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# Quality Estimation of Soil Body during Construction of Foundations with Curved Contact Surface using Harrington's Desirability Function

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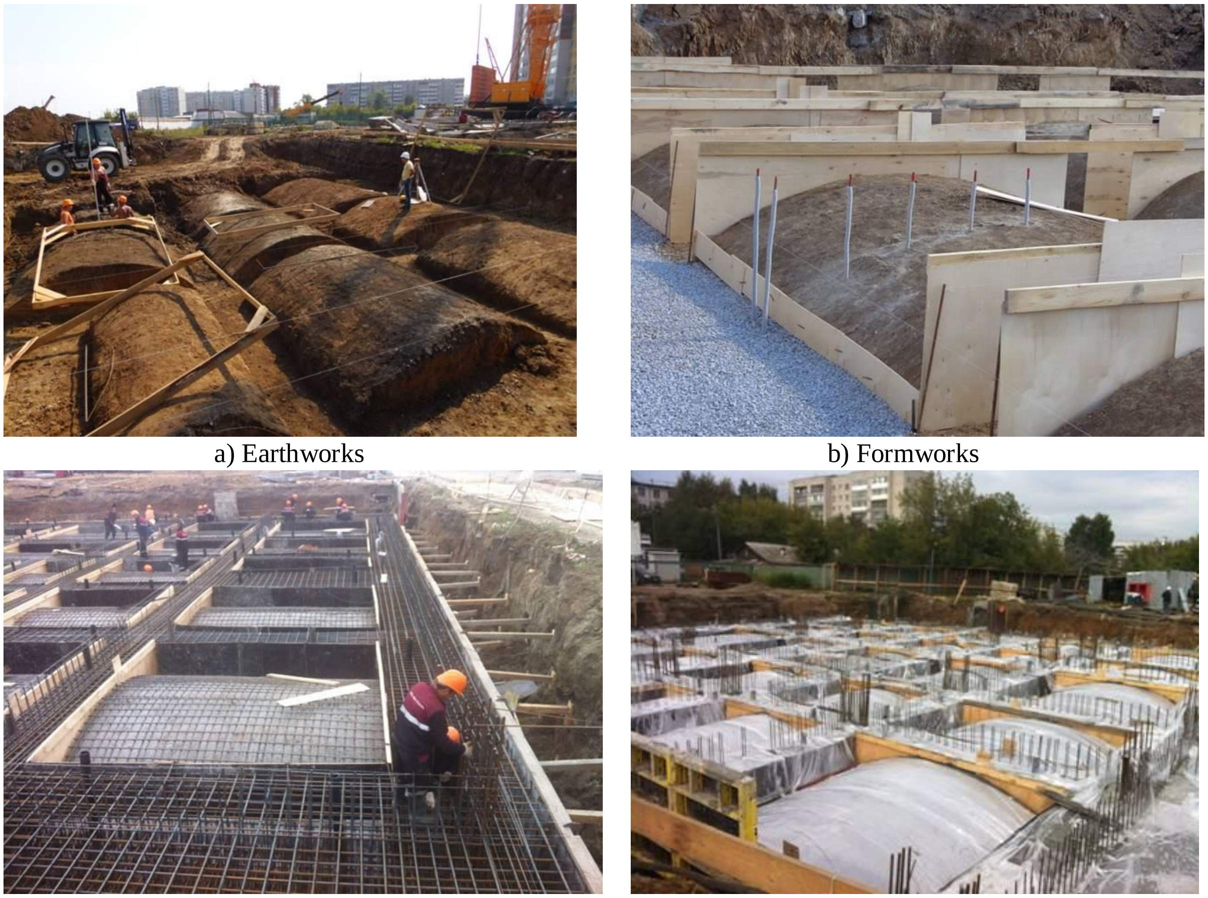
## ABSTRACT

This work is aimed at determination of optimum physicomechanical properties of subshell body, which is important for construction of foundations with curved contact surface. The initial variables are comprised of physicomechanical properties of soil, curvature of formation of soil body under reinforced concrete shell, labor intensity during excavation, inclination of natural slope. Using generalized Harrington's desirability function, six variants of soil bodies with various output parameters have been considered. The use of Harrington's desirability function resulted in determination of optimum physicomechanical properties of subshell body. Optimum properties of subshell body allow to design and construct foundations with curved contact surface capable to take loads of above structures using lower amounts of concrete and reinforcement, as well as to decrease labor intensity of excavation operations during construction of such foundations.

**Key words:** foundation, construction method, strip shell foundation, Harrington's desirability function.

## 1. INTRODUCTION

Nowadays foundations with curved contact surface (strip shell foundations) are widely applied in Tyumen and southern area of Tyumen oblast, Russia [1]. This foundation designs are convex upward cylindrical (or axisymmetric) reinforced concrete shells installed on natural soil or artificial base. The reinforced concrete shells join the supporting structures located along main lines of building [2] (Fig. 1).



a) Earthworks b) Formworks

c) Reinforcing d) Concrete operations

**Figure 1:** Construction of strip shell foundation

Advanced foundation designs, including those with curved contact surface for Ural and Tyumen oblast, were described in early 1970-s by Tetior [3].

The engineering features were analyzed by numerous researchers, such as Pronozin, Rachkov [4], Poroshin, Epifantseva [5], Ter-Martirosyan, Kiselev [6], Stepanov and Volosyuk [7].

The main engineering difficulty upon erection of such foundations is formation of soil block for reinforced concrete shell. Herewith, the erection quality of soil block effects the quality of overall foundation design, its bearing capacity, strength, activation of reinforced concrete shell, foundation settlement. In the case of improper construction of soil base for reinforced concrete shell, the soil body should be additionally pressed [7].

According to procedure of excavation operations during construction of strip shell foundation, it is required to perform mechanical earthworks to the upper level of shell base, mechanical earthworks in trenches for supporting structures, manual formation of soil block aiming at cylindrical concave upward base for reinforced concrete shell of foundation. Designing earth profile of strip shell foundation is exemplified in Fig. 2 [8].

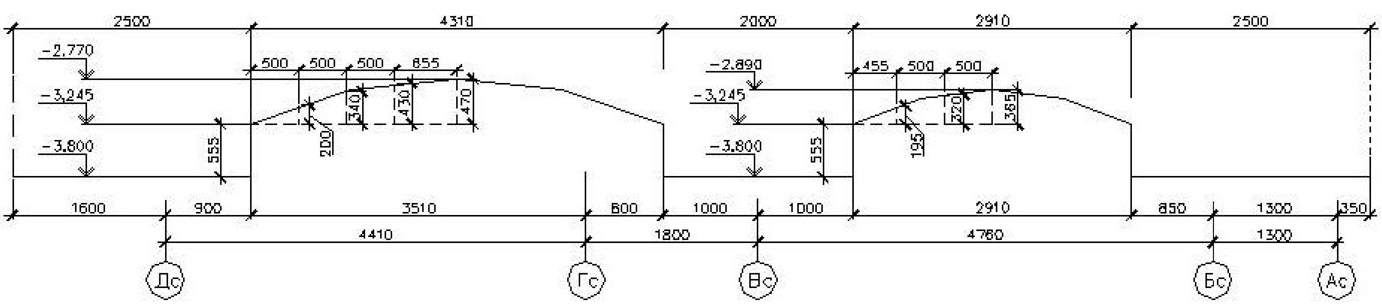



**Figure 2:** Designing earth profile of strip shell foundation [8].

It is obvious that for such foundation type, the earthworks are among the most important engineering operations, the most labor intensive and vital ones. Hence, more stringent requirements are applied to the quality of earthworks

## 2. METHODS

The quality of subshell body formation depends on the required ***curvature of subshell space,*** which determines the curvature and quality of reinforced concrete shell; ***physicomechanical properties of soil*** (*density of soil block*; *soil humidity*; *soil cohesion; internal friction angle, etc.),* which effect quality, strength and stability of soil block; as well as ***difficulty of soil excavation,*** which determines duration and labor intensity of operations.

The influence of shell curvature (that is, ***the curvature of subshell space***) on the work of foundation design and variation (decrease) of foundation settlement is described in details in [9]. It is proved that such shell depth f is optimum, at which $1/8 \le f/l \le 1/5$, where *l* is the shell span. Higher shell depth involves higher amount of soil under the shell into work, thus decreasing settlement of overall foundation [9]. Shell depths as a function of shell span are summarized in Table 1.

**Table 1:** Shell depth as a function of shell span

| No. | f/l ratio | Shell depth f as a function of shell span l | | |
|---|---|---|---|---|
| | | l = 5 m | l = 6 m | l = 7.5 m |
| 1 | f/l = 1/8 | 0.625 m | 0.75 m | 0.94 m |
| 2 | f/l = 1/7 | 0.71 m | 0.86 m | 1.07 m |
| 3 | f/l = 1/6 | 0.83 m | 1.0 m | 1.25 m |
| 4 | f/l = 1/5 | 1.0 m | 1.2 m | 1.5 m |

***Physicomechanical properties of soil*** determine efficient technology of operations, selection of earthmoving equipment, economic efficiency, improvement of activities. In addition, physicomechanical properties effect the formation quality of soil block upon creation of curved contact surface.

Six soil variants were considered for formation of subshell bodies (1 - Stiff loam; 2 - Stiff loam; 3 – Fine sand, water saturated; 4 – Plastic loam; 5 – Plastic clay; 6 - Fine wet sand); their physicomechanical properties are summarized in Table 2.

**Table 2:** Physicomechanical properties of soil blocks

| No. | Physicomechanical properties | Variant of soil block | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | *Natural moisture content* | 0.21 | 0.24 | 0.22 | 0.3 | 0.27 | 0.05 |
| 2 | *Moisture at limit of liquidity* | 0.28 | 0.31 | - | 0.35 | 0.32 | - |
| 3 | *Moisture at limit of roll-out* | 0.17 | 0.19 | - | 0.19 | 0.14 | - |
| 4 | *Plasticity number* $I_p$ | 0.11 | 0.12 | - | 0.16 | 0.18 | - |
| 5 | *Consistency* $I_I$ | 0.36 | 0.42 | - | 0.69 | 0.73 | - |
| 12 | *Density of soil particles,* $P_{S,}$ *g/cm*$^3$ | 2.70 | 2.70 | 2.66 | 2.71 | 2.72 | 2.65 |
| 13 | *Soil density P, g/cm*$^3$ | 1.86 | 1.87 | 1.96 | 1.91 | 1.88 | 1.82 |
| 14 | *Dry density,* $P_d$ *, g/cm*$^3$ | 1.54 | 1.51 | 1.61 | 1.47 | 1.48 | 1.62 |
| 15 | *Porosity, n, %* | 43.1 | 44.1 | 39.4 | 45.9 | 45.5 | 38.7 |
| 16 | *Porosity coefficient, e, unit fractions* | 0.75 | 0.82 | 0.90 | 0.96 | 0.88 | 0.21 |
| 17 | *Degree of humidity, Sr, unit fractions* | 0.75 | 0.82 | 0.90 | 0.96 | 0.88 | 0.21 |
| 18 | *Specific cohesion, C, kPa* | 21 | 18 | 1 | 14 | 33 | 2 |
| 19 | *Internal friction angle, degrees.* | 29 | 28 | 33 | 24 | 20 | 32 |
| 20 | *Deformation modulus, E, MPa.* | 11 | 9 | 21 | 5 | 8 | 25 |

***Difficulty of soil excavation*** depends on physicomechanical properties of the soil and influences labor intensity of mechanized and manual excavation operations. In addition, it is required to account for inclination of natural soil slope, since upon formation of soil blocks, crumbling can occur leading to fault of formation of subshell space. For instance, for the considered variants of soil blocks, the soil groups in terms of excavation difficulty and slope inclinations are summarized in Table 3.

**Table 3:** Specifications of soil blocks

| No. | Specifications | Variant of soil block * | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | *Soil group in terms of excavation difficulty* | II | II | I | II | II | I |
| 2 | *Slope inclination at excavation depth from 3 to 5 m* | 1:0.75 | 1:0.75 | 1:1 | 1:0.75 | 1:0.5 | 1:1 |

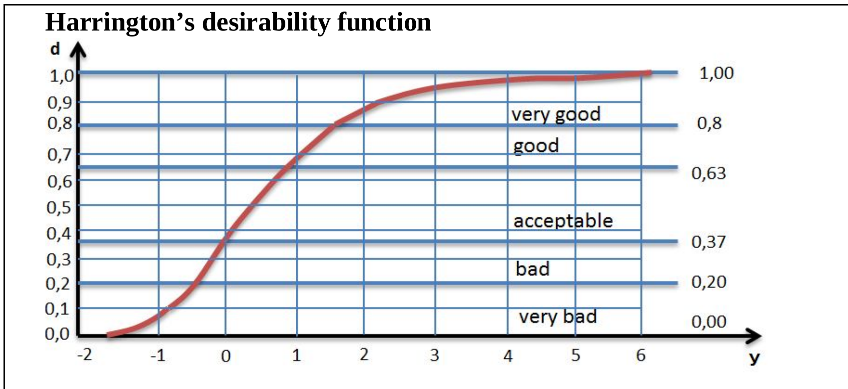
**1 - Stiff loam; 2 - Stiff loam; 3 – Fine sand, water saturated; 4 – Plastic loam; 5 – Plastic clay; 6 - Fine wet sand.*

Six variants of soil blocks with certain physicomechanical properties and shell depth to shell span ratio were analyzed, the obtained main output parameters required for quality estimation of subshell body are summarized in Table 4.

**Table 4:** Experimental output parameters

| $y_i$ | Output parameters | Number of soil block variant | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| $y_1$ | *f/l ratio, at l=6 m* | 1/8 | 1/6 | 1/5 | 1/7 | 1/8 | 1/8 |
| $y_2$ | *Degree of humidity, Sr, unit fractions* | 0.75 | 0.82 | 0.90 | 0.96 | 0.88 | 0.21 |
| $y_3$ | *Deformation modulus, E, MPa.* | 11 | 9 | 21 | 5 | 8 | 25 |
| $y_4$ | *Specific cohesion, C, kPa* | 21 | 18 | 1 | 14 | 33 | 2 |
| $y_5$ | *Internal friction angle, degrees* | 29 | 28 | 33 | 24 | 20 | 32 |
| $y_6$ | *Soil group in terms of excavation difficulty* | II | II | I | II | II | I |
| $y_7$ | *Slope inclination at excavation depth from 3 to 5 m* | 1:0.75 | 1:0.75 | 1:1 | 1:0.75 | 1:0.5 | 1:1 |

The quality of subshell space of six variants is estimated on the basis of optimality criteria obtained by Harrington's desirability function using standard marks on desirability scale [10] (Fig. 3). This generalized function is based on the concept of conversion of natural values of partial responses into dimensionless scale of desirability or preferability [10].




| **Standard marks on desirability scale** | |
|---|---|
| Very good | 1.00 – 0.8 |
| Good | 0.80 – 0.63 |
| Acceptable | 0.63 – 0.37 |
| Bad | 0.37 – 0.20 |
| Very bad | 0.20 – 0.00 |

**Figure 3:** Harrington's desirability function

According to [10], the natural responses are converted into dimensionless scale of desirability and denoted as *du* (*u*=1,2…6), they are referred to as partial desirabilities (Addendum 1).

The Harrington's desirability function *D* is determined by the equation below, it is the geometrical mean of partial desirabilities:

$$D = \sqrt[n]{\prod_{u=1}^{n} d_u}$$

While computing:

$D_1 = \sqrt[7]{d_1 \cdot d_2 \cdot d_3 \cdot d_4 \cdot d_5 \cdot d_6 \cdot d_7}$ is the generalized desirability function for all responses;

$D_2 = \sqrt[3]{d_1 \cdot d_6 \cdot d_7}$ is the generalized desirability function for engineering responses.

## 3. RESULTS

The experimental results are summarized in Addendum 1.

It can be seen that all soil blocks, except for variant No. 4 in terms of $D_1$, are estimated as acceptable; in terms of $D_2$, all variants are also estimated as acceptable.

The bottom line of Addendum 1 presents the variant with the superior properties allowing to be estimated as good in terms of $D_1$ and as very good in terms of $D_2$, thus determining the required parameters of soil block for curved shell of foundation.

**Addendum 1.** Natural and generalized by desirability function responses

| № | Natural responses | | | | | | | Partial desirability | | | | | | | D1/ Estimate | D2/ Estimate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *y1* | *y2* | *y3* | *y4* | *y5* | *y6* | *y7* | *d1* | *d2* | *d3* | *d4* | *d5* | *d6* | *d7* | | |
| 1 | 0.75 | 0.75 | 11 | 21 | 29 | 2 | 0.75 | 1 | 0.35 | 0.3 | 0.42 | 0.56 | 0.37 | 0.35 | 0.439/ Accept. | 0.506/ Accept. |
| 2 | 1 | 0.82 | 9 | 18 | 28 | 2 | 0.75 | 1 | 0.28 | 0.26 | 0.37 | 0.53 | 0.37 | 0.35 | 0.407/ Accept. | 0.506/ Accept. |
| 3 | 0.83 | 0.9 | 21 | 1 | 33 | 1 | 1 | 1 | 0.21 | 0.5 | 0.1 | 0.61 | 1 | 0.2 | 0.386/ Accept. | 0.585/ Accept. |
| 4 | 1.17 | 0.96 | 5 | 14 | 24 | 2 | 0.75 | 1 | 0.18 | 0.2 | 0.31 | 0.47 | 0.37 | 0.35 | 0.352/ Bad | 0.506/ Accept. |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 0.75 | 0.88 | 8 | 33 | 20 | 2 | 0.5 | 1 | 0.26 | 0.24 | 0.61 | 0.40 | 0.37 | 0.5 | 0.433/ Accept. | 0.570/ Accept. |
| 6 | 0.75 | 0.21 | 25 | 2 | 32 | 1 | 1 | 1 | 0.7 | 0.63 | 0.12 | 0.6 | 1 | 0.2 | 0.483/ Accept. | 0.585/ Accept. |
| Reference | 0.75 | 0.21 | 25 | 33 | 33 | 1 | 0 | 1 | 0.7 | 0.63 | 0.61 | 0.61 | 1 | 1 | 0.773/ Good | 1.00/ Very good |

## 4. DISCUSSION

The obtained results have demonstrated that natural soils characterized by natural physicomechanical properties, do not completely comply with all requirements to subshell bodies.
In addition, it has been demonstrated that responses of natural variant contradict with each other and are actually unavailable. Therefore, it is required to develop artificial subshell space meeting all necessary requirements [11–13].

## 5. CONCLUSION

It is recommended to erect an array of assembled soil concrete blocks as an alternative to natural soil base upon arrangement of curved foundation surface. At present the main area of application of soil concrete compositions is construction of roads and agricultural facilities. The following variants are available: soil concrete materials with mineral and organic additives of road bases and agricultural facilities, complex soil lime binder, and others. These specifications are proposed for further studies and application aiming at creation of high quality, stable, strong subshell body during construction of foundations with curved contact surface.

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