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GRADUATE REVIEW ARTICLE

Analysis of the Weak Soil Behavior, Modified Through Cementation

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ABSTRACT

The purpose of the study is to conduct thorough theoretical research and literature overview regarding possible ways of soil stabilization on the basis of this practice increasing demand. In particular an emphasis is made on the chemical technique for weak soils strengthening, due to its prevalence and various practical and economic advantages. Great amount of promiscuous data was analyzed and organized; in addition on its basis an attempt is made to provide convincing calculation technique for further usage in engineering soils` stabilization practice. Besides, various factors which could influence on the results` accuracy are identified with corresponding recommendations for further possible research on this issue.

Keywords: Cemented soil, Existing buildings` redevelopment, Mortar strength, Soil stabilization.

1 Introduction

Modern architectural and urban development activities tend to the dense building tendency enhancement, causing both the existing building superficiality increase and more optimal usage of vacant urban sites. According to paper [1] this trend could be explained by the great number of both economical (rational development of valuable urban areas and saving resources for the construction of engineering and transport networks), architectural-planning (the historical town center value, possibilities for creative architectural solutions), as well as psychological and demographical reasons. Therefore, recent times, the issue of existing structures` redevelopment has occupied significant place in the engineering practice of both residential and industrial buildings` amplification. Such perspective could be associated with the increase of various negative impacts on both the major construction elements and ground soil. Further necessity of soil stabilization with the use of appropriate technique is obvious, which could confirm the topicality of the problem discussed in this study.

1.1 Problem formulation

Choose of an appropriate approach in each particular situation could become the assured prerequisite of obtaining environmental and economic advantages. In this study the chemical technique of soil stabilization (namely cementation) is discussed as one of the most common approaches to the existing building basement strengthening. Such a method does not only cost-effectively bring soil into the alignment with the required geotechnical needs in terms of strength resistance, moreover resistance to water, frost and inclement conditions damaging will be significantly increased.

1.2 Objectives and topicality of the study

Objectives of the study include the following: theoretical research and literature overview regarding possible ways of soil stabilization, providing convincing calculation technique for indication of the cemented soil strength. The article topicality and practical importance is associated with proposition of possible calculation approach which could be used in actual engineering practice and fformulation of possible ways for further issue development

2 Literature review

The multi-storeyed building construction could be associated with great structural load on the ground and geological situation in the building area changes. In accordance, this could lead to wide range of negative impacts including destruction of neighbor buildings` foundations, deterioration of the highways and pedestrian roads` coatings, damage of the surrounding area landscapes, the slopes` landslides, the ground water systems` contravention, as was described in work [1]. Obviously,according to [2] in such situations the foundation bearing capacity as well as adjoining soil properties and behavior could be crucial in structure sustainability. Subsequently, as common renovation practices anticipate for construction scheme changes and applied load impacts` increase, correspondent measures on the soil bearing capacity have to be discussed.

If the construction project secure is not ensured by the existing ground conditions in terms of soil load-bearing capacity, stability, compaction properties, corresponding soil stabilization technique has to be introduced. According to [3] soil stabilization includes wide range of methods, practices and technologies aiming to change natural soil to meet an engineering purpose through physical, chemical, mechanical and biological methods, namely to increase its weight bearing capability, tensile strength, overall performance and durability, etc. As was described in [4] among various types of chemical techniques the main principle could be identified which rely on chemical reactions between certain stabilizer and soil minerals, either cementitious or puzzolanic in nature, depending on the particular site conditions investigated.

In recent studies ([5],[6]) were analyzed particular properties of the newly created cementitious phase and aspects, influencing its formation. Cementing job is virtually of the transformation of the cement to a liquid slurry and its pumping down the wellbore. Further interphase transformations on the both macro- and microscopical levels could be associated with cement particles flocculation and paste viscosity increase. Simultaneously, the uniform distribution of the stabilizer particles will be disturbed as separate aggregates stop participating in the paste flow. Henceforth the chemical bonds between the individual cement particles tend to overgang van der Waals and electrostatic forces that are responsible for flocculation. Further chemical bonds increase is accompanied with formation of three-dimensional solids network, paste deformability decrease and cured material strength enhancement, which could be confirmed by recent studies ([7],[8]).

Generally speaking, soil response to lime treatment is rather complex and could associated with synergic effect of several effects including cation exchange, pozzolannic reactions, carbonation and flocculation, which was described above. Although the great number of attempts was made, aiming to formulate the adequate hypothesis, the lime-soil interaction mechanism description is not complete jet. In the number of comparative studies ([9],[4]) authors affirm, that the key aspect needs to be considered to properly

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determine the stabilization processes` proceeding it is important to analyze chief particular soil conditions, including permeability, compressibility, strength and volume stability. These key factors could be indicated by corresponding laboratory tests followed by field tests.
In the paper [10] the specific features of cemented sand soils are discussed. An assumption is made that the cementation between sand grains and sandstone could be approximated to the bonds` formation. As the result, no movement between particles takes place. Therefore, it could be assumed that the newly-created artificial stone acts as over consolidated soil and certain non-uniformity in its behavior could be omitted. In addition the behavior of such material under the loading is described. Specifically, the cementation yield surface location features were noted: the elastic stress-strain behavior inside and elastoplastic outside the surface. Thus, the authors conclude that the cemented soil behavior could be analyzed in the similar way as for soils modeling.

3 The calculation methodology & formulation

For more evidence in this work the actual construction situation is analyzed and on its basis the calculation technique is developed. In the towns with long-term historical background the typical situation in the construction practice includes redevelopment of existing building with its superficiality increase. Characteristics of the building, accepted as the demonstrable situation in this study are given in the table 1 and figures 1, 2.

Table 1: *Comparative characteristics of the existing building and demonstrable redeveloping project*

Characteristic feature	Characterized object	
	Existing non-residential building	Redevelopment project
Number of storeys	3	6
Major construction bearing elements	brick walls, (640 mm)	1-3 storeys –as in the initial building, 4-6 storeys-concrete columns (500x500 mm)
Floors construction	unalterable, in situ concrete over steel beams (spacing 1 m), as shown on fig. 1	
Foundation construction	0,8 m thickness` tape foundation with combined construction (0,3 m of rubble stone and 0,3 m of brick)	
Attic	Non-residential, with wooden floor construction	demolished
Construction bearing scheme	Walls, spacing 5 m are subjected to the loading with the loading area of 5 m^2	1-3 storeys-as in the existing building, 4-6 storeys- concrete columns spacing 5x6 m are subjected to the loading with the loading area of 30 m^2
Load	362,9 kN	1200 kN

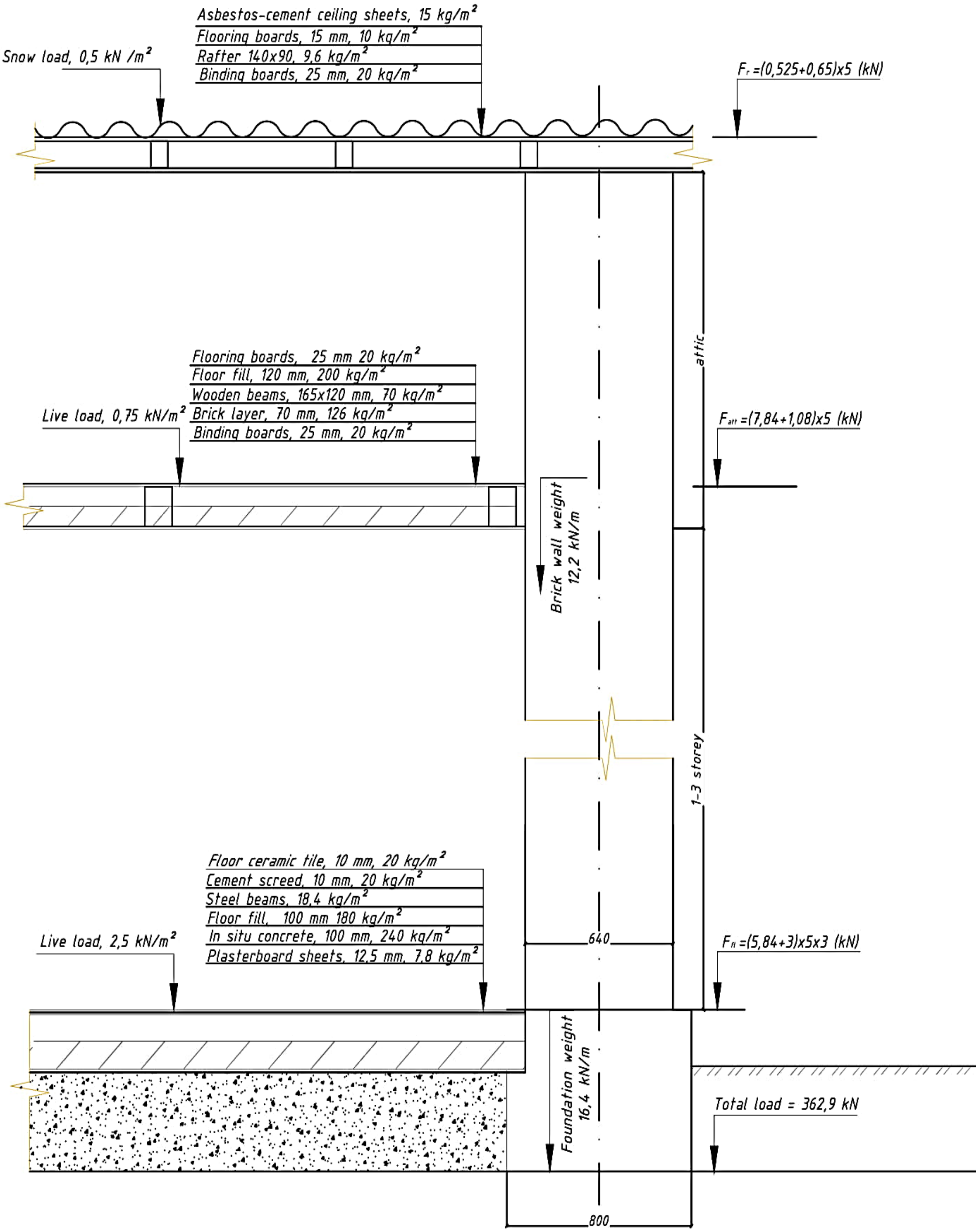

Figure 1: *Loading scheme for the typical existing building*

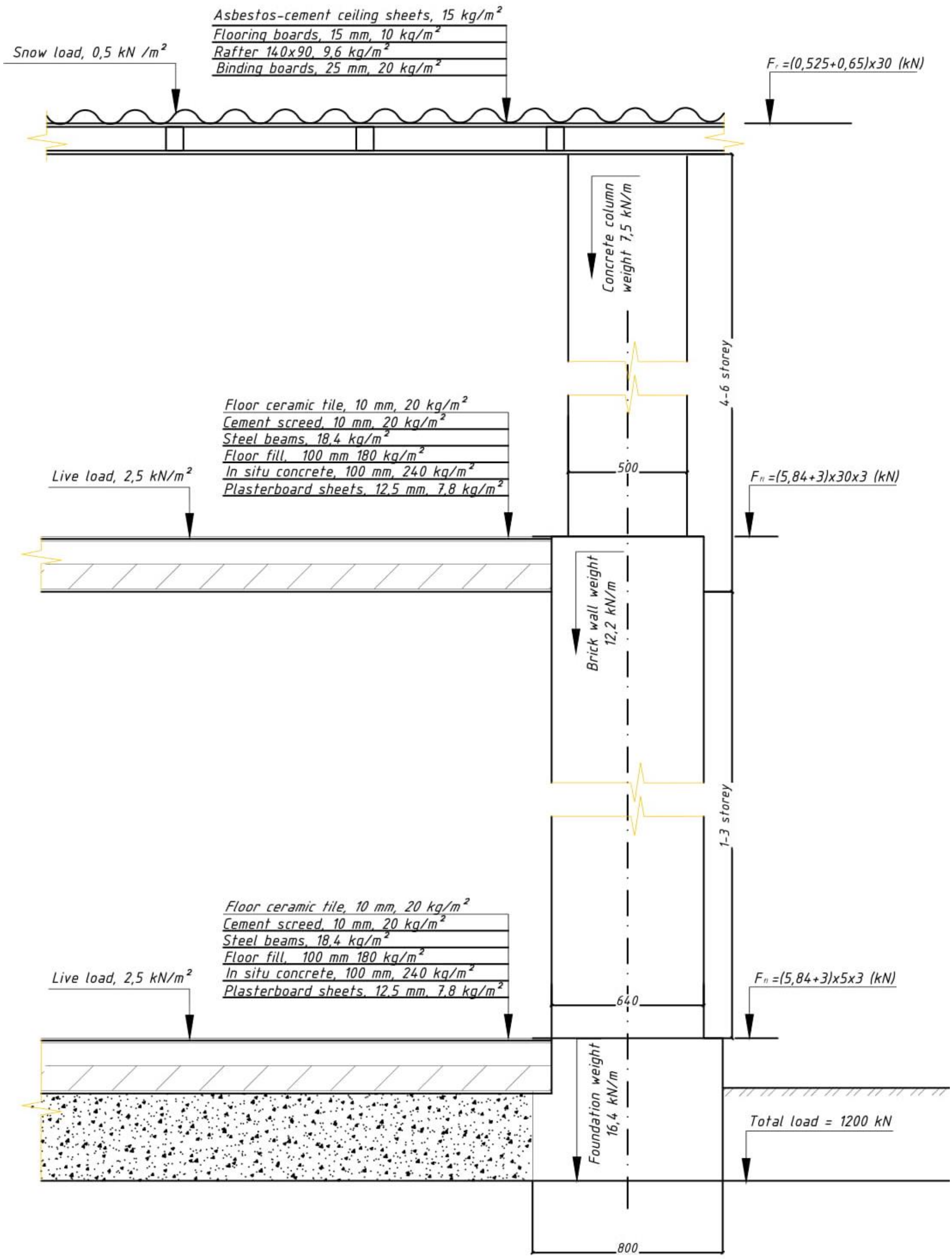

Figure 2: *Loading scheme according to the typical redevelopment project*

The specific redevelopment project includes overbuilding of three additional floors according to the pre-prepared project. The typical redevelopment project, common in engineering practice is shown on the figure 3.

Figure 3: *Example of typical redevelopment project (Architector: Trophymenko O.)*

The load bearing capacity of the foundations was checked in the most loaded place- under the middle load-bearing wall. The most critical cross-section of the construction element is expected to be at the lower part of the basement wall. The major structural elements construction is assumed as for typical buildings of such type (figures 1,2) and therefore corresponding determination of the actual load applied on 1 linear meter of the existing foundation (equations. 1,2). For the initial building the loading area is equal to the bearing walls spacing (5 m^2) and therefore the total load on the 1 linear meter of foundation:

$$N_{innit}=(0,525+0,65)\times\cdot 5+(7,84+1,08)\times 5+(5,84+3)\times 5\times 3+11,8+168=362,9\ \kappa N \quad (1)$$

As in the redevelopment project the overbuilding of three addition floors with structural columns spacing 5x6 m (loading area of 30 m^2) following calculations could be given:

$$N_{redev}=(0,525+0,65)\times 5+(5,84+3)\times 30\times 3+(5,84+3)\times 5\times 3+11,8+168+85,4=1200\ \kappa N \quad (2)$$

As additional load on the main construction elements is expected to be applied, corresponding calculations for defining particular strength properties of the soil, subjected to loading should be conducted (equations 3-5). Initial data required for calculation include characteristics of the soil subjected to loading construction and material of actual existing foundation as well. The soil characteristics required for further calculation are taken as the typical for the area (Lviv region, Ukraine), according to the number of geological researches conducted (11]). The ground conditions within the building site are represented by well-graded sand with low humus percentage and specific weight of 1,82 kg/cm^3. Soil strength properties R_o, kPa, under the existing foundation sole was calculated according to recommendations of corresponding normative documents, namely annex E, DBN V.3.1.-1-2002, [12]. Concordantly, additional increase in strength characteristics of the soil due to its long-term consolidation by the existing building is considered.

Therefore, following prerequisites are used for calculation:

- Attic walls` area, subjected to loading F=0,8 m²;
- Initials soil strength R_o =18,2 kg/cm²=182 kPa;

Consolidated soil strength could be calculated as following:

$$R_t = R_o \times m \times K_s \qquad (3)$$

where R_o –initial unconsolidated soil strength according to SNIP 2.02.01, [13] assumed as for new construction;

m –coefficient, which takes into account changes of soil mechanical properties due to operational processes of the building, depending on consolidation stage P_0/R_0. Accordingly, for P/R_0>0,8 m=1,3; for P/R_0=0,7–0,8; m=1,15; for P/R_0 <0,7, m=1,0;

P– pressure under the existing foundation sole, kPa.

In this particular case P=N_{innit}/F=36274,4/8000=4,53 kg/cm², R_0=1,82 kg/cm², therefore P/R_0 =2,49> 0,8, m=1,3

K_s–coefficient which accounts changes in soil consolidation properties and is taken according to the table 1., DBN V.3.1.-1-2002,([12]) as a function on the limit foundation sinking realization (ratio of sinking S_k under the calculated particular pressure and its limit value S_u.). For dusty-clay soils with the plasticity number of $I_l \leq 0,5$ (for the operational time of the building of more than 15 years) the value of the coefficient K_s for S_k / S_u,= 0,2 is equal to 1,1. Hence, the design soil resistance R_t (kPa) under the existing foundation sole, if taking into account soil consolidation could be calculated as the following:

$$R_t=R_o \times m \times K_s=1{,}82 \times 1{,}3 \times 1{,}1=2{,}603 \text{ kg/cm}^2=260{,}3 \text{ kPa} \quad (4)$$

The actual stress, applied on the ground from the foundation sole:

$$N_{redev}/F=120000/8000=15 \text{ kg/cm}^2 \geq R_t=2{,}63 \text{ kg/cm}^2 \qquad (5)$$

The strength condition is not provided. It could be concluded that ground soils and foundations cannot bear the loading from 3 additional floors without soil strengthening. In order to ensure further secure exploitation of the building it is necessary to take reinforcement measures. In this study the attempt will be made to provide the appropriate calculating technique in order to ensure necessary soil properties (equations 4-10). The corresponding considerations and calculations are provided on the basis of two possible calculation approaches from two different sources. It is important to note that the actual cementation conditions could be complicated by non-uniformity of the soil properties, temperature and moisture effects, unfaithful data on soil features, etc. All these aspects, which could influence on the mortar hardening process as well as non-uniformity of water cement solution distribution are taken into account by the use of safety factor 1,3 in the equations 7,9. The condition which would describe the reliable situation of the soil performance could be indicated as following:

$$N_{redev}/F \leq R_t', \qquad (6)$$

where R_t' is the minimum bearing capacity of the soil, which could provide reliability of the building. Thus, the process of mortar compound projecting should result in formation of the artificial stone with the strength properties, which would exceed the design pressure. Namely, $R_t' \geq$1,5MPa and minimum acceptable mortar grade is M200 (B15). The hardened mortar strength could be determined with the use of empirical equitation, proposed by M. A. Popov cited in the textbook [14]:

$$R_t'=K \times R_{cem}(C-0{,}05)+4, \qquad (7)$$

In this equation R_{cem} refers to the average strength of the cement, used for cementation. For the cementation of the ground soil (well-graded sand) will be used water-cement solution and the accepted Portland cement grade is B15 with the average strength for this grade of R_{cem}=196,5 kgf/cm². According to this will be chosen coefficients` value in further calculation. Coefficient K identifies the soil conditions and is assumed to be

equal to 1,4 according to the geological exploration results as for well-graded sand. The value of C is the cement consumption calculated as for 1 m^3 artificial stone formation
After substituting the actual numerical values in the equation 7 the following is accepted:

$$1,3\times15\leq1,4\times196,5\times(C\text{-}0,05)+4; \qquad (8)$$

Correspondingly, the cement consumption calculated as for 1m^3 artificial stone formation is C≥0,129 t/m3. Also, the mortar strength could be calculated as the function of cement consumption calculated for 1 m^3 of sand (Q_{cem}) as was proposed in [15]:

$$R_t'=\kappa_1\times R_{cem}\times Q_{cem} \qquad (9)$$

Coefficient κ_1 is assumed depending on the binder type. For the mortar, where the Portland cement is used as the binder, κ_1 could be taken equal to 1. According to the equation 9:

$$1,3\times15\leq1,0\times196,5\times Q_{cem} \qquad (10)$$

Q_{cem} =0,1 t/m^3 of sand. In the consideration of safety aspects, the value, obtained from the equation 8 is accepted as the bigger one (C≥0,129t/m^3). The water cement ratio W/C is mostly dependent on the required rheological properties of the water-cement solution. According to the construction experience, for productive and effective injection process is taken equal to W/C=3/1. It is assumed that the principle of fine fillers (sand) and water-cement solution cooperation is represented as uniform distribution of suspension under the foundation sole in width, slightly greater than the sole thickness (approximately 1 m). Therefore, one injection of certain amount of water-cement solution would result in formation of artificial stone with dimensions 1,0x 1,0 x1,0 m and volume of 1 m^3, as shown on the figure 4.

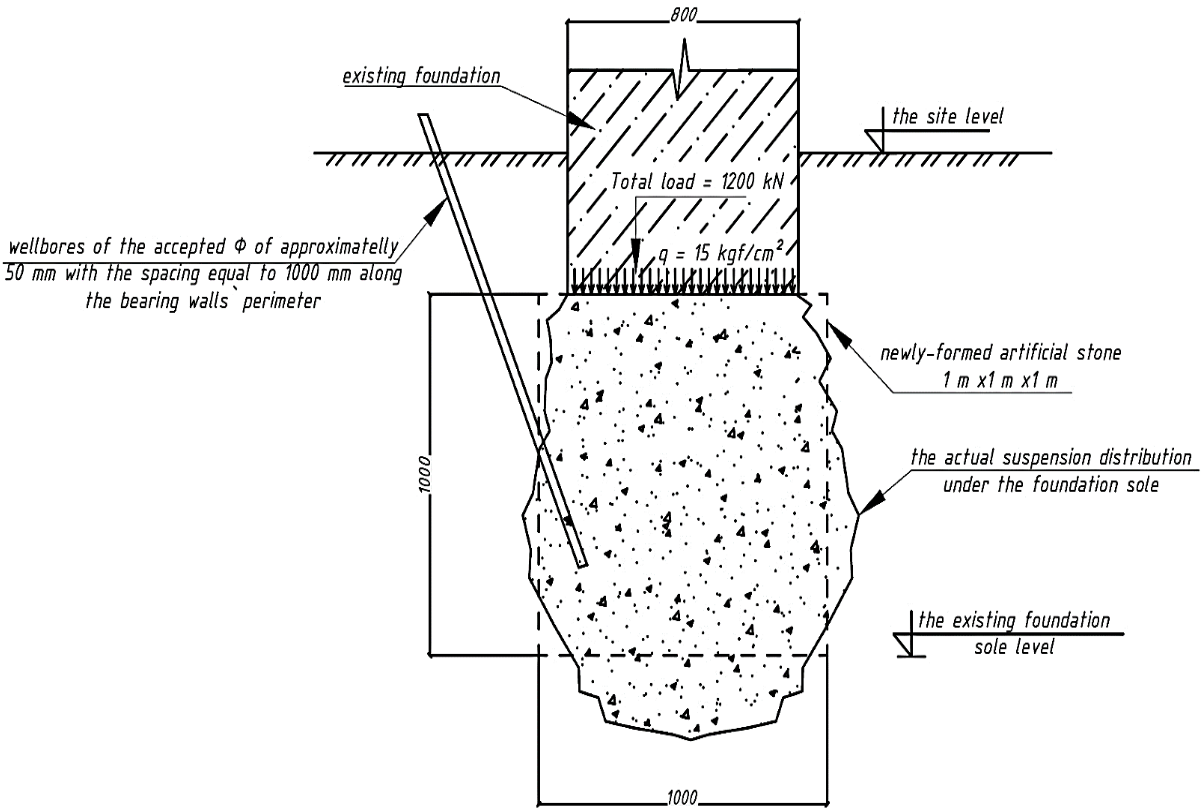

Figure 4: *The principal scheme of fine fillers` and water-cement solution cooperation.*

Finally, the materials` consumption for one-point injection is:
W=390 l
C=130 kg.

4 Discussion

In this work recent trends in construction practice were analyzed and the most topical research areas were identified. According to previously conducted literature review, thorough evaluation and discussion of available results of numerous experimental and theoretical studies were conducted. Consequently, the great actuality and importance of soil stabilization for reassuring existing buildings` sustainability could be taken as the basis for calculation development. Scientific investigation was done through detailed calculation according to requirements and recommendations of normative regulations and other literature sources. It could be concluded that in order to reassure required bearing capacity of the ground soils it is necessary to conduct injection of water cement solution of volume 0,5 m^3 with water-cement ratio 1/3 with the spacing of 1 m. The spacing of 1 m between one-point injections is accepted, because such an approach could provide the most uniform properties of the newly formed artificial stone. However, the actual injection scheme could differ, depending on particular site conditions and should account for technical-economical reasoning and various external factors. The results of this work show high correspondence with the formally expected ones and provide rather good systematization, taking into account great number of chemical, technological and geotechnical aspects. The accuracy of obtained results could depend on both actual soil properties (its consolidation stage, chemical composition, moisture content and temperature), as well as other unforeseen independent impacts. In addition, it is important to note that the lack of complete theoretical knowledge on the issue of cementation process could also become the decisive reason for possible errors and results` inaccuracy. Moreover, the expediency for further precise experimental and theoretical research can be stated, as the initial data completeness is obviously prerequisite for further methodology development.

5 Conclusions

The study was conducted in order to investigate various aspects of the cementation processes` proceeding and further cemented soil behavior under the applied design load. Actuality of the problem, due to modern trends towards the existing buildings redevelopment and corresponding soil mechanics issues was discussed. An attempt is made to formulate the appropriate method for evaluating the cemented soil properties, its behavior and provide the tentative technique for further usage in particular situations in engineering practice. The specific analysis was developed on the basis of actual example formulated through the analysis of current engineering practices. According to literature review and mathematical calculations the necessity of more precise consideration of this issue was emphasized. In addition, external impacts which could influence the resultative soil properties and become decisive in the whole structure performance and reliability were identified. It could be concluded that although rather satisfactory results were obtained, the equations, which were proposed, need further improvement through more detailed theoretical initial data determination.

6 Declarations

6.1 Study Limitations

The research outcome could be affected by the lack of appropriate data available.

6.2 Competing Interests

The authors declared that no conflict of interest exist in this publication.

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