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Validation of explicit method to predict accumulation of strain during single and multistage cyclic loading

Validation d'une méthode explicite pour prédire l'accumulation de déformation lors d'un chargement cyclique à une ou plusieurs étapes

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ABSTRACT: The present paper validates an innovative explicit method to predict the accumulation of soil deformation during cyclic loading condition. The accumulation of strains is produced by reducing a fictive elastic shear modulus of the soil based on cyclic contour diagrams. This connection is integrated into the finite element software PLAXIS 3D by means of a remote scripting interface. The paper will provide an insight into how to interpolate the permanent shear strain in 3D cyclic contour diagrams from single-stage cyclic tests with a sand, which is typical for the North Sea. A mathematical framework is proposed which helps to ease the interpolation. After this, the validation of the link between the stiffness degradation method and the 3D cyclic contour diagram is provided by modeling single stage tests in PLAXIS 3D. Further, the explicit method is compared against multistage tests to understand the link between the stress history of cyclic stress parcels.

RÉSUMÉ: Le présent article valide une méthode explicite innovante permettant de prédire l'accumulation de déformations du sol sans des conditions de chargement cycliques. L'effet de l'accumulation de déformation est pris en compte en réduisant un module de cisaillement élastique fictif du sol sur la base de diagrammes de déformation cycliques. Cette connexion est intégrée au logiciel de calcul par éléments finis PLAXIS 3D au moyen d'une interface de script à distance. L'article explique comment interpoler la déformation plastique moyenne sur des diagrammes de déformation cycliques 3D à partir d'essais cycliques à une étape pour un sable typique de la mer du Nord. Un cadre mathématique est proposé pour faciliter l'interpolation. La validation du lien entre la méthode de dégradation de la rigidité et le diagramme de déformation cyclique 3D est fournie par la modélisation des tests à une étape dans PLAXIS 3D. En outre, la méthode explicite est comparée à un test à plusieurs étapes pour comprendre le lien entre l'historique des contraintes de parcelles de contraintes cycliques.

Keywords: Finite element modelling; cyclic loading; strain accumulation; explicit method

1 INTRODUCTION

The design of foundation structures for offshore wind turbines requires assessment of the soil-structure-interaction (SSI) subjected to cyclic loading conditions (DNV-GL, 2017). It must be ensured that the rotational accumulation does not exceed the limit prescribed by the wind turbine manufacturer and that a possible pore pressure build up is not affecting the stability of the foundation. Being able to accurately verify these requirements leads to an improved risk assessment of the foundation structure and an optimization of the design of offshore foundations.

It is common practice to gather information about the cyclic behavior of soil by means of cyclic laboratory tests. Mainly stress-controlled cyclic direct simple shear tests or cyclic triaxial tests are performed. Often the response of the soil is tested under undrained conditions (constant volume). Different regular cyclic loading packages with varying average and cyclic stresses are tested in relation to the possible stress variation, which the soil will be exposed to during the design storm event. Engineering judgement, experience from previous projects, simplified models and three-dimensional finite element models (3D FEM) can help to extract the stress conditions appropriate for the laboratory test campaign.

Reliable methods are needed to make use of the obtained information from the laboratory test campaign to predict the behavior of the soil under the design load scenario (i.e. significant storm event or earthquake event). Occasionally a "soil fatigue model" is used in geotechnical engineering projects. One model of this type, also recommended by DNV-GL, is the cyclic contour diagram established with laboratory testing of the investigated soil material.

Different cyclic contour diagrams can be established for different “fatigue variables” such as:

- Average and cyclic plastic strain
- Average and cyclic pore pressure
- Damping
- Dynamic stiffness
- Post-cyclic stiffness

Based on the considered geotechnical verification, e.g. verification of permanent rotations/displacements, liquefaction analysis or dynamic analysis, different assumptions can be made for the final assessment of the SSI under cyclic loading.

The construction of the cyclic contour diagrams is a challenge because it is derived from a three-dimensional interpolation of data from usually only a few cyclic laboratory tests. Moreover, those diagrams must be integrated in a 3D FEM domain to quantify a realistic stress level distribution and hence allow for a better assessment of the foundation behavior under cyclic loading conditions.

Finally, the irregular load series of the selected storm event is broken down to a series of ascending parcels with constant mean and amplitude loads and number of cycles. This stress history is usually considered by utilizing the "equivalent number of cycles"-procedure.

This paper validates the method explained in Zorzi et al. (2018) which predicts the strain and displacement accumulation for a severe storm event. It is based on 3D cyclic contour diagrams in which the fatigue variable is the permanent shear strain. The integration in the 3D FEM model is done by means of a stiffness degradation of the soil in a cluster-wise division. The software PLAXIS 3D 2017 was used for this integration because it allows the use of a remote scripting interface.

This method has shown different advantages, such as, flexibility for automating the design and the application on different types of offshore foundations (Zorzi et al., 2018). The present paper will explore the behavior of the method closely for single and multistage cyclic laboratory tests.

The creation of cyclic contour diagrams from single stage tests is presented for a sand, which is typical for the North Sea environment. A mathematical framework is proposed, which can help to reduce the uncertainty and ease the interpolation procedure. The link between the stiffness degradation method and the strain contour diagrams is validated based on the single stage cyclic laboratory tests. Lastly, the explicit method is compared to multistage cyclic laboratory tests test to investigate the link between the stress history of the parcels.

2 FATIGUE CONTOUR DIAGRAMS

A series of single and multiple stage two-way cyclic simple shear tests have been performed at the Soil Mechanics Laboratories of the Technical University of Berlin. The tests have been performed on a soil reconstituted to a relative density of 90% and with a granulometric curve of $d_{0\%}$ = 0.06 mm, $d_{50\%}$ = 0.2 mm and $d_{100\%}$ = 2 mm.

The tests were carried out undrained (constant volume) with different average and amplitude stresses. Prior to cyclic loading the soil was consolidated to a vertical consolidation pressure of 200 kPa. No pre-shearing was done prior to the cyclic loading. The average stress was applied under drained condition. Table 1 presents an overview of the test campaign. The Average Stress Ratio (ASR), which is defined as the ratio between the average shear stress and the vertical effective stress in the tests, ranges from 0.00 to 0.26, while the Cyclic Stress Ratio (CSR), which is the ratio between the cyclic shear stress and vertical effective stress in the tests, ranges from 0.02 to 0.26. The present methodology is focused on the prediction of the strain accumulation. Therefore, the fatigue variable extracted from the tests was the *accumulated permanent shear strain*, γ_p, at the end of each stress cycle.

Table 1. Summary of the test campaign.

# Test	ASR	CSR
1	0.000	0.029
2	0.029	0.029
3	0.058	0.029
4	0.087	0.029
5	0.000	0.058
6	0.058	0.058
7	0.116	0.058
8	0.174	0.058
9	0.000	0.116
10	0.116	0.116
11	0.232	0.116
12	0.000	0.232
13	0.232	0.232

All data was assembled in a three-dimensional matrix (ASR, CSR, number of cycles *N*) and a three-dimensional interpolation of γ_p was done to map the entire 3D space. Due to the variability of the data, a mathematical formulation had to be fitted. Different two-dimensional slices at different ASR were extracted. In each slice a power law function for different strain levels was calibrated. The power law function is in the form of Equation (1).

$$CSR = a * N^b + c \quad (1)$$

The parameter b represents the shape of the curve, a is a scaling factor and c is the intersection with the CSR axis.

The fitting of a mathematical formulation provides smooth diagrams avoiding the test uncertainties to cause an unrealistic shape of the cyclic contour diagrams.

During the fitting procedure, the shape parameter b has been kept constant at -0.35 for the different strain levels and different ASR.

Figure 1 and Figure 2 show a satisfactory agreement between the power law fit and the laboratory measurements.

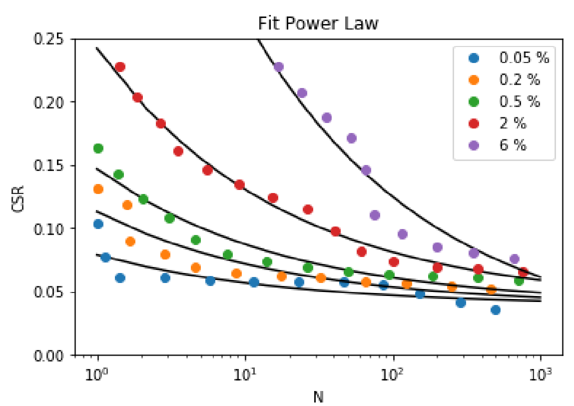

Figure 1. Two-dimensional slice showing curves of average shear strain versus the number of cycles and CSR. ASR=0.06.

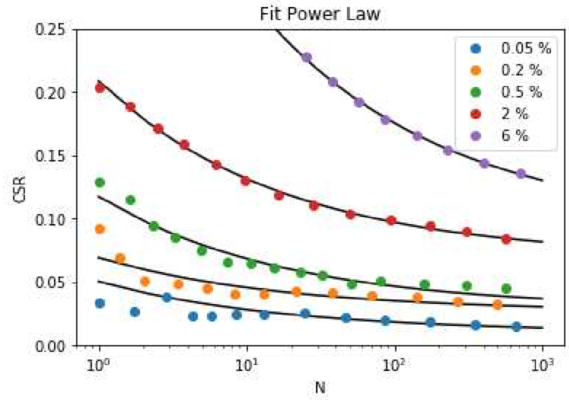

Figure 2. Two-dimensional slice showing curves of average shear strain versus the number of cycles and CSR. ASR=0.22.

Boukpeti et al. (2014) also adopted a power law function to approximate the strain contour diagrams of carbonate silt sediments. In this case the shape factor *b* was calibrated for different strain surfaces as well, and the values for the different strain contours were found to vary from -0.40 to -0.37. This is supporting the assumption that keeping the shape factor constant and further the chosen value of -0.35 is in good agreement with Boukpeti et al. (2014).

Finally, the functions for each slice are grouped together and interpolated between each other to establish a smooth final 3D matrix.

3 VALIDATION WITH SINGLE STAGE TESTS

The first validation is done against the single stage tests used in Table 1. The link of the stiffness degradation approach with the 3D cyclic contour diagram is validated by modelling different simple shear tests in PLAXIS 3D and comparing the predictions to the laboratory test results.

3.1 3D FEM model of simple shear test

The simple shear tests used in section 2, are modelled as a cube with sides of 1 m in length. A coarse mesh is used to speed up the computation. The linear elastic perfectly plastic Mohr-Coulomb model, cf. PLAXIS (2017), is used. The soil parameters (Table 2) are calibrated against monotonic simple shear tests with the same relative density and vertical effective stress as used for the cyclic tests.

Table 2. Soil model parameters.

Soil Parameters	**Values**
G [MN/m^2]	30.0
ν [-]	0.2
φ [°]	36.0
ψ [°]	0.0
γ_{sat} [kN/m^3]	18.0
γ_{unsat} [kN/m^3]	9.0

The modelling of the shear tests in finite element calculation was carried out in three steps:

1. Initialization of a unit soil cube
2. Application of the vertical load (200 kPa) to reach the K0-consolidation. The bottom of the cube is fixed in all directions, the sides of the cube are fixed in the normal direction and the top of the cube is not fixed.
3. Application of surface displacement along X-axis (red axis in Figure 3). At the top of the model, a uniform displacement is applied and at the sides, the displacement varies linearly from zero at the bottom to the maximum value at the top.

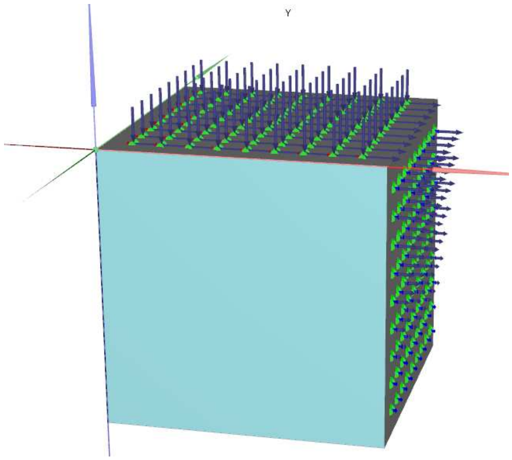

Figure 3. FE model of cyclic direct simple shear test.

Due to the presence of stress concentrations along the boundaries on the FEM model, a small soil volume in the center has been considered, which ensures a uniform stress and strain distribution. The inner soil volume is a cube with side lengths of 0.5 m as shown in Figure 4.

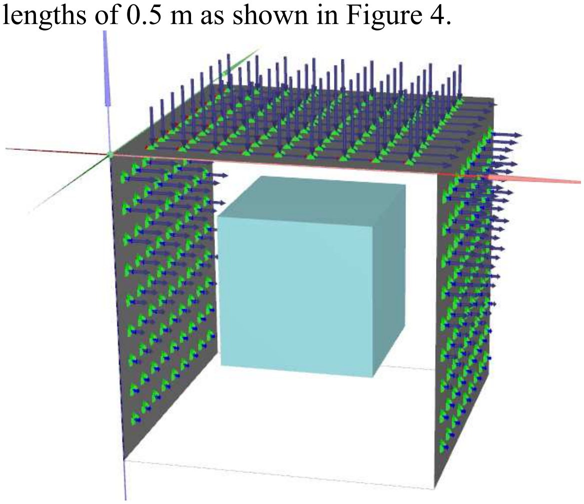

Figure 4. Illustration of inner soil volume in FE model.

3.2 Validation of the method

The concept of the stiffness degradation method is to degrade the initial stiffness based on the accumulated plastic strain extrapolated from the contour diagrams at a certain stress level. This procedure is shown in Figure 5. The blue line represents an idealization of the cyclic test, the thick black line with an initial shear stiffness of G_{ini} is the assumed linear elastic behavior. G_N is the degraded fictive stiffness which leads to an accumulation of strain of $\gamma_{ini} + \gamma_n$.

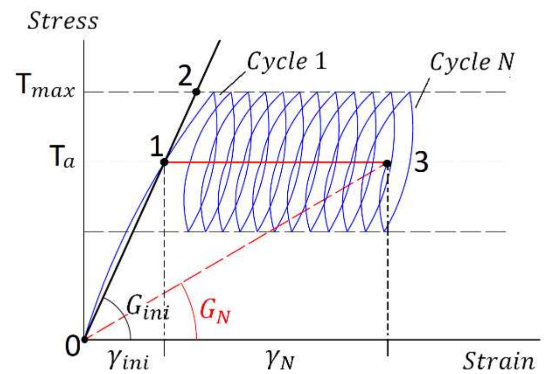

Figure 5. Stiffness degradation concept.

The following procedure has been applied in the numerical model:

0. Initialization of the sample and K0-consolidation
    a. Average of the cartesian stress and strain tensor in the inner soil volume ($\boldsymbol{\sigma}_{ini}$, $\boldsymbol{\varepsilon}_{ini}$).
    b. Average of the vertical effective stress σ_v.
1. Shearing of the sample until T_a (from phase 0).
    a. Average of the cartesian stress and strain tensor in the inner soil volume ($\boldsymbol{\sigma}_{avr}$, $\boldsymbol{\varepsilon}_{avr}$).
    b. Subtraction of the initial stress and strain (from 0.a).
    c. Principal stress transformation in which $\tau_a = \tau_{max}$, $\gamma_{ini} = \gamma_{max}$.
2. Shearing of the sample until T_{max} (from phase 1).
    a. Average of the cartesian stress tensor in the inner soil volume ($\boldsymbol{\sigma}_{max}$).
    b. Subtraction of the average stress (from 1.b).

c. Principal stress transformation in which $\tau_{cly} = \tau_{max}$,
d. Extrapolation of γ_N from the contour diagram based on τ_a, τ_{cly}, σ_v and N.

3. Degradation of the initial stiffness and shearing of the sample until T_a (from phase 0).

Figure 6, Figure 7 and Figure 8 show the cyclic loading test results in blue for different stress levels. The FEM monotonic behavior with G_{ini} = 30 MPa is shown in black. The dashed red line is the FEM monotonic behavior with the degraded fictive stiffness. The yellow square is the predicted strain.

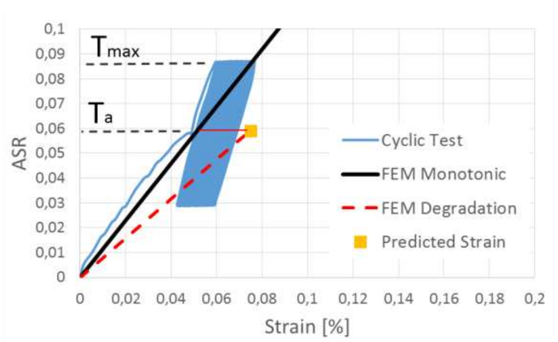

Figure 6. Comparison between FE predictions and laboratory tests for single-stage test with ASR=0.058, CSR=0.029 and N=800.

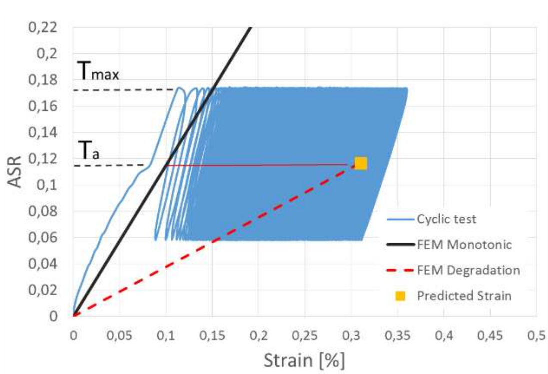

Figure 7. Comparison between FE predictions and laboratory tests for single-stage test with ASR=0.11, CSR=0.058 and N=200.

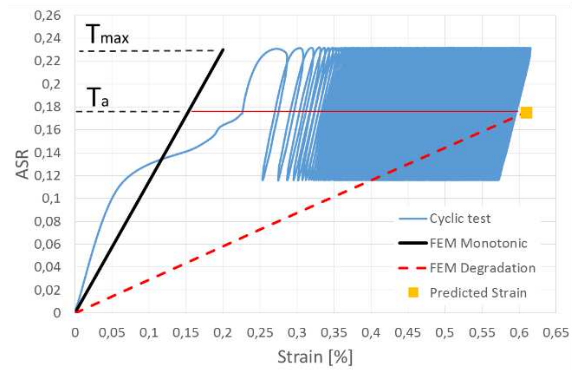

Figure 8. Comparison between FE predictions and laboratory tests for single-stage test with ASR=0.17, CSR=0.058 and N=500.

The FE model utilizing the explicit degradation method provides satisfactory results as a good agreement with the laboratory tests are obtained.

4 VALIDATION AGANST MULTISTAGE TESTS

A validation of the explicit method against two multistage cyclic direct simple shear tests have been performed. This validation is relevant to elucidate the methods capability to simulate load events with varying magnitude such as a design storm event. The multistage cyclic tests consist of three identical stages (in terms of stress level and number of cycles).

For one multistage test, the pore water pressure was allowed to dissipate after the application of each load parcel. This test can be related to the behavior of the foundation during the lifetime for which it is likely that pore pressure can dissipate between storm events.

The second test was done without re-consolidation between each parcel. This case can be related to the behavior of soil during a single design storm event in which the soil condition can be assumed (close to) undrained.

Table 3 summarizes the test conditions for the two tests.

Table 3. Summary of the cyclic stages for the two multi-stage tests. Similar stress levels and number of cycles was adopted for the two tests.

Stage no.	**ASR/CSR**	N	σ'_v	**ID**
1	0.029/0.029	500	200	90
2	0.058/0.058	500	200	90
3	0.116/0.116	100	200	90

The explicit method considers the accumulation procedure denoted as "Method 2" in Zorzi et al. (2018). For this method, the stress history is modelled by means of the number of equivalent load cycles. This value is extracted independently from the cyclic contour diagram based on the actual stress level and the previous strain that the soil has already experienced. For example, the equivalent number of load cycles for load parcel 2 shall be determined such that the permanent strains accumulated for load cycles with stresses corresponding to load parcel 2 equals the permanent strains of all the previous load parcels.

4.1 Inter-parcel with consolidation

Figure 9 shows the accumulation of strain versus the number of cycles. The equivalent number of cycles from the accumulation procedure is predicted to 1 for load parcel 2 and 3. This means that the stress level of the following parcel is reaching the accumulated deformation in the first cycle. This low number of equivalent load cycles is predicted due to the significant difference in cyclic stresses between the three considered stages.

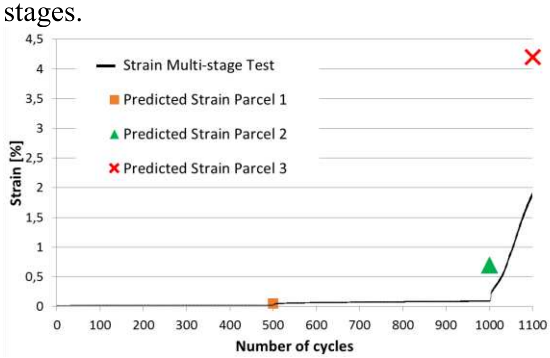

Figure 9. Strain accumulation: Multistage test vs predicted strain.

It is observed that the explicit method overpredicts the accumulated cyclic strain. This is caused by the changes in soil fabric due to the pore water pressure dissipation between cyclic stages. The explicit method does not account for this effect.

4.2 Inter-parcel without consolidation

The second cyclic test was performed without consolidation between cyclic stages. For this test a better agreement is found between the predictions of the explicit method and the laboratory results, cf. Figure 10.

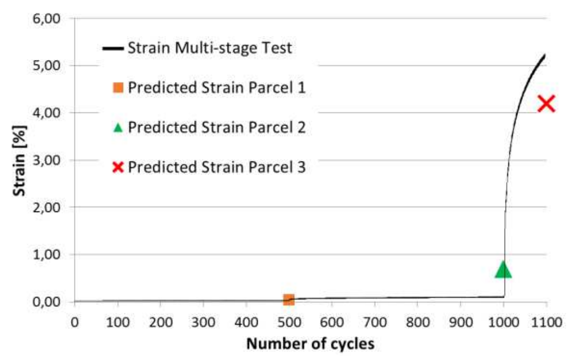

Figure 10. Strain accumulation: Multistage test vs predicted strain

5 CONCLUSIONS AND FUTURE RESEARCH

The paper shows that the linking between the stiffness degradation method and the 3D cyclic contour diagrams is a valid and simple method to predict the soil deformation under regular one-staged cyclic loading conditions.

The explicit method has also been compared to multistage cyclic tests. Here, the method in its current form is not applicable for cyclic laboratory tests allowing pore-pressure dissipation between cyclic stages. However, the method has shown to provide a reasonable match with a multistage laboratory test which does not allow pore-pressure dissipation between cyclic stages. As pore-pressure will likely not dissipate during a design storm event, whilst it will likely dissipate between significant storm events, the explicit method is expected to provide accurate predictions for single storm events.

It is noted that the method has only been validated against two multistage tests and that these tests were performed with a significant variation in stress conditions between the cyclic stages. To further validate the explicit method, additional multistage cyclic laboratory tests will be performed and compared against the explicit method.

6 ACKNOWLEDGEMENTS

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