VERIFICATION OF GEOTECHNICAL NUMERICAL SIMULATIONS BY MODEL TESTS USING PIV TECHNIQUE

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Abstract
Shallow foundations located near cantilever retaining walls are complex foundation – subsoil – external loading (FSL) systems. Interaction of two different shallow foundations has essential influence on the stability of each of them. Model tests for this system have been carried out in plane strain state in natural soil (dry sand) and analogue Taylor-Schneebelli medium. Trajectories and isoplots of displacement as well as progressive shape and range of slip surfaces was determined using Particle Image Velocimetry (PIV) technique. Qualitative and quantitative results of model tests, according to the Experimental Soil Engineering (ESE) concept, have been next used for verification of numerical simulations described in Part 2 of the paper.

Streszczenie
Fundamenty bezpośrednie posadowione w sąsiedztwie kątowych ścian oporowych stanowią złożony układ fundament – obciążenie – podłoże gruntowe (FLS). Wzajemne oddziaływanie na siebie dwóch różnych fundamentów bezpośrednich ma istotny wpływ na stateczność każdego z nich. Badania modelowe dla tego układu (FLS) wykonano w płaskim stanie odkształcenia w gruncie naturalnym (suchy piasek) i w ośrodku analogowym Taylor-Schneebeli. Trajektorie i izopola przemieszczenia oraz progresywny rozwój kształtu i zasięgu powierzchni poślizgu określono techniką Particle Image Velocimetry (PIV). Jakościowe i ilościowe wyniki badań modelowych – zgodnie z koncepcją Experimental Soil Engineering (ESE), wykorzystano do weryfikacji metodyki symulacji numerycznych opisanych w części 2.

Keywords: **Stability of shallow foundations; Model tests; Particle Image Velocimetry (PIV) technique; Bearing capacity and displacement fields.**

1. INTRODUCTION

Reliable analysis of interaction and stability of foundation-loads-subsoil (FLS) systems for complex state of external loads and subsoil conditions requires individual approach which usually should be based on carrying out both modern experiments and numerical simulations. In order to fulfil both requirements the concept of Experimental Soil Engineering (ESE) proposed originally by *Jamiołkowski* [2] was used.

In the engineering practice, particularly in morphologically inhomogeneous areas and transport construction the retaining walls of various type are applied, which are often additionally loaded by shallow foundations of other structures located nearby. Such foundations are subjected also to inclined and eccentric loads.

In such complex foundation system of two different shallow foundations the problem of interaction appears, which determinates the stability of the individual foundation, particularly the upper one with respect to its bearing capacity and deformations in relation to the distance between them.

The motivation for more careful analyses of the described problem was the lack of standard calculation principles for the system of shallow foundations in current Polish standards as well as insufficient knowledge published in the literature of the problem.

Shallow foundations located near cantilever retaining walls are complex foundation-loads-subsoil (FLS) system, the interaction of which influences the stability of each. In order to analyse the problem respective model tests have been carried out, the results of which have been next verified by numerical simulations. First stage of the analysis were model tests carried out in years 2009-2010. The tests have been made in plane-strain state for natural subsoil (dry sand) as well as analogue material (Taylor-Schneebeli). The vectors of displacements filed as well as progressive development of shape and range of slip surfaces were determined using Particle Image Velocimetry (PIV) technique. According to ESE concept the test results were the basis for verification of numerical simulations. In the paper the results of model tests are presented. The numerical analyses will be described in Part II of the paper, issued in next volume.

2. MODEL TESTS

2.1. General remarks

Necessary conditions for reliable geotechnical model tests have been comprehensively described in other papers of the Authors [3, 5, 6, 7]. For the model tests presented in this paper the conditions have been fulfilled by application of the following methodology:

- determination of respective loading schemes and boundary conditions,
- investigations made in plane-strain state obtained in well equipped lab stands,
- the tests made on analogue material and natural soil, the geotechnical parameters of which have been determined in three independent national laboratories (Gdańsk University of Technology, Silesian University of Technology, Institute of Hydro-Engineering of the Polish Academy of Sciences),
- selection of the material and its roughness for rigid models of foundations,
- gradual loading and its control,
- application of modern technique for measurement of soil deformations and foundation displacements,
- graphical interpretation of the test results in terms of displacement trajectories and isoplots.

The qualitative and quantitative results of models test, presented in next sections, were the basis for verification of numerical simulations.

2.2. Scope and quantitative model test results

A scheme of analysed complex FLS system as well as dimensions of cantilever retaining wall model and shallow foundation are shown in Fig. 1.

Rigid models of shallow foundation and cantilever retaining wall have been made of steel plates. In the tests, as a natural soil dry medium dense sand called Rybaki 3 with the following parameters has been used:

- density index $I_D = 0.5$,

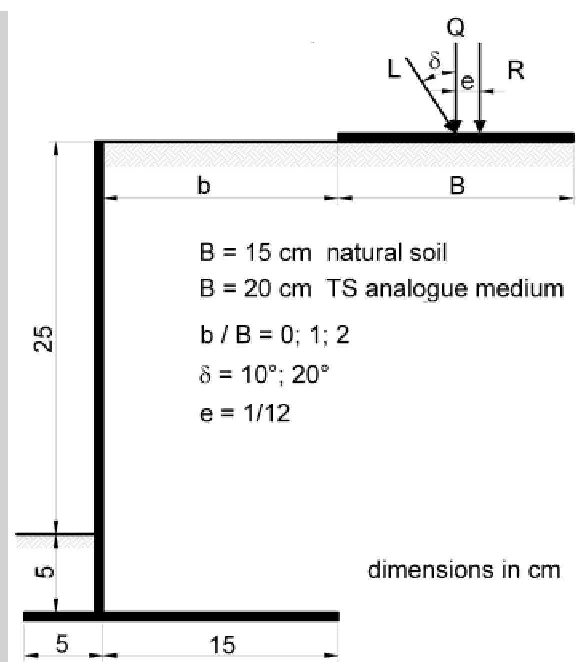

Figure 1.
Scheme and parameters of analysed FLS system

Table 1.
The results of 16 model tests

Distance from retaining wall b / B [-]	Angle of inclined force δ [-]	Eccentricity *e* [-]	Ultimate force *Q* [kN]	Settlement s [mm]
0	0	0	8.32	4.73
1	0	0	5.86	4.23
2	0	0	9.28	6.00
∞	0	0	17.71	10.61
0	10 L	0	7.78	4.70
0	10 R	0	4.95	3.83
0	20 L	0	7.72	3.35
0	20 R	0	3.23	2.98
1	10 L	0	8.17	5.38
1	10 R	0	5.04	2.88
1	20 L	0	5.91	2.25
1	20 R	0	2.35	1.45
0	0	1/12 L	4.79	3.05
0	0	1/12 R	8.98	5.28
1	0	1/12 L	6.25	3.78
1	0	1/12 R	7.22	2.70

– angle of internal friction $\phi = 35.2°$,
– unit weight $\gamma = 16.22$ kN/m^3.

In case of Taylor-Schnebelli analogue material the angle of internal friction was $\phi = 27°$ and unit weight $\gamma = 21.7$ kN/m^3.

For both materials all together 16 tests have been performed including the following options:

– alternate distance of shallow foundation from cantilever retaining wall equal to $b/B = 0$; 1 and 2,
– various types external loads of shallow foundation such as:
  – axial and vertical one,
  – axial, inclined towards and from retaining wall at the angles $\delta = 10°$ and 20°,
  – vertical eccentric load $e = 1/12$ towards (L) and from (R) retaining wall.

The results of 16 tests made in natural soil were collated in Table 1 (notation as in Fig. 1).

Reducing influence of cantilever retaining wall on the bearing capacity of shallow foundation located on the surcharge (for various inclinations and eccentric loads depending on the relative distance b/B from the wall (Fig. 1) was presented in Table 2. Besides values of bearing capacity there were also shown the empirical values of n factor determining these influences.

Table 2.
Reducing influence of cantilever retaining wall on the bearing capacity of shallow foundation

Q [kN] *n*	*b/B* 0	1	2	∞
$\delta = 0$ $e = 0$	8.32	5.86	9.28	17.71
n	0.47	0.33	0.52	1.00
$\delta = 10°$L $e = 0$	7.78	8.17	–	15.01
n	0.52	0.54	–	1.00
$\delta = 10°$R $e = 0$	4.95	5.04	–	15.01
n	0.33	0.33	–	1.00
$\delta = 20°$L $e = 0$	7.72	5.91	–	6.48
n	1.19	0.91	–	1.00
$\delta = 20°$R $e = 0$	3.23	2.35	–	6.48
n	0.49	0.36	–	1.00
$\delta = 0°$R $e = 1/12$L	4.97	6.25	–	13.38
n	0.37	0.46	–	1.00
$\delta = 0°$R $e = 1/12$R	8.98	7.22	–	13.38
n	0.67	0.54	–	1.00

Comparison of the values presented in Table 2 leads to the following conclusions:

– for vertical and axial loads essential reduction of the bearing capacity of foundation depending on

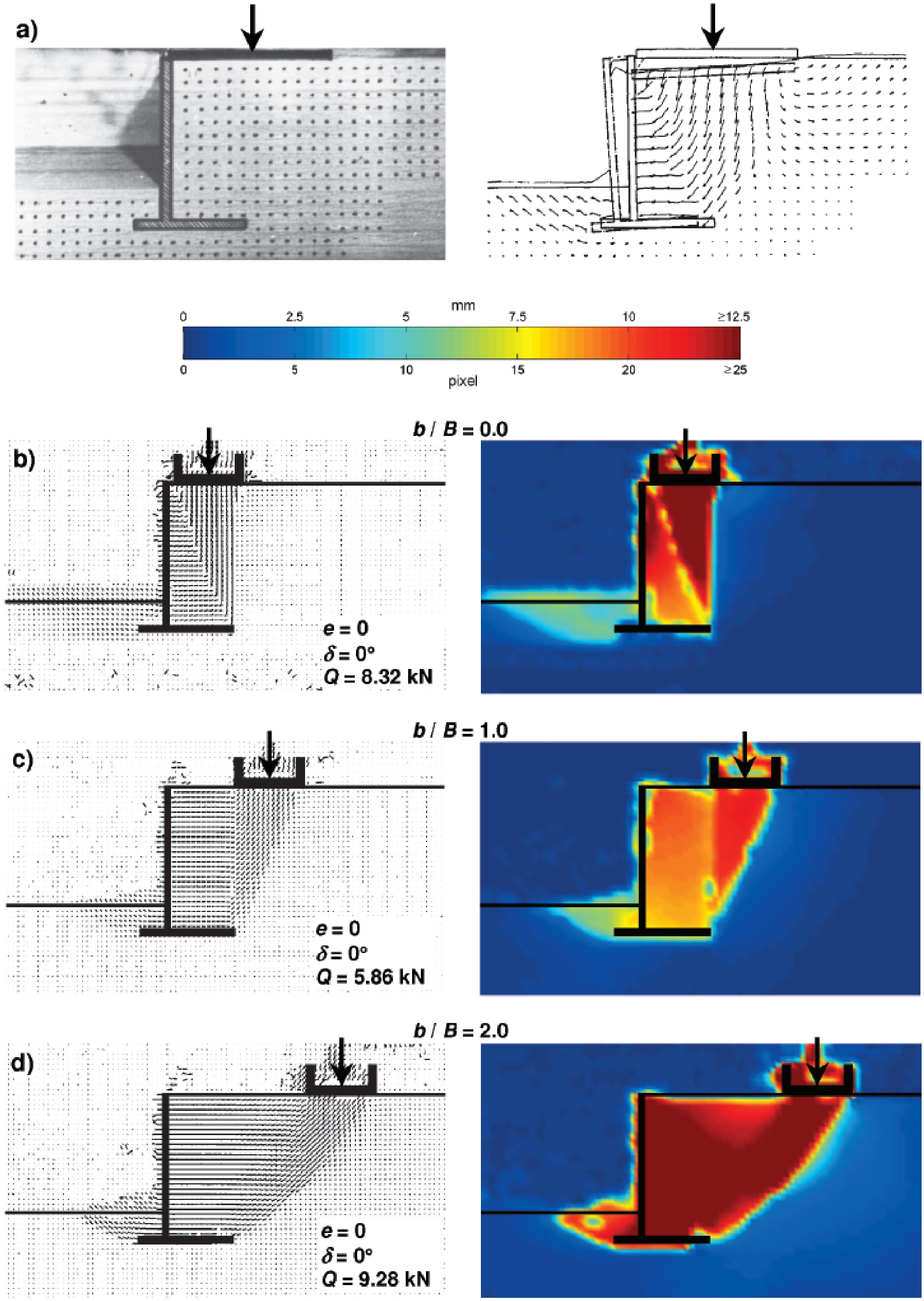

Figure 2.
Trajectories and isoplots of displacement obtained by photogrametry (a) and PIV technique (b) in natural soil. Axial and vertical loads

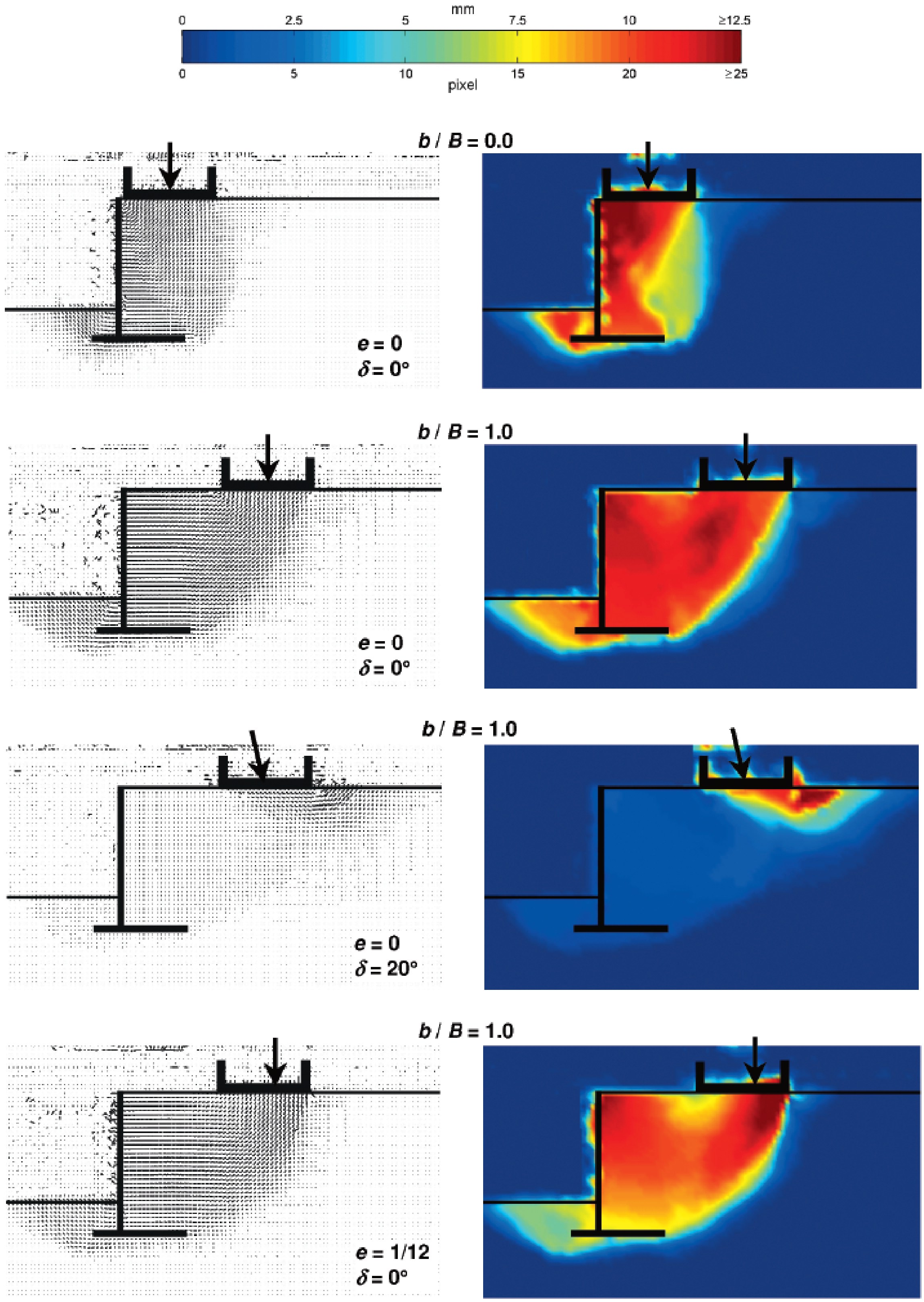

Figure 3.
Trajectories and isoplots of displacement obtained by PIV technique in Taylor-Schnebelli analogue medium. Vertical axial or eccentric loads as well as axial inclined loads

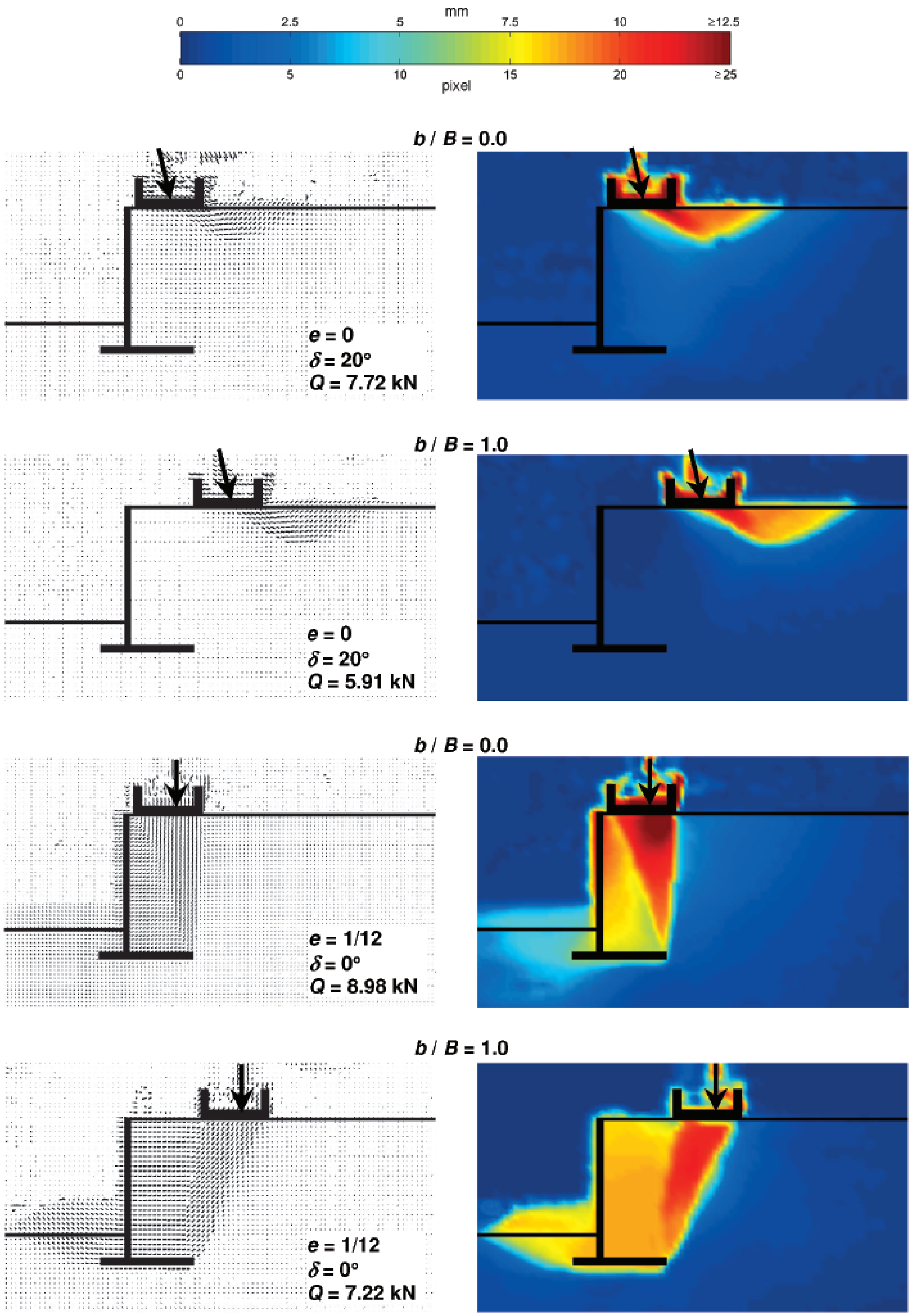

Figure 4.
Trajectories and isoplots of displacement obtained by PIV technique in natural soil. Axial inclined and vertical eccentric loads

the distance from retaining wall is observed, at $b/B = 0$ and 2 of 50% reduction whereas at $b/B = 1 – 33\%$ reduction of bearing capacity corresponding to $b/B = \infty$,

- for axially inclined loads $\delta = 10°$ and 20°, acting towards the retaining wall the reduction of foundation bearing capacity is larger, depending on the distance from retaining wall, $b/B = 0$ and 1 ($n = 0.33 – 0.49$) than in case of load inclined opposite (from the wall) – ($n = 0.52 – 0.91$),
- for vertical loads acting eccentrically ($e = 1/12$) towards the retaining wall, the reduction of the bearing capacity is higher ($n = 0.37 – 0.46$) than on the eccentricity acting opposite ($n = 0.54 – 0.67$).

The differences in the behaviour of the structures analysed are the result of essentially different interaction mechanisms and displacement fields as well as shear zones, which are presented in Fig. 2÷4.

2.3. Qualitative results of model tests

Shape and range of displacements, shear zones and slip surfaces for FLS system analysed for two media i.e. natural soil and Taylor-Schneebelli analogue material in the form of displacement trajectories and isoplots determined using PIV technique are presented in Fig. 2÷4.

Based on the analysis of the results shown the following conclusions can be drawn:

- the tests are mostly of cognitive type,
- the cantilever retaining wall causes significant changes of the shape and range of displacements, shear zones and slip surfaces under the shallow foundation located nearby,
- the changes are of the similar type in both natural (Fig. 2 and 4) as well as analogue medium (Fig. 3),
- for axial and vertical load acting on shallow foundation the displacements occur under the foundation as well as behind and in front of cantilever retaining wall, depending on the distance between these structures. (Fig. 2).
- depending on the relative distance b/B and direction and inclination angle of the acting force, direction and value of eccentricity of load, zones of large displacements develop in the following areas:
  - in the subsoil under the foundation, exclusively,
  - in the subsoil under the foundation and behind the wall,
  - in the subsoil under the foundation and behind and in front of the wall,
- displacement trajectories have different directions and values:
  - vertical and inclined one under the foundation,
  - horizontal one behind the wall,
  - inclined in front of the wall.
- no vertical displacements under the cantilever retaining wall are monitored.

Observed differences in displacement trajectories and interaction mechanisms between shallow foundation and cantilever retaining wall have significant impact on the bearing capacity of shallow foundations and reducing impact of decreasing distance between the structures (see Table 2).

3. SUMMARY

The results of model tests preformed by the Authors in natural soil and T-S analogue medium are the source of important quantitative and qualitative data which can be used in the engineering practice. The data can also be treated as practical guidelines for the assessment of the stability of the foundations tested as well as database for the verification of numerical simulations including various shear strength criteria. The methodology and the results of such a verification will be presented in Part 2 of the paper in the next issue of the journal.

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