Experimental sensitivity analysis of subsoil-slab behaviour regarding degree of fibre-concrete slab reinforcement

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Abstract. The paper is focused on the sensitivity analysis of behaviour of the subsoil – foundation system as regards the variant properties of fibre-concrete slab resulting into different relative stiffness of the whole cooperating system. The character of slab and its properties are very important for the character of external load transfer, but the character of subsoil cannot be neglected either because it determines the stress-strain behaviour of the all system and consequently the bearing capacity of structure. The sensitivity analysis was carried out based on experimental results, which include both the stress values in soil below the foundation structure and settlements of structure, characterized by different quantity of fibres in it. Flat dynamometers GEOKON were used for the stress measurements below the observed slab, the strains inside slab were registered by tensometers, the settlements were monitored geodetically. The paper is focused on the comparison of soil stresses below the slab for different quantity of fibres in structure. The results obtained from the experimental stand can contribute to more objective knowledge of soil – slab interaction, to the evaluation of real carrying capacity of the slab, to the calibration of corresponding numerical models, to the optimization of quantity of fibres in the slab, and finally, to higher safety and more economical design of slab.

1. Character of subsoil – structure interaction and its determinant factors

Interaction of the building structure with the rock environment determines the basic behaviour of the foundation structure and the whole upper building structure. The building structure, due to its load, causes both stress and deformation changes in the subsoil and as a result of these changes, additional forces and deformations can be brought back into the upper structure. The qualitative and quantitative nature of this interaction depends on many determinant factors. One of them is the relative stiffness of the entire cooperative system, which is determined by both the properties of the structure itself and the subsoil.

Soil materials below the slab are generally very heterogeneous and their behaviour under external loading depends on the following fundamental factors:

- the strength and deformation characteristics of the soil, in the case of cohesive soils, especially with respect to their humidity;
- consolidation processes in the soil (especially in the case of soft, low-permeable clay soils);
- changes of soil properties in time (soil rheology);
- sizes and load characteristics;
- history of loading;
- loading speed;

Relative stiffness of the collaborative “structure-soil“ system is often defined by the Schultz relationship:
\[ k = \frac{E_f}{E_s} \left( \frac{t}{l} \right)^3 \]  

(1)

where \( E_f \) = Young’s modulus of the slab material, \( E_s \) = Young’s modulus of the soil (weighted average module of layers), \( t \) = thickness of the slab, \( l \) = length of the slab. For relative stiffness \( k<1 \) is the foundation classified as flexible, for \( k>1 \), it is considered as a rigid foundation.

The behaviour of rigid and flexible foundations is significantly different in qualitative and quantitative terms, which is reflected in qualitative and quantitative differences of internal forces in the structure. It is generally known that, in the case of a flexible foundation (\( k<1 \)) a significant deflection of the foundation structure occurs, and the contact stress is uniform [1]. For a rigid foundation (relative stiffness greater than 1), the contact stress concentrations are manifested below the edges and corners of the foundation and consequently, depending on the shear strength and corresponding development of the plastic strains, they are subsequently redistributed [2] - Fig. 1. At a small load, the plastic manifestation of soil occurs in a very small area below the foundation edge (or corner). In this case the distribution of the contact stresses is very close to the theoretical result with infinitely large contact stresses below the edge (corner) of the rigid foundation [3, 4, 5, 6]. When the load increases, the plastic zone expands, and the contact stress corresponds to a saddle-shape, adequate settlements are approximately uniform [7]. Further increase of the load causes redistribution of the contact stresses towards the axis of the foundation and the development of the contact stresses corresponds to the parabolic shape. If the shear strength of the foundation soil is exceeded, the stress concentration increases below the foundation axis and the contact stresses correspond to a bell-shaped pattern. The nature of the contact stresses therefore depend very much on the strength characteristics of the soils [8, 9]. In the case of the cohesive subsoil, the contact stress in the rigid foundations is predominantly saddle-shaped, in the case of non-cohesive subsoil, the contact stress often has a parabolic shape.

![Figure 1](image)

**Figure 1.** Various shapes of contact stresses under the rigid foundation.

To ensure reliable design of the foundation from the point of view of the interaction with the subsoil, the change of stiffness of the entire cooperating system must be considered during the loading. This change in stiffness results from the changes in both the soil material and the structural material. When a certain load value is exceeded, the softening of some parts of the structure may occur due to microcracks. On the other hand, the development of plastic strains, seasonal precipitation fluctuations and the consolidation of the soil environment can also induce a change in the stiffness and strength of the subsoil during loading. These aspects can then change the relative stiffness of the foundation and consequently change the entire investigated interaction.

2. **Characterization of experimental works**

Our experimental research was focused on the behaviour of the foundation fibre-concrete slab of square shape supported directly by the cohesive soil. Dimension of the square concrete slab was 2 x 2 m,
The thickness of 0.15 m. The basic matrix of slab corresponds to the concrete C25/30, three different quantities of fibres DRAMIX 3D 65/60 BG were added to the concrete [10].

The geological profile below the slab corresponds to loam F4 (minimal thickness of 5 meters), character of deeper soil is not known in detail, but a soft soil is assumed in deeper horizons too. The original soil was rather inhomogeneous due to the building intervention into the ground during the construction process of the stand. Therefore the subsoil was homogenized before the start of the experiment. Homogenization included the digging of the original soil to the depth of approximately 1.2 m (depth corresponding approximately to the depth of the location of the stand foundation), mixing of excavated soil so as to achieve quasi-homogenized material, back-refilling the dig with the homogenized soil and compaction in partial layers [11, 12]. Water level was not reached until bottom of the dig. Homogenized subsoil was tested using both laboratory and in-situ methods. Static load plate test was used not only for the evaluation of the deformational modulus of the subsoil, but also for the verification of quality of homogenization. Material parameters of quasi-homogenized subsoil obtained from laboratory and field testing (carried out in July 2017) are shown in Table 1.

### Table 1. Material parameters of quasi-homogenized subsoil under tested foundation.

|                | Unit weight | Deformational modulus | Poisson’s number | Cohesion | Friction angle |
|----------------|-------------|------------------------|------------------|----------|----------------|
| Homogenized subsoil | 19 kN/m³    | 12.9 MPa               | 0.35             | 9.3 kPa  | 19.3 degree    |

The deformation and strength characteristics of the tested fibre-concrete materials were determined on cylindrical (diameter of 150 mm, height of 300 mm) and cubic samples (150 x 150 x 150 mm) in the Laboratory of Building Materials at the Faculty of Civil Engineering of VSB-Technical university Ostrava and their average values are presented in the following table No. 2. This table contains also the calculated relative stiffness according Schultz formula (corresponding to the Young modulus of soil 12.9 MPa) and information related to the precipitation in the previous 14 days before testing. Three slabs differing in the content of fibres were tested, the slabs labelled G05, G06 and G07 corresponded to the addition of fibres of 25 kg/m³, 50 kg/m³ and 75 kg/m³ respectively.

From the calculated relative stiffness of the tested slabs (at a constant value of the Young’s modulus 12.9 MPa) follows that the slabs can be considered as flexible foundations. The mentioned precipitation before the tests of individual plates shows that the real relative stiffness of the foundation could be affected not only by the change in the contents of the fibres in the slabs but also by the potential degradation of the deformation properties in their subsoil, especially in the near-surface layers.

The slabs were loaded in the central part by gradual variable surcharge applied by a hydraulic press (Figure 2). Loading was performed using a special strutted steel structure (experimental stand), applied step by step at uniform velocity until the slab failed (partial loading step corresponds to 75 kN) [13]. The experimental measurements of slab settlement and vertical stresses in the subsoil below the slab were carried out during the loading process.

Results of monitoring related to settlements and strain inside the slab are not the focus of this paper, they were presented in papers [14, 15, 16, 17, 18]. This paper is focused on monitoring of vertical stresses in subsoil below the slab, which was performed using 9 vibrations wire flat cells GEOKON [19] located at three depth levels (marked X), as is shown in Figure 3 (localization on contact surface (X=1), 0.35 m below the contact surface (X=2), 0.8 m below the contact surface (X=3)). In each of the three depth levels three flat cells are located, one cell is placed in the centre of the slab (Y=1), the second one at the centre of the edge of the slab (Y=2) and the third cell is located at the corner (Y=3). Thus, flat cells located at the contact surface are marked 1.1., 1.2, 1.3, cells at 0.35 m (resp. 0.8 m) below the surface are marked 2.1, 2.2, 2.3 (resp. 3.1, 3.2, 3.3).
Table 2. Characteristics of tested slabs labelled G05, G06 and G07.

| Slab label | Precipitation (mm) | Date of the test | Content of fibres kg/m³ | Compressive strength (MPa) (cylindrical samples – an average of 3 tests) | Compressive strength (MPa) (cubic samples – an average of 6 tests) | Young’s module of elasticity (GPa) (cylindrical samples – an average of 3 tests) | Relative stiffness (Schultz) |
|------------|-------------------|------------------|------------------------|---------------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------|
| G05        | 23                | 21.6.2017        | 25                     | 24.86                                                              | 30.9                                                            | 19.7                                                            | 0.644                       |
| G06        | 44                | 18.9.2017        | 50                     | 22.1                                                               | 24.4                                                            | 18.5                                                            | 0.605                       |
| G07        | 17                | 26.10.2017       | 75                     | 23.6                                                               | 28.2                                                            | 18.3                                                            | 0.598                       |

Figure 2. Scheme of experimental measurements on the stand

Figure 3. Localization of flat cells in experiment (in plan and cross section)
3. Results of experimental works

In the following Figure 4 are presented the total vertical stresses below the three variant slabs marked G05, G06 and G07. Evaluation is carried out under the assumption that the self-weight of the slab and original stress (soil weight above the measuring cell) is removed.

The first row in the Figure 4 corresponds to stresses in two various depths below the centre point of the slab (one sensor stopped working at the depth of 0.35 m, so only two depths were investigated and evaluated) for all tested slabs G05, G06, G07. The second row represents the stresses in three various depths below the centre of the slab edge, the 3rd row illustrates the situation below the corner of slab.

Figure 4. Assessment of monitored stresses below the slabs G05, G06, G07

Results obtained from the cell 1.1 (contact cell located below the centre point of slab) are presented in Fig. 5. Contact stresses below the centre of slab G05 (the slab with the high relative stiffness) increase significantly until the loading 180 kN is achieved, at higher load we registered a lower gradient of contact stresses at this monitoring point.

In the case of slab G06, the contact stress increases with the lower gradient at lower load level, when this load of 300 kN is exceeded, the gradient of the contact stresses continuously increases. Due to the softening of the subsoil due to the increased moisture in the subsoil layer below this slab G06 (higher moisture is induced by stronger rainfall before testing) the relative stiffness increases. Compared with other slabs, it is very important to note that relative stiffness of foundation increases due to the expected (but not quantified) softening of the subsoil below this slab G06 due to the significant precipitation prior
to its testing. This impact is registered and documented (in accordance with the theory) by decreasing of contact measured stresses in the central zone below the slab G06 and by increasing of contact stresses below the corner.

In the case of the G07 slab test, the increased gradient of the contact stress is evident mainly in the middle of the loading interval (200-300 kN). Outside of this loading interval the gradient of contact stresses is lower.

![Figure 5. Load - contact stress curve below the centre of slab](image)

Fig. 6 shows a load - contact stress curve below the centre of the slab edge. The results of the measurements document the reduction in the stresses at a specific load level resulting from a significant deflection of the slab that was observed during the test. This deflection leads to an uplift of the edges and corners of slab and a gap between the soil and slab opens in some part of contact surface (contact surface is reduced).

A more significant impact of the uplift of the slab corners is documented in Figure 7. The results presented in Fig. 6 and Fig. 7 show that a loss of contact between the slab and the subsoil at the slab corners occurs at lower load compared to the load required to create a gap on the edge of the slab.

![Figure 6. Load - contact stress curve below the centre of slab edge](image)
The test results did not show too great differences in the final load value, which corresponds to the extrusion of the slab (the maximum extruding force is approximately equal to 500 kN).

The pressure cell located at the maximum investigated depth below the slab (depth of 0.8 m) does not record any significant differences in the values of the vertical total stresses under the slabs (Fig. 8). Some minor differences are visible for G05 slab, but there are observed for the load higher than 350 kN only.

![Figure 7. Load - contact stress curve below the corner of slab](image)

![Figure 8. Load - stress curve below the centre of slab (depth 0.8 m)](image)

4. Conclusions

- Slab-subsoil interaction is a complex problem depending on many factors, including the properties of the structure and the subsoil. This interaction has a significant rheological character confirmed by the results of measurements. The relative stiffness of the foundation may not be identical throughout the whole load cycle. Corresponding changes in stiffness can be caused, among other factors, by changes in the subsoil below slab (influence of soil moisture variation, etc.).

- Experimental stress measurements indicated some decrease in the effective contact surface between the slab and the subsoil during the loading due to the uplift of the corners and edges of slab.
The vertical contact stresses induced by the vertical axial load of the slab reach the maximum values below its centre, regardless of the slab variant. Lower contact stresses are reached below the edge of the slab, the lowest stresses are monitored below the corner of the slab. In this context, however, it is important to note, that the uplift of the edges and corners of the slab is manifested during test. This phenomenon results into the reduction of vertical stresses at these measuring points during the loading.

Different contact stresses are evident for the individual tested slabs, but it is not possible to clearly distinguish the effect of the different degree of reinforcement of slab (among of fibres) on the one side and change in the properties of the subsoil on the other side.

Some differences in vertical total stress are identified for specific slabs at a depth of 0.35 m below the contact surface. Because the monitoring pressure cell located below the centre of the slab showed a defect at the beginning of measurement already, the values of vertical total stresses below the centre could not be evaluated. The performed measurements show, that up to the load approx. of 300-400 kN the significant differences of the vertical stresses below the centre of the slabs G05 and G06 are not indicated. If this load limit is exceeded, the vertical stresses below the slabs G05 and G06 gradually drop probably due to the uplift of edges and corners of the slabs. A different situation occurs at this depth under the slab G07. Below this slab the stresses below the centre of the edge increase with the increasing loading up to the maximal applied load (unlike the situation below the slabs G05 a G06 the monitoring did not detect a significant stress drop).

The influence of corner uplift corresponding to the specific loading is manifested at the depth of 0.35 m under the contact surface too. At this depth level the vertical stress under the corner of slab G05 drops to a force of 150 kN, under the slab G06 to 180 kN and under the slab G07 to 200 kN. The maximal value of the induced vertical stress at this depth achieves approx. of 20 kPa independently of the type of slab.

At a depth of 0.8 m below the contact surface (maximum investigated depth), the effect of the different contents of the fibres in the slab as well as the potential degradation of soil characteristic is eliminated already (registered stresses are practically identical).

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