Field test of compactability of soaked subsidence soil using heavy tamper

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Abstract. Dynamic compaction, including heavy compaction, is a widespread method throughout the world for improving the physical and mechanical characteristics of subsidence and low-density soils. The results of theoretical and experimental studies have established that the depth of compaction and the density of compacted soils depend on the weight, shape of the bottom, the height of the tamper and humidity, the type of structural connection, and the granulometric composition of the compacted soil. This article discusses the results of compaction with a heavy tamper when soaking loess-like subsidence soil, widespread in the city of Darkhan, Mongolia, to optimal moisture.

Key words: loess soil, regional peculiarity, pre-soaking, technological regime, compaction nomogram.

Introduction

Loess deposits are widely distributed in arid, semi-arid and other regions and account for 4,255,600 km² of area covered by loess and 3.2% of the land area of the globe (Kadyrov E.V. [1]). In many countries of the world, experimental and theoretical research is being actively carried out to artificially increase the physical and mechanical characteristics of loess subsidence soils and a variety of methods and technologies are used, including the method of compaction with heavy compaction, taking into account the regional characteristics of the soil conditions of the construction area (Pankrath H. et al [2], Robert W. Day. [3], Bagdasarov Yu.A., et.al. [4], Zhang Y. et al. [5]), Currently, it is possible to perform work on compacting subsidence soils using the method compaction with heavy compaction and, as a result, the parameters of the physical and mechanical properties of the compacted soil increase to the required level (Alexia Cindy Wagner [6], Ian Jefferson et al. [7]).

The method of surface compaction with heavy tamping was invented in the 50s of the twentieth century in the USSR in order to increase the strength and reduce the compressibility of the underlying soils of the foundation, and Yu.M. Abelev and V.B. Shvets [8] developed instructions for surface compaction of foundations with heavy tampers. The essence of the heavy tamping compaction method is to freely fall the tamper, usually (with a weight of 50...500 kN and from a height of 6...30 m) to create shock waves and dynamic stress in the foundation soil, so that the foundation base can achieve high density and mechanical strength. properties (Ilyichev V.A. [9], Minaev O.P. [10])

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The heavy ramming method was first used in France in 1969 by Menard and Broise [11], in the USA in 1971 (Lucas [12]) and in the UK in 1973 (Leonards et al. (1980) [13]. Rollins K.M., Jihyoung Kim J. [14] and Guo et al. [15] applied the tamping method to subsidence soils, which are strong and stable in their natural state, but when soaked, they lose stability and undergo significant subsidence.

However, at first glance, the method of compacting soil with heavy tamping does not seem complicated, but in fact, a careful design solution is required, taking into account the regional characteristics of soil conditions, the choice of technological techniques and the weight of the tamper, and methods for creating the optimal moisture regime necessary for compaction (Rollins K.M. et al [16], Bagdasarov Y.A. et al. [17], Il'ichev B.A. et al. [18], Fujun, N. et al. [19] Jhon Henry Rodriguez-Pomajulca et al. [20]).

Currently, a large number of civil buildings and industrial facilities with wet technological processes are being built in Mongolia, where subsidence clay soils are common, then the use of the method of compacting such soils with heavy compaction can be highly effective. Based on this situation, field tests were carried out on compaction using the heavy compaction method.

**Methods and materials**

**Regional features of subsidence soils.** Loess soils, common in the Eurasian region, were most actively formed in the extreme climatic conditions of the Pleistocene period of world development, approximately 8...800 thousand of epigenetic and syngenetic origin. For example, the origin of loess soils common in Mongolia is associated with the last, or Altai-Tunguska, ice age, which covered most of the Eurasian region, about 15...18 thousand years ago.

According to the hypothesis of Minervin A.V.[21] primary silty deposits as a result of repeated freezing-thawing and frozen evaporation (sublimation) of ice located in the structure of frozen soil led to a decrease in soil moisture (up to W = 4.2...5.9%) and porosity (n = 49.2...58.3% with macropores) increase, density (ρ_d=1.38...1.62 g/cm3) decrease, and also subsidence properties exhibiting with increasing humidity have formed. Due to the force of expansion of frozen water contained in the pores of the soil, with repeated freezing and thawing, the minerals of loess soil crack and fragment to values of 0.05...0.005 mm. The content of the silty part is more than 50% and the carbonate content is relatively high, including the calcide compound CaCO3 about 15...20%, easily soluble sulfate and chloride salt compounds are about 3...5%, so loess soils have a high degree of aggregation with cementation-crystallization structural connections. The thickness of loess deposits common in Mongolia is 4.5...10.0 m, in rare cases greater than these values.

**Soil conditions of the experimental site:** Collapsed sandy loam soils of type I in terms of subsidence in their natural state have relatively high mechanical properties, but due to the weakening of structural bonds during soaking, the mechanical properties decrease sharply, including adhesion force values up to 4.6 kPa, internal friction angle up to φ =15.1°, deformation modulus up to 4.61 MPa. In laboratory tests, subsidence begins at pressure P = 1.5 kg/cm2 and humidity W = 9.6%, here the relative subsidence indicator is ε_sl> 0.01. At pressure P=2.0 kg/cm2 and W=8.2% and at pressure P=2.5 kg/cm2 and W=6.9)% subsidence begins. These moisture values are calculated accordingly at given pressures as the initial subsidence moisture W_sl.

**Methodology of field experiments:** The methodology of field natural experiment and modeling on a two-layer base for compacting subsidence soil with heavy compaction is compiled in accordance with (MNS) standard requirements after preliminary soaking to optimal moisture content. In the test, a heavy rammer with a diameter of 1.5 m and a weight of 5.0 tons was used and the soil was compacted with 10, 15 and 18 rammer blows. Table -1 shows the performance of the field test.
Table 1. Characteristics of compaction of subsidence soil

<table>
<thead>
<tr>
<th>Test options</th>
<th>Number of blows</th>
<th>Tamper diameter, m</th>
<th>Tamper weight, tons</th>
<th>Tamper drop height, m</th>
<th>Impact energy, kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>10</td>
<td>1.5</td>
<td>5.0</td>
<td>7.0</td>
<td>3.22</td>
</tr>
<tr>
<td>II</td>
<td>15</td>
<td>1.5</td>
<td>5.0</td>
<td>7.0</td>
<td>4.75</td>
</tr>
<tr>
<td>III</td>
<td>18</td>
<td>1.5</td>
<td>5.0</td>
<td>7.0</td>
<td>5.10</td>
</tr>
</tbody>
</table>

Results

After completion of the compaction test, samples were taken every 1.0 m from the surface to a depth of 6.0 m and the following parameters were determined in the laboratory: \( W = 0.12...0.15 \), soil density \( \rho_d = 1.73...1.87 \) g/cm³, and the change in the surface level of the compacted soil was 37...42 cm (Fig. 1).

Fig.1. Dependence curves \( \Delta h=f(n) \) to determine the value \( \Delta h \) from the number of blows (10, 15 and 18)

Physico-mechanical characteristics of compacted soil. A comparative analysis of the results of compaction of subsidence sandy loam soil with a natural structure by heavy compaction and after compaction revealed the following growth patterns for a number of calculated characteristics. From each 1.0 m depth of pre-moistened \( (W_{\text{opt}} \approx 0.12...0.15) \) silty-sandy soil of the experimental site, 42 samples with an undisturbed structure were selected. Table 2 shows the test results in the soil mechanics laboratory.

Table 2. Physico-mechanical parameters of compacted subsidence soil

<table>
<thead>
<tr>
<th>Soil sample of blow</th>
<th>Physical indicators</th>
<th>Mechanical indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Si</td>
<td>W_{opt}</td>
</tr>
<tr>
<td>S</td>
<td>m</td>
<td>g</td>
</tr>
</tbody>
</table>

Fig.1. Dependence curves \( \Delta h=f(n) \) to determine the value \( \Delta h \) from the number of blows (10, 15 and 18)
A comparative analysis of the results of laboratory tests (Table 2) of moistened soil with humidity $W_{opt}$ and $W_{sat}$ after compaction with the natural structure of silty-sandy soil shows the following pattern of increase and decrease.

**a. Relative subsidence $\varepsilon_{sl}$** In figure 2 shows a comparative diagram of the relative subsidence $\varepsilon_{sl}$ of a soil sample compacted with 10, 15 and 18 impacts and tested by loading at a pressure $P = 0.3$ MPa according to the results given in the table 2.
criteria of subsidence soil $\varepsilon_{s\ell} > 0.01$

Fig 2. Diagram of the average dependence of the relative subsidence of compacted soil $\varepsilon_{s\ell} = f(n, W_{opt})$.

The indicator of the relative subsidence of the settling soil of a natural structure at a pressure $P = 0.3$ MPa is equal to $\varepsilon_{s\ell} = 0.021$, then after compaction with 10 impacts of a tamper, the indicator of the relative subsidence of the pre-moistened soil to $W_{opt}$ is equal to $\varepsilon_{s\ell}^{10} = 0.0068$ at a pressure $P = 0.3$ MPa; after 15 impacts of the rammer $\varepsilon_{s\ell}^{15} = 0.0051$; after 18 impacts of compaction $\varepsilon_{s\ell}^{18} = 0.0039$ or compared to $\varepsilon_{s\ell}^{10}$ by 3.1 times $\varepsilon_{s\ell}^{15}$ by 4.4 times and $\varepsilon_{s\ell}^{18}$ by 5.4 times decreases from the value of $\varepsilon_{s\ell}$ soil with natural structure. These facts of a decrease in $\varepsilon_{s\ell}$ from 3.1 to 5.4 times are explained by the weakening of the cementation crystallization structural connection, a decrease in the distance between solid particles as a result of squeezing out pore water, due to the phenomenon of relaxation after quasi-liquefaction formed from shock dynamic influences and others processes formed due to pre-soaking.

b. Adhesion force ($s$). In Fig. Figure 3 shows a comparative diagram of the adhesion force ($c$) of soils compacted with 10, 15 and 18 blows and determined tested at pressure $P = 0.3$MPa according to the results given in Table 2.

Fig 3. Diagram of the dependence $c = f(n, W_{opt})$ of compacted soil.
Table 3 presents the results of a comparative analysis of the increase in adhesion force after compaction with 10, 15 and 18 blows to soil with a natural structure and moisture content.

### Table 3. Results of comparative analysis of the dependence \( c=f(n,W_i) \)

<table>
<thead>
<tr>
<th>Number of blows</th>
<th>( C_0 ) natural soil, kPa</th>
<th>( C_{\text{sat}} ) at humidity ( W_{\text{sat}} ), kPa</th>
<th>( C_{\text{opt}}^n ) of compacted soil with moisture content ( W_{\text{opt}} )</th>
<th>( C_{\text{sat}}^n ) of compacted soil with moisture content ( W_{\text{sat}} )</th>
<th>Comparison, times</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=10</td>
<td>12.0</td>
<td>4.6</td>
<td>31.56</td>
<td>18.3</td>
<td>2.61 / 2.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.98 / 3.98</td>
</tr>
<tr>
<td>n=15</td>
<td>12.0</td>
<td>4.6</td>
<td>46.4</td>
<td>30.9</td>
<td>2.61 / 3.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.72 / 6.72</td>
</tr>
<tr>
<td>n=18</td>
<td>12.0</td>
<td>4.6</td>
<td>52.1</td>
<td>38.9</td>
<td>2.61 / 4.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.46 / 8.46</td>
</tr>
</tbody>
</table>

According to Table 3 of the comparative analysis: the adhesion force \( C_0 \) of natural soil decreases by 2.61 times when saturated with water. Then \( C_{\text{opt}}^n \) of soil compacted with 10, 15 and 18 blows after moistening to \( W_{\text{opt}} \) increases by 2.63...4.34 times compared to \( C_0 \). Then the adhesion force of water-saturated soil \( C_{\text{sat}}^n \) with humidity \( W_{\text{sat}} \) compacted with 10, 15 and 18 blows is 3.98...8.46 times higher than the value of the adhesion force \( C_{\text{sat}} \) of water-saturated soil, which is the result of compaction of subsidence soil with heavy compaction after preliminary soaking to the value \( W_{\text{opt}} \).

d. Angle of internal friction (\( \phi \)). The following diagram is constructed by comparing the change in the value of the angle of internal friction \( \phi_{\text{opt}}^n \) of type I silty-sandy soil in terms of subsidence to the values of compacted soil with 10, 15 and 18 blows of a tamper, after soaking to the moisture value \( W_{\text{opt}} \) and \( W_{\text{sat}} \).

![Diagram of the dependence \( \phi = f(n, W_i) \) of compacted soil.](image)

Table 4 presents the results of a comparative analysis of the values of the angle of internal friction \( \phi_{\text{opt}}^n \) and \( \phi_{\text{sat}}^n \) of soil soaked to \( W_{\text{opt}} \) and \( W_{\text{sat}} \), obtained after compaction with 10, 15 and 18 blows to soil with natural structure and moisture.
According to Table 4 of the comparative analysis: the angle of internal friction $\varphi_0$ of soil with natural moisture decreases by 1.39 times compared to the values of $\varphi_{sat}$ when the soil is saturated with water. Then the angle of internal friction of the soil after preliminary soaking and compaction is 1.30...1.42 times greater than the parameters $\varphi_{opt}^n$ and $\varphi_0$ of natural soil, and also the parameter $\varphi_{sat}^n$ of soil with humidity $W_{sat}$, compacted with 10, 15 and 18 blows, compared with values of 1.23...1.38 times greater, and the angle of internal friction $\varphi_{sat}^n$ of the soil after compaction, as indicated above, is 1.71... 1.91 times higher than the $\varphi_{sat}$ index of non-compacted soil with humidity $W_{sat}$. The improved indicators listed are the results of compaction of moistened subsidence soil by compaction.

e. Deformation modulus (E). The following diagram was constructed as a result of a comparative analysis of the change in the deformation modulus $E_{opt}^n$ of compacted silty-sandy soil, compacted with 10, 15 and 18 blows, after wetting with a heavy tamper from Table 2.

![Diagram of dependence E = f(n, W)](image)

Table 5 shows the results of the analysis of the pattern of changes in the angle of internal friction $E_{opt}^n$ and $E_{sat}^n$ of pre-soaked sandy loam soil compacted with heavy compaction, depending on the number of blows n and the humidity values $W_{opt}$ and $W_{sat}$.

<table>
<thead>
<tr>
<th>Number of blows</th>
<th>$\varphi_0$ natural soil, grad</th>
<th>$\varphi_{sat}$ at $W_{sat}$, grad</th>
<th>$\varphi_{opt}^n$ of compacted soil with moisture content $W_{opt}$</th>
<th>$\varphi_{sat}^n$ of compacted soil with moisture $W_{sat}$</th>
<th>Comparison, times</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=10</td>
<td>21.0</td>
<td>15.1</td>
<td>27.25</td>
<td>25.80</td>
<td>1.39 1.30 1.23 1.71</td>
</tr>
<tr>
<td>n=15</td>
<td>21.0</td>
<td>15.1</td>
<td>28.50</td>
<td>27.96</td>
<td>1.39 1.36 1.33 1.85</td>
</tr>
<tr>
<td>n=18</td>
<td>21.0</td>
<td>15.1</td>
<td>29.80</td>
<td>28.90</td>
<td>1.39 1.42 1.38 1.91</td>
</tr>
</tbody>
</table>
### Table 5. Comparison of dependence $E = f(n, W)$ of compacted soil

<table>
<thead>
<tr>
<th>Number of blows</th>
<th>$E_0$ natural soil, MPa</th>
<th>$E_{sat}$ at $W_{sat}$, MPa</th>
<th>$E_{opt}$ compacted soil with moisture $W_{opt}$, MPa</th>
<th>$E_{sat}$ compacted soil with moisture $W_{sat}$, MPa</th>
<th>$E_0/E_{sat}$</th>
<th>$E_{opt}/E_0$</th>
<th>$E_{sat}/E_0$</th>
<th>$E_{sat}/E_{sat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=10</td>
<td>14.80</td>
<td>4.61</td>
<td>19.40</td>
<td>17.76</td>
<td>3.21</td>
<td>1.31</td>
<td>1.20</td>
<td>3.85</td>
</tr>
<tr>
<td>n=15</td>
<td>14.80</td>
<td>4.61</td>
<td>21.22</td>
<td>19.01</td>
<td>3.21</td>
<td>1.43</td>
<td>1.29</td>
<td>4.12</td>
</tr>
<tr>
<td>n=18</td>
<td>14.80</td>
<td>4.61</td>
<td>22.54</td>
<td>20.04</td>
<td>3.21</td>
<td>1.52</td>
<td>1.35</td>
<td>4.35</td>
</tr>
</tbody>
</table>

According to Table 5 of the comparative analysis: the deformation modulus $E_0$ of sandy loam soil with a natural moisture structure decreases by 3.21 times upon transition to a water-saturated state. Then the parameter $E_{opt}^n$ of the soil, compacted after pre-wetting until $W_{opt}$ is reached with 10, 15 and 18 blows, is 1.30...1.42 times greater than $E_0$ of natural soil. And the parameter $E_{sat}^n$ of wet soil compacted with 10,15 and 18 blows of a tamper is 1.23...1.38 times greater. The deformation modulus $E_{sat}^n$ after compaction with 10, 15 and 18 blows and with humidity $W_{sat}$ is 3.85...4.35 times greater compared to the deformation modulus $E_{sat}$ of uncompacted soil. The listed increases in deformation modulus are the results of compaction with heavy compaction after preliminary moistening of subsidence soil.

**Nomogram for density analysis.** Figure 6 shows a calculated nomogram constructed by comparative indicators of compacted soil with heavy tamping $\rho_{d^{10}}, \rho_{d^{15}}, \rho_{d^{18}}$ and the density of natural soil $\rho_d = 1.49 \text{ tons/m}^3$ (Nyamdorj S. [22]).
After preliminary moistening of the silty sandy loam soil to $W_{\text{opt}} = (0.12 \ldots 0.15)$ and compacted with 10, 15 and 18 blows of a heavy rammer with a mass of 5.0 tons, the density of the compacted soil $\rho_d^{10}, \rho_d^{15}, \rho_d^{18}$ is analyzed and are compared with density $\rho_d = 1.49$ tons/m$^3$ the results are shown in Table 6.

**Table 6. Analysis of heavy tamper compaction test results**

<table>
<thead>
<tr>
<th>Number of blows</th>
<th>Density on the surface, tons/m$^3$</th>
<th>Depth of compaction to density 1.65 tons/m$^3$, m</th>
<th>Depth of density reduction to 1.65 tons/m$^3$, m</th>
<th>Depth reached density $\rho_{d,n}^n$, m</th>
<th>Maximum density $\rho_{d,max}$, tons/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.53</td>
<td>0.55</td>
<td>3.15</td>
<td>2.00</td>
<td>1.73</td>
</tr>
<tr>
<td>15</td>
<td>1.52</td>
<td>0.45</td>
<td>4.30</td>
<td>2.00</td>
<td>1.83</td>
</tr>
<tr>
<td>18</td>
<td>1.58</td>
<td>0.35</td>
<td>4.65</td>
<td>2.00</td>
<td>1.87</td>
</tr>
</tbody>
</table>

**Discussion**
Analyzing according to the nomogram, it is possible to compact to the minimum density required by standards $\rho_d = 1.65$ tons/m$^3$ at depths of 3.15 m under 10 blows, at depths of 4.30 m under 15 blows, at depths of 4.65 m under 18 blows. However, up to a density $\rho_d = 1.75$ tons/m$^3$ it is impossible to compact in 10 18 blows of a tamper, only it can be compacted in 15 and 18 blows.

It is proposed to use a nomogram to determine the depth of compaction and the required number of blows depending on the required amount of soil compaction as a standard for buildings of classes III and IV according to the level of responsibility. And for buildings of I and II classes of responsibility, use them for comparison with field test values. As a result of using the proposed nomogram, economic effects can be obtained and the reliability of buildings built on subsidence soils can be achieved.

Conclusions

1. With an increase in the moisture content of subsidence soil with a natural structure to water saturation, the adhesion force decreased by 2.61 times; after preliminary soaking to the moisture content $W_{opt}$, the relative subsidence index, density, adhesive force, angle of internal friction and the calculated value of the soil deformation modulus improved by 1.23...4.35 times.

2. The pattern of growth in the mechanical indicators of compacted pre-moistened soil using the heavy tamping method is explained by the transition of cementation-crystallization structural bonds to relaxation to a certain extent as a result of an increase in humidity and the action of the impact dynamic energy of heavy tamping. And the processes of primary consolidation caused by incomplete displacement of pore water and relaxation after quasi-liquefaction formed by the dynamic action of the impact also influence.

3. When the humidity of subsidence soil compacted by heavy compaction increases to the state of water saturation ($W_{sat}$), the values of the calculated mechanical parameters change relatively little, which indicates that the newly formed structural strength and deformation characteristics of the soil are relatively well preserved provided that the soil of the foundations of buildings and structures is re-wetted, the latter is a very important property of the heavy tamping method.

4. The use of the method of compacting forest soils with heavy tamping in the condition of preliminary soaking is more effective when the thickness of subsidence soil is up to 10 meters for preparing the foundations of civil and industrial buildings with a wet technological regime, such as mining and processing plants and processing plants for agricultural and livestock products. Since the properties of subsidence soils compacted with heavy ramming are relatively well preserved during technogenic soaking of the base of buildings and structures.

Reference


