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# Full-scale field testing: Opportunities and challenges through example case studies

T.M.H. Le & J.S. L'Heureux
*Department of Geotechnics and Natural Hazards, Norwegian Geotechnical Institute (NGI), Trondheim, Norway*

Y. Shin
*Department of Geohazards and Dynamics, NGI, Oslo, Norway*

C. Zwanenburg
*Technical University Delft, Delft, Netherlands*
*Department of Geo-engineering, Deltares, Delft, the Netherlands*

T. Peters
*Department of Geo-engineering, Deltares, Delft, the Netherlands*

**ABSTRACT:** Full-scale field testing is critical for benchmarking and validating geotechnical methods, hypotheses and solutions. Over the years, the Norwegian Geotechnical Institute (NGI) and Deltares have conducted full-scale field testing for various problems and geotechnical solutions including piles, suction bucket foundations, slopes, embankments, dikes, different soil investigation techniques and instrumentations. NGI has developed a set of six well-characterised geotest sites with various ground conditions specifically for field testing (i.e. clay, silt, sand, quick clay, permafrost and snow/avalanche). This paper presents the geotest sites and discusses the opportunities and challenges with full-scale field testing though our experiences. The experiences are exemplified with 2 case studies: a cut slope in cold climate in Norway and a dike failure in the Netherlands. The case studies show that full-scale field modelling can provide unique opportunities to investigate geotechnical problems in realistic operational environment without requirement for sample preparation and scaling laws. However, field models can be costly, time-consuming and dependent on the weather conditions. Integration of physical modelling between different scales (e.g. centrifuge testing, large-scale testing in the lab and field modelling) is therefore one of the keys to enable advancement of knowledge and innovative solutions from theory to practice.

**Keywords:** full-scale, field testing, test sites, field experiment, benchmark

## 1 INTRODUCTION

Full-scale field testing is critical for benchmarking and validating geotechnical methods, hypotheses and solutions. It is possible to conduct full-scale field test for almost any geotechnical problem. Full-scale field test is required before introducing, for example, a new soil investigation method or an innovative foundation design in the built environment. Full-scale field testing can be performed either in the actual operational environment or in well-characterised benchmark geotest sites. The former can be used for various reasons, for example if no suitable benchmark site is available. The latter can be cost-effective as it requires no or little additional soil investigation, and there is often data available from earlier tests for comparison and benchmarking.

Full-scale field testing provides unique opportunities to investigate geotechnical problems in realistic operational environment without requirement for sample preparation as opposed to controlled man-made condition such as in a centrifuge or a test pit. Results from full-scale field tests can be used directly and are not subjected to scaling laws. Due to the costs, site conditions and preparation time, a field test involving large structures is normally difficult to repeat. Integration of physical modelling between different scales can be used to supplement information and refine experiment design in order to achieve good results.

Over the years, the Norwegian Geotechnical Institute (NGI) and Deltares have conducted full-scale field testing for various problems and geotechnical solutions. NGI has developed a set of six geotest sites with different ground condition specifically for field testing (NGI, 2022). The NGI's geotest sites are integrated with a suite of 6 Geo-Centrifuges of different sizes and capabilities, a Geo-Model Container, a Static Liquefaction Tank, a Geotechnical Test Pit, a Large-scale Triaxial Apparatus and a Railway Track Simulator to provide opportunities for physical modelling at different scales in the EU-funded project GEOLAB (GEOLAB, 2022).

This paper will discuss the opportunities and challenges with full-scale field testing exemplified though two case studies: a cut slope model at the Øysand geotest site in Norway and a dike model in the Netherlands. These case studies demonstrate the employment of different instrumentation and technology for monitoring data in the field. The collected data were used as input parameters and calibrated numerical studies and back calculation of failure.

## 2 THE NGI'S GEOTEST SITES

The geotest sites research infrastructure is a unique research facility in Norway, established specially for field testing and modelling (Fig.1). These test sites are well-characterised and instrumented with basic monitoring system for pore pressure and temperature to provide field "laboratories" for the testing. The sites cover the different soil conditions and various geotechnical problems can be explored.

### 2.1 Soft clay geotest site – Onsøy

The Onsøy site provides field environment for testing in/on soft marine clays with over-consolidation ratio (OCR) decreases from about 4 near the surface to 1.2 at 30 m depth (Gundersen et al., 2019). The natural water content varies between 45 and 65%. Similar clays are found extensively in the Northern hemisphere, but also in Japan and southeast Asia. The Onsøy clay is also remarkably similar to clays found offshore at, for example, the Troll, Gjøa, Luva and Aasta Hansteen oil and gas fields.

### 2.2 Quick clay geotest site – Tiller

Deposits of sensitive marine clay can be found over large areas of Scandinavia and north America. Such deposits are extremely challenging for stability,bearing capacity and settlement. The Tiller-Flotten geotest site is composed of homogenous marine clay, defined as quick (remoulded strength less than 0.5 kPa) from 7 m below terrain and until a depth of 25m with sensitivity of about 150 (L'Heureux et al., 2019).

### 2.3 Silt geotest site – Halden

The Halden silt site consists of a uniform low plasticity marine silt up to 10 m thick. Such intermediate soils are challenging materials in geotechnical design. Soil classification charts suggest the Halden silt to be in the zones at the interface between "transitional soil" and "silt and low rigidity index '$I_r$ ' clays (Blaker et al., 2019).

### 2.4 Sand geotest site – Øysand

The Øysand test site provide testing environment for glaciofluvial and deltaic loose to medium dense sand. The deposit is approximately 20-25 m thick, relatively homogenous, and consists mostly of fine to medium uniform sand with predominance of quartz minerals, some plagioclase and micas (Quinteros et al., 2019).

### 2.5 Permafrost geotest sites – Svalbard

Two permafrost sites available for testing in Longyearbyen on Svalbard (Gilbert et al., 2019). These sites were selected as they are representative of the soil conditions in Svalbard and other Arctic locations. Field testing in permafrost investigate topics including, for example, effect of climate change, foundation methodology, site investigation techniques, embankment behavior, and artificial cooling systems in saline marine clays and intermediate permafrost soils.

### 2.6 Snow avalanche test site–Ryggfonn

Ryggfonn is one of the few full-scale avalanche paths in the world instrumented for full scale experiments. The avalanche path in Ryggfonn has a vertical drop of 900 m and a total length of about 2100 m. The size of the avalanches usually varies from 2 (small) to 5 (max, could destroy a village up to 40 ha) measured in the Canadian classification for avalanche and the avalanche speed can reach up to 60 m/s.

Fig. 1. Location of the geotest sites in Norway/Svalbard map.

## 3 Example 1: SLOPE STABILITY IN COLD CLIMATE

Climate change is forecasted to intensify seasonal freezing-thawing of soils. This can cause stability problem to infrastructures such as road, railways in countries with cold climate such as Norway. A field model of a man-made cut slope was generated in the Øysand geotest site in Norway to investigate slope stability under freezing-thawing cycles.

A slope area was identified based on a site investigation, laboratory tests, and numerical analysis specific for this study. A man-made cut slope was then generated and instrumented with a remote monitoring system to observe its behavior against the factors governing slope stability (Fig. 2). Monitoring was carried out between November 2019 and March 2020. The soil conditions and monitored data were used to calibrate the coupled thermal-hydro-mechanical numerical model in GeoStudio, see Shin et al. (2020) for details.

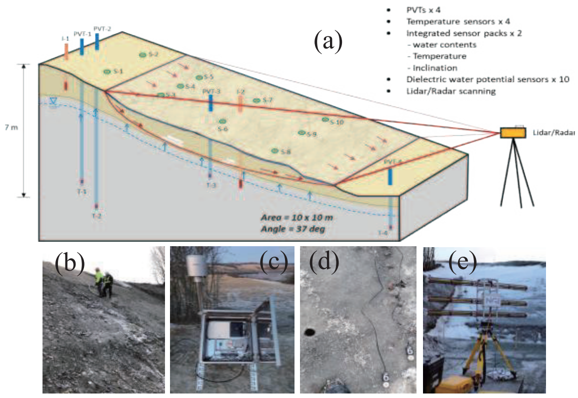

Fig. 2. Test slope at Øysand Trondheim Norway: (a) layout of sensor locations; (b) inclinometer installation on 37 degree man-made test slope; (c) data logger box at top of the slope; (d) MPS-6 sensors; (e) Lidar system.

Fig. 3. Man-made slope in Øysand site before (left, November 2019) and after failure (right, April 2020)

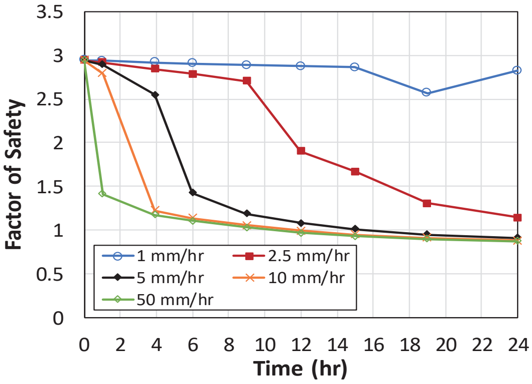

Fig. 4. Calculated factor of safety for the tested slope against different rainfall intensities.

The study shows that the slope stability was only slightly impacted by the freezing–thawing cycle during the monitoring period when air temperature varied between -10 and +20 °C. The slope failed in April 2020 after a heavy precipitation event (Fig. 3) but it was not possible to recover key monitoring data due to malfunction of sensors damaged by the failure. Back-calculations showed that the most likely cause was heavy rainfall with intensity over 5 mm/hr which increased pore water pressure and decreased the matric suction (Fig. 4). This resulted in reduction of shear strength leading to failure.

The study demonstrated that field model testing could capture the freezing-thawing cycles and rainfall infiltration. Furthermore, since the ground condition is already well-characterised, only a minimum of additional site characterization was needed. The challenge with field modelling is illustrated by loss of data during failure in April 2020. Costs and required construction time prevented rebuilding of the slope and continuation of the test with new sensors immediately. The captured data and behavior however provide important background for designing new experiments with field testing of slope at Øysand test site in the future.

## 4 Example 2: DIKE STABILITY – ORGANIC SOILS

A considerable part of the Dutch population lives in the areas that are vulnerable to flooding. The consequences of climate change and the corresponding sea level rise requires therefore continuous update and regular improvement of dikes. In this process the increasing urbanization forms a complicating factor, reducing the space for dike improvement and increasing the risk for damaging private property when building dike reinforcements. Consequently, the accuracy of geotechnical design methods for dikes and required improvements is under constant debate. This resulted in the execution of several field trials. Some of these field trials contained tests on old dikes that were no longer in use, e.g. Van et al (2005), Zwanenburg et al (2012), Muraro (2019), Breedeveld et al (2019), while other trials include embankments made for the purpose of testing, e.g. Zwanenburg et al (2012), Zwanenburg & Jardine (2015).

An example is the IJkdijk project, which focused on the question of how modern sensor technology could be used in early warning systems for dike failure. The project included piping and slope stability failure modes, for which different trial embankments were built. The trial embankment for slope stability was 6 m in height, 100 m in length with a slope angle of 1(V): 1.5(H). This embankment consisted of a sandy core with a clay cover. The sub soil contained 2 - 3 m thick peat deposit underlain by a Pleistocene sand layer (Zwanenburg et al 2012). The trial embankment was built and safely brought to failure in a controlled manner shortly after completion of construction. The study not only provided information on the application of sensor technology for early warning of dike failure but also provided the opportunity to test geotechnical prediction models.

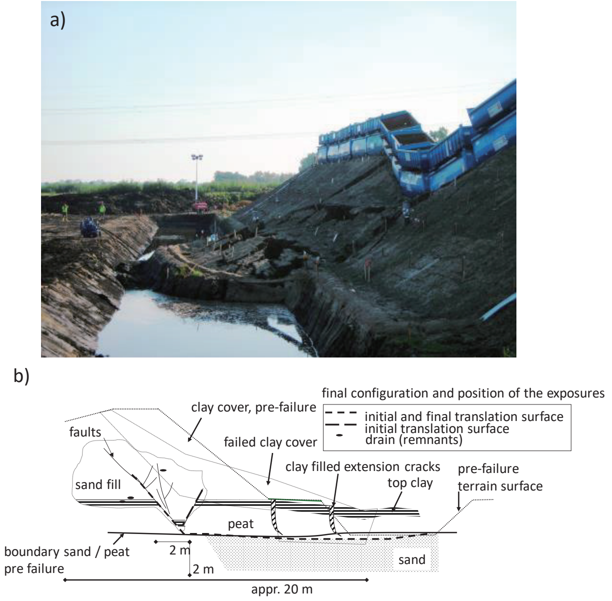

Fig. 5. a) Failure of the IJkdijk test embankment, the blue containers represent an additional loading mechanism b) deduced failure mechanism, from: Zwanenburg et al (2012)

The failure, Fig. 5a, was induced by excavating the peat and organic clay layer at the toe followed by infiltration of water in the sandy core. It should be noted that the excavation represents the ditch which is typically present at the inner toe of a dike. The containers, placed at the crest, could be filled remotely adding extra weight to the dike. Infiltration of the sandy core caused failure, thus loading by filling the containers was not needed.

After securing the situation, the embankment and sub soil were partly excavated to establish the failure mechanism (Fig. 5b). A numerical simulation of the test is presented by Den Haan & Feddema (2011). The failure mechanism is dominated by lateral displacement of the peat layer, with a horizontal sliding plane at the transition between the peat and Pleistocene sand. The results are consistent with other field trials including organic soil which showed that failure planes are typically found at the transition of soft organic layers and the stiffer sandy layers, (Muraro, 2019). Therefore, circular shaped sliding planes, which are typically used in limit equilibrium methods, should be applied with care in these conditions as they do not represent the shape of the failure plane correctly.

## 5 CONCLUSIONS

This paper outlines the opportunities and challenges with full-scale field testing through two example cases. Field testing provides unique possibility to test any geotechnical problems without requirement for sample preparation and limitation by scaling laws. The use of benchmark test sites can be advantageous as the ground condition is well-characterised and supplementary data from previous studies is available. Well-designed experiments with using, for example, centrifuge model or laboratory physical model in test pit or previous field test as preliminary studies, is the key for obtaining useful and good results from full-scale field testing.

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## REFERENCES

Blaker, Ø., Carroll, R., Paniagua, P., DeGroot, D. J. & L'Heureux, J.-S. (2019). Halden research site: geotechnical characterization of a post glacial silt. *AIMS Geosciences,* 5(2)**,** pp.

Breedeveld J., Zwanenburg C., Van M., Langkeek H.J., (2019) Impact of the Eemdijk full-scale test programme, Proceedings of the XVII ECSMGE-2019 DOI: 10.32075/17ECSMGE-2019-0398 8

Den Haan E.J., Feddema A. (2011) Deformation and strength of embankments on soft Dutch soil *Geotechnical engineering*, dx.doi.org/10,1680/geng.9,00086

GEOLAB. 2022. *Science for enhancing European's Critical Infrastructure* [Online]. Available: https://project-geolab.eu/.

Gilbert, G. L., Instanes, A., Sinitsyn, A. O. & Aalberg, A. (2019). Characterization of two sites for geotechnical testing in permafrost: Longyearbyen, Svalbard. *AIMS Geosciences,* 5(4)**,** pp 868-885.

Gundersen, A. S., Hansen, R. C., Lunne, T., L’Heureux, J.-S. & Strandvik, S. O. (2019). Characterization and engineering properties of the NGTS Onsøy soft clay site. *AIMS Geosciences,* 5(3)**,** pp 665-703.

L'Heureux, J.-S., Lindgård, A. & Emdal, A. (2019). The Tiller-Flotten research site: Geotechnical characterization of a very sensitive clay deposit. *AIMS Geosciences,* 5(4)**,** pp 831-867.

Muraro S. (2019) The deviatoric behaviour of peat: a route between past empiricism and future perspectives *PhD thesis* Technical University Delft

NGI. 2022. *NGTS - Norwegian Geotest Sites* [Online]. Available: https://www.ngi.no/eng/Projects/NGTS-Norwegian-Geo-Test-Sites.

Quinteros, S., Gundersen, A., L'Heureux, J.-S., Carraro, J. A. H. & Jardine, R. (2019). Øysand research site: Geotechnical characterisation of deltaic sandy-silty soils. *AIMS Geosciences,* 5(4)**,** pp 750-783.

Shin, Y., Choi, J. C., Quinteros, S., Svendsen, I., #039, Heureux, J.-S. & Seong, J. (2020). Evaluation and Monitoring of Slope Stability in Cold Region: Case Study of Man-Made Slope at Øysand, Norway. *Applied Sciences,* 10(12)**,** pp 4136.

Van M.A., Koelewijn A.R., Barends F.B.J. (2005) Uplift phenomenon: Model, Validation and Design International Journal of Geomechanics 2005.5:98-106

Zwanenburg C., Den Haan E.J., Kruse G.A.M., Koelewijn A.R. (2012) Failure of a trial embankment on peat in Booneschans, the Netherlands Géotechnique 62 no 6, p 479-490 DOI: 10.101680/geot.9.P.094

Zwanenburg C., Jardine R.J., (2015) Laboratory, in situ and full-scale load tests to assess flood embankment stability on peat, Géotechnique 65 no 4, DOI: 10.1680/geot,14.P257 309-326