Uncertainty of soil data spatial distribution between CPT points and its impact on soil-footing-structure system behavior

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ABSTRACT: CPT points on a site are usually spaced as far as 15-20 m, therefore uncertainties of 3D distributions of soil parameters between the CPT points are inevitable and add up to the scatter of measured values of soil parameters. The volume of tested soil on any site is about 10^{-6} of the subsoil total volume while the cost of geological investigations is as low as 0.05-0.1% of the overall project cost. The resulting uncertainties of derived soil data cause uncertainties of soil-footing-structure system (SFSS) interaction. This paper describes the application of 3D Shepard functions to numerical analysis of uncertainties of soil parameters between CPT points and SFSS sensitivity to uncertainties of input data. An example of application of characteristic values of c and φ (as per Eurocode 7) is given to show that SFSS can have tilts on a uniform subsoil due to c and φ scatter

1. DEFICIT AND AMBIGUITY IN GEOTECHNICAL INVESTIGATION DATA

There are two main issues related to geotechnical investigation (GI):

- very low cost of GI - just 0.05-0.1% of a project completion + service;
- very small volume of tested soil: just 10^{-6} of the surface volume below structure (Ziangirov, 1967; Clayton, 2010).

Stages	GI	Project Design	Construction	Life
Duration, years	0.2	0.5-1.0	1-3	50-100
Relative cost, %	0.05-0.1	3-5	80-90	10-15

Table 1. Relative costs and duration of project stages (Ziangirov, 2007)

Table 1 shows the percentage cost of a project at various stages versus its overall cost (Ziangirov, 1967). The GI cost deficit could be compensated by either increased project safety at the design stage or subsequent corrective measures during project construction and life that could be multiple times more expensive than any GI. The deficit of GI data is compensated by many assumptions, e.g. in manual processing of scarce data into stratigraphic units. Such operation is done intuitively by drawing boundaries of stratigraphic units within vertical cross-sections. Meanwhile design engineers need 3-D numerical arrays of soil data of soil data rather than these stratigraphic units, therefore, they unpack the stratigraphic units and usually assume the *minimal values* of the indicated soil parameters in order to be on the safe side. .

In computer software codes the 3-D numeric arrays are usually approximated by *linear triangulation* with the help of *linear interpolation*, however, the boundaries between stratigraphic units are only required for visualizing soil data as “pictures” of cross-sections but these boundaries do not participate in computations of subsoil-structure analysis.

All soil tests (in situ or in laboratory), sampling from boreholes and transportation of the samples degrade soil properties. The equations, correlating soil test data into derived/design, values are very approximate, because stress distribution in tested soil samples is far from being uniform. These inevitable uncertainties result in analytical mean settlements that largely differ from the actual ones, obtained by monitoring.

Zaretsky et al. (1989) published case histories of structures, having analytical mean settlements being much greater than the observed ones. Clayton (2010) published data on the cost of highways additional repairing operations during their service period due to underestimation of ground conditions and other factors. Sonoda et al. (2009) gave an example of twofold underestimation of analytical settlements versus actual ones. Discrepancy of analytical and measured settlements is well known. Zaretsky (1989) stated that analytical settlements shall exceed actual ones by 30-100%, otherwise the analytical subsoil model is not realistic. This statement could be disputable, but it is an objective assessment of the accuracy of such analyses, made by a well-known Russian geotechnical specialist.

Analysis of differential settlements is also uncertain. e.g. Big Ben clock tower in London tilted towards Parliament while the analytical tilt was in opposite direction. A more accurate non-linear analysis and accounting for the subsoil stiffness versus depth growth gave the right analytical tilt direction towards Parliament (Clayton, 2010).

100 residential buildings in Santos (Brazil) had inadmissible tilts, largely exceeding allowable values, while their mean settlements were admissible (Goncalves, 2005).

Theoretical models for subsoil deformation analysis are usually based on existence of active soil layer of finite depth, which is determined differently in various countries. This layer existence is an assumption, while soil stiffness grows versus depth faster than shows the linear law. It reflects the fact of soil stiffness degradation due to shear deformations, caused by the man-made structures impact. At greater depths, unaffected by shear, soil stiffness is very high (Clayton, 2010; Mayne 2000) and linear growth is only realistic over a certain depth range (Trufanov et al., 2013).

Field test data have scatter that could be quantified by statistic equations. But it is not possible between soundings, where distribution of values of soil parameters is unknown. Here the concept of *fuzzy sets* could be more realistic, however, soil stratification hypotheses could be made. In such circumstances it is worthwhile to analyze *unfavorable scenarios* of soil parameters distribution between test points by varying the parameters of functions, characterizing their distribution. This approach is in fact recommended by Eurocode 7 that specifies *characteristic* and *representative* values of soil parameters that can be both *greater or less* than mean statistical *derived* values.

Russian State Standard GOST 20522-96 (1997) envisages such possibility, however, in the Regulation of Subsoil Design SP.22.1330 (2011) the design values of all parameters are always less than the respective derived ones. Other scenarios are not considered as is advised by Eurocode 7.

However, GOST 20522 [1997] stipulates:

$$X = X_n(1 \pm \rho_a) \,, \qquad (1)$$

with X, X_n as characteristic and derived values respectively ; ρ_α as accuracy of statistical assessment of X. The two characteristic X values (1) should be applied to the analysis to simulate unfavorable scenarios.

In SP22.13330 (2011) only smaller characteristic values are recommended for soil strength parameters c, φ. The design deformation modulus is assumed to be equal to its derived value E_n. However, Fadeyev (2004) proved that $E = E_n(1 \pm \rho)$ with ρ = 1/3 on the basis of monitoring data.

Eurocode 7 also introduces go*verning* values of parameters i.e. parameters, averaged over the whole soil massif, with associated *representative* (*characteristic*) values. Such approach enables analysis of various unfavorable scenarios even if parameter values are averaged over large soil volumes.

2. SHEPARD FUNCTION INSTEAD OF LINEAR INTERPOLATION.

Shepard functions (Shepard, 1968) are a more realistic approximation of soil parameters distribution in subsoil than linear approximation. A Shepard function coincides with its given values at given points. Shepard applied these functions for approximating earth surface relief. But they can also approximate distribution of soil parameters values in 3D subsoil space. They can reflect different global trends if any, as is shown below.

Consider for example, approximation of an arbitrary function $P = P(x,y,z)$, whose values $P_i = P(x_i,y_i,z_i)$ are given at points (x_i,y_i,z_i) with $i = 1,2, \ldots N$, where i is the number of a collocation point inside subsoil volume $L_1<x<L_2$, $B_1<y<B_2$, $H_1<z<H_2$ and N is the number of such points. Function $P = P(x,y,z)$ can be approximated with the help of the following equation that also accounts for a global trend $S(x,y,z)$:

$$P(x,y,z) = \frac{\sum_i \frac{P_i - S(x_i,y_i,z_i)}{[R_i(x,y,z)]^{T_i}}}{\sum_i \frac{1}{[R_i(x,y,z)]^{T_i}}} + S(x,y,z), \qquad (2)$$

with $R_i(x,y,z) = (x-x_i)^2+(y-y_i)^2+(z-z_i)^2$ as distance between a given point (x_i,y_i,z_i) and an arbitrary point (x,y,z); $S(x,y,z) = Ax+By+Cz+D$ as linear function, reflecting a global trend of function P distribution, A,B,C,D values are determined by least square root approximation over all known points; such trend does not exist if $A,B,C,D \equiv 0$; T_i as shape parameters that varies $P = P(x,y,z)$ function shape between collocation points. Other global trends can be used

2.1. Examples of Shepard functions for 3D distribution of soil parameters

Consider E, c, φ and γ virtual CPT vertical profiles, obtained by a random numbers generator are shown in Figure 1.

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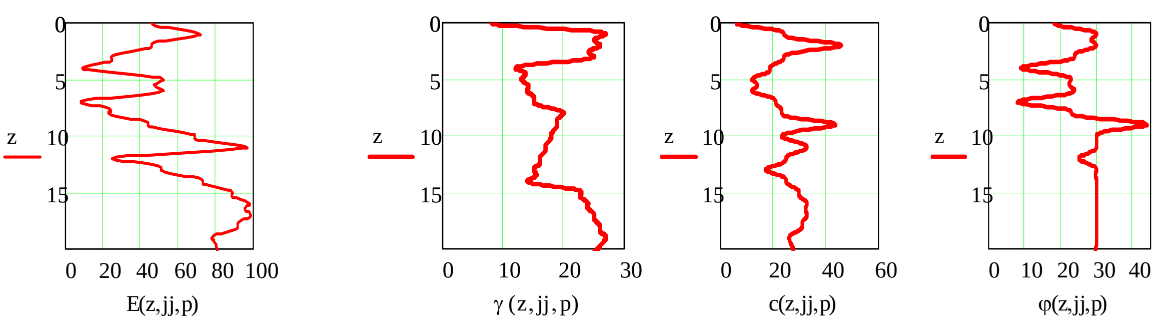
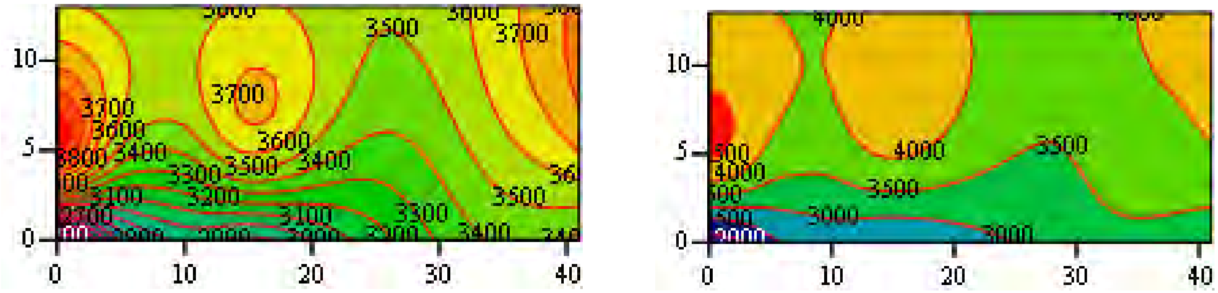


Fig. 1. Distributions of virtual soil parameters from virtual CPT soundings, simulated by random numbers generator.

Figure 2 shows isolines of E, c and φ distributions in the same vertical cross section of 3D distributions in a 40x20x10 m subsoil volume. These distributions are computed with the help of equation (2) for the same geological points with T_i =1 (on the left) and T_i =2 (on the right). Evidently the shapes of the isolines are different for the left and the right sections



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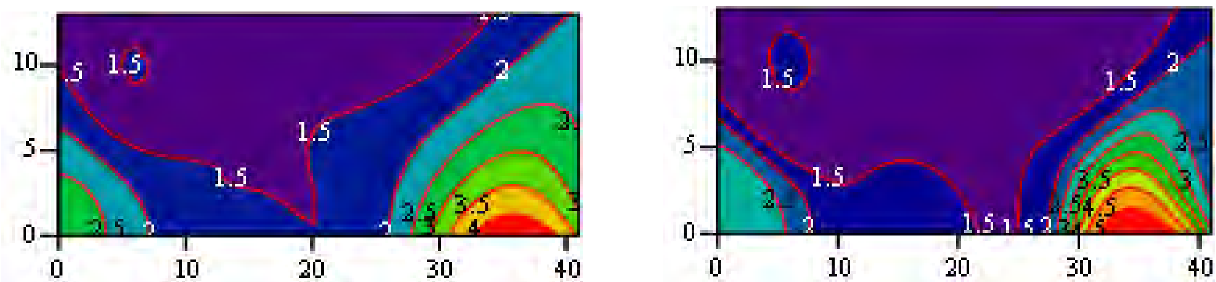

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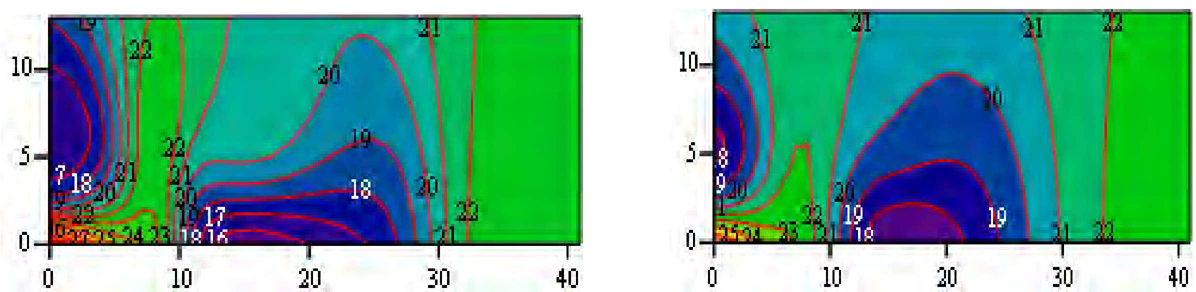

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Fig.2. T = 1 on the left and T = 2 on the right. The difference is evident.

Variation of distributions helps simulate scenarios with *characteristic* values of parameters to find unfavorable cases. There is no need to ”smooth” initial CPT or SPT profiles.

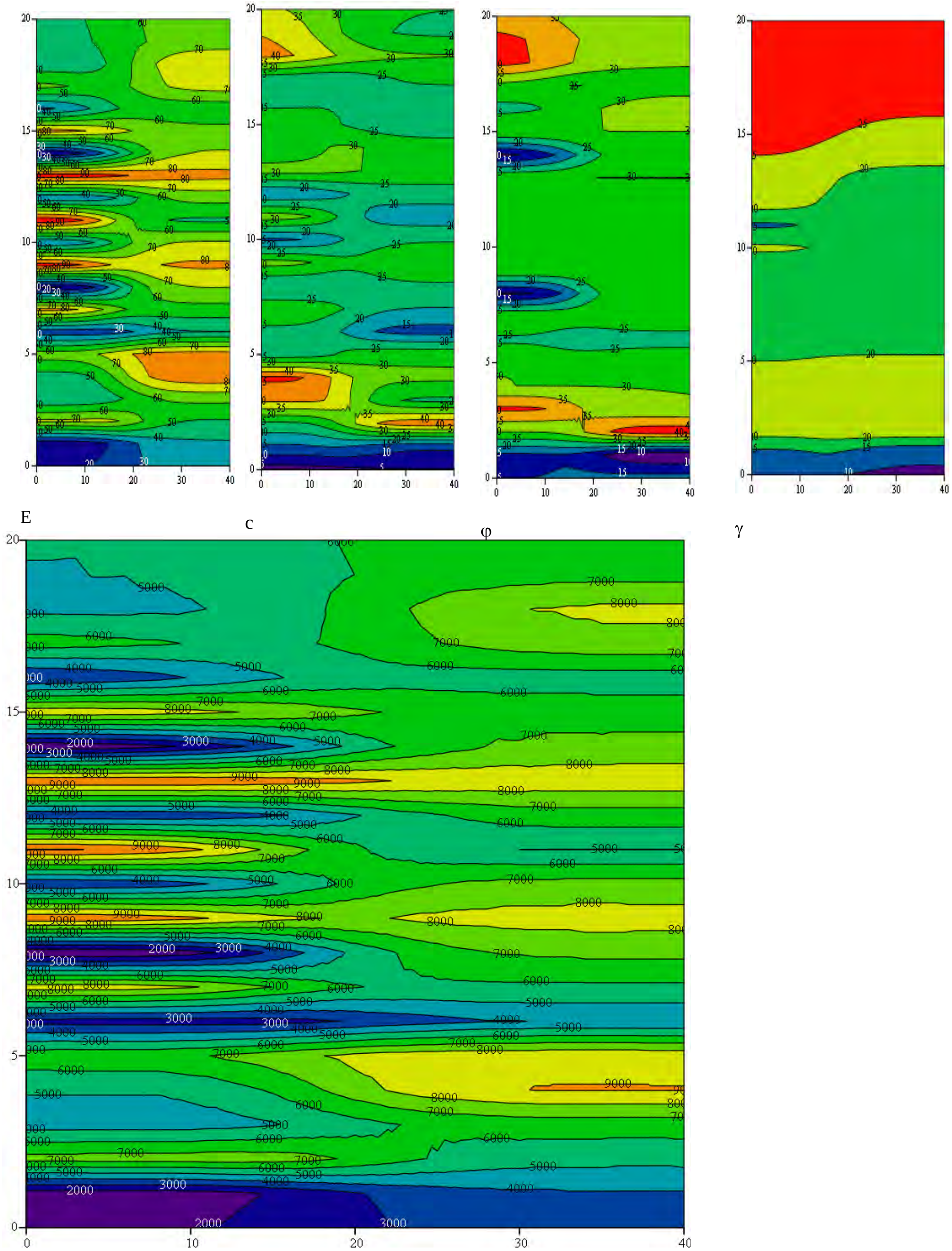

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Figure 3. Above: E, c, φ and γ distributions in a vertical cross-section.
Below: Detailed fragmentation of soils into stratigraphic units.

3. SENSITIVITY OF A STRUCTURE TO SOIL PARAMETERS VARIATIONS

Uncertainty of subsoil properties results in uncertainty of deformations and forces in footings and superstructures. Therefore, it is important to know in advance, to what subsoil uncertainties a structure is especially “sensitive”, e.g. how mean settlements or bending moments in a raft footing “feel” the uncertainties of the ground stiffness. This “sensitivity” evaluation can be described by the “20/80” Pareto principle that reads: “Just a small part of external factors (20%) cause most effects (80%) in a system, while the remaining (80%) external factors cause the remaining (20%) effects”.

Sensitivity of “subsoil-footing-structure” system (SFSS) were investigated by computer simulations of a simplified SFSS analytical model. Multiple numeric experiments (~10000) were carried out to assess SFSS sensitivity to subsoil parameters variations. The sensitivity ratings are given it Table 2.

SFSS footing sensitivity ratings						
Input data	Ratings					
	Mean settlements	Deflections	Tilts	Bending moments		Shear forces
				+	-	
Soil Young modulus *E*	1	1	1	0	0	0
Soil strength parameters c,ϕ	1	1	1	1	1	1
Footing depth *h*	1	1	1	1	1	1
Distribution capacity of subsoil within the range of realistic values (C_2)	0	0	0	0	0	0
Subsurface heterogeneity	0	1	1	1	1	1
Cantilever	0	1	1	2	2	2
Column compressibility	0	0	0	0	0	0
Raft bending stiffness D	0	1	1	0	1	1
Superstructure relative stiffness						
$D_s/D < 5$	0	1	1	1	1	1
$5 \leq D_s/D < 20$	0	1	1	0	0	0
$D_s/D \geq 20$	0	0	0	0	0	0
Superstructure stage-wise erection on linear elastic subsoil	0	0	0	0	0	0
Superstructure stage-wise erection on elasto-plastic subsoil	1	0	0	1	1	0
Influence of nearby construction	0	0	1	1	1	2

Table 2. Sensitivity ratings of settlements (mean values), deflections, bending moments, shear forces to variations of subsoil parameters: 0 – absence or zero sensitivity, 1- mean sensitivity; 2 – high sensitivity.

4. THE IMPACT OF PLASTIC ZONES FORMATION IN SOIL UNDER FOOTING EDGES ON STRUCTURE TILTS

There appear soil plastic zones under edges of loaded footings. These zones are clearly seen in the experiment of a 10 cm wide footing model, pressed into soil (Fig. 5). Plastic zones under the model edges appear even at low loads, they reduce contact pressure concentration under the model edges. The zones were visualized by means of Photo Imaging Velocimetry technique (PIVview User Manual 2013).

Solution of the respective elasto-plastic problem involves given values of soil strength parameters c, φ along footing perimeter. However, GI give such data at maximum 2-3 points along each footing edge that could be insufficient for such analysis and especially so due to high scatter of these values.

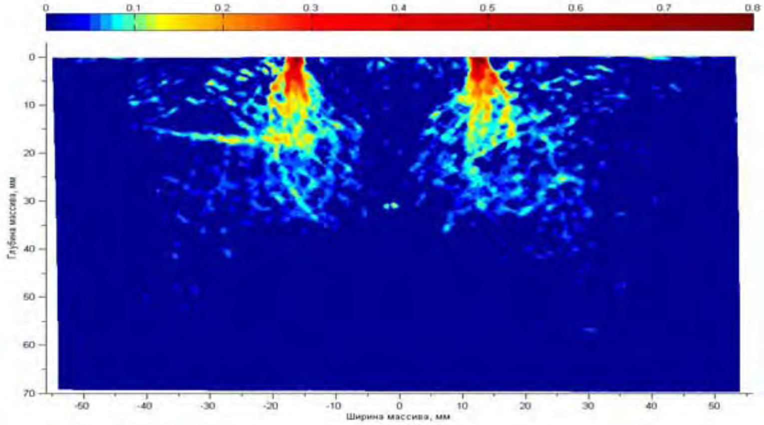
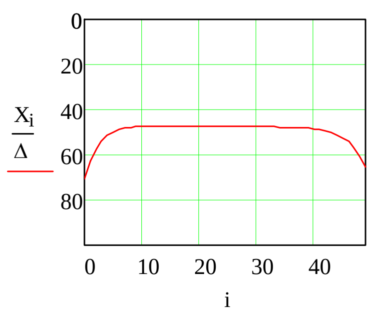


Fig. 5. PIV visualization of soil plastic zones (red) under 10 cm wide footing

Such analysis is usually done for *minimal* c and φ *characteristic values* while the most unfavorable scenario shall include both *minimum* and *maximum characteristic values*, but under *opposite* footing sides respectively that contributes to footing tilts on subsoil, having uniform stiffness.



a) Contact pressures
at the final loading stage

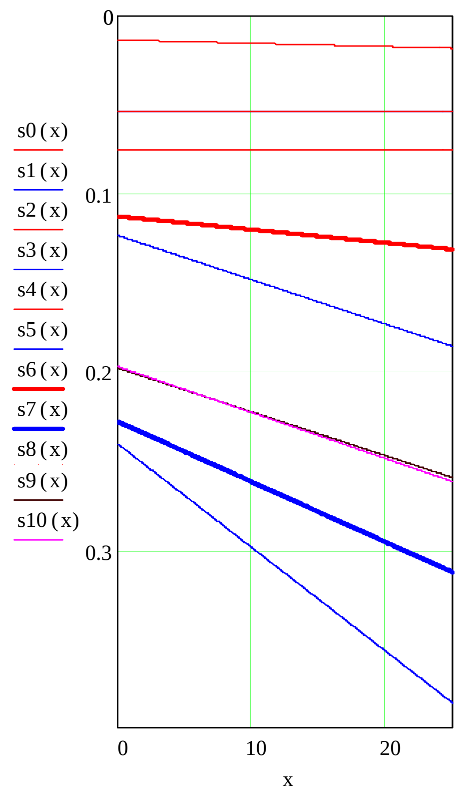


Figure. 6. Rigid 25 m wide footing, under uniformly distributed load q = 50 t/m^2 (0.5 MPa);
a) Contact pressures profile;
b) Footing settlements and tilts
at different stages of loading; with Young modulus E=20 MPa, and soil strength parameters under
- left edge c_{left}= 10 кПа, φ_{left}=25°,
- right edge c_{right}=30кПа,φ_{right}=18.5°.

Results of the above analysis show that the contact pressure profile is not symmetric. The final mean settlement s = 31 cm while differential settlement Δs = 14.5 cm. The same ratio roughly holds at two previous stages as plastic zones of different depths form up under footing edges.

It looks like in this particular case (Terzaghi and Peck, 1967) criterion $\Delta s = 0.5$s is fulfilled.

5 CONCLUSIONS

1. CPT soundings (same as all other in situ tests) measure properties of infinitesmal volumes of soil on any construction site.
2 Cost and volume of geotechnical investigations on construction site are too low for detailed subsoil quantification.
1. Approximation of soil parameters values distribution between test points on site may produce quite uncertain results at the design stage;
2. Manual delineation of stratigraphic units is subjective and inadequate for “soil-footing-superstructure” system analysis.
3. Deficit of geotechnical data can be compensated by approximation with modified Shepard functions, having free dimensionless parameters, which can be varied to identify unfavorable scenarios.
4. Terzaghi-Peck equation relating mean with differential settlements is realistic.

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