About Irreversible Changes in Soils Strength Properties after Dynamic Loads

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Abstract. The impact of dynamic effects on soil change in properties depends both on the intensity of the loads, the frequency, the duration of their action, and on the soil type, its humidity and density. That is, for each type of soil it is necessary to determine the quantitative dependencies inherent only to it. To establish the regularity of irreversible changes in the adhesion and the internal friction angle after dynamic loads, experimental studies were performed. The article presents the results of experimental data processing, the obtained dependences on the determination of the strength characteristics of soils after dynamic loads.

1. Introduction

The adhesion of cohesive soils with an increase in weight moisture, as is known, decreases sharply. First of all, it depends on the composition, genetic conditions of formation and other factors, i.e. for each type of soil, it is necessary to determine the quantitative dependencies inherent only to it [4, 5].

The determinative values of adhesive force coefficient of friction are the density and humidity of soils, with an increase in porosity, the adhesion decreases sharply. The data on the change in the internal friction coefficient are contradictory: in some cases, a decrease in porosity is accompanied by its decrease, in others - an increase. An increase in humidity leads to a decrease in the internal friction coefficient [1, 2, 3, 8, 9].

In cohesive soils, an increase in density leads to a closer contact of the particles. The water layers thickness, surrounding the particles in fine soils, is commensurate with the size of the particles. These layers serve as lubricant, reducing the internal friction coefficient. In cohesive soils, an increase in density as a result of external loads, caused both a decrease and an increase in adhesion. The logarithm of the adhesion of compacted soil samples is proportional to the density \( \rho \) and inversely proportional to the coefficient of volumetric humidity [7, 8]:

\[
\lg \tau_0 = \frac{m \rho}{1 + 0.01 \omega_v},
\]

where \( m \) varies depending on soil composition.

2. Experimental part

Compaction of the samples was carried out in a closed cylinder under a press in the pressure range 1-500 kgf/cm² (0.1-50 MPa). Obviously, when compacted by such loads, the soil structure is broken, and the strength of the samples increases.
In the paper [6], the results of studies on the determination of adhesion changes in compacted by explosion drift clays are presented. According to the results of a single charge explosion with weight 412 kg at a depth of 21.5 m, a graph of adhesion variation with distance from the strip contour was constructed. It is described by the empirical dependence of the adhesion $\tau_0$ from the initial adhesion $\tau_0^*$ and distances to trip borders $r$:

$$\tau_0 = \tau_0^* + K \frac{e^{\alpha r}}{e^{0.001}}$$

(2)

where $K$ and $\alpha$ – coefficients depending on the magnitude of the charge and soil properties.

To establish regularities of irreversible changes in the adhesion and the angle of internal friction after dynamic loads, experiments were performed. Standard methods using Maslov-Lurie shear devices were determined the indicated strength properties of soil samples subjected to shock loads, as well as samples taken from compaction zones during explosions. Soil samples of natural and disturbed structure were investigated.

After strength tests, the humidity was determined again. In all cases, the humidity content of soils of disturbed and natural structures as a result of dynamic loads and shear tests is decreased. The greatest decrease was observed in soils, where it was initially more significant.

After statistical processing it was found that with the initial $S_{0} = 0.7-0.8$, the decrease occurs by 0.06, with $S_{0} = 0.5-0.6$ - by 0.045 and with $S_{0} = 0.4$ - by 0.033 of its magnitude. Deviations from these average values $S_{0}$ as a rule, are within ± 0.01, less frequently 0.015 (no more than 20-25% of the measured value).

In samples from the soil mass, subjected to explosive loads, a decrease in humidity in comparison with the initial one was also noted. However, in some parts of the array there was some increase. This is due to water migration in the area of the explosion. The data on irreversible changes in the adhesion and the angle of internal friction of soils of the disturbed structure subjected to shock loads are shown in Figure 1.

**Figure 1.** Adhesion (compact curves, half-filled points) and the coefficient of internal friction. (dashed curves and filled points) of loam of damaged structure, subjected to dynamic loads:
- 1 - according to the shear tests;
- 2 - according to the calculation of discharging curve stress

The final values of adhesion and angle of internal friction of the soils, determined when tested for shear on sheared devices, are 15–25 and sometimes 30–35% higher than those calculated from the change in normal stresses on the unloading curve. This is explained not only by a decrease in humidity during the shear tests, but also by the fact that the shear is made on the surface fixed by the sheared device, and the deformation in the test chamber of the monoaxial compression unit covers the entire volume of the soil sample. Similar results were obtained when testing also samples of soils of natural structure.

The change in adhesion was determined depending on the magnitude of irreversible volumetric deformation for wet cohesive soils ($S > 0.4$) with a predominance of elastic skeletal bonds.

When testing for soils samples cutting, previously subjected to dynamic loads, the following pattern of irreversible change in adhesion depending on the magnitude of the volume deformation was determined (Fig. 2). With small volumetric deformations (up to 0.01-0.015), a decrease in adhesion to 0.7-0.8 of its initial value was observed. During the subsequent soil compaction, the adhesion
increased, reaching an initial value with a volume strain of 0.02-0.025, and then significantly exceeding it. Such changes are approximated by the formulas:

\[(1 - 3.65K_0 \theta)\tau_0 \text{ при } \theta<0.01;\]

\[K_0 \theta^{0.46}\tau_0 \text{ при } \theta>0.015,\]

where \(K_0\) – loam coefficient equal to 5.57, 
\(r_0 = 0.7)\).

Figure 2. Dependence of adhesion change on irreversible soil deformation.

In dry soils with \(S_{r0} < 0.4\) no significant increase in adhesion was observed. In the most dry soils (with \(S_{r0} < 0.3\)), as the load and irreversible deformation increase, the adhesion tends to decrease practically to zero. This is especially clearly appeared in loess.

Quantitative changes in adhesion after dynamic loads of very dry soils of a natural structure were not measured. However, some conclusions can be made on the basis of experimental studies of explosions action made by the hammer-stone DorNII in loams and loess [10].

Plastered loam and loess were studied by weight humidity 0.04-0.046 and 0.06, respectively. The density of soil particles of loam is 1.67, loess is 1.49 g / cm³, relative humidity is 0.1 and 0.095, respectively. The explosions of vertical well charges were carried out with an initial consumption of ammonite number 6ZHV 3 kg / m. Charge length is 2-4, temping is 0.5-0.4 m.

In Fig. 1 it is shows the strength overall index \(\tau'\), which is the natural logarithm of the DorNII number \(\tau l = \ln D\), and the calculated volume strain determined by the formula (4) with \(\lambda = 2\), \(\theta^* = 342\) and \(\delta = 1.62\) for loams and \(\theta^* = 257\), \(\delta = 1.64\) - for loess.

\[\theta = \theta r_0(1-r)/\delta; \sigma = \sigma_0 r^{(1-\lambda)/\delta}\]

where \(\sigma_0\) – coefficient with stress dimension; \(\theta^*, \delta, \delta'\) - dimensionless coefficients; \(r_0 - r/r_3\) – relative (in \(r_3\)) distance from the center (axis) of the charge; \(\lambda\) – a central field divergence equal to two for a flat field (around a cylindrical charge), and three for a spatial (around a concentrated charge).
Table 1. The strength overall index and the calculated volume strain.

| Index                                                                 | In plastered loam with $S_{r0} = 0.1$ | In loess with $S_{r0} = 0.005$ |
|-----------------------------------------------------------------------|---------------------------------------|---------------------------------|
| Calculated deformations at a relative distance from the charge axis   |                                       |                                 |
| with $r_0 = 10$                                                       | 0.15                                  | 0.175                           |
| $r_0 = 20$                                                            | 0.0175                                | 0.0195                          |
| $r_0 = 30$                                                            | 0.004                                 | 0.005                           |
| Number of DorNII:                                                     |                                       |                                 |
| in an undisturbed array                                               | 45-47                                 | 40-42                           |
| with $r_0 = 10$                                                       | 3                                     | 2                               |
| $r_0 = 20$                                                            | 5-6                                   | 3-4                             |
| $r_0 = 30$                                                            | 10-14                                 | 10-12                           |
| Generalized strength indicator:                                       |                                       |                                 |
| in an undisturbed array                                               | 3.85                                  | 3.75                            |
| with $r_0 = 10$                                                       | 1.1                                   | 0.7                             |
| $r_0 = 20$                                                            | 1.7                                   | 1.3                             |
| $r_0 = 30$                                                            | 2.55                                  | 2.45                            |

The given data, despite the conventionality of the obtained strength index, give an idea of the changes in adhesion in dry soils with hard skeletal bonds predominance. In such soils, with an increase in the volume deformation, the adhesion not only increases, but significantly decreases; this is especially noticeable in the loess, which, under dynamic loads, passes into an incoherent mass. In dry loams, usually visible violations of the connectedness do not occur, but their strength decreases several times. This effect is used in blasting operations to weaken an array during excavation.

Irreversible changes in the angle of internal friction in the explosion area are related to the soil humidity. The change in the angle of internal friction obviously determines the process of soil compaction, and not only the accompanying changes in humidity. The change in humidity accompanying the volumetric deformation and the inevitable dispersion of the test results made it impossible to determine their presence and qualitative character. Because of water migration, it was experimentally established the presence of zones of high and low values of the angle of internal friction around the explosion centre. The zone of increased values coincides with the drainage zone, and the zone of reduced values - with the zone of humidity. When camouflage charges explode in cohesive soils with $W_0 = 0.6-0.7$ near the cavity boundary, the coefficient of internal friction is 15-20% higher than in the natural state of the soil, while in the high humidity zone $\tan\phi$ is less than the initial one.

The curve $\tan\phi = f(r_0)$ can be approximated by the following relationship:

$$\tan = \tan_0 + \Delta(r_0)$$  \hspace{1cm} (5)

Here $\Delta\tan\phi(r_0)$ is the change in the coefficient of internal friction in the area of the explosion.

Similar dependences were obtained in the study of soils strength in the compacted zone around the centre by a less laborious method of testing for a rotational slice of the PKZ-1 density impeller.

The essence is as follows: press the working body of the impeller - the mutually perpendicular blades - 4 into the drilled wells with a diameter of 50 mm to the required depth; turning the handles, we obtain the torque value recorded on the recorder drum.

Soil sampling to determine a baseline characteristic in laboratory conditions is minimized (only a few).

Soil resistance to cut $\tau_K$ is determined by the formula [3]:

$$\tau_K = \frac{M}{C}$$ \hspace{1cm} (6)

where $M$ – maximum moment of soil reactive resistance on blades, kgf/cm²; $C$ is the impeller constant taking into account the height and outer diameter of the blades, cm³.
Table 2. Changing the cohesion and the angle of internal friction of the soil deformed by explosion.

| Strength indicators | Undeformed array | Deformed array at relative distances r1 |
|---------------------|------------------|----------------------------------------|
| Cohesion after explosion, kgf / cm² | 0.82 0.50 0.26 0.22 0.26 0.35 0.37 | 0.22 0.34 |
| in 6-8 days          | 0.39-0.43        | 1.06 0.72 0.34 0.28 0.34 0.38 0.42 | 0.32 0.40 |
| in 32-40 days        | 1.06 0.82 0.34 0.31 0.35 0.39 0.42 | 0.33 0.42 |
| Angle of internal friction, degree | - - 1.26 - 0.67 - | 0.35 0.33 0.42 |
| After explosion      | 24.5 22.8 21.5 21.5 | - - 23.5 23.0 21.5 21.0 |
| in 10-40 days        | 21.0-21.5        | 26.0 23.5 21.5 21.5 | - - 24.0 23.5 21.5 21.5 |

In other words, C - the static moment of the cut surface relative to the axis of impeller rotation is determined as follows:

1) when the impeller is pressed until the ground surface coincides with its upper edges

\[ C_1 = \frac{\pi d^2}{2} \left( b + h \right) \]  \hspace{1cm} (7)

2) when pressing the impeller below the ground surface

\[ C_2 = \frac{\pi d^2}{2} \left( \frac{d}{3} + h \right) \]  \hspace{1cm} (8)

Here \( d \) – diameter of the cut out soil cylinder, is equal to the impeller diameter; \( h \) - the height of the blades, is equal to the height of the soil cylinder.

If the immersion depth of the impeller does not exceed the height of the blades, then the compaction of the soil in the sector until the full clearance of the sliding surface is unevenly in depth, i.e. the height of the blades. In the upper part, the compaction is several times larger than that of the lower base of the soil cylinder, and decreases evenly and proportionally to the depth in the interval of the blades height.

This phenomenon is due to the presence soil extrusion in the direction free from the surface load. To eliminate this phenomenon, the impeller was pressed below the bottom of the well to a depth of at least 13-15 cm from the upper edges.

The absolute value of \( \tau_k \), as a rule, exceeds the adhesion values obtained when testing soil samples on shear devices in the range of 0.05-0.45 kgf / cm².

It was found that as the distance from the cavity walls increases, \( \tau_k \) decreases sharply. Directly at the walls, it exceeds 2-2.5 of the initial value, then decreases to 0.5-0.4 and again increases to the initial value.

When blasting cylindrical charges with a linear consumption of 1-2 kg of explosives, the zone of residual deformations increases by 3-4 times as compared with the concentrated charges obtained by the explosion and amounts to 170-220r₁. Within this zone, the strength characteristics of compacted soils change. At the walls of the vertical cavity, the resistance of the soil to the rotational slice is increased by 2-3 times compared to the initial one. Then, as the distance from the center of the explosion is wide enough, from (3.5-75) r₁ to (190-240) r₃, the value of \( \tau_k \) is reduced to a value, 1.5-2.2 times lower than the initial one (Fig. 3).
Figure 3. Change in shear resistance with relative distance from the source of explosion of concentrated (1) and cylindrical (2) charges.

Experiments were also carried out to determine the strength properties of cohesive soils after deformation of the shear without noticeable volumetric deformation. Soil samples in the form of parallelepipeds with height – to – middle side ratio of 1.5: 1 to 1.9: 1 were subjected to loading at a speed of 10–20 kgf / cm². After loading, the adhesion and the angle of internal friction were determined when tested for shear according to a standard procedure on a Maslov-Lurie shear device. The results of the experiments are given in table. 3. With such loading, the greatest significant decrease in strength properties is observed in dry soils ($W_0 < 0.4$) with a predominance of rigid bonds. The cohesion during the deformation of the simple shear without perceptible compaction did not increase.

Table 3. The results of the experiments.

| Soil         | $W_0$  | The change in shape and volume compared with the original | Visible interruptions of the sample continuousness | Change in adhesion with respect to the original |
|--------------|--------|---------------------------------------------------------|---------------------------------------------------|-----------------------------------------------|
| Light loam   | 0.4-0.5| 0.85-0.90, 1.05-1.08, 0.003 | infrequent cracks                                      | 0.42-0.66                                      |
|              | 0.6-0.7| 0.80-0.90, 1.05-1.12, 0.002 | infrequent cracks                                      | 0.52-0.80                                      |
|              | 0.8-0.85| 0.90-0.95, 1.00-1.05, 0.001 | not observed                                          | 0.60-0.94                                      |
| Green clays  | 0.6-0.7| 0.80-0.90, 1.05-1.12, 0.001 | not observed                                          | 0.65-0.90                                      |
|              | 0.8-0.9| 0.90-0.95, 1.02-1.05, 0 | not observed                                         | 0.82-0.99                                      |
|              |        |                                                         | not observed                                         | 0.65-0.84                                      |
|              |        |                                                         | not observed                                         | 0.70-0.92                                      |
|              |        |                                                         | not observed                                         | 0.72-0.94                                      |
|              |        |                                                         | not observed                                         | 0.88-0.99                                      |

Deformations of pure shear not only without compaction, but with some soil decompaction occur near free surface during camouflet explosions and ejection explosions. In this regard, experiments were carried out to determine the number of DorNII in the areas of decompression, adjacent to the explosive excavations during construction by explosions in the canals. Measurements were made before and after explosions of 0.3-0.4 m from the side ditches and further at a distance of 2 and 4 m. The grounds where preliminary (before the explosion) measurements were made were marked with flags. After the explosion, after 1-2 hours, these grounds were cleared from the pile of soil and the main measurements were carried out. Then, 6–7 days after the explosion, measurements at the same sites were repeated.
3. Conclusions
In light loams with $W_0 = 0.60-0.70$, the DorNII number in the undeformed array was 4-5; directly and in 6-8 days after the explosion - 2-3 at the edge and at a distance of 2 m and 3-4 - at a distance of 4 m. In heavy loams with $W_0 = 0.65-0.75$ before the explosion - 8-10, after the explosion - 4-5, 5-6 and 7-8. In dry plastered loams with $W_0 = 0.2-0.3$ before the explosion 24-28, after the explosion - 8-12, 15-20 and 18-25, after 6-8 days - 10-15, 16-22, 18-27.

Adhesion during loams compaction with relative humidity 0.55; 0.62; 0.75 and 0.83 the coefficient $K_c$ was equal respectively to 6.0; 6.7; 7.2 and 9.6. We can use the formula (3).

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