Soil areas numerical determination aimed at correction of a building tilt

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Abstract. The analysis of the soil area in the base of an absolutely stiff building has been proposed in the article. Influencing this area it is possible to correct the tilt. The authors of the paper provide an overview of various methods of the tilt correction. The study of the soil spreading in the basement soil has been carried out; the soil area is less deformed under eccentric loading than under central loading. This area is proposed to be called the area of "deficit" strains. The first series of numerical computations has shown that this area depends only on the tilt of an absolutely stiff building; it is described in accordance with a linear law when using simple geometric shapes: a sector and a segment. The second series of computations has illustrated that when decreasing deformation and strength characteristics of this area, the building tilt is corrected. In here, the entire area of the "deficit" strains is not required to be used, just its basic area incorporating a part of a sector and a segment. These areas are concentrated at the edge of the footing. The optimal range of values for a single coefficient which lowers the basic mechanical characteristics of soil has been established. Conclusions on the computations have been drawn and plan for further research has been proposed.

1. Introduction
It often happens that buildings or structures suffer from the excess differential settlements due to underestimation of soil properties, inaccuracies in design, construction or operation [1]. This is resulted in the changed of geometric position of structures in space, i.e. tilts.

The most dangerous situation is when the rate of tilt development remains constant and does not reduce. In this case, immediate emergency measures are required. Stable tilt is less dangerous, but the emergency repair is also required. In both cases, an engineer should make responsible decisions in a very short period of time.

1.1 Brief overview
The Leaning Tower of Pisa [2], the Nevynsk Tower, the Millennium Tower in San Francisco and many others [3] are well-known examples of structures that have suffered from the excess differential settlements.

Many researchers studied the causes of appearing tilts of buildings and structures and the ways of their correction: A.K. Bugrov, S.S. Vyalov, M.I. Gorbunov-Posadov, A. Zh. Zhusupbekov, Yu.K. Zaretsky, V.A. Ilyichev, V.V. Lushnikov, L.V. Nuzhdin, V.M. Malyshev, A.V. Pilyagin, Ya.A. Pronozin., A.S. Sakharov, V.I. Solomin, Z.G. Ter-Martirosyan, A.B. Fadeev, V. Berengo, John W. Burland, Rolf Katzenbach, Rozbeh B. Moghaddam, E. Ovando-Shelley, et al.
To correct the tilts of buildings many technologies and methods have been developed and introduced into practice of construction [4], [5], [6], [7]. The field of their application, advantages and disadvantages are not considered in this paper.

The essential methods are:

1. Application of plate jacks [8], [9], [10]. In the world practice they began to be used in 1879. "Interbiotech" is the original developer of plate jacks in Russia.

2. Application of electro-hydraulic lifting systems. The method is a continuation of plate jacks use, when jacks are monitored by a hardware control [11], [12]. "Interbiotech", SAARTECH, HyBauTech, DMT and Kwant are the original developers of these systems.

3. Application of a counterweight to create extra deformations in the area of insignificant foundation settlements.

4. Application of regulated wetting from the side of insignificant settlements of a building or structure; it is used for the bases composed of collapsible soils [13].

5. Application of injection which was first introduced in France in the 19th century. The method was theoretically and practically developed in Russia by A.A. Adamovich, V.M. Bezruk, B.E. Vedeneev, L.V. Goncharov, V.V. Lushnikov, et.al. At present the hydraulic fracture is being widely used [14], [15], [16].

6. Drilling-out of soil from under the foundation footing from the side of insignificant settlements [17], [18]. V.S. Glukhov, O.V. Sergeychu., A.M. Zotov, M.V. Zotov, V.P. Dyba, M.G. Skibin, Ya.A. Pronozin, et.al studied this method.

2. Research

2.1. Hypothesis
At present, the methods of determining the soil area in the base of a building by influencing on which it is possible to return its verticality are still should be studied. The following hypotheses have been put forward in order to develop one of these approaches. The confirmation of these hypotheses is the objective of the paper:

1. If the natural stress state of soils is homogeneous, then with a differential settlement of foundation (tilt) of absolutely stiff building soils are deformed asymmetrically.

2. The asymmetry of deformations in the soil bed is expressed in two areas existing in it: with a "deficit" and "surplus" of deformations in relation to deformations in the soil bed with the gradual settlement.

3. The asymmetry of deformations in the soil bed depends on the value of the relative differential foundation settlement (building tilt) and on the mechanical characteristics of soil.

4. To return the building its verticality it is necessary to decrease the mechanical characteristics of the soil area with "deficit" deformations.

2.2. Description of the computational model
All numerical calculations have been performed by the specialized MIDAS GTS NX software version - 2019.1.1.

In order to confirm the suggested hypotheses a two-dimensional computational model of plane deformation has been taken. It makes possible to analyse the stress-strain-state only in the vertical plane. Deformations and displacements perpendicular to the given plane are assumed to be equal to zero. Deformations and stresses arise only in the plane under consideration.

The assumptions of plane deformation are suitable for modelling the structure performance and soil behaviour with a mainly constant cross-section. Their stress state must be significantly developed in the third dimension (e.g. linear tunnels, embankments, trench pits, etc.).

The computational model of the problem to be solved is represented by a slab foundation of 12.0 m in width, located on the surface of a homogeneous soil massif of 50x25 m in size. In accordance with the Building Codes (8.8.10 of SP 22.13330.2016) in order to describe the soil behaviour the authors
have used an elastically ideal plastic model with the Mohr-Coulomb strength criterion and the associated law of plastic flow [19]. The computations have been carried out for three different soil beds; their parameter values are given in Table 1.

The foundation slab has been loaded with the uniformly distributed load equal to 1200 kN/m. The foundation slab performance has been described by the elastic material model [1]; the values of its parameters are presented in Table 1.

The foundation slab is assumed to be absolutely stiff for the purpose of its identical effect on the soil bed [20], [21].

On the basis of the created geometric model it has been made a mesh composed of quadrangular finite elements [22]. Taking into account that the problem has required insignificant computation power and time of solution fine grinding of mesh equal to 0.375 m has been chosen.

### Table 1. The used models and their parameters.

| Symbol | Term                      | UOM          | Material model          | Elastic  |
|--------|---------------------------|--------------|-------------------------|----------|
|        |                           |              | Mohr-Coulomb            |          |
|        |                           |              | Soil 1                  | Soil 2   |
|        |                           |              | Soil 3                  |          |
| $E'$   | Deformation modulus       | kN/m$^2$     | 10000                   | 15000    |
|        | (elasticity)              |              | 15000                   |          |
|        |                           |              | 30000000                |          |
| $\nu$  | Poisson's ratio           | -            | 0.37                    | 0.35     |
|        |                           |              | 0.3                     |          |
| $c$    | Specific cohesion         | kN/m$^2$     | 15                      | 25       |
|        |                           |              | 5                       |          |
| $\phi$ | Internal friction angle   | degrees      | 5                       | 15       |
|        |                           |              | 30                      |          |
| $\psi$ | Dilatancy angle           |              | 0                       | 0        |
| $\gamma$ | Specific gravity      | kN/m$^3$     | 19                      | 19       |
|        |                           |              | 17                      |          |
|        |                           |              | 24                      |          |

2.3. Stages of the first computation

When carrying out any geotechnical analysis by means of the FEM, it is necessary to take into account the sequence of the technological procedures. Therefore, any computation consists of sequential stages resulting in a computation scenario.

In the frames of numerical study calculations have been carried out in accordance with two scenarios (figure 1): St.0-St.1-St.2.1 modeling central loading; St.0-St.1-St.2.2 modeling eccentric loading. Both scenarios have two common initial stages: St.0 is the stage for creating the initial stress state; St.1 is the stage for creating the foundation of an absolutely stiff building.

At stage St.2.1, the central load $N_0$ of 1200 kN/m has been applied. At stage St.2.2, the eccentric load $N_i$ has been applied. At that, calculation has been carried out for different displacement of the load $N_i$ in relation to the central axis: $N_1$ - 2 m, $N_2$ - 4 m, $N_3$ - 6 m. The notation of computation scenarios are presented in table 2.

The maximum value of the equilibrium error has been 0.5%. Newton-Raphson method has been used for solution [23].

### Table 2. Notation of computation scenarios.

| Type of loading | Load | Soil bed |
|-----------------|------|----------|
|                 |      | Soil 1   |
|                 |      | Soil 2   |
|                 |      | Soil 3   |
| Central         | $N_0$| P1       |
|                 |      | P5       |
|                 | P9   |         |
| Eccentric       | $N_1$| P2       |
|                 |      | P6       |
|                 | P10  |         |
|                 | $N_2$| P3       |
|                 |      | P7       |
|                 | P11  |         |
|                 | $N_3$| P4       |
|                 |      | P8       |
|                 | P12  |         |
2.4. Results and analysis of the first computation

If the central load is applied, a symmetrical stress-strain-state pattern is formed in the soil bed in relation to the central axis (figure 2a). The pattern significantly differs from the stress-strain-state under eccentric loading (Figure 2b).

The isolines of vertical deformations developed in the soil bed have been the analysed results of computation [24]. Besides, the analysis has been carried out with regard to the difference between the results of two scenarios but regardless of the specific results of the computation scenario (Figure 1, right-hand side). MIDAS GTS NX has made it possible to complete the procedure.

The analysis can be considered in detail, see (figure 2). Similar isolines being the result of the computation in accordance with the scenario P4 (figure 2b) have been subtracted from the isolines of vertical deformations in the soil massif (figure 2a) resulted from the calculation after the scenario P1 (table 2). The difference in values has been determined at the nodes of the finite elements.

Thus, vertical isolines of the difference between the scenarios P1-P4 (figure 2c) have been obtained with two characteristic areas in the soil bed: the area incorporating negative values of deformations (“deficit” of deformations) located on the left, and the area incorporating positive values of deformations.
deformations located on the right ("surplus" of deformations). Similarly, the vertical isolines of the difference between the scenarios have been obtained for all examined eccentric loads and all soil conditions.

It is possible to return the vertical position to the building in case of external influence of negative values of deformations on the soil bed area ("deficit" of deformations). A technological process that lowers the mechanical characteristics of soil, e.g. drilling-out can be considered as external influence. In order to illustrate this area all differences in vertical deformations (e.g. figure 2c) have been visually rebuilt to display only negative values - the area of “deficit” deformations (figure 3a, b, c).

Figure 3. Analysis of the difference between the results of the computation scenarios.

It has been found that when the external load is displaced from the centre to the edge of the building, i.e. with an increase in eccentricity, there is an increase in the relative differential settlement of the foundation and the area of "deficit" deformations develops. The minimum values of this area are concentrated at the quoin; when the differential settlements grow, they develop in the horizontal and vertical directions.

In order to reveal the dependence of the area of "deficit" deformations development on the soil parameters and the tilt size we describe it with two geometric areas (figure 3d):

- half of the segment (area 1) which includes part of the area of "deficit" deformations under the foundation;
- sector (area 2) centred on the edge of the foundation which includes part of the area of “deficit” deformations beyond the foundation.

The geometric shapes have been chosen on the assumption that their joint shape describes the area of "deficit" deformations quite accurately, and the sum of their areas contains up to 80% of its values. To create these geometric shapes (half a segment and a sector), two values are required (figure 3e): R -
radius of the sector (area 2) simultaneously with half of the chord of the segment (area 1); a - segment height (area 1). The radius R1 (figure 3e) is determined as: 
\[ R_1 = \frac{a^2 + R_2}{2a} \]

Changes in the parameters \( a \) and \( R \) for various soil beds have been analysed depending on the expected values of the relative differential settlements (the tilt of an absolutely stiff building) describing the developed area of "deficit" deformations. It has been stated that these values develop in accordance with the linear law. For the whole of considered soil conditions, the determination coefficient for the value \( R \) is in the range of 0.94-0.99, and for the value \( a \) - in the range of 0.89-0.92. The total dependence of \( R \) and \( a \) for the whole of considered soil conditions is also linear and has high values of the determination coefficient - 0.91 and 0.79 respectively (figure 4). Thus, to determine the area of "deficit" deformations it is possible to use the dependences obtained.

![Graph of the developed geometric parameters R and a of the "deficit" deformations for the whole considered soil conditions.](image)

**Figure 4.**

2.5. **Stages of the second computation**

To return the building to a vertical position it is necessary to have an impact that decreases the mechanical characteristics of soil in the area of "deficit" deformations. A series of computations have been carried out in order to assess the degree of the required decrease in the mechanical characteristics of soil. Computation has been performed following the scenario (figure 5a): St.0-St.1-St.2-St.3 simulating eccentric loading. Initially, the contour of the "deficit" deformations in the soil bed has been created at the stage of the initial stress state St.0, (figure 5b).

For this, the previously determined dependencies have been used (figure 4). Then, the foundation of an absolutely stiff building has been constructed at stage St.1. After that, the mechanical characteristics of soil have decreased at stage St.2 (internal friction angle, specific cohesion, deformation modulus) in the area of "deficit" deformations. A single decreasing coefficient \( k \) with different values: 0.8; 0.5; 0.2 has been used to decrease the characteristics. In order to assess their contribution to the building verticality, the area of "deficit" deformations has been divided into constituents at the same stage (figure 5b).

Cases for application of the coefficient \( k \) only to a specific area, as well as to the sum of areas: "1" + "2.1", "1" + "2.1" + "2.2" have been considered. At the final stage St.3, the eccentric load \( N_i \) has been applied. Computation has been carried out for different displacement of the load \( N_i \) in relation to the central axis: N1 - 2 m, N2 - 4 m, N3 - 6 m. This computation scenario has been carried out on the whole soil foundations under study (table 1). The maximum value of the equilibrium error has been 0.5%. Newton-Raphson method has been used for solution [23].
2.6. Results and analysis of the second computation

The analysed computations have illustrated the effectiveness of decreasing the mechanical characteristics of the soil in the area of "deficit" deformations. It is necessary in case of decreasing the differential settlements of the foundation or correcting the tilt (figure 6). It makes no difference for an absolutely stiff building.

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**Figure 5.** Schematic illustration of computation for the decreased mechanical characteristics of soil: (a) is scenario, (b) is division of the area of "deficit" deformations.

**Figure 6.** Graphs illustrating the effectiveness of the decreased mechanical characteristics of soil in the area of "deficit" deformations for the soil conditions 2 and eccentric loading N1 and N3.
It has been stated that the decreased mechanical characteristics of the soil in the area of "deficit" deformations leads to the decreased differential settlements. The area "2.2" is the exception (figure 5b, figure 6). Its influence decreases with the increased eccentricity of loading and, in general, is insignificant. The area "2.1" has less influence on the tilt correction as compared to the area "1". The entire area of "deficit" deformations used (area "1" + "2.1" + "2.2") does not significantly increase the effectiveness of the tilt correction as compared to the sum of areas "1" + "2.1". With small values of the coefficient k (less than 0.35) and elimination of the load from the central axis, counter-tilt occurs. The decrease of the mechanical characteristics is effective if the coefficient k is less than 0.4. Almost complete correction of differential settlements occurs when the coefficient k is less than 0.35.

Thus, in order to decrease the differential settlements, i.e. balance them, it is necessary to decrease the mechanical characteristics of soil using the coefficient k in the range of 0.3-0.4 in the areas of "deficit" deformations - "1" and "2.1". The value of the coefficient is applicable when the relative differential settlements do not exceed 0.007 for the soil conditions given in table 1 as well.

3. Conclusions

1. If the natural stress state of soil is homogeneous, the differential settlement of the foundation in an absolutely stiff building leads to asymmetric deformations developing in the soil bed. The asymmetric deformations involve two areas formed: with a "deficit" and "surplus" of deformations in relation to deformations in the soil bed with gradual settlement.

2. The area of "deficit" deformations depends on the value of the relative differential settlement of the foundation (building tilt) and can be represented by a linear function (R2 is over 0.79). This area is described by two simple geometric shapes: a rectangular sector and a half segment.

3. In order to return verticality to the building (balance of differential settlements), the coefficient k = 0.3 ... 0.4 is required; the mechanical characteristics of soil decrease (internal friction angle, specific cohesion, deformation modulus). The coefficient must be applied for a partial area of "deficit" deformations: the 45-degree sector and half of the segment in relation to the corner of the building.

4. Summary

The analysis and the very correction of the building tilt is a more responsible and risky procedure than designing a new building. This field of geotechnical engineering is still being developed and none of the approaches has become classical for certain soil conditions. Therefore, the development of various computations for correcting the building tilt will be relevant. These studies are likely to be the basis for choosing the most appropriate technology for correction of the building tilt in each specific case.

The study does not cover a wide range of challenges, namely: effect of the stiffness of structure, groundwater, individual mechanical and rheological properties of soils, technological processes and many others.

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