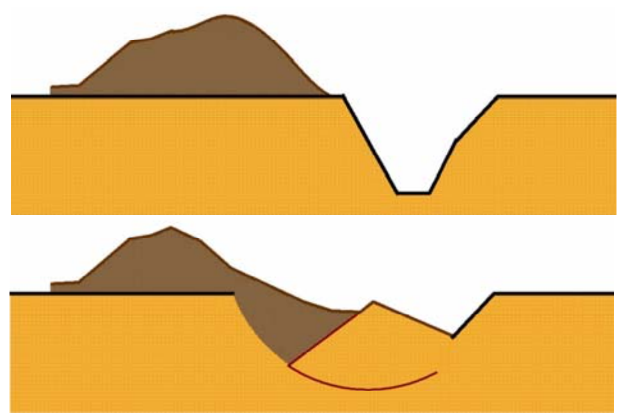

Fig. 1. Possible scenario of trench collapse.

CENTRIFUGE MODEL TEST

For many years, the centrifuge modeling has been commonly used as a research tool to study a wide range of geotechnical problems because of its ability to reproduce the same stress levels in a small-scale model as those present in a full-scale prototype. A model test container with acrylic transparent wall on one side was constructed to provide visualization of trench model during the centrifuge test. The internal dimensions of the model test container are 20cm wide, 50m long and 41cm high. Several ports were provided at other sidewalls of the container for instrumentations and service channels. In this paper, a computer-controlled in-flight sand hopper was utilized to provide a simulation of placing of excavated material during the trench excavation. Figure 2 shows the in-flight sand hopper, the main components are a sand hopper, a speed control motor, a reversible servomotor and toothed belts. The in-flight sand hopper can deliver the sand layer by layer or at one particular location to construct the embankment on the ground model during the centrifuge test. A real-time control of the in-flight sand hopper was provided by a computer from the control and data acquisition room. Several control options can be assessed in the control program such as position and flowing speed of the sand hopper to construct the embankment based on the designed geometry.

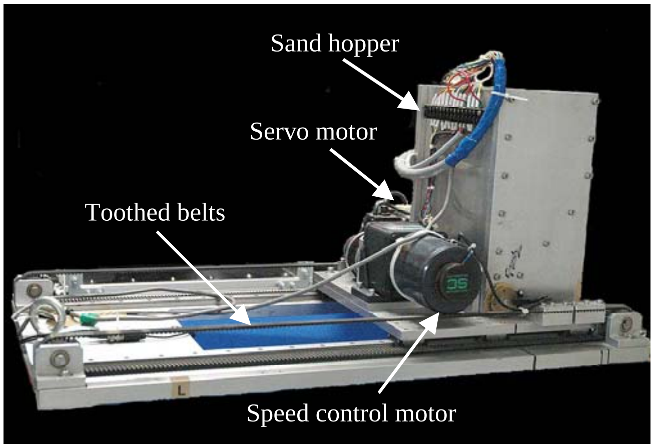

Fig. 2. In-flight sand hopper.

Preparation of Trench Model

The ground model was prepared by mixing the Fujinomori clay (liquid limit LL = 62.7%, plastic limit PL = 27.8%, particle density of soil ρ_s = 2.72 g/cm^3) with water content of 90% in the soil-mixing machine. The soil-mixing machine equipped with a vacuum pump was used for de-airing purpose and producing homogeneous soil mixture slurry. After the mixing was completed, the slurry was then placed into the model test container and pre-consolidated under a consolidation pressure of about 75 kPa, the compression load was imposed by means of belofram cylinder through a stiff plate. After the completion of primary consolidation, the resulting block of ground model was trimmed in the shape of designed trench geometry. Pore water pressure transducers (PPT) were installed at various locations into the trench model as shown in Fig. 3 to monitor build up and dissipation of pore water pressure during the centrifuge test. These transducers are very small and they are not considered to have significantly affected the failure mechanism of the trench model. To observe the deformation of the trench model, grid markers were placed within the trench model and stationary reference points were also attached on the model test container. Before placing the trench model in the container, the sidewalls of the container were lubricated with the water-resistant grease to minimize the sidewall friction.

Test Procedure

The soil package was loaded onto the centrifuge static platform along with its counterweight and the in-flight sand hopper containing air-dried Toyoura sand (Japanese standard sand, mean particle size D_{50} = 0.18 mm, ρ_s = 2.65 g/cm^3) was installed above the model test container. Figure 4 shows the centrifuge model test setup. The digital video camera and the 3.3 Mega pixel CCD camera were installed in front of the model test container to provide a visual observation of the trench model during the centrifuge test. Six halogen lamps were mounted on the platform to ensure the homogeneous illumination of the trench model. The centrifuge was accelerated to the acceleration of 40g (40 times of the earth's gravity) where the trench model will represent 4m deep trench with slope angle of 60 degree corresponding to the prototype scale. At the 40g the ground model was consolidated for about 40 minutes, after achieving pore water pressure equilibrium, the in-flight sand hopper placed the sand layer by layer to construct the embankment on the trench model. At first, the side clearance was kept constant about 1.8m in the prototype scale and it was decreased during the embankment construction as presented in the Fig. 3. The centrifuge test was terminated when trench collapse occurred.

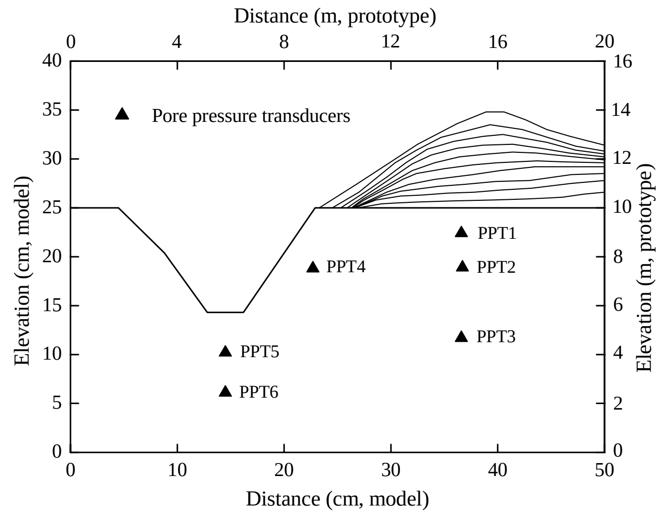

Fig. 3. Arrangement of pore water pressure transducers and sequence of embankment construction.

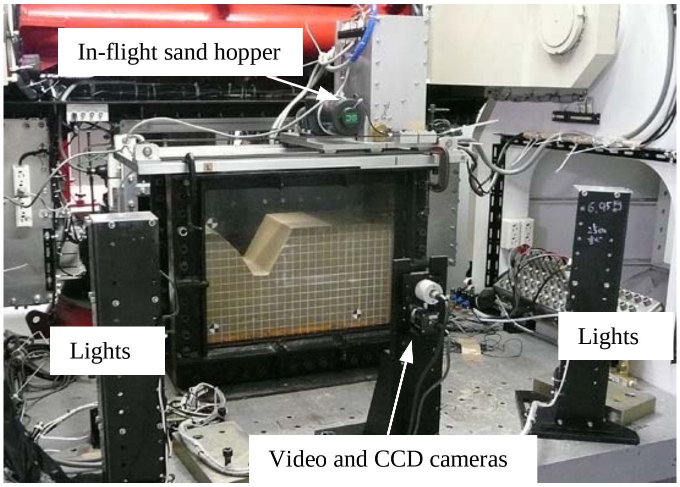

Fig. 4. Centrifuge model test setup.

Centrifuge Test Results

The trench collapse was observed after the 10th layer of embankment construction where the average height of the embankment was about 4m in the prototype scale as shown in Fig. 5. It is clear from the figure that the slip surface is circular and the occurrence of undrained slope failure is also clearly evident since the trench wall slope fail instantaneously.

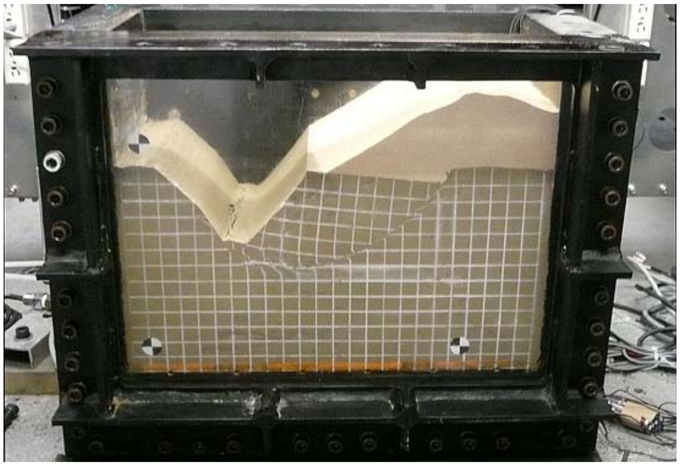

Fig. 5. Trench model after failure.

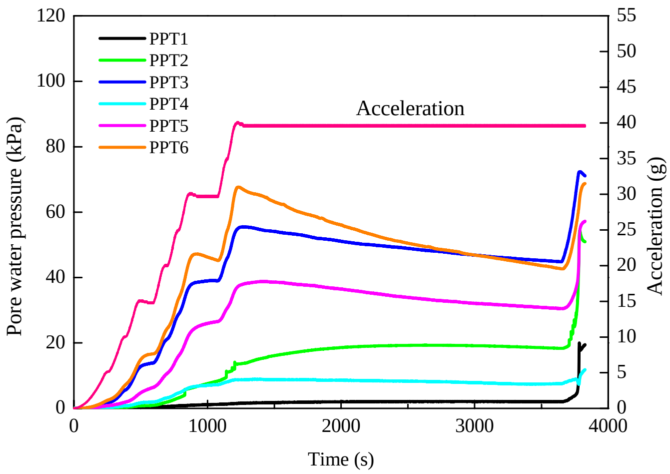

Fig. 6. Distribution of pore water pressure in centrifuge test.

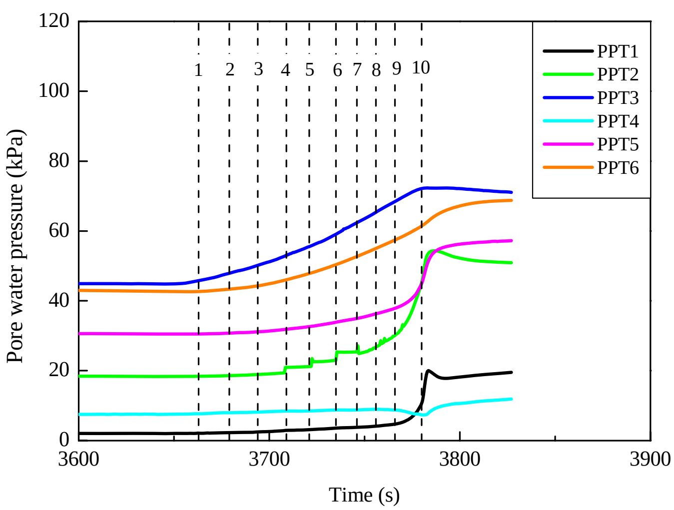

Fig. 7. Distribution of pore water pressure during the embankment construction.

Figures 6 shows the measured pore water pressures of the trench model during the centrifuge test. During the gravity turn on process from 1g to 40g, the rapid increase in pore water pressure can be observed. The pore water pressures reach to the equilibrium state after the consolidation as can be seen in the figure. Figures 7 shows the detail of distribution of pore water pressure during the embankment construction, the number on the line in the figure represents the corresponding number of the embankment layers. The rapid generation of positive pore water pressure can be clearly observed during the embankment construction and before the trench collapse. This phenomenon might be useful to predict the occurrence of the trench collapse in the future. From the centrifuge test results, it was verified that the trench collapse was mainly induced by the generation of positive pore water pressure due to the excessive surcharge load of excavated material.

NUMERICAL ANALYSIS

In this paper, the finite element method (FEM) analysis was carried out using PLAXIS (Brinkgreve *et al.*, 2004). The FEM analysis was based on the centrifuge model stress history and boundary conditions, thus allowing direct comparison of the results. The clay layer and sand embankment were modeled using a standard linear elastic-perfectly plastic Mohr-Coulomb model. The soil parameters used in the numerical analysis are Young's Modulus E = 2000 kPa, undrained shear strength c_u = 25 kPa, friction angle ϕ = 0°, unsaturated unit weight γ_{unsat} = 17 kN/m^3, saturated unit weight γ_{sat} = 18 kN/m^3, permeability k = 6.89×10^{-9} m/s for Fujinomori clay and E = 6000 kPa, c = 1 kPa, ϕ = 35°, γ_{unsat} = 16 kN/m^3, γ_{sat} = 20 kN/m^3 for Toyoura sand. The clay layer was assumed to behave as undrained to allow development of excess pore water pressures and the sand embankment was assumed to behave in a drained manner owing to the relatively high permeability. The undrained shear strength parameters of the clay layer were obtained from a number of unconfined compression tests. It should be noted that a small value of cohesion c = 1 kPa was specified for the sand embankment to avoid numerical instability near the toe of the embankment. The boundaries were horizontally restrained at lateral boundaries and fixed in both directions at the bottom boundary; for consolidation process the lateral boundaries were closed, allowing drainage at the water table and the bottom boundary only.

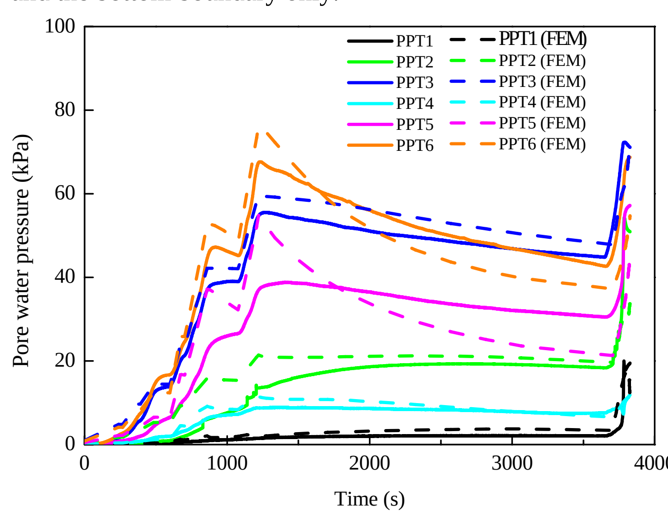

Fig. 8. Comparison of pore water pressures.

The calculation consists mainly of four phases. First the initial stress field of the trench model during the gravity turn on process (from 1g to 40g) was calculated by gravity loading that implement in PLAXIS. After the first calculation phase, a consolidation period of 40 minutes was introduced to allow the excess pore water pressure to dissipate. The third calculation phase is the embankment construction; the same construction sequence during the centrifuge model test was applied to the analysis. After each embankment layer was constructed, the safety analysis of the trench wall slope was performed using the Phi/c reduction calculation.

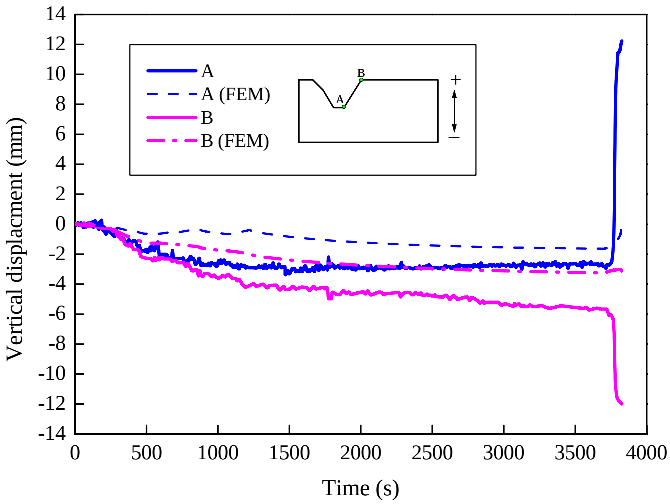

Fig. 9. Vertical displacement in centrifuge test and FEM.

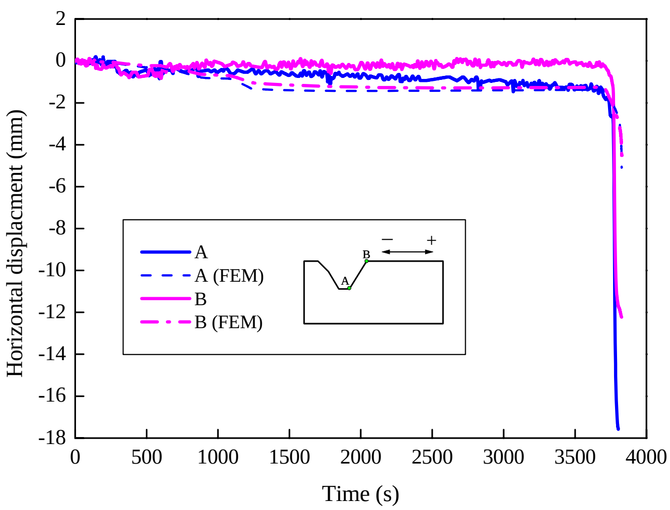

Fig. 10. Horizontal displacement in centrifuge test and FEM.

Comparison between the calculated and the measured pore water pressure shows that the pore water pressure in the trench model corresponded well in the centrifuge test and FEM analysis as presented in Fig. 8. Due to the limited space for installation of displacement transducer, the displacement of trench model was determined using the MOVIAS motion analysis software, which allows the automated tracking of target on the digital video. Figures 9 and 10 show the comparison of vertical and horizontal displacements between the centrifuge and FEM analysis at the toe (A) and crest (B) of the slope, respectively, good agreement of the displacements could be observed. The rapid increase in the vertical and horizontal displacements was clearly monitored just before the trench collapse. This behavior provides valuable information for development of warning system for the trench excavation in future. Table 1 shows the stability of the trench wall slope during the stockpiling of excavated material. It is clearly see that the safety factor of the slope decreases with the increasing height of the embankment, and the trench collapse occur after the 10^{th} layer of embankment (FS = 1.0). Based on the FEM analysis results, it was possible to simulate the centrifuge model test procedure by means of FEM analysis.

Table 1. Slope stability during embankment construction

Embankment layers	Factor of safety (FS)
0	1.68
1	1.67
2	1.57
3	1.47
4	1.36
5	1.28
6	1.21
7	1.14
8	1.08
9	1.03
10	1.00

CONCLUSIONS

The centrifuge model test was conducted to investigate the mechanism of trench collapse and to provide quantitative data for numerical validation. It was found that the excessive load of stockpiled material was a major reason of the trench collapse. Generation of pore water pressure, development of displacement and slope stability obtained from numerical analysis agree well with the centrifuge test results. The rapid increase of pore water pressure and displacement before the trench collapsed was clearly observed. This behavior provides valuable information for future design and development of effective measures to prevent the trench collapse in future.

ACKNOWLEDGEMENT

The authors would like to acknowledge the JSPS for providing the financial support for this research.

REFERENCES

Horii, N., Itoh, K., Toyosawa, Y., and Tamate, S. [2006]. “Development of the NIIS Mark-II geotechnical centrifuge”, *The 6th International Conference on Physical Modeling in Geotechnics*, Hong Kong, pp. 141-146.

Brinkgreve, R.B.J., Broere, W. and Waterman, D. [2004]. “*PLAXIS 2D Version 8 Manual*”. Delft, Netherlands.