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Post-cyclic shear strength of Warsaw tills – a pilot study

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Shear strength of the soil is one of the most important soil properties. The paper presents the result of a series of laboratory monotonic and cyclic triaxial tests carried out to study the effect of cyclic loading on the monotonic shear strength of till deposits. A dynamic triaxial testing system was used to investigate the undrained shear resistance of undisturbed soil samples taken from the Nowoursynowska testing field in Warsaw.

Key words: till, cyclic loading, post-cyclic strength, dynamic triaxial testing system

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INTRODUCTION

Soil strength degradation under dynamic loads often results in a damage to buildings and engineering structures. The behaviour of soils under dynamic loading is different from the behaviour of soils under monotonic loading because excessive settlement, liquefaction, pore pressure generation cause bearing capacity reduction. As documented in numerous studies, soil response to cyclic loading ranges from a complete loss of strength due to liquefaction of saturated sands (Seed, Peacock, 1971) to an increase or decrease of strength in clays (Seed, Chan, 1966; Andersen, 1983; Kaczynski, 1987).

There are a wide variety of environmental situations in which soils are subjected to dynamic loading, such as earthquakes, sea wave loading, machinery vibrating or traffic loading. The majority of the published data deal with earthquake and wave loading conditions (Vucetic, Dobry, 1988; Erken, Ulker, 2007; Moses et al., 2003), since ocean engineering has been developing rapidly in the last decades. In onshore conditions, especially in aseismic areas, the most important role is played by loadings caused by traffic and heavy machinery (Gadeikytė, 2007).

Determination of static undrained shear strength reduction before and after applying dynamic loading is reported in this pilot study. Monotonic and cyclic tests were conducted on undisturbed soil specimens. Post-cyclic shear strengths were evaluated after various cycles of dynamic loading and compared with data on pre-cyclic undrained shear strength.

SOIL TESTS

For this study, samples of till were obtained from boreholes drilled in the Nowoursynowska testing field in Warsaw, Poland. It is a lodgement till of Middle Polish Glaciation (Trzcinski, 1998). The index properties of Nowoursynowska Lodgement Till (NWT) are presented in Table 1. These properties indicate that NWT is classified as stiff, sandy clay of low plasticity.

Soil samples were taken from a depth of 2.5 to 3.0 m below the ground surface.

Table 1. **Index properties of test soil**

Properties	
Natural moisture content *m*, %	11.9
Liquid limit w_l, %	23.0
Plastic limit w_p, %	12.5
Plasticity index *PI*, %	10.5
Consistency index *CI*,	0.96
Specific density ρ_s, Mg/m³	2.66
Volume density ρ, Mg/m³	2.17
Clay, %	10
Silt, %	21
Sand, %	69

TESTING METHOD

Soils were tested using a dynamic triaxial testing system (DYNTTS), a combined triaxial cell and dynamic actuator, the axial force and axial deformation being applied through the base of the cell.

For the strength study, undrained triaxial monotonic shear tests under strain-rate control conditions (0.016%/min) were conducted.

In undrained cyclic tests, all samples were subjected to two-way cyclic loading with a sine input wave form under displacement control conditions. Considering the highest recorded values of the acceleration of traffic vibration in the Nowoursynowska area (Kaczynski i in., 2008), cyclic axial loads with a 10 Hz frequency and a double amplitude DA = 0.4 mm were applied.

SPECIMEN PREPARATION

All tests were run on the cylindrical specimens minimum 72 mm high and 35 mm in diameter, carefully cut from an undisturbed tube sample. Specimens were sealed in a rubber membrane and confined in a triaxial chamber.

Every test was conducted starting with saturation by applying simultaneous increase of the chamber and back pressure in steps. The measurement value of parameter B was determined when the saturation was complete. Then the specimens were consolidated isotropically with a desired effective stress. Then the consolidation loading was applied, monotonically in the static test and cyclically in the dynamic test.

TESTING PROGRAMME

The testing programme consisted of three series, each designed to investigate a particular effect of the undrained static or post-cyclic behaviour of NWT.

Series I included the undrained triaxial monotonic shear test.

Series II included the undrained triaxial cyclic test followed by the undrained triaxial monotonic shear test. 20,000 cycles were applied in the dynamic phase.

Series III included the undrained triaxial cyclic test followed by the undrained triaxial monotonic shear test. In this series, 200,000 cycles were applied in the dynamic phase.

In each series, specimens were consolidated with various effective stress σ'_c: 100, 200 and 400 kPa, respectively.

RESULTS AND DISCUSSION

The results of undrained static shear tests are shown for the relationships between deviator stress $\sigma_1-\sigma_3$ versus axial strain ε, principal stress ratio σ'_1 / σ'_3 versus axial strain ε, and pore water pressure change Δu versus axial strain ε (Figs. 1–3) for each series.

For each specimen the maximum value of principal ratio σ'_1 / σ'_3 was located and denoted as a moment of failure by $(\sigma'_1 / \sigma'_3)_f$ (Head, 1986). Sets of values corresponding to the point

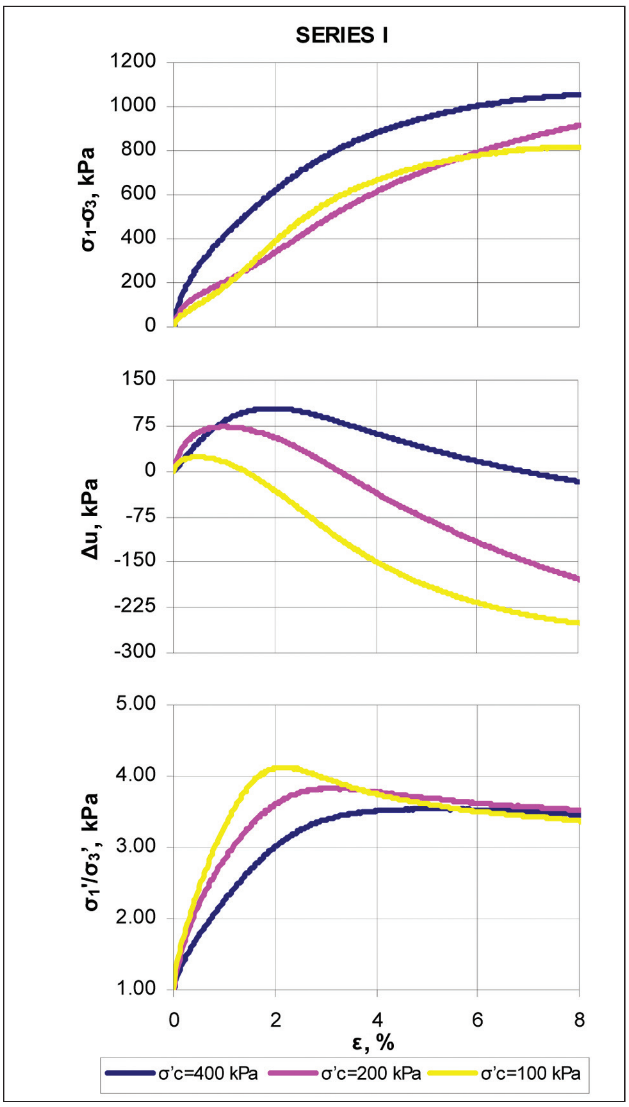

Fig. 1. Relationships between deviator stress $\sigma_1-\sigma_3$, pore water pressure change Δu, and principal stress ratio σ'_1 / σ'_3 versus axial strain ε for Series I.
σ'_c – effective stress at consolidation

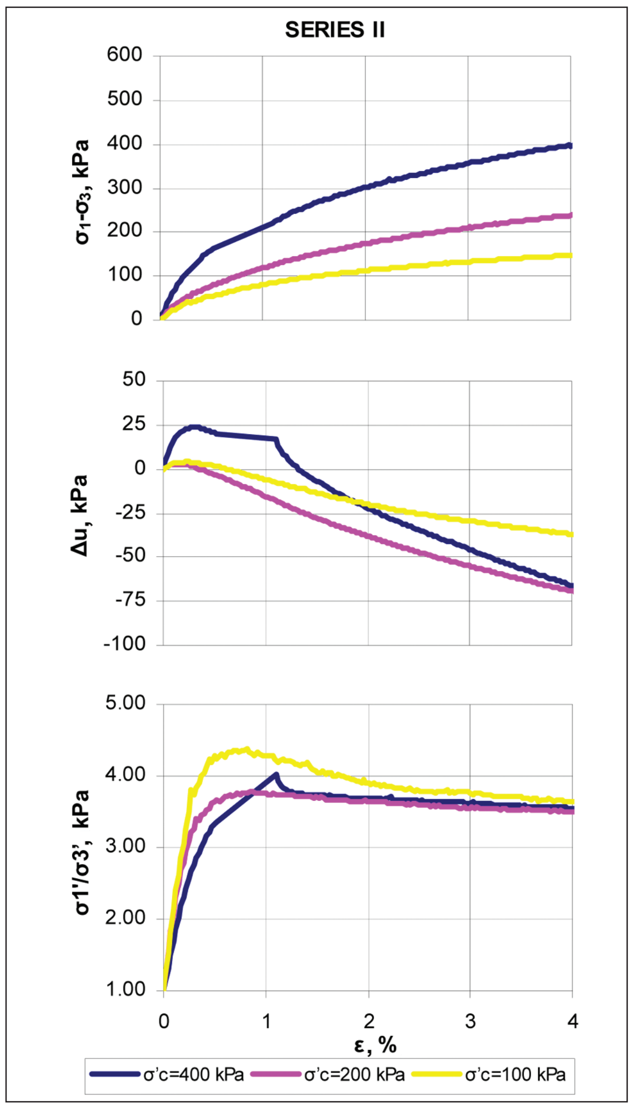

Fig. 2. Relationships between deviator stress $\sigma_1-\sigma_3$, pore water pressure change Δu and principal stress ratio σ'_1 / σ'_3 versus axial strain ε for Series II.
σ'_c – effective stress at consolidation

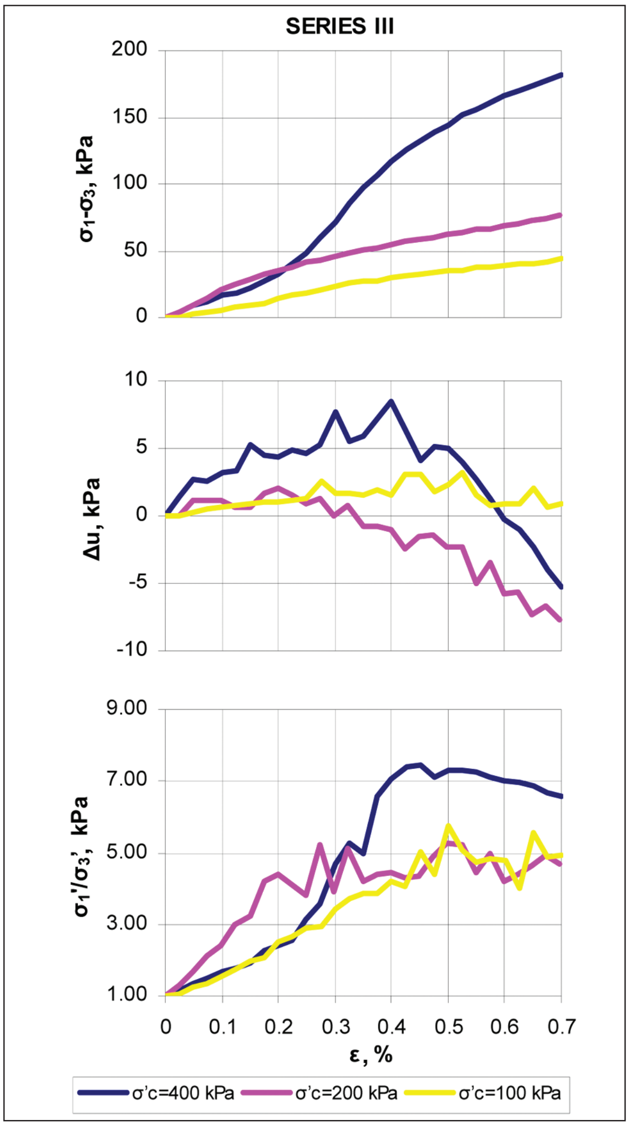

Fig. 3. Relationships between deviator stress $\sigma_1 - \sigma_3$, pore water pressure change Δu and principal stress ratio σ'_1 / σ'_3 versus axial strain ε for Series III. σ'_c – effective stress at consolidation

Table 2. **Failure conditions in undrained static shear tests**

σ'_c	$(\sigma'_1 / \sigma'_3)_f$	ε_f	$0.5(\sigma_1 - \sigma_3)_f$	$0.33(\sigma'_1 + 2\sigma'_3)_f$
kPa		%	kPa	kPa
		Series I		
100	4.13	2.14	207.09	270.55
200	3.84	3.20	257.62	353.32
400	3.55	5.13	480.56	697.94
		Series II		
100	4.38	0.82	36.62	46.08
200	3.78	0.87	54.77	75.98
400	4.02	1.10	109.92	145.93
		Series III		
100	5.73	0.50	17.33	18.88
200	5.27	0.50	30.90	35.06
400	7.44	0.45	66.36	64.83

σ'_c – effective stress of consolidation. $(\sigma'_1 / \sigma'_3)_f$ – maximum principal stress ratio. ε_f –axial strain at failure. $(\sigma_1 - \sigma_3)_f$ – deviator stress at failure. $0.33\,(\sigma'_1 + 2\sigma'_3)_f$ – mean total stress at failure.

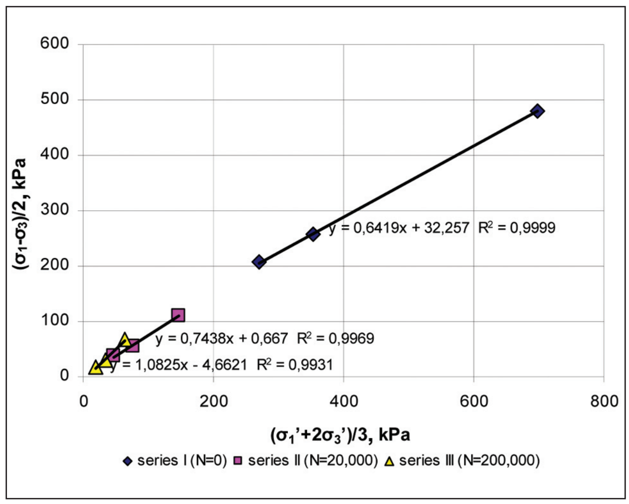

Fig. 4. Failure envelopes in terms of effective stresses

of the maximum principal stress ratio were read off as shown in Table 2. The shear strength parameters for each series were derived from a set of points representing the moment of failure. Failure envelopes in terms of effective stresses for each series are shown in Fig. 4.

Cyclic loading causes a reduction in the shear resistance of soil. Post-cyclic shear stress decreases with an increase of the number of stress application cycles; a rapid decrease is noted in the first 50,000 cycles (Fig. 5). After 20,000 cycles, post-cyclic shear stress is around 0.2 of monotonic shear stress and after 200,000 around 0.1 of monotonic shear stress.

An excess pore water pressure, due to the low permeability of tills, is likely to be generated under cyclic loading, consequently the shear strength decreases since the effective stress gets reduced. The development of pore water pressure during cyclic loading in series III is shown in Fig. 6. Pore water pressure increases sharply in the first 50,000 cycles, then almost stabilises and increases very slowly.

The values of the pore water pressure change in the monotonic shear test phase, as shown in Figs. 1–3, decrease with the number of cycles of stress application. In the static conditions (series I) the pore water pressure change is up to 100 kPa, after 20,000 cycles (series II) the pore water pressure change is not higher than 25 kPa, while after 200,000 cycles (series III) pore pressure change does not reach the level of 10 kPa.

The analysis of failure envelopes in terms of effective stresses reveals a considerable shift towards the left, indicating a decrease of effective stresses caused by development of pore pressure during cyclic loading (Fig. 4). Failure envelopes get steeper with an increase of the number of cycles, which gives an interesting consequence of the rising values of angles of internal friction φ', while the values of cohesion *c*' get reduced with the number of cycles of stress application (Table 2).

The failure did not appear under cyclic loads of accelerations equal to the recorded accelerations of the Warsaw traffic load. Considering the behaviour of pore pressure during the cyclic

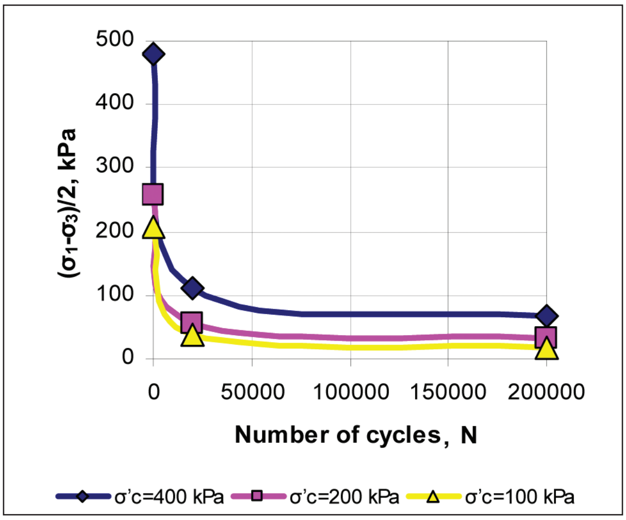

Fig. 5. Reduction of the shear stress $(\sigma_1-\sigma_3)$ / 2 with the number of cycles. σ'_c – effective stress at consolidation

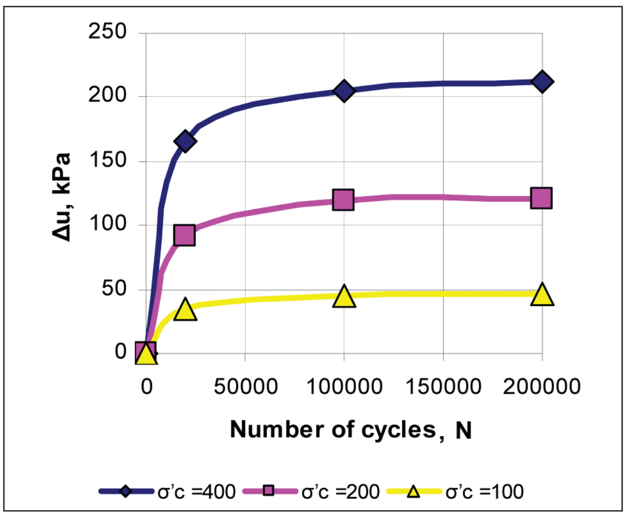

Fig. 6. Development of pore water pressure change Δu with the number of cycles in Series III. σ'_c – effective stress at consolidation

loading, a failure in the cyclic load phase may occur after far more cycles. The higher values of applied acceleration may also cause a failure in the cyclic loading phase.

CONCLUSIONS AND FURTHER RESEARCH PERSPECTIVES

1. Cyclic loading causes a substantial decrease in the shear resistance of tills. Post-cyclic shear stress decreases with increasing the number of cycles of stress application; a rapid decrease is noted in the first 50,000 cycles.

2. The development of pore water pressure during cyclic load is substantial. Pore water pressure increases sharply in the first 50,000 cycles and then almost stabilises.

3. The values of pore water pressure change in the monotonic shearing phase decrease with the number of cycles of stress application.

4. The values of cohesion *c*' get reduced with the numbers of cyclic loads, while the values of angles of internal friction φ' increase.

5. Determination of the cyclic shear strength of tills is a problem for further studies. Tests under higher values of amplitude and frequencies are going to be conducted.

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MORENINIO PRIEMOLIO POSTCIKLINIS STIPRIS KERPANT EKSPERIMENTINĖJE AIKŠTELĖJE VARŠUVOJE

Santrauka

Stipris kerpant yra viena iš svarbiausių grunto savybių. Straipsnyje pateikiami statinių ir dinaminių laboratorinių tyrimų rezultatai. Tyrimui moreninio priemolio bandiniai buvo paimti iš Novoursynovsko eksperimentinės aikštelės Varšuvoje. Tyrimų tikslas – įvertinti ciklinės apkrovos poveikį grunto stipriui kerpant. Bandymai atlikti dinaminiu prietaisu DYNTTS. Natūralios sandaros bandiniai tirti per 3 ciklus, nustatant statinį ir postciklinį nedrenuotą stiprį kerpant. Postciklinis stipris mažėja didėjant ciklų skaičiui. Labiausiai stiprio vertės sumažėja esant 50 000 pradinių ciklų. Stiprio verčių mažėjimas siejasi su porų slėgio didėjimo per laiką dinamine faze. Dinaminio apkrovos ciklų didėjimo metu mažėja sankabos vertė ir didėja vidinės trinties kampo vertė. Esant pasirinktai ciklinės apkrovos amplitudei ir dažniui, gruntas nesuiro. Numatomi bandymai su didesnėmis amplitudėmis ir dažniais.

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POST-CYKLICZNA WYTRZYMAŁOŚĆ NA ŚCINANIE GLIN LODOWCOWYCH Z REJONU WARSZAWY

Streszczenie

Wytrzymałość na ścinanie jest jedną z najważniejszych właściwości gruntów. W pracy przedstawiono wyniki statycznych i dynamicznych badań laboratoryjnych wykonanych w celu określenia wpływu obciążeń cyklicznych na statyczną wytrzymałość glin lodowcowych z poletka 'Nowoursynowska' w Warszawie.

Badania przeprowadzono w dynamicznym aparacie trójosiowego ściskania (DYNTTS). Próbki gruntu o nienaruszonej strukturze poddano trzem seriom badań, które pozwoliły określić statyczną i post-cykliczną wytrzymałość na ścinanie w warunkach bez drenażu.

Z uzyskanych rezultatów wynika, że obciążenia cykliczne powodują spadek wytrzymałości na ścinanie. Post-cykliczna wytrzymałość na ścinanie maleje wraz ze wzrostem liczby obciążeń cyklicznych, przy czym największy spadek następuje w pierwszych 50 000 cyklach. Zmniejszenie wytrzymałości jest związane z generacją ciśnienia porowego podczas fazy dynamicznej. Wartość ciśnienia porowego zwiększa się wraz z liczbą przyłożonych cykli; największy przyrost następuje do granicy 50 000 cykli. Wzrost liczby obciążeń cyklicznych prowadzi do spadku wartości spójności, przy równoczesnym wzroście kąta tarcia wewnętrznego.

Zniszczenie gruntu w fazie obciążeń cyklicznych o zadanej amplitudzie i częstotliwości nie nastąpiło. Planowane jest wykonanie badań w warunkach wyższych amplitud i częstotliwości w celu kreślenia cyklicznej wytrzymałości na ścianie glin lodowcowych.

Анна Банковска

ПОСТЦИКЛИЧЕСКОЕ СОПРОТИВЛЕНИЕ СДВИГУ МОРЕННЫХ СУГЛИНКОВ НА ПЛОЩАДКЕ В ВАРШАВЕ

Резюме

Сопротивление сдвигу является одним из важнейших свойств грунта. В статье представлены результаты лабораторных статических и динамических испытаний на сдвиг. Исследовались образцы моренных суглинков, полученные на экспериментальной Новоурсиновской площадке в Варшаве. Цель исследований – установить влияние циклической нагрузки на сопротивление грунта при сдвиге. Был использован динамический прибор DYNTTS. Испытания проводились тремя циклами на образцах естественного сложения при замерах статического и постциклического недренированного сопротивления сдвигу. Постциклическое сопротивление уменьшается при увеличении количества циклов. Наименьшее значение сопротивления сдвигу зафиксировано при 50 000 начальных циклов. Уменьшение сопротивления тесно связано с повышением порового давления во время динамической фазы. При увеличении циклов динамической нагрузки уменьшается значение сцепления и увеличивается значение угла внутреннего трения. Деструкции грунта при заданной амплитуде и частоте не произошло. Планируется провести испытания при увеличенных амплитудах и частотах.