FOUNDATION SYSTEMS FOR SUSTAINABLE REVITALISATION OF SPOIL DUMP AREAS

SYSTEMY FUNDAMENTOWANIA W ZRÓWNOWAŻONEJ REWITALIZACJI TERENÓW ZWAŁOWISK POGÓRNICZYCH

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The design of foundations systems is well established in the literature and codes of practice. However, these are generally applicable to well characterised, homogenous ground conditions. Spoil materials represent a significant challenge when implementing these design procedures due to their time-dependent characteristics, their spatial variability , and the likelihood that they will consist of low strength/stiffness materials. As such, careful consideration is required when designing foundation systems on spoil materials, especially for sensitive structures such as wind turbines. Physical modelling experiments using a geotechnical centrifuge were conducted to study the spoil-foundation system interaction. In these tests, an equivalent spoil was used that provided satisfactory reproduction of key physical and mechanical characteristics of a real spoil material. Three types of foundation systems were considered in the centrifuge tests: (1) raft foundation, (2) pile-group foundation, and (3) pile-raft foundation. The long-term cyclic loading of 87kN, 171kN and 460kN maximum cyclic load were used for the raft foundation. A higher cyclic load of 501kN was applied to the pile-group and pile-raft foundations. To evaluate the effect of climatic condition variations on spoil-foundation interactions, the centrifuge tests were carried out at different water table levels within the spoil material. The experimental results were analysed in terms of foundation rotation and foundation vertical settlement. The raft foundation rotated around 0.1-0.2 degrees and vertically displaced by 5-10 mm, whereas the pile-group rotated about 0.6-0.8 degrees and vertically displaced by 20-30 mm due to long-term cyclic loading. The pile-raft foundation displayed better response as compared to pile-group foundation.

Keywords: *physical modelling, centrifuge test, spoil material, foundation systems, pile foundation, raft foundation*

Projektowanie systemów fundamentowych jest dobrze ugruntowane w literaturze i w praktyce. Systemy te mają jednak zastosowanie do dobrze scharakteryzowanych, jednorodnych warunków gruntowych. Materiały zwałowe stanowią poważne wyzwanie przy wdrażaniu procedur projektowych ze względu na ich charakterystykę zależną od czasu, ich zmienność przestrzenną oraz duże prawdopodobieństwo, że będą się składać z materiałów o niskiej wytrzymałości/sztywności. W związku z tym, projektowanie systemów fundamentowych na zwałowiskach, szczególnie w przypadku wrażliwych konstrukcji, takich jak turbiny wiatrowe, wymaga starannego podejścia. W celu zbadania interakcji pomiędzy materiałem zwałowym a systemem fundamentowym przeprowadzono eksperymenty modelowania fizycznego z wykorzystaniem wirówki geotechnicznej. W badaniach tych zastosowano materiał równoważny, który zapewniał zadowalające odzwierciedlenie kluczowych cech fizycznych i mechanicznych rzeczywistego materiału. W badaniach wirówkowych rozpatrywano trzy rodzaje systemów fundamentowych: (1) fundamenty płytowe, (2) fundamenty wielopalowe oraz (3) fundamenty palowo-płytowe. Dla fundamentów płytowych zastosowano długotrwałe obciążenie cykliczne o maksymalnej wartości 87kN, 171kN i 460kN. Dla fundamentów wielopalowych i palowo-płytowych zastosowano większe obciążenie cykliczne - 501kN. W celu oceny wpływu zmienności warunków klimatycznych na interakcje zwałowisko-fundamenty, przeprowadzono badania wirówkowe przy różnych poziomach zwierciadła wody w obrębie zwałowiska. Wyniki eksperymentów analizowano pod kątem rotacji fundamentu i jego osiadania pionowego. W wyniku długotrwałego obciążenia cyklicznego fundament płytowy obrócił się o około 0,1-0,2 stopnia i przesunął w pionie o 5-10 mm, natomiast fundament wielopalowy obrócił się o około 0,6-0,8 stopnia i przesunął w pionie o 20-30 mm. Fundamenty palowo-płytowe odznaczały się lepszą reakcją w porównaniu do fundamentu wielopalowego.

Słowa kluczowe: *modelowanie fizyczne, badanie wirówkowe, materiał zwałowy, systemy fundamentowe, fundament palowy, fundament płytowy*

Introduction

Spoil dumps consist of heaps of overburden materials that are excavated during resource extraction processes. The spoils can contain a wide range of rock fragments and soil types. Randomness in the dumping process, various methods for the excavation and transportation, and local site effects can influence the spoil composition (and subsequently material behaviour) in a dump site (Zevgolis et al. 2021). Hence, dump spoil materials are usually considered as heterogeneous and exhibit a time-dependent mechanical behaviour. Reclamation options for mining spoil dumps include the development of renewable energy infrastructure (e.g. wind turbines, photovoltaic cell). This paper focuses on the design of wind turbine foundation systems since this problem poses challenges from an engineering perspective. The foundation design for similar types of structures has been previously studied (Bhattacharya et al. 2014, McMahon & Bolton 2014), however most of these studies were done on well characterised, homogeneous and fairly uniform soil. However, the heterogeneous, anisotropic and time-dependent nature of spoil material makes it very challenging to directly implement existing foundation design procedures.

There has been no previous research conducted into modelling the long-term response of spoil-foundation systems where both long-term cyclic loading of the foundation systems and climatic condition variations have been considered. These parameters can significantly impact the performance of foundation systems. This study involved geotechnical centrifuge tests to investigate the long-term response of spoil-foundation systems within a reduced-scale physical model, thus providing original and innovative insights into spoil-foundation structure interactions. The experimental data obtained from representative centrifuge tests can also be used to validate numerical models.

Design of foundation systems

A thorough investigation of various possible foundation systems has been carried out. As a result, one shallow foundation type (raft foundation), and two deep foundation types (pile-group and pile-raft foundations) have been selected as feasible foundation systems for the reclaimed mine sites. Following the design guidelines in codes and from a thorough literature review, traditional circular raft foundation and pile group foundations were designed, focusing on the ultimate limit state and serviceability limit state. The designs were then used to develop centrifuge models of the foundation systems, which could then be used to study of the response of the foundations to cyclic loading and environmental changes (i.e., change in water table level). A schematic view of the prototype scale final model foundations is shown in Fig. 1.

Experimental plan for physical modelling

Spoil material properties

The centrifuge models were prepared using an equivalent spoil material (50% silt + 30% bentonite + 20% kaolin mixture), which was developed after carefully considering the physical and mechanical characteristics of a real spoil material. More details regarding the characterization of real spoil material and the development of the equivalent spoil can be found in Garala et al. (2022). A series of soil characterisation tests were performed to evaluate the index and engineering properties of equivalent spoil samples to provide parameters for the foundation design. In addition, the unsaturated characteristics of equivalent spoil were also determined to better understand the results of centrifuge tests with climatic condition variations (water level change). The geotechnical properties of the equivalent spoil are summarised in Table 1.

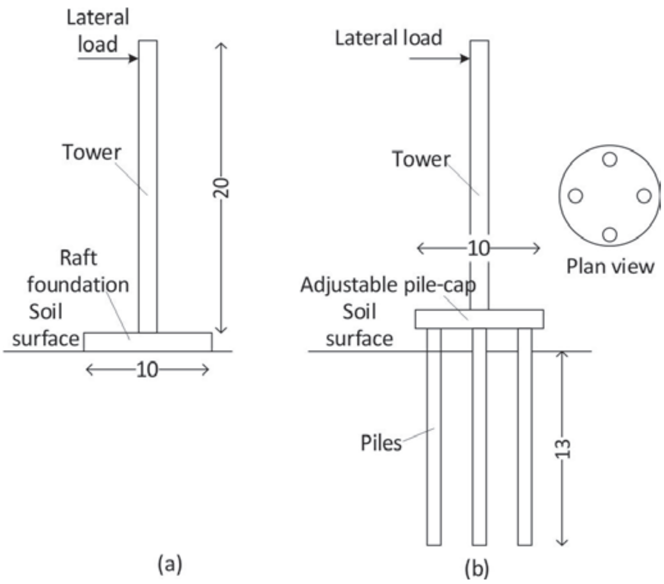

Fig. 1. Schematic diagram of centrifuge model in prototype scale: (a) raft foundation, (b) pile-group and pile-raft foundation (dimensions in m)
Rys. 1. Schemat modelu wirówkowego w skali prototypowej: a) fundamenty płytowe, b) fundamenty wielopalowe i palowo-płytowe (wymiary w m)

Tab. 1. Geotechnical properties of equivalent spoil
Tab. 1. Właściwości geotechniczne materiału równoważnego

Geotechnical Property	Value
Specific gravity, G_s	2.52
Sand fraction (%)	0
Silt fraction (%)	50
Clay fraction (%)	50
Liquid limit, LL (%)	46
Plasticity index, PI (%)	25.6
Compression index, C_c	0.545
Recompression index, C_r	0.07
Effective friction angle, φ' (degree)	28
Undrained shear strength, (kPa)	26
Air entry value, AEV (kPa)	280 (drying curve), 130 (wetting curve)

Spoil model preparation

The raft footing centrifuge test was conducted using the equivalent spoil that was consolidated from a slurry. On the other hand, the pile and pile-raft foundations were tested using equivalent spoil that was compacted; the compacted models were prepared to be equivalent to the consolidated model but required significantly less time to prepare. The consistency between the consolidated and compacted spoil models was evaluated and verified using cone penetration test (CPT) data; more details of this evaluation and detailed model preparation are available in Garala et al. (2022).

Tab. 2. Experimental plan for centrifuge testing foundation systems
Tab. 2. Plan eksperymentu dla badań wirówkowych systemów fundamentowych

Foun. Type	Exp No	Water Table[a]	Max. Cyclic Load (kN)	N[b]	f (Hz)
Raft	1	GL	87	1000	0.2
	2	GL	171	210	0.1
	3	7.5m BGL	87	1000	0.2
	4	7.5m BGL	171	175	0.1
	5	7.5m BGL	460	5	0.02
Pile-Group	6	GL	501	980	0.06
	7	6m BGL	501	350	0.06
Pile-Raft	8	GL	501	930	0.06

Notes: [a] GL = at ground level, BGL = below ground level; [b] N = maximum number of cycles

Centrifuge model preparation and experimental plan

The geotechnical centrifuge facility at the Nottingham Centre for Geomechanics, University of Nottingham (UoN), was used, with tests conducted at 65g (65 times Earth's gravity). The experiments can be classified into 8 cases, as presented in Table 2.

The foundation models were placed onto the surface of the prepared spoil sample. For the deep foundations, four holes corresponding to the pile locations/diameter/depth were first excavated, followed by insertion of the piles. The pile-group and pile-raft experiments were conducted using the same foundation model and same spoil sample. The pile-cap was fabricated in a such a way that it could be lowered to put it in contact with the soil surface for the pile-raft foundation experiment. When not in contact with the soil, it worked as a pile cap for pile-group, whereas it worked as a raft for the pile-raft foundation when it was firmly in-contact with the soil.

Four pore pressure transducers (PPTs) were installed to measure the pore water pressure variation within the model. The location of PPTs for shallow/deep foundation is shown in Fig. 2a. The model was then moved onto the centrifuge platform and the model then spun up over time to 65g in increments of 10g to allow for some of the consolidation process to occur. The horizontal movement of the foundation was prevented during consolidation by installing a temporary support around it. The water level was maintained constant at the spoil surface. Once a satisfactory degree of consolidation (≈ 90%) was achieved, the model was spun down to 1g in order to remove the temporary support and to install the loading actuator. The model was then spun back up to 65g and then cyclic loading was applied using the installed actuator (Fig. 2b, 2c). The cyclic loading was in the form of a triangular one-way waveform and applied at a fixed point of the tower structure of the foundation. The number of loading cycles (N), cyclic loading frequency (f) and maximum cyclic load in each cycle for different foundation types are provided in Table 2. During this loading, the water table was maintained constant at the spoil surface. The experimental setup during cyclic loading for shallow and deep foundations is shown in Fig. 2b and 2c. After cyclic loading, the model was spun down to 1g. A CPT test was then conducted using a miniature CPT device (Garala et al., 2022) to obtain the spoil's undrained shear strength profile with depth.

The model was then spun back up to 65g for the next part of the test where the water table level was changed. The water inside the model was allowed to drain to a lower water table level. The next phase of cyclic loading was then performed under

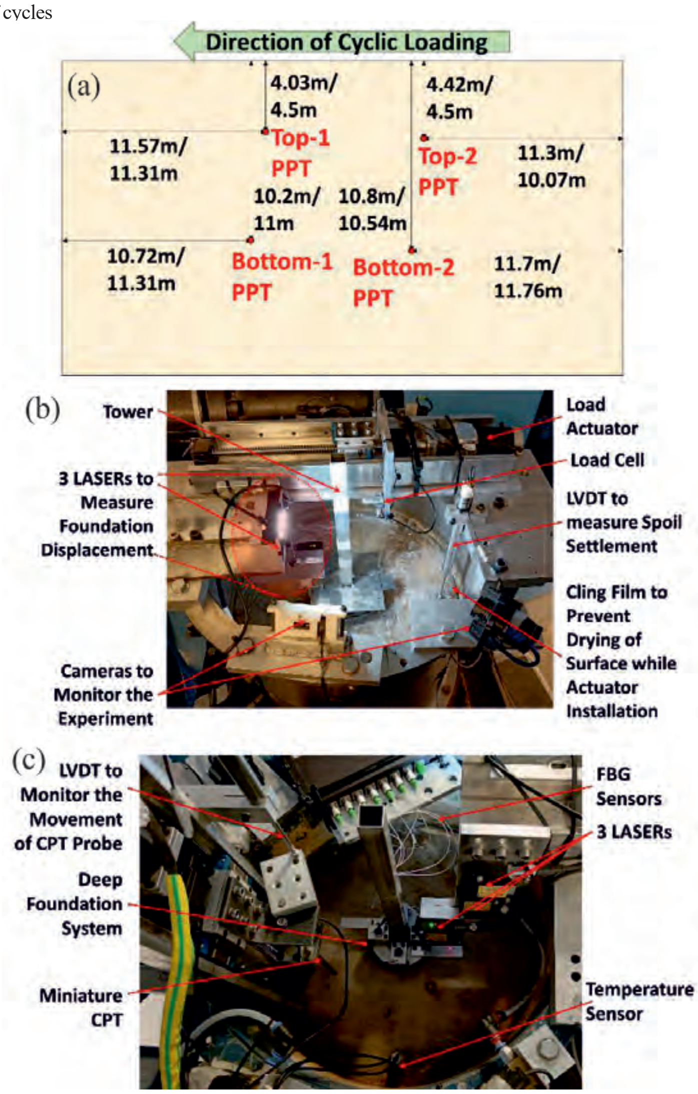

Fig. 2. Physical model of foundation system: (a) PPT locations, (b) Raft foundation, (c) Pile-group and Pile-raft foundation
Rys. 2. Model fizyczny systemu fundamentowego: (a) lokalizacja PPT, (b) fundamenty płytowe, (c) fundamenty wielopalowe i palowo-płytowe

partially saturated conditions (Table 2). Finally, the model spun down to 1g and additional CPT tests were conducted. During the entire experiment, the horizontal and vertical foundation movements were measured using the set of LVDTs and Lasers indicated in Figure 2.

Results and discussion

The results of physical modelling are presented and discussed in the context of moment-rotation and load-displacement analysis. During the cyclic loading, the horizontal displacement of the foundation was measured using two lasers. Equation 1 was then used to determine the rotation of the foundation using these measurements.

$$\theta = \tan^{-1}\left(\frac{\Delta H_1 - \Delta H_2}{L}\right) \tag{1}$$

where ΔH_1= horizontal displacement from the upper laser, ΔH_2= horizontal displacement from the lower laser, L=distance between the two lasers. A schematic diagram is also presented in Fig. 3. Moments were calculated at the centre of the base of the raft foundation and the centre of pile-cap for the pile-group and pile-raft foundations. The vertical displacement was measured using a laser at the side of the foundation. The vertical displacement at the centre was calculated using Equation 2 and Equation 3.

$$\tan\theta = \frac{\Delta V_m}{x} \tag{2}$$

$$\frac{\Delta V_m}{x} = \frac{\Delta V_c}{\frac{B}{2} - x} \tag{3}$$

where ΔV_m=measured vertical displacement, ΔV_c=calculated vertical displacement at the centre of the foundation, x=distance of point of rotation from the opposite side of cyclic loading, B=diameter of the foundation. The soil settlement outside of the foundation influence zone has been assumed negligible during cyclic shearing to develop the above equation.

The spoil material had a dry unit weight of 14.7kN/m^3 and water content of around 35% at the start of the centrifuge test for both compacted and consolidated models. The over consolidation ratio (OCR) decreased from 15 to 1 as depth of spoil layer increased from near the surface to 10 m, and remained constant after that.

Consolidation stage

Table 3 shows the settlement data (prototype scale) during centrifuge tests at the end of the consolidation stage for both water table levels. The raft foundation settled nearly the same as that of the spoil material (measured remotely from the foundation - see Fig. 2). In contrast to the raft foundation response, the pile-group foundation settled more as compared to the spoil material, likely a result of the larger self-weight of the deep foundation system. The settlement observed as a result of lowering the water table level was due to shrinkage of the upper spoil layers under unsaturated conditions.

Cyclic loading on raft foundation

Fig. 4 presents the experimental results of cyclic loading on the raft foundation. In the case of water table at ground level, the foundation was rotated by about 0.05-0.07 degrees for 87 kN (Exp=1) and 0.1 degrees for 171 kN (Exp=2). However, the spoil-foundation system remained predominately elastic for both loading conditions since the rotation was observed to be reversible for each cycle. Hence, a very low residual or accumulated rotation of 0.011 degrees and 0.015 degrees was noted for the 87 kN and 171 kN loading cases, respectively. These results were expected as the loading intensity was decided based on the serviceability limit state. These results also indicated the very low degradation of cyclic stiffness of the spoil material. The higher OCR of the spoil in the foundation influence zone can also be one of the reasons for the lower cyclic degradation of the spoil. The vertical displacement calculated at the centre of the foundation also indicated a similar elastic response with nearly 3mm and 6mm vertical movement during the 87 kN and 171 kN cyclic loading cases, respectively. The negative values of vertical displacement were due to the location of the centre of rotation, as shown in Fig. 5a. This means that the foundation was actually uplifted at the centre position. This might be due to the one-way nature of the applied cyclic loading as the load was continuously applied only in one direction from zero to maximum. The residual settlement at the end of the cyclic loading was minimal at -0.5 mm and -1.7 mm for 87 kN and 171 kN loading cases, respectively.

In the partially saturated cases, the foundation was rotated by about 0.08-0.09 degrees for 87 kN, 0.15-0.17 degree for 171 kN and 0.48 degree for the 460 kN cases. The spoil-foundation system remained predominately elastic for the 87 kN and 171 kN load cases. However, the high accumulation rate of rotation for the 460 kN cyclic loading case indicated possible elastoplastic response and yielding of the spoil material. The accumulated rotations at the end of cyclic loading were 0.007 degrees, 0.018 degrees and 0.027 degrees for the 87 kN, 171 kN and 460 kN cyclic loading cases, respectively. The higher values of foundation rotation in comparison to the saturated case may be due to the following: (1) the spoil material in the raft foundation influence zone already underwent two long-term cyclic loadings of 87 kN and 171 kN in the fully saturated condition prior to the current load application, which may have lowered the

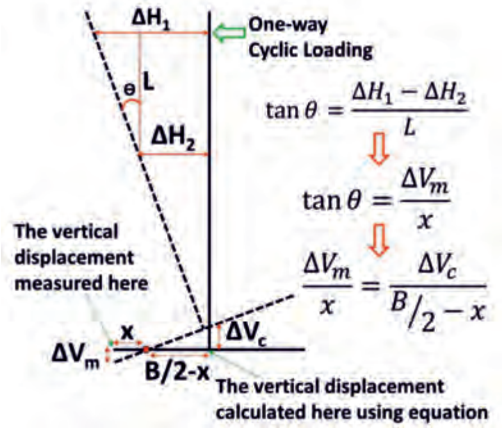

Fig. 3. Schematic representation of various measured and calculated parameters
Rys. 3. Schematyczne przedstawienie poszczególnych mierzonych i obliczanych parametrów

Tab. 3. Consolidation data of foundation system
Tab. 3. Dane dotyczące konsolidacji systemu fundamentowego

Foundation Type	Water Table	S_{spoil} (mm)	$S_{foundation}$ (mm)
Raft	GL	307	286
Pile-Group	BGL	746	643
Pile-Raft	GL	423	328
Pile-Group	GL	555	350
	BGL	1169	541

spoil's cyclic stiffness. (2) The formation of desiccation cracks at the spoil surface around the raft foundation. The vertical displacement calculated at the centre of the foundation also indicated a similar response with nearly 4 mm, 8.5 mm and 27 mm vertical movement during the 87 kN, 171 kN and 460 kN cyclic loading cases, respectively.

Cyclic loading on pile-group foundation

Fig. 6 presents the experimental results of cyclic loading on deep foundations. The foundation was rotated by a maximum of about 0.9-1 degrees and 0.8-0.9 degrees under the 501 kN load for fully and partially saturated cases, respectively. The spoil-foundation system yielded and showed an elastoplastic response as the rotation was seen to accumulate for each consecutive cycle and didn't stabilise at the end of long-term cyclic loading. The rate of increase in foundation rotation was high for the first few cycles (N≈50-60). Thereafter, the rate decreased with subsequent loading. At the end of 980 cycles, a 0.365 degrees rotation remained as a permanent deformation of the foundation for the Exp=6 case. In contrast, 0.527 degrees accumulated after 350 cycles for the Exp=7 case. This indicated the continuous reduction in the spoil's cyclic stiffness with repeated loading. At the end of 980 cycles in Exp=6, a residual deformation of 47.5 mm and 7.5mm were noted for the measured and calculated vertical displacements, respectively. The calculated settlement at the centre of foundation started initially with negative values and became gradually positive with continuous cyclic loading. The negative values of vertical displacement were due to the location of the point of rotation for the pile-cap (towards the left pile), as shown in Fig. 5b. This means that the foundation was actually uplifted at the centre position. However, the point of rotation shifted and moved towards the right-side pile with cycles as shown in Fig. 5c.

Cyclic loading on pile-raft foundation

The experimental results of pile-raft foundation are shown in Fig. 6. The foundation was rotated by a maximum of about 0.85 degrees. The spoil-foundation system yielded and showed an elastoplastic response with a significant amount of accumulated rotation within the first few cycles (N≈50-60). Thereafter, the rate of rotation accumulation decreased and became almost constant after 150 cycles. At the end of 930 cycles, 0.269 degrees of rotation remained as a permanent deformation of the foundation. Vertical displacement continuously accumulated with the number of cycles, but its rate decreased with cycles. At the end of 930 cycles, a residual deformation of 39.8 mm and 12.6 mm were noted for the measured and calculated vertical displacements, respectively. Similar to the pile-group foundation, the calculated vertical settlement at the centre of the foundation also shifted from the negative to positive side with continuous cyclic loading, indicating a shift of the rotation point from the left side pile to the right side pile (Fig. 5c).

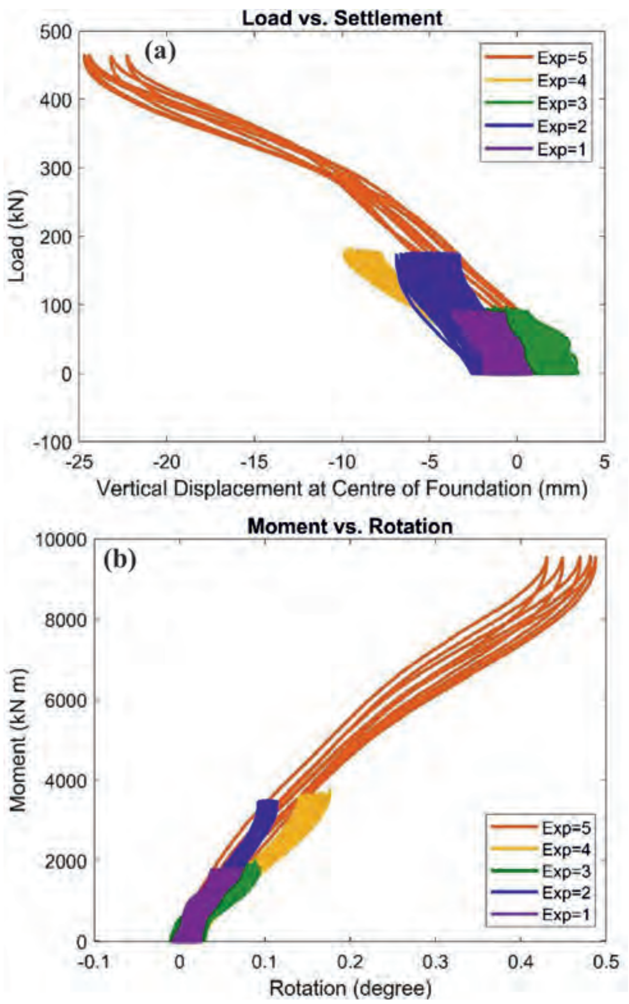

Fig. 4. Centrifuge experiment results of raft foundation: (a) Load-settlement, (b) Moment-rotation, (c) Excess pore water pressure response

Rys. 4. Wyniki eksperymentu wirówkowego dla fundamentów płytowych: (a) obciążenie-osiadanie, (b) moment-rotacja, (c) reakcja na nadmierne ciśnienie wody porowej

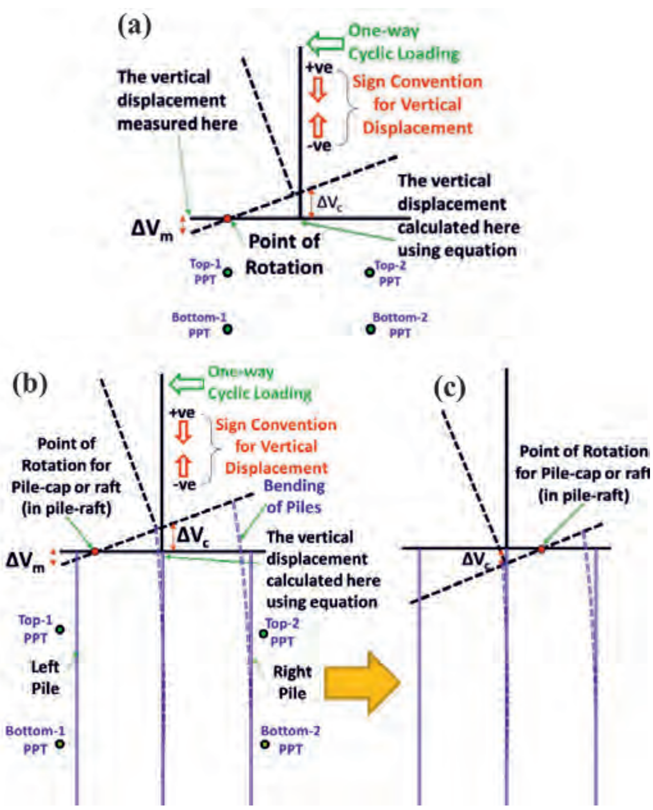

Fig.5. Schematic representation of foundation rotation during cyclic loading: (a) Raft, (b, c) Pile-group and pile-raft

Rys. 5. Schematyczne przedstawienie obrotu fundamentów podczas obciążenia cyklicznego: (a) płytowych, (b, c) wielopalowych i palowo-płytowych

Conclusions

Geotechnical centrifuge tests were conducted to simulate the foundation-spoil interaction response. Three types of foundation systems have been designed and modelled to understand the complex behaviour of foundation systems under various long-term cyclic loading conditions and climatic-conditions variations. The long-term cyclic loading of 87kN, 171kN and 460kN maximum cyclic load were used for raft foundation. The higher cyclic load of 501kN was applied to the pile-group and pile-raft foundations. The climatic condition variations were simulated by varying water table level. The results indicated that the raft foundation rotated by 0.1-0.2 degrees and vertically displaced by 5-10mm during the cyclic load, which was decided based on the serviceability limit state. Similarly, the pile-group foundation vertically displaced by 20-30mm and rotated by 0.6-0.8 degrees during cyclic loading. As compared to pile-group foundation, the system of pile-raft foundation displayed better response in terms of deformations during cyclic loading. The generation and accumulation of excess pore water pressure in spoil mass was observed low for all types of foundation system due to very low permeability characteristics of spoil media. The OCR has very significant impact on the overall deformation and pore pressure response of foundation system. The cyclic stiffness degradation of spoil material under continuous long-term loading led to change in the deformation pattern and centre of rotation for the cases of deep foundations. The vertical displacement increased significantly under partially saturated case (lower water table) as compared to fully saturated (water table at ground level) spoil mass. The experimental data obtained from these extensive centrifuge testing program can also be used to validate the numerical models. The numerical models can then be used to simulate different spoil materials, external loading factors and a more comprehensive range of geometric scenarios.

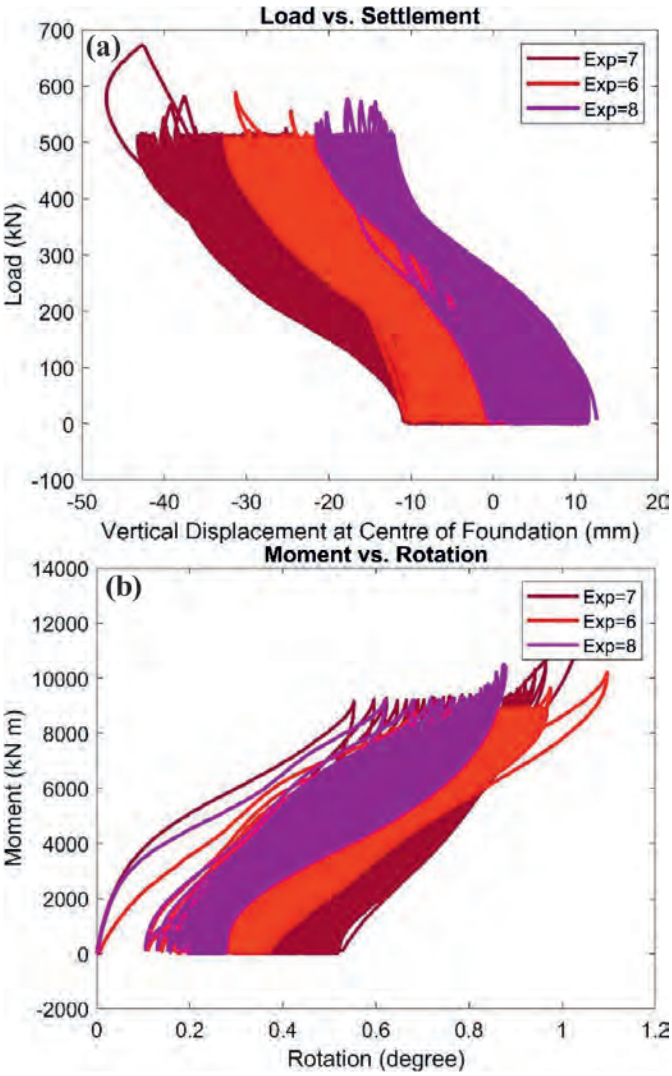

Fig. 6. Centrifuge experiment results of pile-group and pile-raft foundation: (a) Load-settlement, (b) Moment-rotation, (c) Excess pore water pressure response

Rys. 6. Wyniki eksperymentu wirówkowego dla fundamentów wielopalowych i palowo-płytowych: (a) obciążenie-osiadanie, (b) moment-rotacja, (c) reakcja na nadmierne ciśnienie wody porowej

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