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Testing of innovative foundations of 400 kV OHL transmission towers

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Abstract: The work describes structural solutions and tests of geotechnical capacity of innovative monolithic-prefabricated foundations. The investigated foundations were shaped as sloped footing pad foundations intended for the foundation of lattice steel 400 kV OHL transmission towers. Full scale geotechnical field tests according to standard PN-EN 61773:2000 were conducted. The test results were compared with those obtained by the FEM method using advanced nonlinear analysis with Hardening Soil Small (HSS) models.

Keywords: uplift capacity, lattice tower foundations, transmission tower foundations, field tests

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Introduction

The significantly higher requirements currently imposed on transmission tower support structures implemented by the dedicated PN-EN 50341-1 (2013) and PN-EN 50341-2-22 (2016) standards have become an incentive for extensive research and development work in the power industry. This applies in particular to the solutions for the most widespread highest voltage power lines in the country, ranging from 110 to 400 kV. The research work covered both steel support structures and their foundations. The two development paths involved scientific inquiry within the implementation of tasks for Enprom's research project from NCBIR resources under the Project No. POIR.01.01.01-00-0789/17 entitled "Development

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of a new series of types of 400 kV transmission towers and their matching foundations, including foundations for the use in soils with particularly unfavourable geotechnical parameters". One of the two key research paths involved mushroom footing pad foundations for steel lattice towers with enhanced safety requirements in line with current standards.

Relatively few tests of foundations exposed to uplift forces have been performed so far in Poland and worldwide, in particular very few full-scale tests. A tabulation of tests performed worldwide is presented in the works by Biarez & Barraud (1968) and Meyerhof & Adams (1968), while selected tests performed in the former USSR are described in the work by Kananyan (1966). Refer to the work by Żmudzinski (1986) for a more extensive analysis along with a description of national research work. There have been no major research projects in this area subsequently. A few work describes a new tests in this subject like: Pacheco et al. (2008), Deshmukh et al. (2010), Srinivasan & Ghosh (2020). But the scale of tested samples are small or the number of the tests are not sufficient. As part of the Project No. POIR.01.01.01-00-0789/17, various types of reinforced concrete pad footing foundations were subjected to field tests, including a series of standard prefabricated structures, a series of prefabricated foundations with special overlay plates and innovative monolithic-prefabricated foundations. A description of tests on standard foundations with rectangular base is presented in the work by Labocha et al. (2020), while tests on foundations with prefabricated reinforcing overlay plates are described in the work by Paluszyński et al. (2020). This paper presents the results of tests and theoretical analyses of innovative reinforced concrete monolithic-prefabricated foundations. Due to their qualities, these foundations have already been implemented in the construction of the latest 400 kV power lines (Mikułowa-Czarna and Piła-Krzewina-Plewiska). A view of one of the tower sites using the innovative L-type foundations developed in the research project is shown in Figure 1.

Fig. 1. View of innovative monolithic-prefabricated foundations at the Piła-Krzewina-Plewiska tower site (Enprom Report, 2018)

1. Field tests of foundations

Foundation tests were performed on the full-scale structures, compared to adequate foundations actually used on 400 kV power lines. The dimensions and design details of the innovative monolithic-prefabricated pad foundation intended for the series of tests are shown in Figures 2 and 3 respectively.

The field tests focused on the evaluation of the ultimate uplift capacity of foundations. The uplift capacity is in practice most often critical for the selection of split direct foundations in the form of mushroom pad footings for lattice towers. The research project was conducted in cooperation with the Institute of Roads and Bridges, Faculty of Civil Engineering, Warsaw University of Technology, which, *inter alia*, performed field and laboratory tests on the properties of the backfill soil used in the tests.

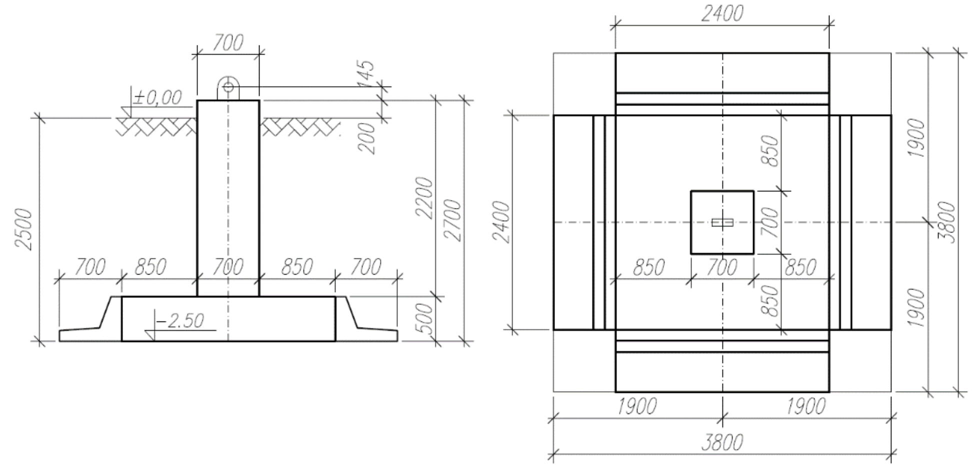

Fig. 2. Overall dimensions of the foundation to be tested (Enprom Report, 2018)

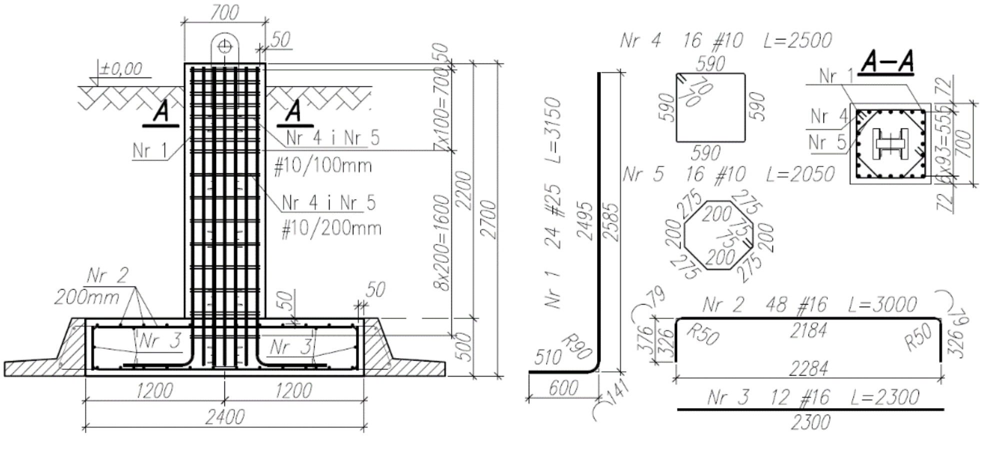

Fig. 3. Design details of the foundation to be tested (Enprom Report, 2018)

Figure 4a shows a view of the layout of the reinforced concrete precast base slab of one of the tested foundations, along with the prepared reinforcement of the monolithic part of the slab and the reinforcement of the shaft. Figure 4b, on the other hand, shows the head of the finished foundation with anchor. The foundation depth was 2.5 m. A view of the test site with the main beam and additional support structures for the displacement sensors is shown in Figure 5.

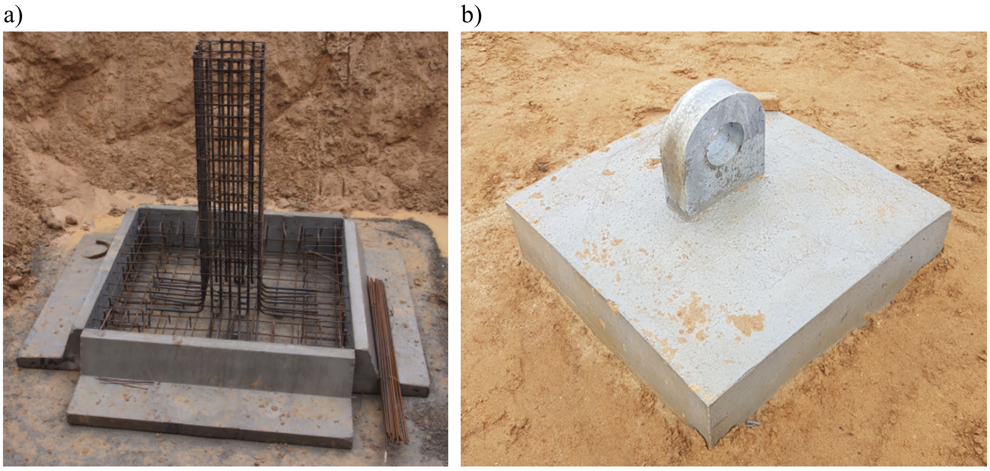
a) b)

Fig. 4. View of the test foundation: a) precast base slab and shaft reinforcement, b) foundation head with anchor (Enprom Report, 2018)

Fig. 5. View of the test site (Enprom Report, 2018)

The tests of the foundations covered two series of tests, 3 tests each of identical foundations placed in homogeneous soil conditions of two types. Homogenised soils lying in the subsoil on the testing ground were used for backfill. The tests performed at the Warsaw University of Technology laboratory described in the WIL PW Report (2018) classified them as Pg (Sa) and Gp (saCl). Soil designations were adopted according to the nomenclature of PN-B-03322 (1980) approved for the foundation of transmission towers pursuant to the guidelines of PN-EN 50341-2-22 (2016). The relevant designations in brackets are those coherent with EN 1997-1 (2008) and EN 1997-2 (2009). The values of geotechnical parameters of the backfill soils used are summarised in Table 1.

Table 1. Geotechnical parameters of soils used in the tests

Soil symbol	Bulk density	Initial loading modulus	Poisson ratio	Internal friction angle	Cohesion
	ρ [t/m^3]	Eo [MPa]		φ [°]	c [kPa]
Pg (Sa)	1.968	50	0.3	32.0	12.9
Gp (saCl)	2.209	20	0.3	26.6	18.9

The tests were conducted in accordance with the requirements of PN-EN 61773 (2000). During the tests, the main objective of which was to evaluate the ultimate load capacity of the foundations, relevant displacement measurements were also performed. The measurement methodology, including the relevant load steps and their timing, was adapted to the requirements of PN-EN 61773 (2000). Displacement readings were recorded using four inductive sensors with an accuracy of 0.01 mm at 5-minute intervals and immediately after load change. The forces were measured using an electronic dynamometer placed between the actuator piston and the main beam. The testing in each test was performed until the ultimate force in the measuring system was reached, i.e., when the readings on the actuator pressure gauge indicated no increment in force at the recorded displacement increments. The values of the limit forces determined by the above method and the corresponding displacements in all tests are summarised in Table 2. Figure 6 shows the force-displacement curves obtained from the tests for all the tests performed.

Table 2. Summary of test results

Test stage/ Test site	Type of backfill soil	Maximum force obtained in the test load	Maximum displacement	Constant displacement
		[kN]	[mm]	[mm]
III/P1	Pg (Sa)	1600	85.63	15.56
III/P2	Pg (Sa)	1550	75.80	12.50
III/P6	Pg (Sa)	1170	96.86	22.76
III/P3	Gp (saCl)	1200	179.33	19.80
III/P4	Gp (saCl)	1350	136.51	21.83
III/P5	Gp (saCl)	1350	139.13	22.13

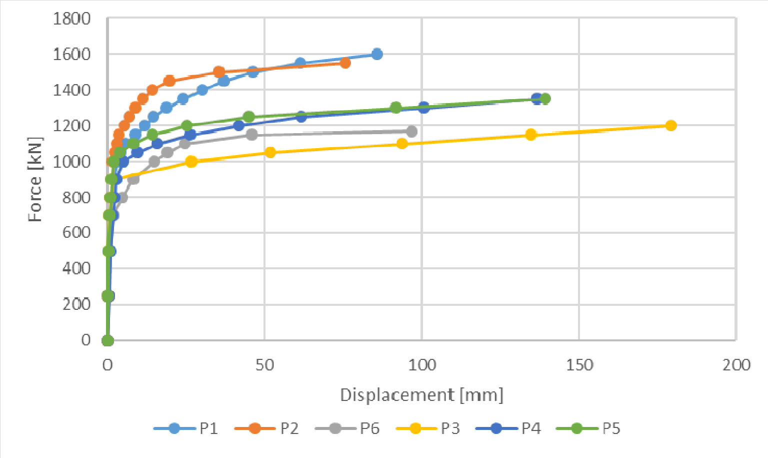

Fig. 6. Force-displacement curves obtained from the tests

2. Numerical FEM analyses of foundations

The results of the field tests were compared with the results obtained from FEM calculations, using the Midas GTS software. Volumetric models representing 1/4 of the tested system were developed. The foundation structure was modelled with elements having linear elastic properties corresponding to C25/30 concrete. The soil was modelled by elements with elastic-plastic properties based on the Mohr-Coulomb destruction theory with parameters specified in Table 1. The values given were also the basis of recommended parameter estimates for the Hardening Soil Small (HSS) models implemented in the Midas GTS software.

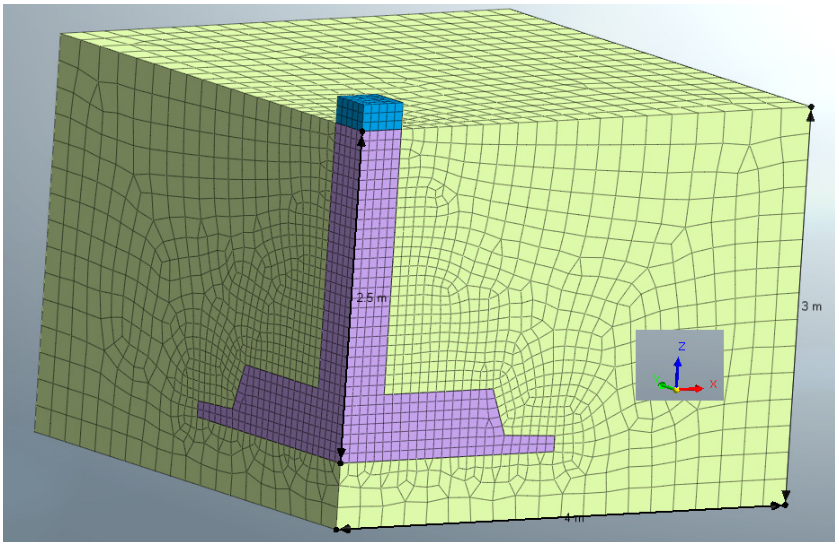

Fig. 7. View of the FEM model and mesh

Surface interference contact elements with a reduction factor of 0.7 were used at the interface between the concrete elements and the soil. A general view of the FEM model including meshing is shown in Figure 7, while a typical deformation pattern in the destruction phase is shown in Figure 8. 30211 parabolic volumetric finite elements were used in the model. The total number of nodes was 78712. A force-controlled nonlinear elastic-plastic analysis of the models was performed. It was assumed that the ultimate load capacity was obtained when the displacements increased significantly, and the convergence of the solver solution was lost. A summary of the analysis results is shown in Table 3. Figure 9 shows the force-displacement curves SEP (static equilibrium paths) obtained from the FEM analysis.

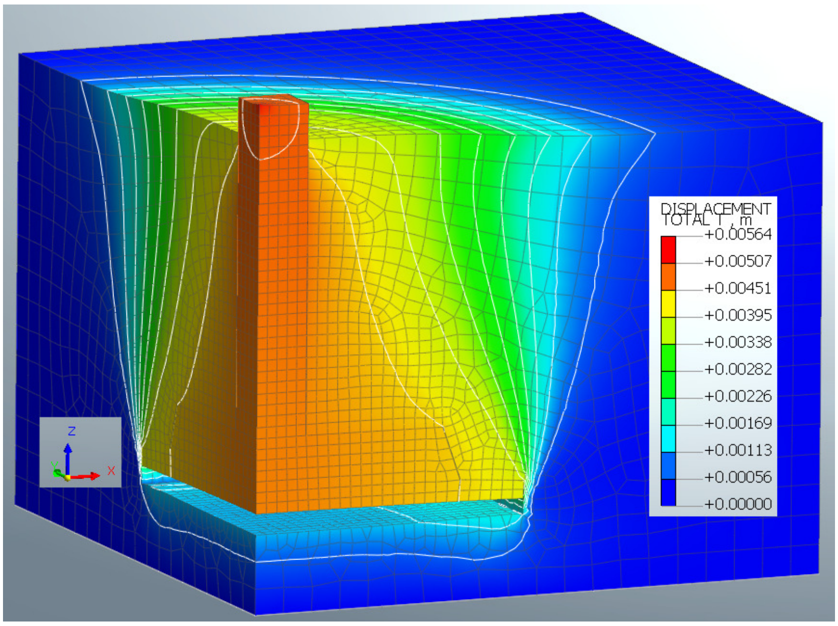

Fig. 8. Deformation maps for the destruction phase in the FEM model

Table 3. Comparison of the results from tests and theoretical analyses

Test stage/Test site	Type of backfill soil	Maximum force obtained in the test load	Mean value of tests	FEM analysis Model HSS
		[kN]	[kN]	[kN]
III/P1	Pg (Sa)	1600	1575 (1440)	1560
III/P2	Pg (Sa)	1550		
III/P6	Pg (Sa)	1170		
III/P3	Gp (saCl)	1200	1300	1480
III/P4	Gp (saCl)	1350		
III/P5	Gp (saCl)	1350		

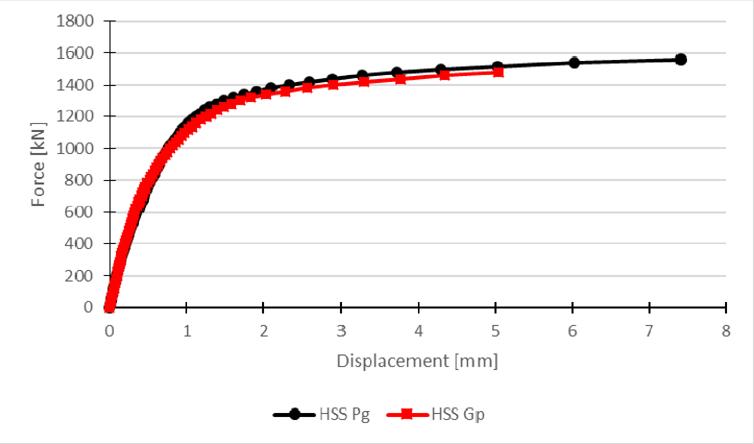

Fig. 9. Force-displacement curves obtained in the FEM analysis

It is observed that the limit capacity values determined by FEM are close to the values obtained during the tests, but the values of the corresponding displacements are significantly lower despite the use of the HSS model. Improved adaptation in deformation can be achieved using displacement control in nonlinear FEM analysis.

3. Analysis of results

All the field tests performed were characterised by a continuous displacement increment, with a constant or slightly decreasing value reading on the gauge at the level of the maximum force, considered to be the ultimate at the time. Relatively high repeatability of results was obtained, but it should be noted that the underestimated P6 test result differed from the rest due to changes in backfill soil moisture caused by rainfall in the days preceding the tests. Hence, in Table 3, the mean value for this series of tests is given with its inclusion in brackets.

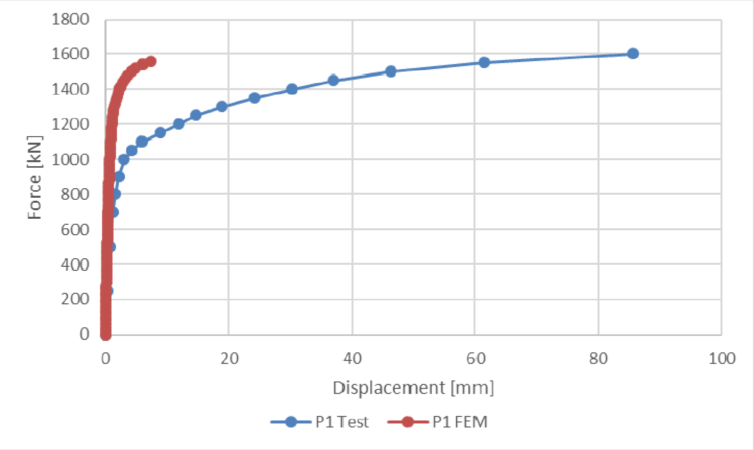

Fig. 10. Comparison of MPCs obtained from tests and FEM analyses for the III/P1 test

An example comparison for the III/P1 test of the force-displacement curves, i.e., the SEP (static equilibrium paths) from testing and FEM analysis is shown in Figure 10.

These curves look analogous for the other tests. The presented results of advanced 3D FEM analysis of innovative foundation structures with unusual base slab shapes in terms of ultimate load capacity show high similarity between theoretical results and field tests. However, the limit values in the FE analysis were obtained with much smaller displacements in the soil and the foundation itself.

Conclusion

The field tests allowed the following observations to be made:

- when the foundation was uplifted, irregular cracks appeared on the upper surface of the soil, mainly parallel to the edges of the base and curvilinear in the area of the corners of the base, and the soil around the foundation lifted,
- the cut of the uplifted lump of soil was at an angle to the base, with part of the soil near the corners also being lifted,
- the reinforced concrete foundations were not damaged in any way, no cracks or scratches were found on the surfaces of the uplifted test elements, and no loosing of the prefabricated elements from the monolithic part occurred.

It can be concluded on the basis of the observations that the assessment of the load capacity of the tested innovative foundations with a complex base geometry can also be estimated by means of a substitute foundation model with a square base, or even a substitute circular base.

The evaluation of the load capacity of pad foundations under the uplift forces using the FEM method and the HSS model with the standard approach to the stiffness parameters of the soil, provides a very good estimate of the true ultimate load capacity of the foundations, but with a significant underestimation of their displacements.

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