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Numerical analysis of the load distribution under the piled raft foundation of the high-rise building

GRZEGORZ KACPRZAK[1], SEWERYN BODUS[2]
[1] Faculty of Civil Engineering, Warsaw University of Technology, Poland
[2] WARBUD SA, Warsaw, Poland

Abstract: *Numerical analysis of the load distribution under the piled raft foundation of the high-rise building*. In this paper, the problem of a pile-raft foundation of a high-rise building located in Warsaw in typical soil and water conditions was presented. In order to describe the soil–foundation interaction, regarding load distribution, an analysis was made based on finite element method (FEM) with the use of the hardening soil with small strain soil model (HSS) in the ZSoil and Autodesk Robot Structural Analysis (ARSA) program. The article contains basic information about the pile-raft foundation, description of ground-water conditions together with the estimated parameters for the HSS model of soil applied in ZSoil calculation. It also shows a block diagram, as a kind of algorithm, presenting the proceedings in designing, modelling and numerical analysis between ZSoil and ARSA program. Own load distribution analysis in CPRF elements based on the numerical procedure enables the comparison with the measurements results of the load distribution carried out by Mandolini with associates in 2005.

Key words: combined pile-raft foundation, FEM modelling, HSS model

INTRODUCTION

The issue of interaction and influence between a building construction and soil is a quite complex engineering problem. The foundation of a high-rise building, constructed in difficult soil conditions and in the neighbourhood of existing buildings, requires making the right assumptions in technology of the execution. In such cases, it is common to use piled raft foundations in the technology of barrettes and diaphragm walls. In order to determine the settlement, load sharing between elements of foundation as well as envelopes of internal forces in foundation slabs, diaphragm walls and barrettes, 3D numerical modelling is required. Thus, during the process of building designing it is essential for structural engineer to obtain information regarding stiffness of soil beneath raft and stiffness of foundation elements (defined as load/settlement ratio) which strongly influence internal force distribution in a system.

Thus, at the beginning authors present the possible methodology of structural analysis based on the algorithm of cooperation between ARSA and ZSoil programs. Then, the obtained results were used to determine the load distribution on elements of the pile-raft system (Fig. 1) and compared with case

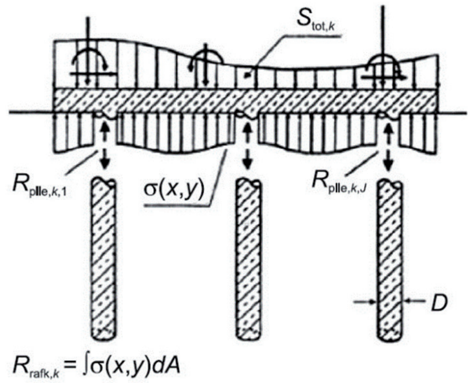
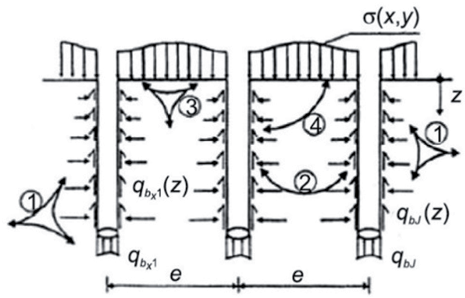


FIGURE 1. Load distribution on raft and piles in CPRF (Katzenbach and Leppla 2015)



Interactions: 1 – soil-pile; 2 – pile-soil-pile; 3 – raft-soil; 4 – raft-soil-pile, where: 1 – settlement of a single pile in a group, 2 – mutual interaction of settlements of the piles in a group, 3 – non-linear elasticity of the soil under a foundation slab, 4 – influence of load transmission on the soil under the slab, on the piles skin friction.

FIGURE 2. Scheme of interaction between the construction and the soil in the CPRF (Katzenbach and Leppla 2015)

histories with observations of the load sharing presented by Mandolini et al. (2005).

The presented analysis concerns one of the high-rise building in typical for Warsaw soil conditions.

Combined pile-raft foundation (CPRF) is a hybrid system, consisting of a slab foundation, a group of piles and soil which are interacting (Katzenbach and Leppla 2015). Figure 2 shows a scheme of existing interactions in a typical pile-raft foundation.

SOIL AND WATER CONDITIONS, PARAMETERS OF HSS MODEL

The construction site is located on postglacial upland. The area is almost flat, with ordinates around 36 m above the “0” level of Vistula river. Under the surface, till the depth of 1.20–10.30 m, there are anthropogenic soils. Thickness of the soil increases in the southern direction reaching their maximum thickness in the direct neighbourhood of railway tunnel. What is more, there have been discovered numerous relicts of foundations and basements of previously existing buildings.

Below the made grounds, there are fine and silty sands of compaction index I_D = 0.70. The cohesive soils such as marginal silty-clay loam, silty-clay and medium sandy clay which are present up to 12–14 m under the surface. Cohesive soils are low plasticity of plasticity index I_L = 0.0–0.1. Below cohesive soils there are sandy soils which compaction index $I_D \geq 0.80$. At the depth of 27.0–35.0 m below the ground level is divided by semi-cohesive soils such as silts, silty-clay and local mud.

At the depth of designed foundation, that is present at around 17 m below the ground level, there are fine and medium sands, with $I_D \geq 0.80$. Figure 3 shows an example of geological cross section of the analysed building.

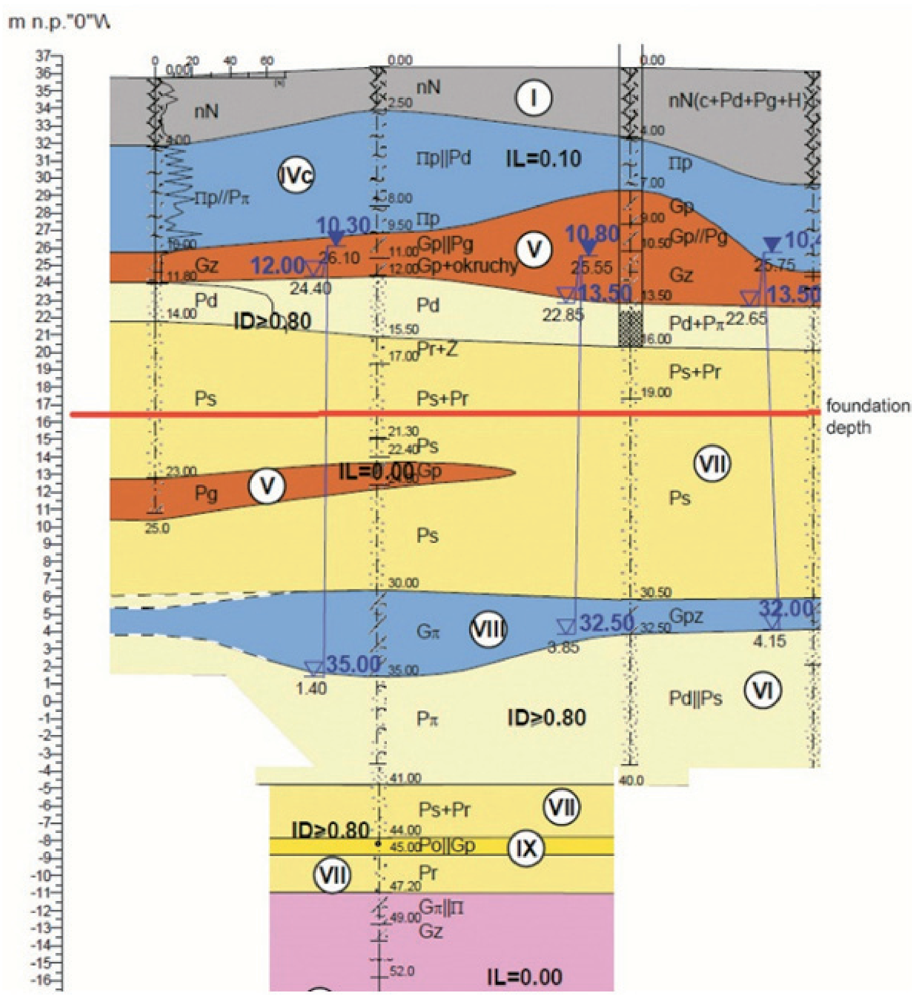


FIGURE 3. Geological cross section sample of the analysed building area

TABLE 1. Material parameters of sand and clay for HSS model

Material	E_{ur}^{ref}	σ_{ref}	ν_{ur}	m	σ_L	E_0^{ref}	$\gamma_{0.7}$	E_{50}^{ref}	σ_{ref}	Φ	Ψ	c'	E_{oed}	σ_{oed}^{ref}	K_0^{NC}
	MPa	kPa	–	–	kPa	MPa	–	MPa	kPa	°	°	–	MPa	kPa	–
Sand	325	100	0.2	0.5	10	960	$1 \cdot 10^{-4}$	110	100	42.5	12.5	0.1	110	251.14	0.3982
Clay	90	100	0.25	0.85	10	275	$2 \cdot 10^{-4}$	30	100	38	13	18	30	260	0.38

Table 1 shows material parameters used for HSS model of sand and clay respectively, which are presented below the foundation slab level. Soil model parameters were interpreted using advanced field and laboratory tests, e.g. CPT/CPTU probing, DMT, oedometer testing and triaxial testing.

METHODOLOGY OF STRUCTURAL ANALYSIS

Static calculations for the building were done by means of ARSA program, for a previously created model of the underground. Adequately collected layout of the reaction forces was directly imported and applied to the foundation slab in underground 3D ZSoil model. For the acquired set of forces and placement of the barrettes in ZSoil, as the result one can get information about the soil and behaviour of the slab and pile system. With values of foundation elements stiffness (defined as load/settlement ratio) already set for the particular elements of the construction, it is possible to return to the ARSA model in order to implement the data and to verify convergence of the calculations. The analysis process as a simplified block scheme is presented in Figure 4.

Figure 5 shows a detailed algorithm regarding numerical solution and analysis of the investigated issue. The scheme of acting may be applied for problems such as setting stress in diaphragm walls or using ARSA for correct designing the foundation slabs, based on information regarding the soil from ZSoil. The differences may appear while modelling the right phases construction working, whether an analysis of the whole construction is required or a single element analysis.

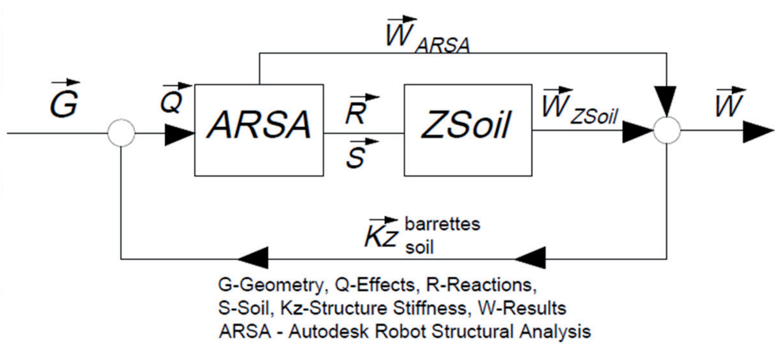


FIGURE 4. Simplified block scheme of the performed analysis

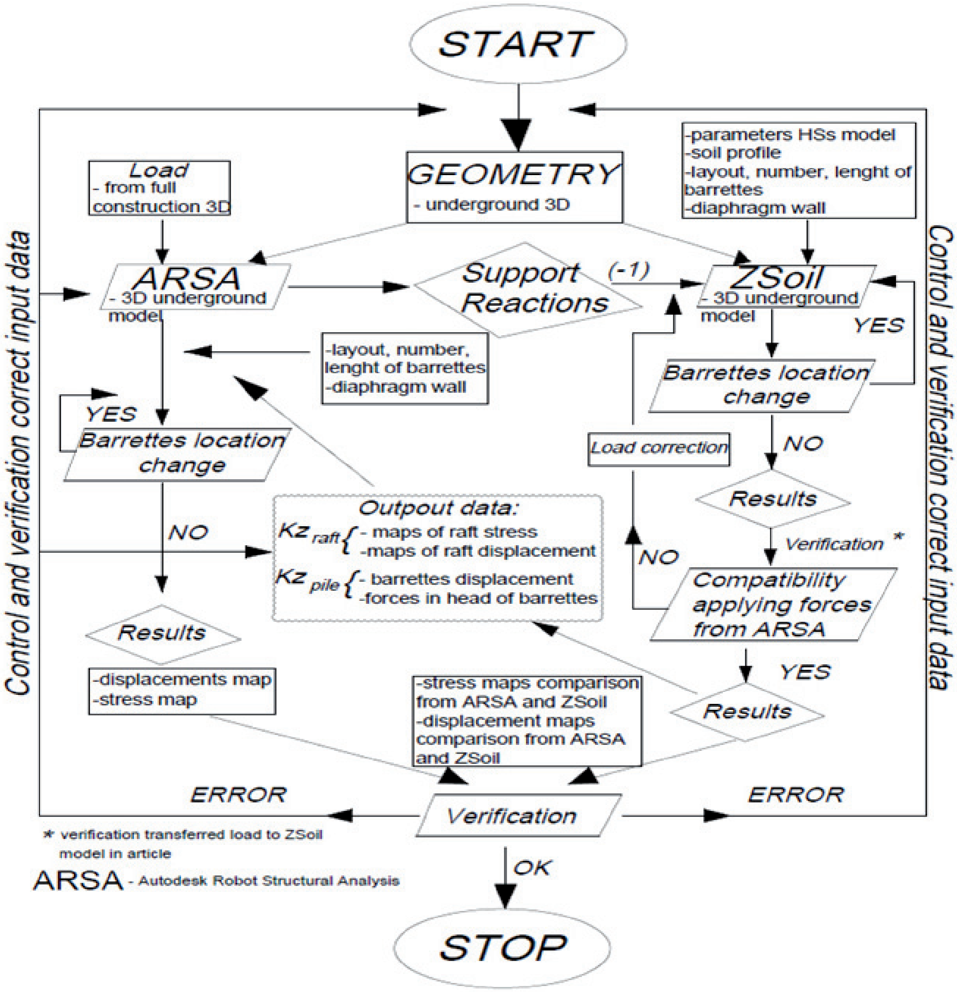


FIGURE 5. A detailed algorithm for the analysis of the construction in cooperation with the ground base

In case of the described issue, when using the algorithm, the results will be clear, if in the both models all the parameters are convergent with those resulted from the ZSoil geotechnical program. Existence functions of construction creating in ZSoil model are shown in Figure 6.

Calculations of this paper were conducted up to the forth step which means to the application full load, limiting the fifth step where the water reconstruction was turned on.

Figure 7 shows a 3D view underground part of the construction that is the diaphragm walls, barrettes and raft. All vertical elements below the foundation slab, i.e. diaphragm wall as well as barrettes were modelled as embedded beams (Fig. 7).

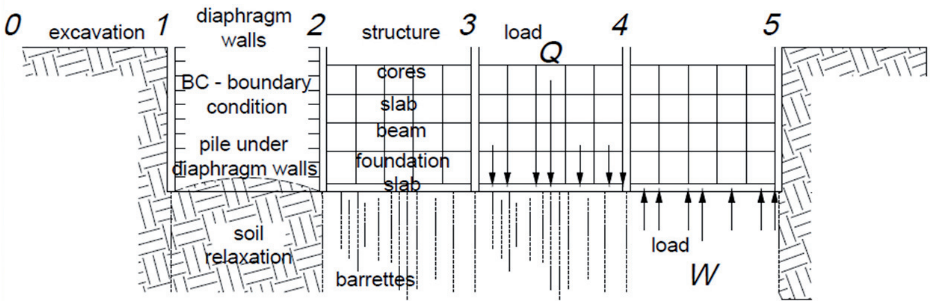


FIGURE 6. Phase of the building model in ZSoil

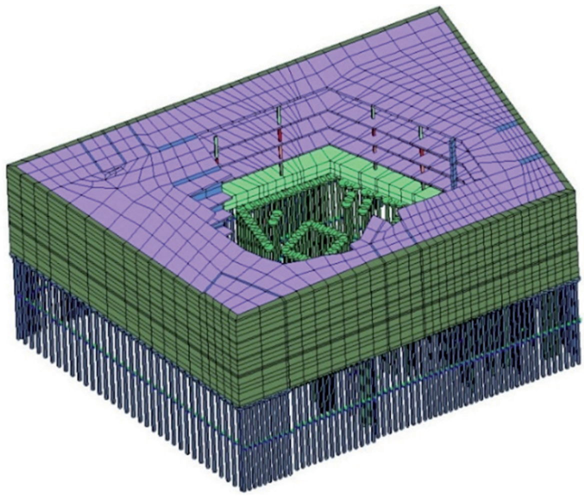


FIGURE 7. The three-dimensional view the underground part of the construction – diaphragm walls, slabs, cores, foundation slabs, piles/barrettes

RESULTS

Here are the results of the calculations from the analysis conducted according to the scheme shown in Figure 5. First, the load distribution in all CPRF system and in its separate parts need to be determined. Later, after having determined the stiffness values of the barrettes and modulus k_z of the soil for CPRF, it will be possible to compare the settlements obtained in ZSoil program with the values in ARSA.

BARRETTES STIFFNESS IN COOPERATION WITH FOUNDATION SLAB

As mentioned above during the process of designing a building it is essential for structural engineer to obtain information regarding stiffness of soil beneath raft and stiffness of foundation elements (defined as load/settlement ratio). The calculated stiffness of each barrette and piles was based on setting the relation between the load and the settlement by

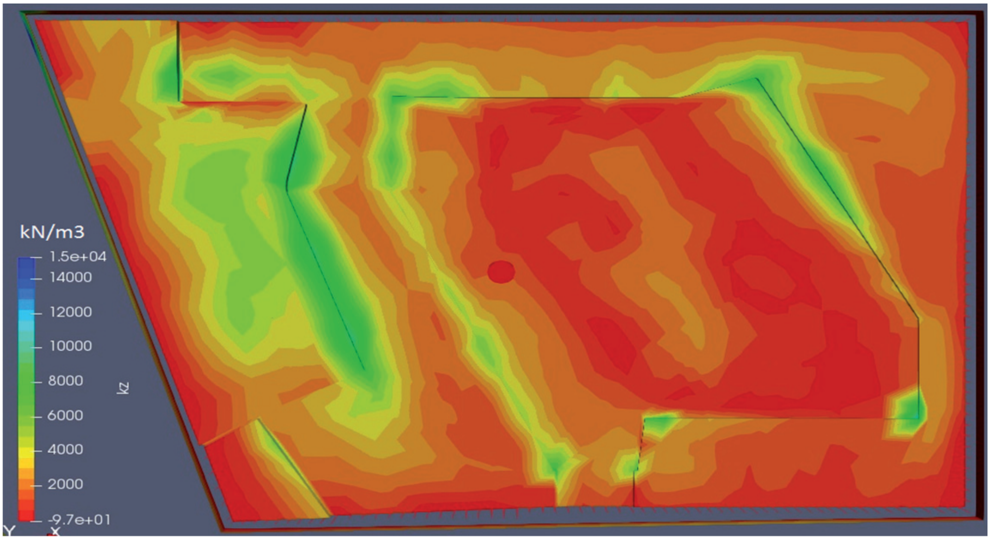


FIGURE 8. Stiffness (k_z) of the foundation slab – map from ParaView program

obtaining the susceptibility modulus (k_z). It is assumed that each beam type element, i.e. piles, barrettes and columns are divided into ten sections.

The foundation slab stiffness was calculated on the basis a quotient total stress occurring on the surface of the interface and the foundation slab, to the displacement each finite element of the slab. The maps of stress and settlements were generated and later put one onto another by means of ParaView program. The view soil susceptibility map under the foundation slab is shown in Figure 8.

COMPARISION ANALYSIS – LOAD DISTRIBUTION

Assumption made for pile raft system is that CPRF does not include the work of the diaphragm wall, so finally the force falling onto such system is:

$$F_y(\text{ZSoil, all}) - N_x(\text{wall}) = \\ = 1{,}626.58 - 507.72 = 1{,}118.86MN = \\ = F_y(\text{barrettes, slab})$$

Thanks to modelling barrettes as well diaphragm wall and piles, i.e. embedded beams, the load percentage falling onto the barrettes and raft is respectively:

$$\frac{N_x(\text{barrettes})}{F_y(\text{barrettes, slab})} =$$

$$= \frac{888.23MN}{1{,}118.86MN} = 0.79 = 79\%$$

and

$$\frac{F_y(\text{slab})}{F_y(\text{barrettes, slab})} =$$

$$= \frac{230.6MN}{1{,}118.8MN} = 0.206 = 21\%$$

Summarizing the conducted load distribution analyses, in the Table 2 there has been described the percentage comparison of the load value by particular element in the raft-pile systems. The elements in the CPRF system, points from 1 to 3, include a foundation slab as a horizontal element and piles/barrettes as vertical elements. Point 4 include a foundations slab, barrettes/piles and the diaphragm wall which were modelled as pile elements starting at the level of the foundation slab.

The overall conclusion based on the analysis is that the slab takes around 15–20% of the falling load. The majority of forces is taken by the barrette, i.e. around 80–85% of the whole load.

Figure 9 shows a foundation slab, with a pile system and point applied forces. it is shown a CPRF system deformation in ZSoil model (Fig. 10).

The building consists of four underground floors and 54 above-ground floors. The foundation slab area is around 3,000 m^2. The "0" level of the building was established to be at ordinate +35.90 m over the "0" level of Vistula river. The main level of building foundation was designed to be at 18.80 m below zero of the building.

It is shown the view of the piled-raft system (barrettes plan) used for calculations (Fig. 11). Barrettes length are from 17.5 up to 20.0 m (the core area) below the foundation slab.

Parameter A_g is the area of the pile group and A is area of the raft. The simple geometrical parameter (s/d) plays a major role in load sharing; the higher the spacing the higher the load taken by

TABLE 2. The percentage load distribution in the raft-pile system

Analysed area	Raft	Piles
The raft	21	79
Core area	7	93
Outside core area	32	68
Pile-raft system	14	86

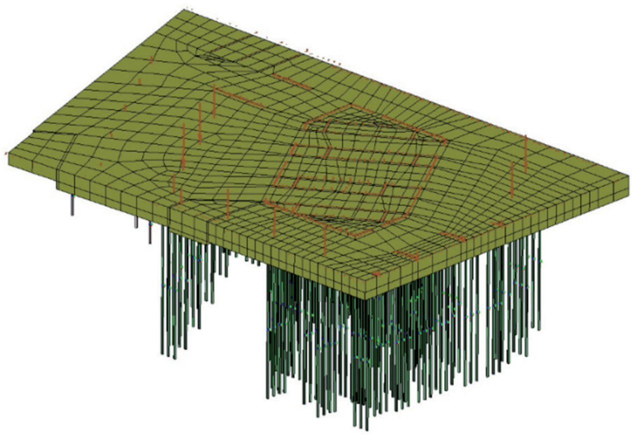


FIGURE 9. System CPRF with point applied forces shown in 3D

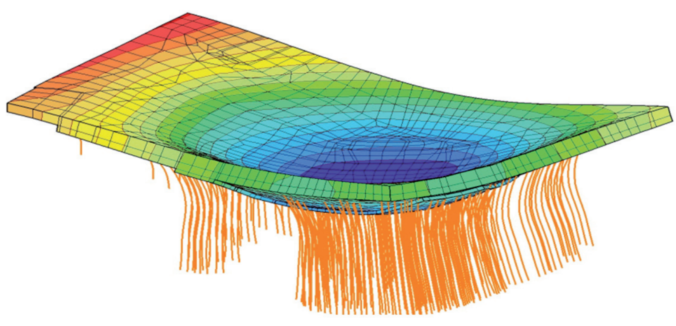


FIGURE 10. The deformation view of the raft-pile system in ZSoil model

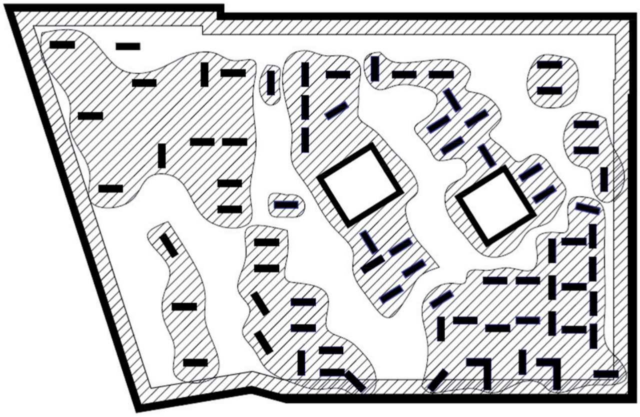


FIGURE 11. Barrettes plan of the pile-raft foundation; area of the walls and barrettes

the raft (Mandolini et al. 2005). Originally Mandolini et al. (2005) examined 22 buildings. Figure 12 presents the resulting relationship between the load sharing and parameter *s/d*. In Figure 13 the load taken by the raft is plotted *versus* the dimensionless parameter $(s/d)/(A_g/A)$. The plot results were extended by the results from this analysis.

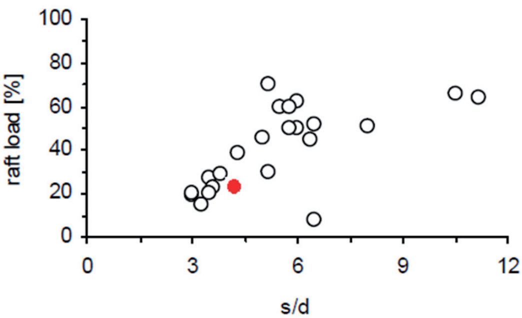


FIGURE 12. Load shared by the raft *versus* spacing

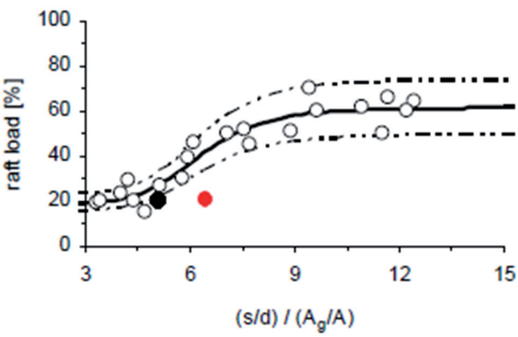


FIGURE 13. Load shared by the raft *versus* spacing divided by the area ratio A_g/A

If the parameter A_g/A was at the level of 0.83, the result would move closer to the presented set of points (see Fig. 13 black point).

Self-conducted load distribution analysis in CPRF elements based on the numerical procedure enables the comparison with the measurements results of the load distribution carried out by Mandolini et al. (2005).

CONCLUSIONS

The article presented the possibility procedure to determine stiffness elements of the CPRF (ground, barrettes). The designer, applying presented algorithm (Fig. 5), with cooperation ZSoil and ARSA programs is capable of calculating and designing in the right way the foundation slab, barrettes and the diaphragm wall.

The load distribution of analysis described in this paper, it may be concluded that high-rise buildings with CPRF and similar type and group of barrettes, around 20% of the load is transferred onto the raft, and the rest that is around 80% of the load is taken by the vertical elements – piles, barrettes and the diaphragm wall.

Presented results was compared with Mandolini et al. (2005). The geometrical and dimensionless parameter $(s/d)/(A_g/A)$ plays a major role in load sharing.

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Streszczenie: *Analiza numeryczna rozkładu obciążenia poniżej układu płytowo-palowego budynku wysokościowego.* W pracy przedstawiono problem posadowienia płytowo-palowego budynku wysokościowego w typowych dla Warszawy warunkach gruntowo-wodnych. W celu określenia współpracy ośrodka gruntowego z fundamentem płytowo-palowym, w zakresie rozkładu obciążenia, przeprowadzono analizę wykorzystującą metodę elementów skończonych (MES) z zastosowaniem modeli gruntu HSS (ang. *hardening soil with small strain*) w środowisku ZSoil z użyciem programu Autodesk Robot Structural Analysis (ARSA). Artykuł zawiera podstawowe informacje dotyczące fundamentów płytowo palowych, opis warunków wodno-gruntowych razem z oszacowanymi parametrami dla modelu HSS przyjętych do obliczeń w ZSoil. Przedstawiony został również schemat blokowy pokazujący ścieżkę postępowania przy projektowaniu, modelowaniu i analizie numerycznej między programami ZSoil i ARSA. Przeprowadzona własna interpretacja rozkładu obciążenia na elementy fundamentu płytowo-palowego według procedury numerycznej umożliwiła porównanie własnych wyników z wynikami pomiarów rozkładu obciążenia przeprowadzonymi przez zespół Mandoliniego w 2005 roku.

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Authors' address:
Grzegorz Kacprzak
Zakład Geotechniki i Budowli Podziemnych
Wydział Inżynierii Lądowej
Politechnika Warszawska
ul. Lecha Kaczyńskiego 16, 00-637 Warszawa
Poland
e-mail: g.kacprzak@il.pw.edu.pl