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MECHANICAL STATE ANALYSIS OF DIFFERENT VARIANTS OF PILED RAFTS

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Abstract. Traditional raft design methods describe unpiled and fully piled rafts. The current paper aims to discuss intermediate raft design variants when the raft is at the same time partially supported by piles and partially rests on the ground. The loading conditions of all variants as well as mechanical properties assumed to be identical, general numerical simulation assumptions are also the same. The task is to analyse the stress and strain state of the raft for all variants (unpiled raft, partially piled raft, fully piled raft), to compare the results and to determine the most rational case. Raft settlements, bending moments and expenses of the materials are compared on the basis of the results.

Keywords: piled raft, soil–raft interaction, variants, finite element analysis, design.

1. Introduction

The transportation constructions form a particular group of the structures in which aesthetic, economic, construction processes, sequence of construction and other factors are largely determined by the building use requirements. If bridges and viaducts are located over the surface of the ground, the open work design is preferred, the tunnels, on the contrary, have different requirements: the structural shell should provide protection of traffic flows from soil collapse and from action of atmospheric and ground waters (Chapman *et al.* 2010). The tunnels are designed as continuous structures, therefore the load-bearing constructions must be settlement-proof.

From the mechanic perspective view-point the upper arch part of a tunnel and its lower plane part function differently due to variety of shapes and different load distribution. The deformation joints are installed each 30–40 m in the road direction, thus, the problem of uneven settlement in adjacent sections becomes rather essential (Fig. 1). Deformation conditions of the tunnel structures are also important as the service time of such kind of constructions can achieve 100 years (*LST EN 1990:2004 Eurocode. Basics of Structural Design*). The aspects of the environment protection from technogenic pollution are equally important. In this case reliability is assured by homogeneity of the structures. Similar solutions are common for structures of oil, chemistry, nuclear and other fields of industrial engineering (Gabrielaitis, Papinigis 2010).

The unpiled rafts are common in raft design practice (Bezvolev 2002; Fedorovskii, Bezvolev 2000), however, fully piled rafts are also generally used (Kameswara Rao 2011; Tomlinson, Woodward 2008). Scientific literature also describes an instance of the raft estimation, when the raft above the vertically reinforced soil is not joined with the piles (Bezvolev 2008; Fedorovskii 2008). In order to ensure even deformations of the building and foundation, when the soil is soft or unevenly distributed, piles are provided to reduce raft settlement. However, it is not clear which

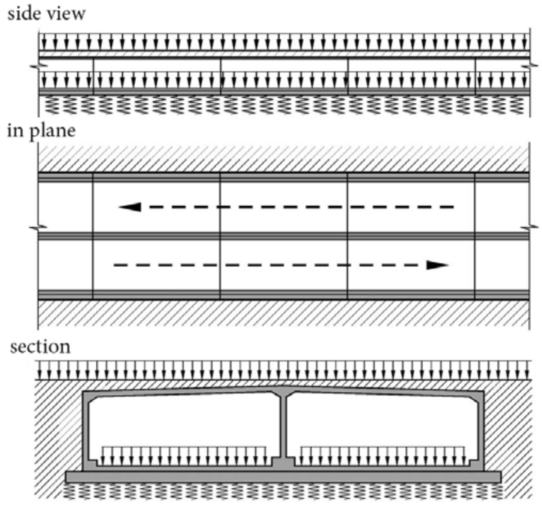

Fig. 1. General views of the road tunnel

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of the above mentioned methods is appropriate for the road rafts in tunnels, where settlement restriction is important only for narrow sections near the deformation joints.

The current paper investigates different pile distribution variants within the raft area when one part of the raft load is transferred to the soil through piles, whereas the other part is transmitted directly by means of a direct soil-raft contact. Such a solution is more cost-effective, but more difficult to estimate. The results of laboratory and natural experiments using piles are rather approximate (in comparison with test results of construction materials and accuracy of mechanisms specifications), it enables to analyse different calculation algorithms by applying various assumptions (Dalili Shoaei *et al.* 2012; Wang *et al.* 2005). The applicability of such assumptions is still debatable. The modern hardware and software allow perform modelling of foundations together with the soil half space taking into consideration the elasticity-plastic properties of the soil (Dirgėlienė *et al.* 2013; Skaržauskas *et al.* 2009).

This paper decides the road raft calculation task by comparison of various practically reasonable variants (Mistríková, Jendželovský 2012). This approach allows to consider the construction unification problem, critical in engineering practice (Sivilevičius *et al.* 2012), otherwise, it would remain to be a theoretical reasoning scholarly and will be not fulfilled. Unpiled and piled rafts are numerically modelled by applying the finite element method (3*D modelling applying Midas Civil, Integrated Solution System for Bridge and Civil Engineering, checked by Structural CAD and 2D by Phase2, Finite Element Analysis for Excavations and Slopes, ver. 8.0*). The soil half space is not analysed directly, i.e. it is not simulated by the finite elements. The foundation counteraction (expressed by reactions and settlements) is modelled by elastic connections with the stiffness values appropriately chosen during iteration stages of the calculation.

The foundation stress and strain state depends on the load, properties of the ground and raft dimensions in plan. The commonly used design methods (*SP 22.13330.2011 Footings for Buildings and Facilities. Regulation of Russia*) suggest choosing the estimated layer of effective limited thickness. However, such analytical solution is not unambiguously defined for the rafts of a different shape in plan. Distribution of internal forces in the raft is affected to some degree by properties of the ground, located just outside the raft contour, where shearing stresses are dominated. There is no doubt, that the raft settlement depends also on the mechanical state of the ground, located outside the raft contour (Fedorovskii, Bezvolev 2000; Perelmuter, Slivker 2003). The above mentioned more extended problems are not discussed in the given paper, assuming that conditions for narrow sections near deformation joints, where settlements are very important, for linearly located road foundation plates are suitable enough.

2. A concept

The calculation algorithms of design codes (*LST EN 1997:2007 Eurocode 7. Geotechnical Design*) tend to focus attention on foundations under columns and walls which are considered as ideally stiff and are used in civil and industrial engineering. The assumption of the ideal stiffness is unsuitable for the raft calculations because the distribution of internal forces between the piles and in the soil half space depends on the raft distortion. When distributed loads affect a relatively small area, the raft, which transfers loading onto the soil and reduces settlements, is being designed. If the ground properties are such, that given max settlement values of the raft do not exceed a limit value, the piles are not constructed. The upper soil layers, to which the raft load is directly transferred, are essential when the unpiled raft is designed. Deformations of these soil layers usually constitute 2/3 of the total raft settlements (Fedorovskii, Bezvolev 2000). If settlement values from calculations are exceeded limit values, the piles, transferring load to the lower layers of a more hard ground, are designed (Sokolov *et al.* 2013). If there are no hard grounds on the pile base level, the piles are elongated until the total calculated load is taken on by the side surfaces of the shear resistant piles.

A decision about the raft designing must be made at certain conditions, which are specified first of all by the load features and a character of the soil foundation. In case of investigation of the raft, which is partially supported by piles and partly rest on the ground, there is a situation under following conditions: properties of the soil are the same along piles; within the area of soil and raft contact the soil is of natural type (it is not destructed or broken by transport or other construction machines); when the load is acted, settling of piles would take place first of all and then the ground will start its compression resistance in the area of a direct contact with the raft.

While designing a raft with densely located piles (when the distance between pile centres is 3–4 diameters), it has been considered that 10% of the total load has been transferred between the piles in the contact zone of the raft and average strength ground (if the foundation is not prepared before concreting the raft), and up to 20% has been transferred if the soil is thickened, its quality is checked and additional layer of gravel has been underlain. The piles take over the rest of the load. Mandolini *et al.* (2005, 2013) theoretically and practically have investigated a case, when the raft on sand or gravel grounds assumed up to 60% of the total load with the piles located far-between.

In all variants of the calculation the task of distributing internal forces between the piles have solved by the iteration stage-by-stage method, based on the analysis results taking into consideration distribution of deformations. Due to technological reasons, it is recommended to construct piles of the same diameter and length. The minimal assumed distance between centres of the piles is 3 diameters. In this case the soil deformation around the pile is traditionally regarded as independent from nearby piles (Mandolini *et al.* 2013). The raft cost-efficiency criterion (concrete and reinforcement expense) limits the max distance between the adjacent piles.

The finite element method has been applied for estimating the raft problem. The aims of the numerical research are as follows:

1) to investigate influence of the piles arrangement on the mechanical state of the raft;

2) to compare results of different calculation variants and analyse their peculiarities;

3) to select the most rational raft construction variant taking into account relative expenses of materials.

The idea of the raft investigation has appeared while calculating, designing and inspecting tunnels, which are currently being built in Lithuania. Thus, particular engineering situations without considering the general optimisation problem shall be discussed below (Mockus *et al.* 2012).

3. Main parameters

In order to formulate this raft problem the main parameters have been specified: properties of the ground, geometric peculiarities of each variant, mechanical characteristic of the materials.

The sandy loam ground has been analysed. For all task variants the soil properties have been considered homogeneous, identical for the entire pile length: selfweight is 21 kN/m^3, internal friction angle is 25 degrees, cohesion is 7 kPa, stress-strain modulus is 15 MPa, cone strength is 2.2 MPa, side friction is 45 kPa, limit strength is 0.35 MPa, Poisson's ratio is 0.3. While calculating it has been assumed that the ground properties are the same over the whole raft area.

For investigation the raft of constant thickness with 38×38 m dimensions in plan have been selected. All piles have been defined of equal 9 m length, which starts from the bottom surface of the raft. Due to technological reasons the 1.0 m distance from the centres of the last rows of piles to the raft edge has been chosen for construction purposes. Piles have been rigidly connected to the raft. The idea of piles disposition variants has been as follows: initial variant I am of an unpiled raft, the last variant V is presented by a fully piled raft. Other variants II, III and IV have been intermediate, when the number of piles and their diameter has been increased, but the raft thickness has been reduced simultaneously. Thickness of the raft has been selected considering more or less identical total concrete discharge. Disposition of piles within the raft area (Fig. 2) has been as follows: in the longitudinal direction a typical 4 m step is employed, which allows to distribute 10 pile rows (variant V). Thus, the raft shall rest on 100 equidistantly located piles. By vacating a middle area of the raft and at the same time thickening the pile step across the raft, three intermediate variants II, III and IV have being formed (Table 1):

I. unpiled raft;
II. raft with 2 rows of piles from each side;
III. raft with 3 rows of piles from each side;
IV. raft with 4 rows of piles from each side;
V. the entire raft area is filled evenly with piles.

Formally, the number of a variant corresponds to the number of pile rows from each side of the raft. A variant with one row of piles has not been considered, because such pile distribution of piles produces a concentrated reaction undesirable when continual systems are designing. By removing piles from the middle area of the raft, the raft plate has been thickened, because the total ground pressure has been increased. The variants of the raft task have been chosen in such a manner that features of a mechanic system would change more or less evenly, when being influenced by the same external loading and at identical conditions of the ground foundation.

In the pile location zone the filling area A_p (m^2) of the efficient raft area A_{ef} (m^2) is expressed by the relative area occupied by piles (in these calculations, a ground area of 3 pile diameters around every pile):

$$\alpha = \frac{A_p}{A_{ef}}, \tag{1}$$

and by a relative spacing ratio of the piles expressed by the geometric distance s (m) between piles and diameter of piles d (m):

$$\delta = \frac{s}{d}. \tag{2}$$

As the piles spacing along the piled raft and across it has been different, then while estimating the distance

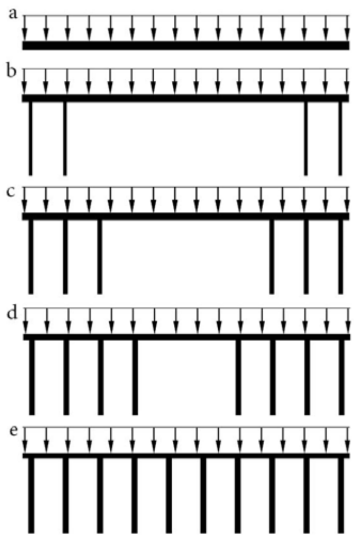

Fig. 2. Distribution variants of the raft piles under the raft (in scale): a – unpiled; b – 2 and 2 rows; c – 3 and 3 rows; d – 4 and 4 rows; e – the whole area is piled

Table 1. Variants of dimensions (mm) of piles and rafts

Variant	Rows of piles	Number of piles	Diameter of piles	Thickness of the raft
I	–	–	–	1000
II	2 + 2	64	400	900
III	3 + 3	84	500	800
IV	4 + 4	96	600	700
V	10	100	650	600

s (m), an averaged value of longitudinal and transversal spacing has been adopted.

In fact, expressions (1) and (2) are interrelated. Thus, in literature (Mandolini *et al.* 2013), it is common to express the capacity of a piled raft and the ratio of settlements by a filling factor:

$$\phi = \frac{\alpha}{\delta}. \quad (3)$$

In the variants of the task the relative parameters (Table 2) indicate that at the areas between piles interaction of the raft and ground have been taken into account. In calculations a rather conservative solution has been assumed, i. e. the raft directly transfers 20% of the total load to the ground.

In Lithuania (according to national economic recommendations) construction of 1 m^3 of the reinforced concrete pile is twice as expensive as construction of 1 m^3 of the reinforced concrete raft. Thus, when calculating the total relative volume, in order to make solutions more cost–efficient, the pile concrete volume has been multiplied by 2. Insignificant difference D between conditional volume calculation results for each variant appears due to unification of pile and raft dimensions (Table 3).

Reliability class of the construction to be considered is RC3 (*LST EN 1990:2004, STR 2.05.03:2003 Basis of Structural Design. Technical Regulation of Lithuania*). A concrete class of the raft has been defined C30/37, Young's modulus 33 GPa. A concrete class of the piles has been adopted C20/25, Young's modulus 31 GPa. Poisson's ratio for the concrete of all classes has been predetermined as 0.2, selfweight 25 kN/m^3. Horizontal reinforcement of the raft has been defined of class S500, vertical reinforcement has been used of class S240. Longitudinal reinforcement of the piles has been of class S500, lateral – of S240. The concrete protective coating over the raft upper reinforcement has been specified as 40 mm, under the lower reinforcement – as 65 mm. The allowed value of cracks opening width in the raft has been of 0.3 mm. The concrete protective coating for reinforcement of the piles has been defined as 60 mm.

The reinforcement construction rules have been taken according to the design standards valid in Lithuania (*LST EN 1992:2008 Eurocode 2. Design of Concrete Structures, STR 2.05.05:2005 Design of Concrete and Reinforced Concrete Structures*).

Table 2. Relative parameters of pile distribution

Variant	Relative area α	Relative spacing δ	Sparseness factor $\frac{1}{\phi}$
I	–	–	–
II	0.158	8.0	51
III	0.195	6.8	35
IV	0.229	6.1	27
V	0.207	6.2	30

Table 3. Volumes (m^3) of piles and rafts

Variant	Volume of piles	Volume of raft	Conditional volume	
			Total	Δ, %
I	–	1444	1444	–
II	72	1300	1444	0.0
III	148	1155	1451	+0.5
IV	244	1011	1499	+3.8
V	299	866	1464	+1.4

4. Calculation model

Before deciding the raft problem acting loads, safety factors, values of deformable soil bed and values of spring stiffnesses for the piles during development of a numerical model have been specified.

The traffic load values have been determined according to the European Union requirements adopted for Lithuania (*LST EN 1991:2005 Eurocode 1. Actions on Structures*), in the considered case a one–way traffic is divided into three lanes, one of which is loaded by 9.0 kPa and others – by 2.5 kPa. Vehicles considered as loads moved in parallel over these lanes being distributed within 1.2×2.0 m area as 300 kN, 200 kN and 100 kN respectively in any combinations. For the analysed constructions the influence of variable loads on the raft has been insignificant.

While analysing the pile impact on the raft mechanical state, one dominated combination of the acted loads has been considered, which involving: structural selfweight, soil weight on the raft longitudinal edges, weight of the tunnel arch, weight of ground and road pavement over the tunnel, traffic load inside and above the tunnel. A short-term load constitutes only 5% of the total load, therefore, in case of the problem the overall load has been considered as a long-term one. Taking into account a thickness of a carrying foundation plate of the unpiled or piled raft, a thickness of an additional road plate over the raft, wide structural supports of the tunnel walls as well as a character of distribution of all acting loads over the raft area, and also the fact of investigating the raft settlement just near technological joints across the tunnel, a simplification has been adopted in the calculation model assuming uniform distribution of the loads affecting the raft over the whole area of the plate (Fig. 2). The equivalent load characteristic value has been taken equal to 91 kPa without selfweight of the piled raft. The tunnel design has been not provided any seismic or any dynamic actions. Also the temperature and concrete shrinkage effects have been not considered. Thus, the general safety ratio for the loads has been taken as 1.35 (*STR 2.05.04:2003 Actions and Loads. Technical Regulation of Lithuania*). Ground safety ratio has been expressed by several values: 1.25 for friction angle tangent, 1.25 for effective cohesion, 1.40 for undrained shear strength, 1.40 for non-restricting compressive strength and 1.00 for selfweight. Safety ratio of 1.00 has been set for deformations estimation. Combination coefficient has been defined at 1.00 for each of the acted loads.

Each pile under the raft interacts with the ground by the side surface and the base area (Tomlinson, Woodward 2008). A resistance of the pile to a vertical load has been the most important in the context of the problem, as the lateral loads have been not acted the raft. In calculation of the piled raft it has been assumed that the piles transfer the entire load to the lower ground level through the base surface (Fig. 3).

The lateral soil stiffness for each pile has been expressed on traditional manner (Avaei *et al.* 2008):

$$K = \frac{0.65E_s}{1-\nu_s^2}\left(\frac{E_s d^4}{EI}\right)^{\frac{1}{12}}, \qquad (4)$$

where E_s and ν_s – the soil elasticity modulus, MPa, and Poisson's ratio respectively; EI – a bending stiffness of the pile, MPa·m^4; d – a pile diameter, m.

The stiffness value is taken assuming that nearby piles do not influence one another through the ground. Distribution of internal forces between the piles is taken place under the influence of strain and stress state of the raft which joins all piles together. Therefore, in the expression (4) a preliminary calculated stiffness has been used only at the first stage of the general calculation for each of variants $c_{horz} = K$, further, after the next iterative stage of calculation strain and stress state results of each pile have been revised and the lateral stiffness value has been recalculated depending on the obtained lateral displacement values and respective values of horizontal support reactions.

Axial stiffness values for vertical springs of the piles have been initially set on the basis of preliminary values of support reactions and appropriate settlements. According to practical observations the settlements have been taken in the range of 3–5% of the pile diameter. The axial stiffnesses of conventional springs at the ends of the piles have been recalculated at each stage of calculation. Upon conducting five iterations the vertical springs stiffness values at the end of the piles have been usually changed insignificantly, i.e. convergence of the solving within 5% has been achieved. At the final stage of calculation the stiffness values for the springs have been unified (Table 4) considering stiffness distribution on the raft area (Fig. 4).

As it was mentioned above, for the problem the influence of horizontal springs on deformation of the mechanical system has been not decisive. However, the horizontal ground resistance to the pile lateral displacements has to be investigated. The horizontal springs have been evenly distributed over the entire length of piles.

Elastically deformable soil bed between the raft and soil has been set after analysis of distribution of support reactions and settlements over the raft area. There are three main cases (Fig. 4): unpiled raft (variant I), partially piled raft (variants II, III and IV), fully piled raft (variant V).

In the case of unpiled raft a value of soil bed distributed on the raft contour are theoretically undefined because stresses in the soil are infinite within this zone due to shear effect (Fedorovskii 2008). In the problem, 2.0 m width border over the raft contour has been selected, where an averaged stiffness value for soil bed has been exceeded that is of the middle zone by a factor of 2. Due to such significant difference, soil bed values in the middle of the raft and on the border zone have been supplemented by two other strips of 2.0 m width, each one having intermediate values, in order to reduce the jump between soil bed stiffnesses (Table 5, Fig. 4).

Partially piled rafts are generally divided into two areas (unpiled and piled) with different soil bed values.

In the case of a fully piled raft the distribution of the soil bed values becomes almost equal for any spacing between piles at any zone of the raft. Therefore, soil–raft interaction has been expressed by a single value of soil bed.

The selection of soil bed values under the plate for all variants has been made on the basis of iterative

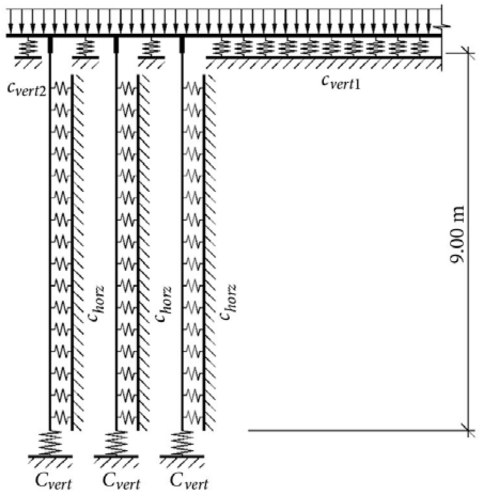

Fig. 3. The soil bed c_{vert1} and c_{vert2} stiffnesses of the raft, vertical C_{vert} and horizontal c_{horz} spring stiffnesses of the piles

Table 4. Vertical spring stiffness values under the piles and horizontal spring stiffness values along the piles

Variant	C_{vert}		c_{horz}	
	MN/m	Relative	MN/m^2	Relative
I	–	–	–	–
II	26.4	0.943	1.86	0.503
III	27.4	0.979	2.92	0.789
IV	27.7	0.989	3.30	0.892
V	28.0	1.000	3.70	1.000

Table 5. Sorted by zones (1st, 2nd, 3rd and 4th) values, MN/m^3, of deformable soil bed between the raft and soil

Variant	1st	2nd	3rd	4th
I	0.39	0.52	0.65	0.77
II	1.50	1.11	–	–
III	1.43	0.89	–	–
IV	1.34	0.73	–	–
V	0.49	–	–	–

stage–by–stage calculation simultaneously with the selection of the pile springs.

5. Analysis procedure

The numerical simulation and calculation problem consisted of several steps: creation of a finite element grid on the raft plate, usage of special finite elements for joints between the raft plate and raft piles, discretization of raft piles by finite elements, setting of elastic springs for the raft piles and elastically deformable soil bed for the raft plate which have been imitated interaction with the ground, development of the interaction with ground parameters of the numerical model during solving the problem at each iteration stage, verification of the results using alternative model, reinforcing of the raft piles and raft plate.

The raft has been divided by a regular finite element grid according to the pile distribution. Around each pile a local fragment (dimensions have been about 1/38 of the raft side total length) of radially located finite elements has been created (Fig. 5). Between such fragments around the joints of pile connection the raft plate has been divided by the regular finite element grid of maximal 0.25 m size, in relative values it is: 1/152 of the raft side dimension, 1/16 of the maximal distance between piles, 1/10 of the minimal distance between piles. For simulation of the raft plate a conventional finite element with 6 degrees of freedom in each node from a used software library have been applied. For example, some parameters of variant I are: 23 409 nodes, 23 104 finite elements, 140 454 degrees of freedom.

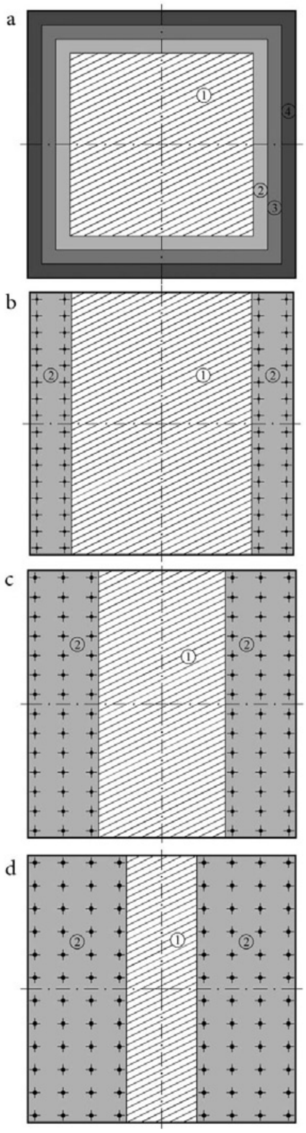

Fig. 4. Distribution of deformable soil bed values: a – unpiled plate; b – 2 and 2 rows; c – 3 and 3 rows; d – 4 and 4 rows

At a field, where the raft plate has directly rested on the ground, their interaction has been simulated by elastically deformable soil bed which has been divided into groups depending on values of settlements and support reactions in different raft zones. An initial value of the soil bed for the finite element analysis has been taken considering an effective area occupied by a single unit within the raft particular zone (3). Later the values of the soil bed zones have been defined more exactly depending on change in values of settlements and support reactions at each iteration stage during solving.

All piles in all investigated variants of the piled raft have been of equal length. The piles have been evenly divided along the length into 18 finite elements. For simulation a spatial finite element with 6 degrees of freedom in each node, based on Hermite polynomials, has been used. The horizontal springs on piles have been distributed evenly along the entire length of each pile. An axial spring, imitating the total pile resistance to the vertical load, has been placed at the pile lower end.

Stiffness values of horizontal and vertical springs on raft piles as well as values of the soil bed for the raft plate have been obtained in a final calculation on the basis of the iterative stage-by-stage calculation results (Tables 4 and 5).

In order to exclude possible distortions near the joints of pile and plate connection and to avoid influence of such distortion on stress and strain state of the raft sectors between piles (Perelmuter, Slivker 2003), the beam–type finite elements of the piles and plate finite elements of the raft plate have been interconnected trough special finite elements with high stiffness, which are recommended by authors of used software (3D modelling by Midas Civil) for a such kind of joints. Thus, the local area of the pile-plate joint has not distorted the calculation common results and was not considered during analysis of the raft mechanical state.

In case of numerical simulation of the unpiled raft due to action of incidental horizontal forces the raft lateral movement has been restricted by specially applied horizontal springs, imitating friction between the raft plate bottom surface and ground. In variants of the piled raft the horizontal springs have not been applied to the raft plate as the lateral movement has been rather effectively restrained by the horizontal springs, located on piles.

After calculating all geometric parameters of the model, creation of all static and kinematic boundary conditions and assignment of mechanical characteristics to materials as well as assignment stiffness values to elastic springs and soil bed, the geometrically non-linear calculation has been performed. The results have been checked by a calculation engineer and then values of the stiffness of springs and soil bed have been re-evaluated. Then the task has been recalculated for the second time and the stiffness values have been specified again. Convergence of the results has been achieved after 5 stages of the calculation.

In order to verify the geometrical parameters and load conditions, the spatial structural model has been simulated completely without simplification, which take in account symmetry properties of the problem and not investigating only a half or a quarter of the model. As the task dimensional representation by degrees of freedom has been insignificant and the iteration process has been provided fast convergence, the question of usage of the computer memory or question about time economy for the raft problem solving has not been important.

For verification of results in all variants of unpiled and piled rafts two different models have been investigated: spatial (Fig. 6) and plane one (Fig. 7). Investigation of various models has been enabled to check correctness and accuracy of formation of the initial parameters, simulation technique and applied engineering assumptions.

Modelling of the raft plane problem (unpiled and piled) has been performed (2D modelling by Phase 2). The problem has been come to the description of a longitudinal line of the infinitely wide raft with respective stiffnesses have been taken from spatial model. The stress and strain parameters have been verified. The difference has not been exceeding 3–5%. Reinforcing of the raft plate and raft piles has been not checked in the plane model.

Reinforcement (according to the requirements of the design codes concerning strength and crack conditions for a cross section of the raft plate) for each finite element of the raft have been calculated by using additional software, taking into consideration bending moments and shear forces. Sections with similar results of reinforcement have been united in zones with reinforcement of the same diameter. Dimensions of such zones have been extended by anchoring length of the reinforcement. Finally, all results have been unified, presenting the general reinforcement by the main and additional one. The raft plate fragments around piles, i. e. small areas with ideally stiff inserts in plate-pile joints, have been reinforced taking into consideration reinforcement of nearby located finite elements.

Reinforcement (according to the requirements of valid design codes for bending and shearing strength conditions for the beam cross sections) for each finite element of the piles has been calculated by using the main software on the basis of the obtained values of bending moments and shear forces.

Reinforcement of raft piles and raft plate has been made on the basis of engineering methods, presented in design codes. With the use of the obtained internal forces (the most important one has been the bending moment) and deformations (the most significant criterion for the reinforcement has been the opening width of cracks) the designing has been performed taking into account the ultimate limit state and serviceability limit state requirements.

6. Comparison of variants

Comparison of the calculation results of the different variants of rafts is presented in the given paper by analysis of bending moments and settlements of the raft plate cross section on the central longitudinal axis (along traffic movement through the tunnel). Expenses of the materials

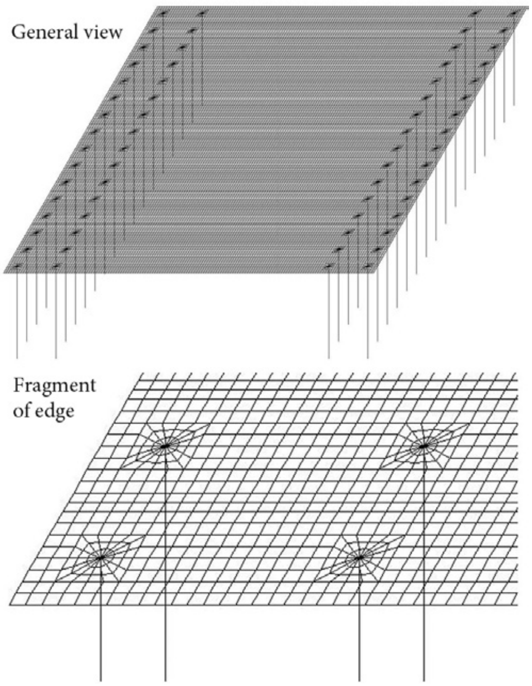

Fig. 5. The spatial numerical model of the piled raft variant II, the finite element grid: general view (a), fragment of edge (b)

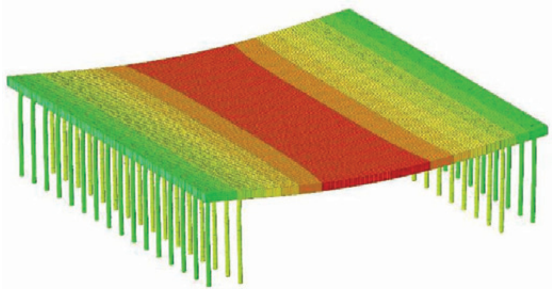

Fig. 6. Spatial numerical model of the piled raft for variant II, general deformable view

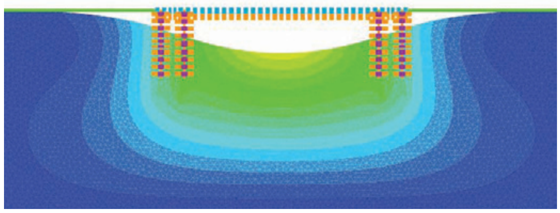

Fig. 7. A deformable view of soil for the piled raft variant II of the plane numerical model

for each of the variants to be considered have been also compared considering obtained results.

Considering the raft section along the central longitudinal axis (symmetry axis across the pile rows) and making general comparison of the raft settlement for all variants (Fig. 8), expressing the results by relative values $\delta = \frac{u}{u_{max}}$, that the unpiled raft (variant I) has settled much more (about 70%) in comparison with other variants. The max characteristic value of settlements is 260 mm. The difference is explained by the effectiveness of piles. The general view of the raft deformed scheme in all variants is similar: the middle section settles more than side sections.

Deformations diagram of the piled raft is expressed by a family of curves, peculiarities of which require a more detailed analysis (Fig. 9). The difference between min and max settlements of each variant (Table 6) decreases rather evenly (values: 0.21, 0.16, 0.09, 0.04). It means, that increase of the area occupied by the piles despite the raft stiffness decrease due to loss of its thickness in each of the next variant, not only reduces settlement of the whole raft but creates the conditions for more uniform settlements.

When generalising the distribution results of bending moments for each variant of the raft (Fig. 10), these results are expressed by relative values $\mu = \frac{M}{M_{max}}$. With decrease of dimensions of an unpiled area in the middle of the raft, values of the bending moment are reduced as it was to be expected. The maximal characteristic value of the bending moment is 1258 kNm.

Considering uniform change of the mechanical system features of alternative variants of the raft (Table 1) and taking into account identical loading conditions and mechanical characteristics of the ground, similar assumptions during numerical simulation of the variants, curves of the bending moments of the raft are being varied rather logically. Generally, the results of bending moment distribution correspond to those of settlement distribution along the raft. Investigation of peculiar features of the discussed

Table 6. Extreme relative values of stress and strain parameters

Variant	Relative settlement		Realative bending moment	
	Min	Max	Min	Max
I	–1.000	–0.800	–1.000	0.005
II	–0.289	–0.081	–0.625	0.030
III	–0.257	–0.095	–0.577	0.134
IV	–0.216	–0.126	–0.363	0.075
V	–0.199	–0.164	–0.094	0.014

Table 7. Qualitative (S240/S500) and quantitative relative reinforcement expenses

Variant	S240/S500	Piles	Raft	General conditional
I	0.081	–	1.00	1.00
II	0.147	1.00	0.58	0.60
III	0.149	0.69	0.59	0.59
IV	0.148	0.45	0.61	0.53
V	0.148	0.30	0.59	0.44

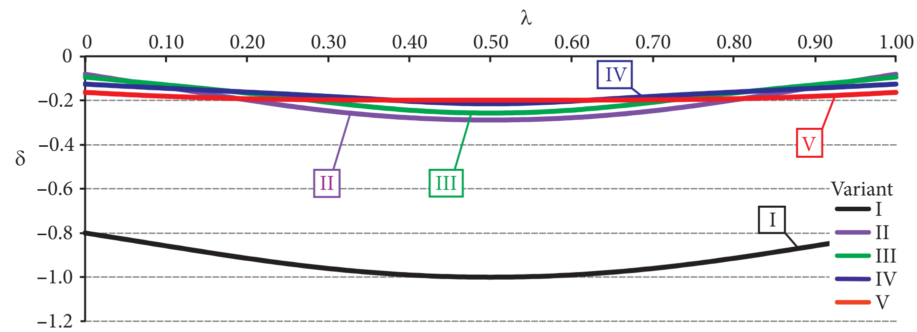

Fig. 8. General distribution of relative settlements (δ, from 0 to –1) along the raft central axis (λ, from 0 to 1)

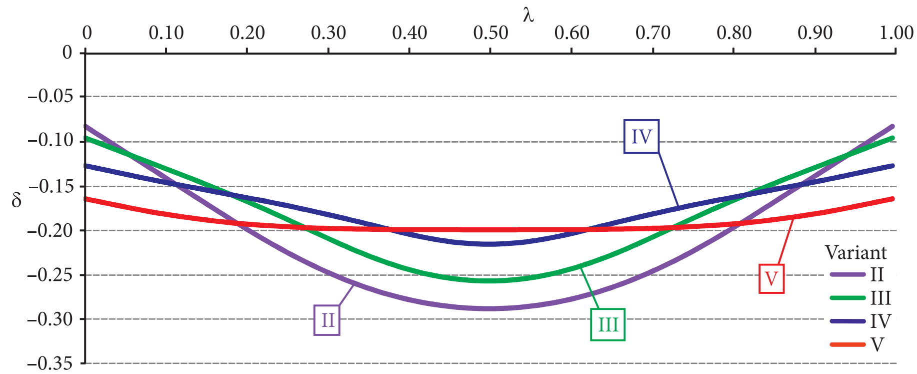

Fig. 9. Detailed distribution of relative settlements (δ, from 0 to –1) along the raft central axis (λ, from 0 to 1)

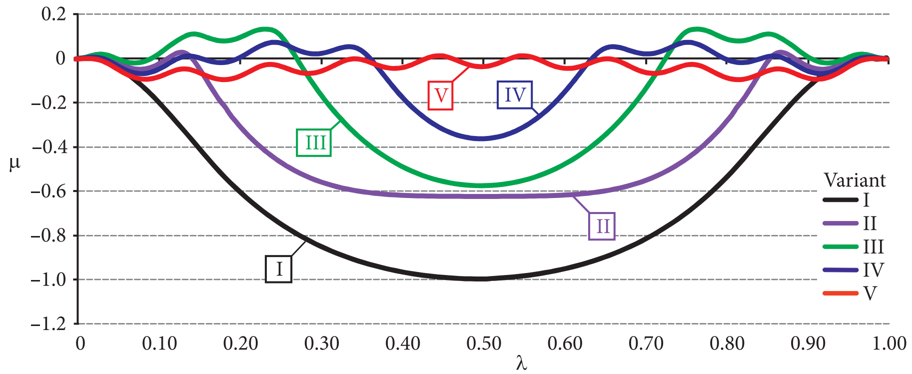

Fig. 10. General distribution of relative bending moments (μ, from 0 to −1) along the raft central axis (λ, from 0 to 1)

variants enables at designing to know a character of distribution of stress and strain parameters.

As far as the problem of economy, with respect to the piled or unpiled raft, is concerned, the reinforcement expenses have been analysed as the concrete conditional expenses are almost equal for all variants (Table 3). Usage of the reinforcement strength expresses a relationship between the number of additional reinforcement of class S240 and the main reinforcement of class S500 (Table 7). Though in Lithuania the market price is almost independent of the reinforcement strength (difference of 5%), the relative value S240/S500 indicate that the reinforcement expenses of class S240 constitute only from 5 to 15% of all reinforcement expenses and are considered to be insignificant.

For the raft piles reinforcement expenses decrease with growth of the piles number. When considering the total reinforcement expenses for the whole raft in the conditional concrete volume, an evident trend toward decrease of reinforcement (by a factor of 2) is observed. From the point of economy view the result is unambiguous: in case of identical initial conditions for all variants of the raft the most reasonable variant is the raft with piles, which are evenly located over the whole raft area.

7. Conclusions

On the basis of analysis of different variants, concerning the raft design, the following conclusions have been made:

1. Comparison of the raft settlements for 5 variants to be considered has illustrated that the unpiled raft has settled considerably more (70%) as compared with the piled raft variants. Generally, the character of deformation for all variants is similar; the difference between the maximum and minimum values is rather regularly decreased, when the raft area becomes full of piles.

2. Distribution of the bending moments along the central longitudinal axis of the raft is changing in each variant with a regular step depending on variation of the problem initial geometric parameters.

3. In case of identical conditions for all variants the economy question is quite clear – the most reasonable variant is usage of the raft with evenly distributed piles under the whole raft area.

Designing of the raft, which rest on the piles distributed under the whole area, is widely used in practice because of economic considerations and clarity of the engineering decision.

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