Calculated and Observed Settlements of Multistory Building Founded on Loess

Sasha D. Milovic
Agra Earth & Environmental Limited, Scarborough, Ontario, Canada

Zuhtu S. Ozden
Agra Earth & Environmental Limited, Scarborough, Ontario, Canada

George S. W. Chow
Agra Earth & Environmental Limited, Scarborough, Ontario, Canada

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CALCULATED AND OBSERVED SETTLEMENTS OF MULTISTORY BUILDING FOUNDED ON LOESS

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Sasha D. Milovic, Zuhtu S.Ozden and George S.W.Chow
Agra Earth & Environmental Limited
Scarborough, Ontario
Canada

ABSTRACT

In the Paper are presented the results of laboratory and field tests which were carried out on loess soil in Belgrade. In order to determine the type of the foundation for the 13-storey building a preliminary investigation was made. In this phase of investigation exploratory borings and sampling were performed in a standard way. On the basis of the available laboratory and field test results it was concluded that the soil was made of macro porous land loess 14-20 m in thickness. It was found that the loess on this location had the dry density varying between the limits $\gamma d = 15.5 - 15.8\ kN/m^3$. Considering that the subsoil has high values of dry density, the designer adopted the shallow foundations. At the end of the period of three years one part of the building settled considerably and the differential settlements reached very high values. Due to the significant values of the angular distortion the building was seriously damaged. By additional investigation the undisturbed loess samples were cut from blocks and the laboratory results have shown much lower values of the deformation parameters than those obtained in the preliminary investigations. Using the deformation parameters and the coefficients of subsidence for the undisturbed samples cut from blocks, a very good agreement between the calculated and observed settlement was obtained.

KEYWORDS

Loess, calculated settlements, observed settlements, sample disturbance, subsidence.

INTRODUCTION

Loess is an eolian sediment transported by wind from the flood plains of glacial rivers. The natural undisturbed loess, know as land loess, is characterized as a loose open structured macro porous soil composed of silt particles separated by clay coatings or aggregates of clay particles (Gibbs and Holland, 1960; Larionov, 1965). Several studies of physical and mechanical parameters of loess indicate that the initial dry density and natural water content are the decisive parameters which govern the behaviour of loaded loess subsoil (Knight, 1963; Berezantzev et al., 1969; Northey, 1969; Milovic, 1967, 1971, 1978, 1988). A comprehensive review of geotecnical investigations of loess is given by Lutenegger et al.

This type of soil is often considered to be unstable as a foundation material because of its potential for large settlement. However, the results of numerous studies indicate that the loess after wetting or saturation, depending on its dry density in the natural state before loading, can be classified as being either loose and susceptible to the subsidence or, sufficiently dense and unlike to subside. Therefore, the quality of the undisturbed loess samples and the degree of their mechanical disturbance is extremely important for the exact determination of settlements at natural water content and also in wetted or saturated conditions. It is of particular interest to note that, generally, water penetrates under one part of the building, producing differential settlements, which are in most cases very dangerous. For all reasons mentioned above, it is of great interest to use the adequate method of sampling in order to obtain the mechanically undisturbed samples of high quality.

SITE INVESTIGATIONS AND SETTLEMENT PREDICTION

On the locations in the vicinity of Belgrade several 13-storey statically identical buildings were constructed. The firm responsible for the field and laboratory investigations has carried out two borings for each building. The depth of boring was 14-20 m. In all borings the subsoil was rather homogeneous. Below the organic soil about 1 m thick, there was a loess deposit (with an interlayer of clayey silt). All borings were finished in the very compacted sand.

The undisturbed soil samples were obtained by piston sampler. On the basis of the laboratory tests, carried out on these "undisturbed" samples, it was found that the dry density varies between the limits γ_d = 15.0 - 15.8 kN/m^3. The calculated values of settlements varied between ρ = 11-15 cm and for this reason the shallow strip foundations were used.

The dimensions of the buildings were Bo = 16 m and Lo = 31 m. The width of the strip foundations was B = 1.7 = 2.9 m and the depth of the foundation was D_f = 1.6 - 2.0 m. The contact pressure beneath the foundations was of the order of p = 150 kN/m^2. The observation of settlements started immediately after finishing the basement. At each corner of the building the bench marks were installed.

In the first phase, two buildings were finished and the comparison between the predicted and observed settlements has shown a satisfactory agreement. On the basis of such experience gained during the construction of the first two buildings, the designer has kept the same type of foundations for the other buildings.

However, from the very beginning, the observed settlements of the Building No.7 were higher than those previously calculated. In Fig. 1 are shown the time - settlement curves for each corner of the building.

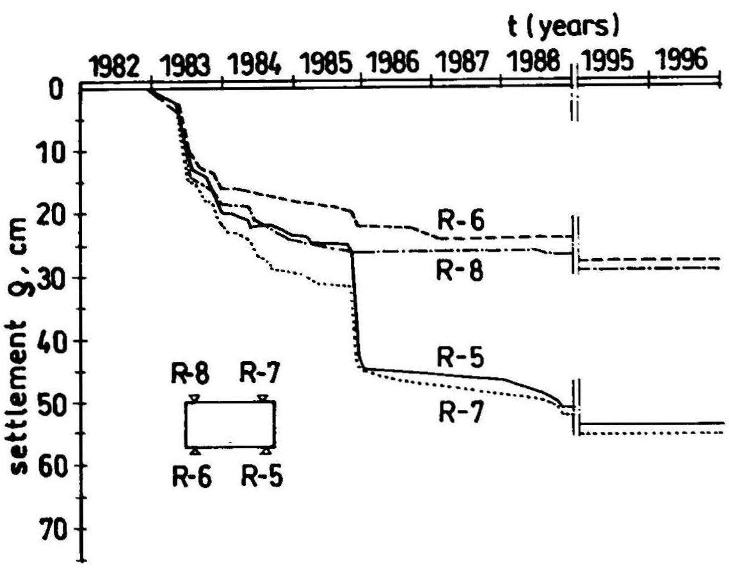

Fig. 1 Time - settlement curves for the Building No. 7.

At the end of the period of three years one part of the building settled considerably and the differential settlements reached the value of the order of 30 cm.

Due to the significant values of the angular distortion the Building was very seriously damaged. This additional subsidence took place because a part of the system of water supply pipes was broken.

FURTHER FIELD AND LABORATORY INVESTIGATIONS

In order to establish the cause of such unusual subsidence the supplementary field and laboratory investigations were performed. Experience gained in the past decades shows that the method of sampling has a very significant influence on the mechanical disturbance of loess soil. It is also important to underline that the sensitivity of loess to the subsidence due to wetting or saturation depends to a large extent on the initial dry density, initial water content and stress level acting during saturation. Having in mind the above mentioned effect of the mechanical disturbance of loess samples and at the same time the fact that the dry density and water content are the most important parameters which govern the behaviour of loess when loaded, a pit was excavated to a depth of 5.0 m. The undisturbed loess samples were obtained from hand curved blocks in this test pit. Besides, the field cone penetration tests were carried out.

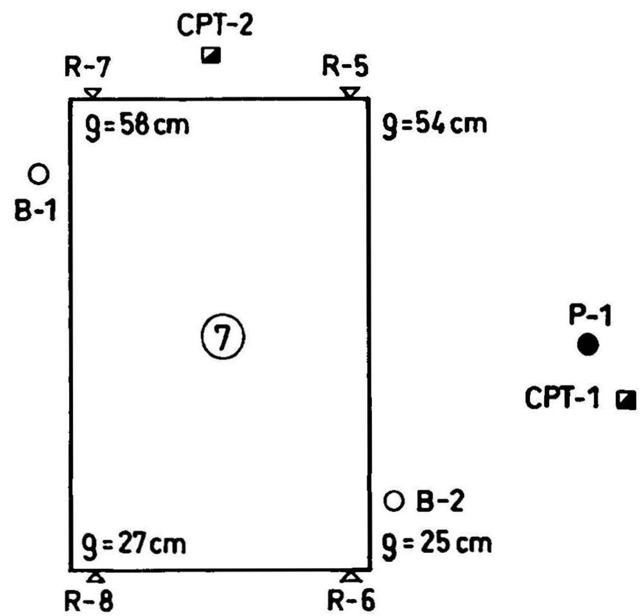

Fig. 2 Plan and position of cone penetration tests (CPT), pit (P) and bench marks (R).

The cone penetration test CPT-1 and the pit P were carried out at a distance of about 15.0 m from the building, where the infiltration of water has not been observed. The other penetration test CPT-2 was performed quite near by that part of the Building where the biggest settlements were observed.

In Fig. 3 are shown the results of the cone penetration tests.

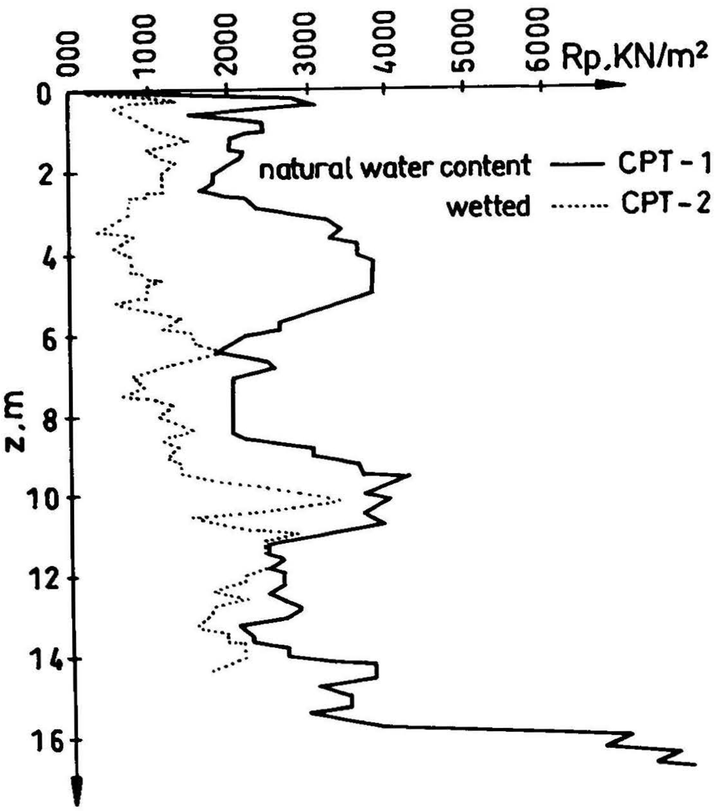

Fig. 3 Cone penetration test results.

The undisturbed samples for the laboratory investigations were removed from test pit. Hand carved blocks of loess, 25 cm by 25 cm by 25 cm were transported to the laboratory, sealed and stored in a moist room until needed for laboratory testing.

Numerous unconfined compression tests have been carried out on the undisturbed loess samples cut from blocks. Table 1 presents the results of the unconfined compression strength qu , of the initial dry density γ_d, of the water content w and of the modulus of deformation E. In the same Table these results are also shown for Piston samples.

Typical results of the unconfined compression tests for Block samples removed from pit and for Piston samples are shown in Fig. 4.

Table 1. Comparison of the results obtained on Block and Piston samples.

	Block samples	Piston samples
γ_d (kN/m^3)	12.0 - 13.0	15.0 - 15.8
w (%)	21.9 - 23.7	21.1 -22.9
Qu (kN/m^2)	28.0 - 36.0	70.0 -155.0
E (kN/m^2)	2500 - 3500	6000 - 13000

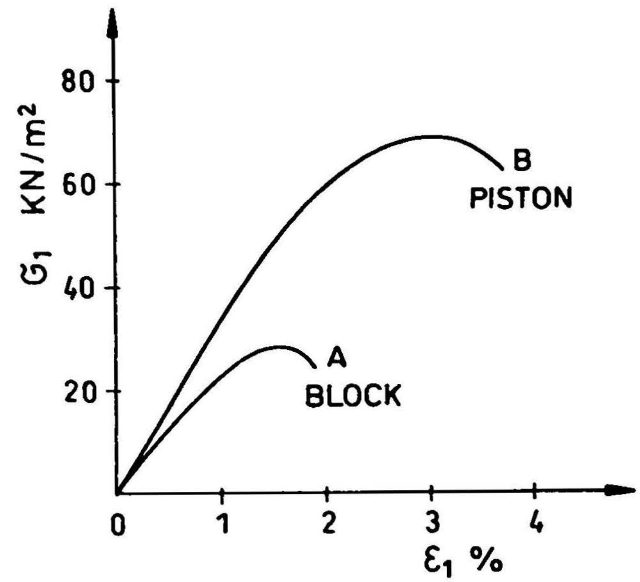

Fig. 4 Unconfined compression test results for Block (A) and Piston (B) samples.

Several groups of the undisturbed loess samples were tested with lateral strain measurements. A strain indicator used in a certain number of tests has registered the lateral deformations. Figure 5 shows the results of the unconfined compression tests.

As shown in Fig. 5, the unconfined compression strength increases with the increasing of γ_d and with the decreasing of w. In order to support this statement, the results from the other site (curves 2 with the high values of γ_d) are also shown. The dots on the curves indicate the stresses which initiated the lateral deformations. For the samples with the relatively high dry density the lateral deformations started at vertical pressures which are equal or smaller than the half of the unconfined compression strength. However, for the samples of low density the lateral deformations were registered under the stresses which were close to the ultimate stress qu. These results could lead to the conclusion that there is no significant difference between the modulus of deformation of loess of low density obtained from unconfined compression test and that obtained from test with restrained lateral deformations.

Consolidation tests have been performed for relatively large number of the undisturbed loess samples cut from blocks, in order to identify the loess soils which could collapse and to determine the amount of collapse that may occur.

The collapse potential, suggested by Knight [1963] is defined as:

$$CP = \Delta H_c / H_0 \quad (1)$$

in which ΔH_c = change in height upon wetting and H_0 = the initial height.

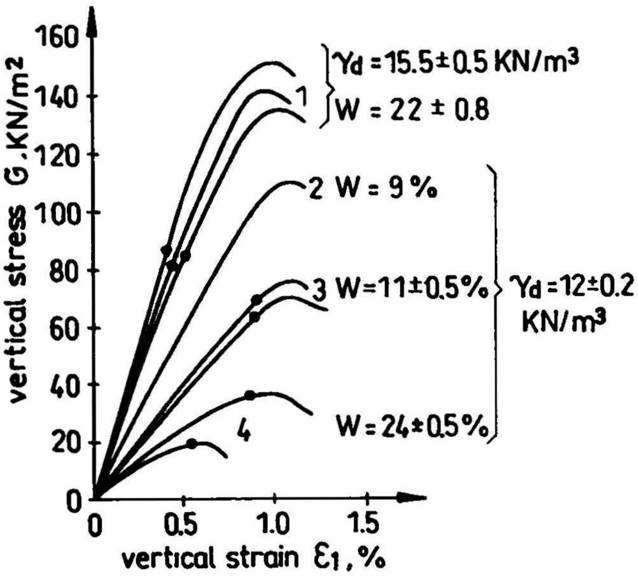

Fig. 5 Unconfined compression test results for Block samples with various values of γ_d and w.

The change of the void ratio during the process of subsidence can be measured by one dimensional vertical compression of the undisturbed loess samples witch are laterally restrained. As a measure of the degree of subsidence the following expression can be used (Milovic, 1967):

$$im = e_n - e_n' / 1 + e_n = \Delta e / 1 + e_n \qquad (2)$$

where e_n = void ratio before flooding, at the vertical stress σ_n and e_n' = void ratio at the end of subsidence, under the same vertical stress σ_n, as shown in Fig. 6

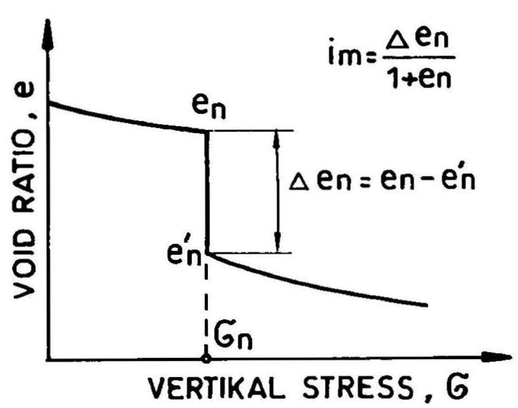

Fig. 6 Typical subsidence consolidation test result.

Figure 7 presents the curves of the coefficient of subsidence im determined from the undisturbed loess samples, removed from pit P-1, with the dry density γd = 12.5 - 13.0 kN/m³. These coefficients have been determined by adding the water at the vertical stresses σn = 100 kN/m², 200 kN/m² and 300 kN/m².

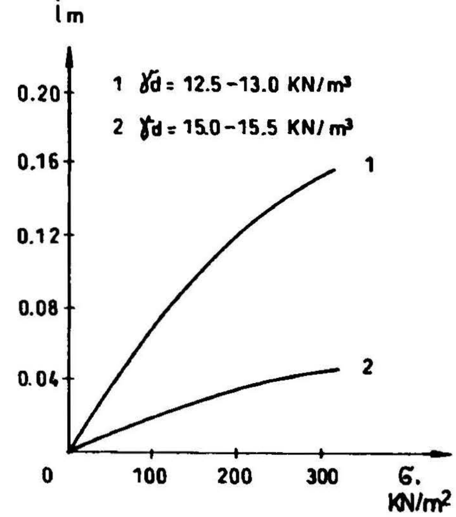

Fig. 7 Coefficients of subsidence im

In the same figure are also shown the coefficients im from the undisturbed loess samples, obtained by Piston sampler, with γd > = 15.0 - 15.5 kN/m³. As can be seen, the loess soils with the lower values of the density are much more sensitive to the subsidence due to wetting or saturation than those with the high values of density.

SETTLEMENT CALCULATION WITH NEW DATA

On the basis of the laboratory test results, obtained on the undisturbed loess samples cut from Blocks and of the cone penetration test, it was assumed that the soil model for settlement calculation is represented by a compressible loess layer underlain by a very dense sand. This sand layer may be considered as a rigid base for stresses involved. Consequently, in the considered case the aspect ratio L/B is equal to 5 (where L and B are the length and the width of the foundation, respectively), and the ratio H/B is equal to 4 (where H is the thickness of the compressible loess layer). The expressions for calculating stresses and displacements due to rectangular load on a layer of finite thickness were obtained by means of the double trigonometric series (Milovic and Tournier, 1971).

In the considered case, for L/B = 5.0 and H/B ~ 4, the dimensionless coefficients Iz for the vertical stresses have been calculated. Before, the convergence of the method was examined by calculating the factors Iz for several values of members m and n in Fourier'series. The stable convergence has been obtained for m = n = 1000.

In Table 2 are shown the dimensionless coefficients Iz for the aspect ratio H/B = 4, with the assumed limited thickness of the compressible layer. Also, in order to show that the presence of the rigid base leads to the concentration of vertical stresses σz, in the same Table are presented the coefficients Iz for the elastic half-space i.e. for $H/B = \infty$.

Table 2. Coefficients Iz for vertical stresses σ_z.

z / B	Iz (for H / B = 4)	Iz (for H/B = ∞)
0	1.000	1.000
0.25	0.948	0.942
0.50	0.823	0.780
1.00	0.565	0.520
1.50	0.407	0.384
2.00	0.315	0.292
2 50	0.258	0.228
3.00	0.216	0.192
3.50	0.192	0.176
4.00	0.143	0.140

When these coefficients are known, the vertical stresses σ_z can easily be determined by:

$$\sigma_z = p * I * z \quad (3)$$

where p = applied load.

The total settlement can be calculated by the following expression:

$$\rho = \sum \Delta\sigma_z / E_{oe} * H_n + \sum i_m * H_n \quad (4)$$

where $\Delta\sigma_z$ = vertical stress at depth z, Hn = thickness of the layer, E_{oe} = modulus of compressibility and i_m = coefficient of subsidence.

The first member in the equation (4) represents the settlement of loess subsoil with the natural water content and the second member represents the additional settlement due to saturation of loess. In the considered case, the total settlement of the Building 7, for the applied load p = 150 kN/m², for the strip foundation with B = 3.0 m and for the modulus of compressibility Eoe = 3500 kN/m², obtained on Block samples (see Table 1), is equal to:

$$\rho = 26.3 + 32.0 = 59.2 \text{ cm}$$

As may be seen, a very good agreement between the calculated and observed settlements has been obtained.

DISCUSSION

On the basis of a large number of the unconfined compression test results and consolidation subsidence test results several correlations have been established. These correlations indicate that the dry density of the undisturbed loess samples and the natural water content are the two most important parameters which govern the shear and deformation parameters of loess soils.

The unconfined compression strength qu increases with the increasing of the dry density γ_d (at the same water content) and decreases with the increasing of the water content (at the same dry density).

The results of hydro consolidation tests, presented in Fig. 7, indicate that the structural collapse due to saturation is pronounced on the samples with low dry density (curve 1). However, the samples of low dry density and relatively high initial water content exhibit great settlement before inundation. On the other hand, the undisturbed samples with relatively high dry density ($\gamma_d > 15$ kN/m³) undergo little structural collapse due to saturation (curve 2).

The modulus of compressibility E_{oe} increases with the increasing of the dry density, at the same water content. For illustration, in Fig. 8 is shown the variation of the modulus of compressibility with the dry density γ_d of the undisturbed loess samples, when saturated.

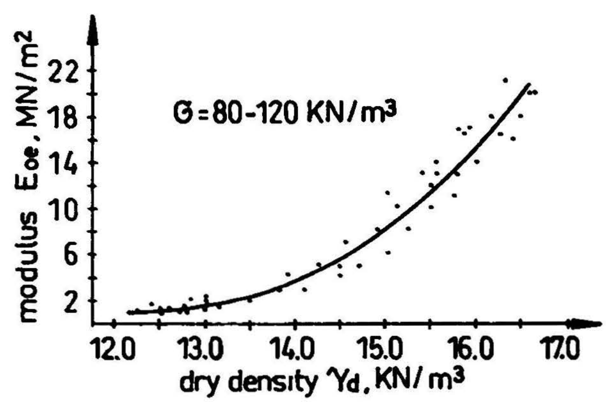

Fig. 8 Variation of the modulus E_{oe} with dry density γ_d > for the saturated loess samples.

Some typical results of field load tests, obtained for various values of the initial dry density are shown in Fig. 9.

These curves illustrate the effect of dry density, at practically the same natural water content, on the stress deformation relationship.

The soil model for the settlement calculation must be defined in a realistic way, particularly with regard to the thickness of the compressible layers. In the compressible layer of finite thickness the vertical stresses are more concentrated than in the elastic half-space. Taking into account this fact it will be possible to increase the precision of the settlement calculations.

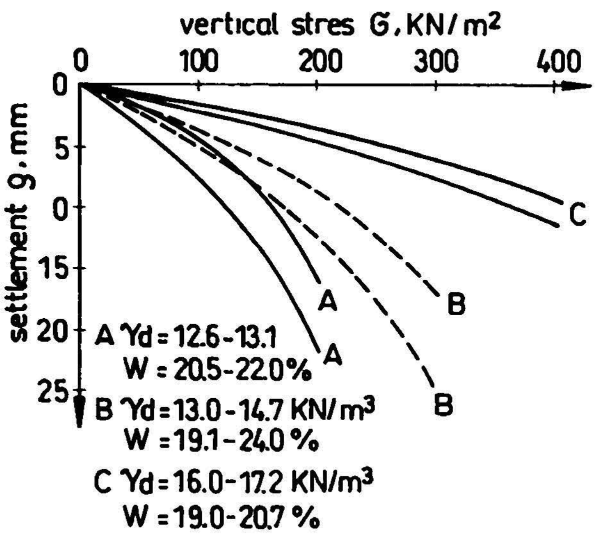

Fig. 9 Field load test results on loess with various values of dry density γ_d.

In a certain number of unconfined compression tests the stresses which initiate the lateral deformations were measured by means of the strain indicator. For the undisturbed loess samples with the relatively high dry density the lateral deformations started at low vertical pressures. However, for the samples of low density the lateral deformations were registered under the stresses which were close to the ultimate stress qu. This phenomenon indicates that the distortional deformations of loess characterized by the low dry density are small; whereas the spherical deformations are dominant.

The method of sampling has a very significant influence on the quality of loess samples. During sampling the sampler is forced into the soil and if the wall friction is high then the soil might be forced to the side. It has been noticed that loess samples taken by piston sampler are usually mechanically disturbed. A comparative laboratory testing has been made on piston samples and on the samples obtained from hand carved blocks in test pits. The results obtained on piston samples were higher than that on block samples. Consequently, the values of qu and E were found to be on the unsafe side.

CONCLUSIONS

The most important factors which govern the shear and deformation parameters of loess deposits are the dry density and the water content in natural state.

Loess deposits are very sensitive to the mechanical disturbance and the inadequate method of sampling can lead to wrong results and, consequently, to wrong choice of foundation type.

The undisturbed loess samples cut from hand carved blocks in test pits give the most satisfactory results in comparison with other methods of soil sampling.

The calculated settlement for the Building 7, based on the results obtained on block samples, are in a very good agreement with the observed values.

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